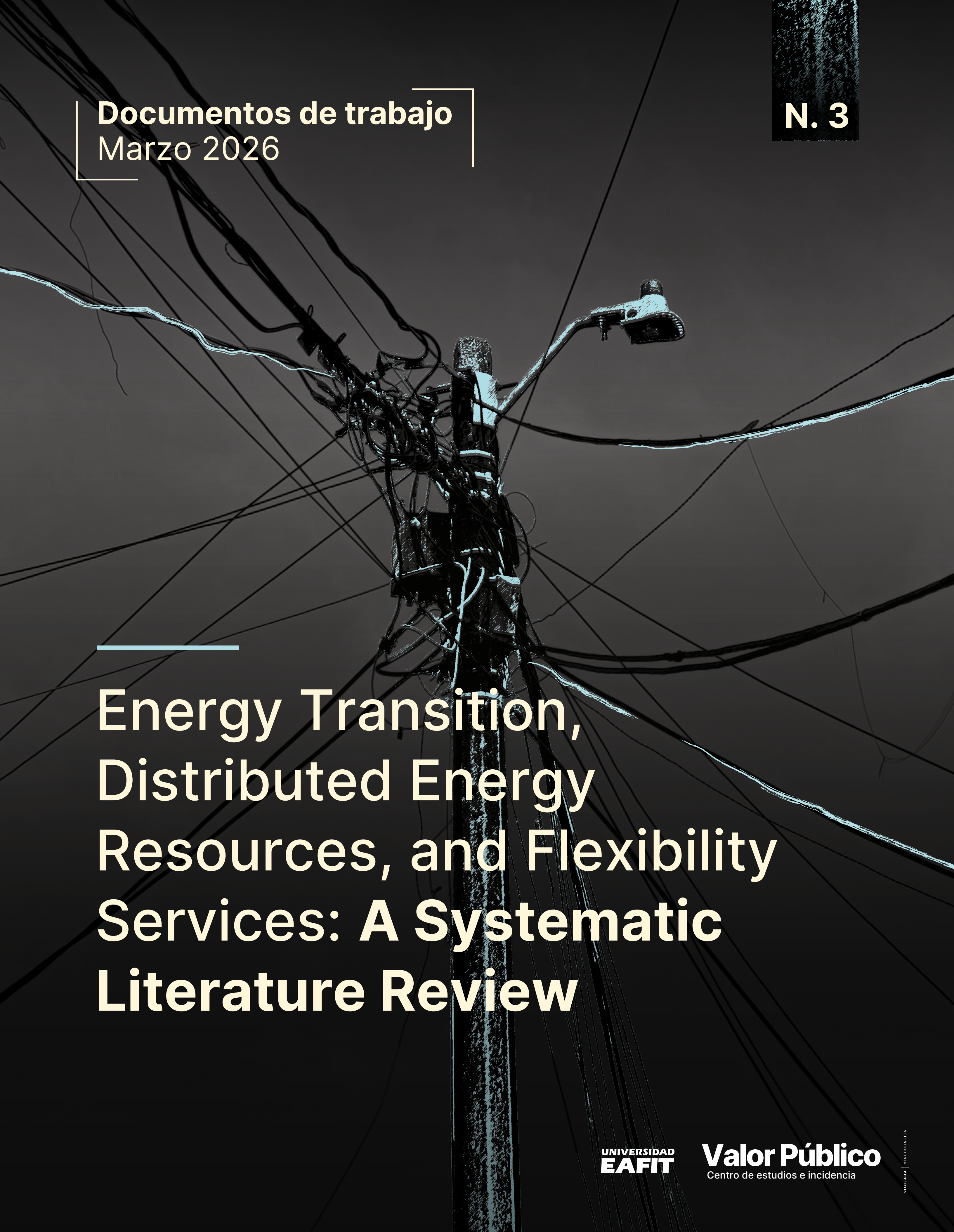

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Energy Transition, Distributed Energy Resources, and Flexibility Services: **A Systematic Literature Review**

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Energy Transition, Distributed Energy Resources, and Flexibility Services: A Systematic Literature Review

John García-Rendón [a,*]
Stephania Mosquera-López [b]

Abstract

The Paris Agreement's worldwide pledge to keep global warming to 1.5°C has sped up the energy transition, and with this, the deployment of renewable energy sources, increasing the demand for electrical systems' flexibility. To investigate the role of Distributed Energy Resources (DERs) in providing flexibility services that support the integration of non-conventional renewable energy (NCRE), this study performs a systematic literature review using the PRISMA approach. DERs enable decentralized, smart grid-based energy models that complement conventional centralized systems. According to the review, which examines 697 papers published between 2010 and February 2024, research has grown exponentially since 2015, especially in Europe. The study examines the functions of emerging agents, such as prosumers, aggregators, and Distribution System Operators (DSOs), and highlights important flexibility services, such as frequency regulation, voltage control, and congestion management, using bibliometric and content analysis. The results show that although DERs greatly improve grid resilience and the integration of renewable energy sources, several institutional, economic, technological, and social barriers prevent their complete implementation. New market mechanisms and regulatory frameworks that promote flexibility and active demand-side participation are needed to address these issues.

Keywords: DER; flexibility services; energy transition; energy management; systematic literature review; electrical system.

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1. Introduction

The challenge of reducing CO2 emissions to contain global warming was agreed at COP 21 with a target of limiting the increase in temperature to 1.5°C above pre-industrial levels [1], which was reaffirmed at COP 28 in 2023 [2]. The energy transition processes underway in economies that have taken on this challenge have created a need to implement flexibility services to address the intermittency of electricity generation from non-conventional renewable energy (NCRE) sources and ensure service security. This study aims to conduct a systematic literature review of the flexibility services that Distributed Energy Resources (DERs) can offer during the energy transition.

The traditional model of centralized energy production, characterized by a generation with economies of scale and passive demand, is gradually being complemented or replaced by a decentralized, smart grid-based energy system, which accommodates DERs with new distributed storage systems and advanced metering infrastructure to enable consumers, retailers, or electricity grid operators to implement active demand-side management mechanisms [3–7].

DERs offer an alternative to the traditional centralized system; they are small, modular energy generation and storage technologies [8]. DERs can provide all or part of the consumer's energy needs, thereby enabling a decentralized energy production system. Different types of DER include photovoltaic (PV) and wind generation, combined heat and power (CHP), energy storage, active Demand Response (DR), Electric Vehicles (EV), microgrids, and energy efficiency (EE) [5]. They are installed next to electricity consumption units, such as homes and businesses, and offer an improved alternative to the traditional power grid. DERs are designed to distribute energy in a smarter way to improve reliability, reduce costs and emissions, increase efficiency, decrease transmission congestion, prevent energy losses, and meet future consumer demands [9–11].

Following the implementation of this new decentralized model of energy generation, traditional companies in the sector have found it necessary to transform their business models and are moving from being energy suppliers to providing energy-related services [12]. Simultaneously, new agents or current ones with new roles are emerging, such as prosumers, aggregators, and Distribution System Operators (DSOs). These agents are necessary for DERs to provide flexibility services to the system.

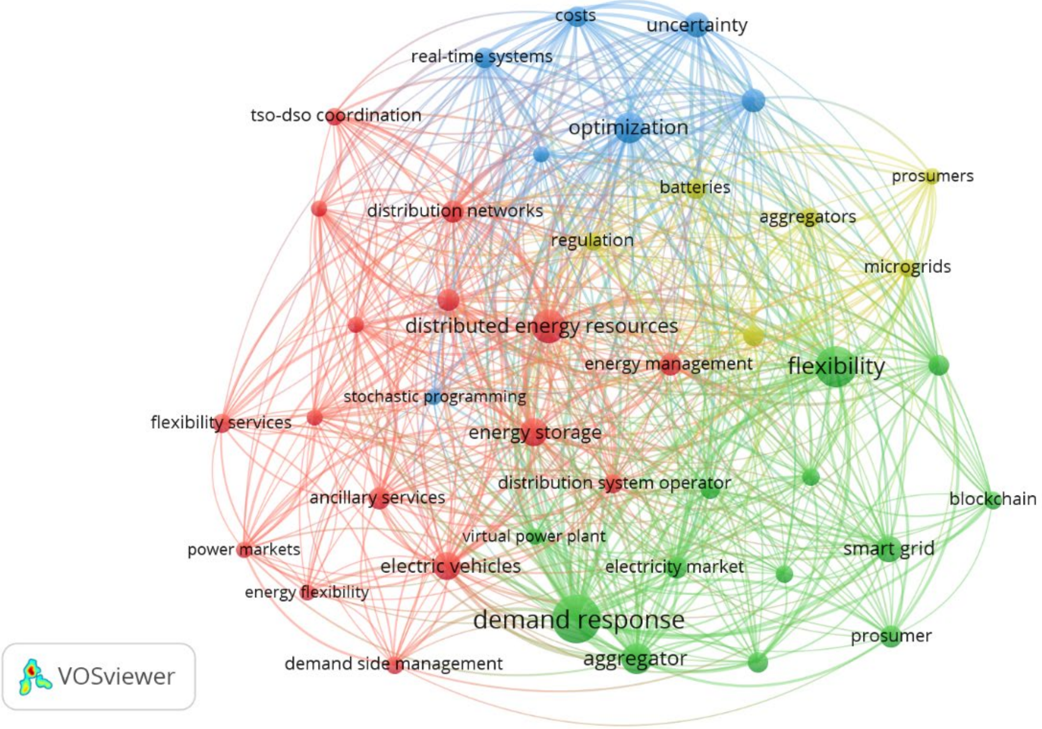
Prosumers are "the consumers who also produce and share surplus energy with the grid and other users" [13–17]. These include energy communities, which are groups of households organized to consume energy from a common, decentralized generation system, such as solar photovoltaic [18,19]. An aggregator enables the provision of demand response and DER services [20]. Their "function is performed by a natural or legal person who combines multiple customer loads or generated electricity for sale, purchase, or auction in any electricity market" [21], to manage local demand constraints by obtaining distribution system flexibility by incentivizing prosumers [22]. DSOs are responsible for managing the electricity distribution system in their area. They must ensure that the system meets reasonable electricity distribution demands [23].

Using the PRISMA methodology, our paper performs a systematic literature review of DER and flexibility services for the energy transition. Figure 1 presents a co-occurrence keywords network for papers related to agents and resources that can offer flexibility services to the electricity system. For instance, the literature has proposed a taxonomy for classifying flexibility resources and mapping them into flexibility services they can offer [24], modeled the integration of several flexibility resources into energy systems [25], reviewed the transaction costs of providing flexibility services within local energy markets [26], identified the stages necessary to enable DERs to provide flexibility to the system [27], or developed business models for agents like aggregators [28]. In this line, Eid et al. [29] analyze the incentives for market design to integrate DERs that offer flexibility services. Therefore, our primary contribution, using screening and eligibility criteria, is to map the main articles discussing DER and flexibility services. We analyze their objectives, contributions, and the primary barriers to developing and providing these services.

The bibliometric analysis was based on 697 articles published between 2010 and February 2024, showing exponential growth in scientific output since 2015, with an average of 46 articles per year and a peak of 165 publications in 2023. This indicates a growing interest in the literature on DER, flexibility resources and services, and related agents. Six of the ten most productive countries in terms of publications are European, consistent with Europe's progress in integrating DER into the electricity system. We focus the analysis on the fundamental role of DERs in providing flexibility, particularly in managing the variability of renewable energy sources, enhancing grid stability, and ensuring the security of supply through services such as frequency regulation and voltage control. We also identify and classify the institutional, economic, technical, and social barriers that hinder the development of DERs and the flexibility services they can offer, emphasizing the need for regulatory redesigns and new market mechanisms to overcome these challenges.

The remainder of this paper is organized as follows. In Section 2, we review the theoretical background of DER and flexibility services, as well as their deployment stages. In Section 3, we outline our bibliometric methodology. In Section 4, we evaluate the bibliometric results, discuss the objectives of the selected papers, and analyze the main challenges of DER in providing flexibility services. Section 5 concludes by summarizing our main findings and discussing future lines of work.

Figure 1. Co-occurrence Keywords Network



Source: Own elaboration on VOSviewer.

2. Theoretical Background

The energy transition has been defined as “the significant transformation of the structure of energy production and consumption from the current fossil fuel-based system to one with zero net carbon emissions. This transition is considered the main strategy to contain global warming; it requires an increase of non-conventional renewable energies such as solar, wind, and hydrogen, in addition to carbon capture, nuclear, geothermal, renewable natural gas, and energy storage systems. It also includes electrification of transportation systems, industry and various domestic end uses, energy efficiency, and profound changes in energy policy, business models, and consumer participation” [30]. This transition has involved high participation of variable renewable energy (VRE), whose generation depends on variable primary sources, such as the sun or wind, thereby introducing uncertainty and variability into the electricity system, unlike other energy sources (whether renewable or conventional) that may be more predictable or dispatchable [29].

To manage this variability, system flexibility is required [24]. IEA [31] defines flexibility in general terms as “the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system to maintain reliable supply in the face of rapid and large imbalances, whatever the cause." Following three scopes, type of flexibility resource, duration of flexibility activation, and incentive for flexibility activation, Degefa et al. [24] define flexibility as "the ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions."

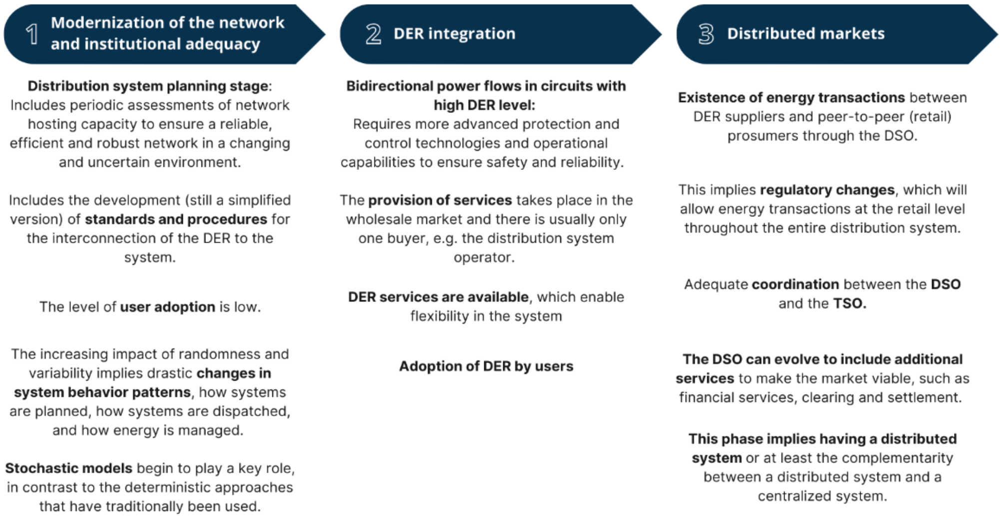
Eid et al. [29], more specifically, define flexibility services as a sustained power adjustment at a given time for a given duration from a specific location in the network. Flexibility services can be characterized by the following attributes: direction, electrical composition in power, and time characteristics defined by their start time, duration, and location basis. Some DERs operate unidirectionally, such as typical household appliances like water heaters, dishwashers, and electric heaters. Others, such as EVs and storage units, have bidirectional capabilities, enabling them to function as both consumers and producers of energy.

In this context, distinguishing flexibility resources from flexibility services is essential. A flexibility resource refers to any asset or system that has the technical capability to modify its electrical energy injection or consumption in response to a system need [24]. In contrast, flexibility service is the specific application or use of a flexibility resource's capacity to meet an operational need of the electricity system [29], thereby supporting the balance between supply and demand. Key flexibility resources can include DERs, energy storage, EVs, smart appliances, and grid infrastructure that enables operational flexibility. Examples of flexibility services include congestion management, frequency regulation reserve, frequency restoration reserve, balancing services, and market-oriented services.

According to Thomas [32], DERs can be defined as "a resource located near customers that can meet all or some of their immediate electricity and energy needs, and which can be used by the system to reduce demand or supply energy, capacity, or ancillary service needs of the distribution grid." DERs comprise three stages of deployment (see Figure 2): (i) grid modernization and institutional adequacy through the development (or even simplification) of rules and procedures for the interconnection of DERs to the distribution system. This is considered a stage mainly of distribution system planning, which includes periodic evaluations of the network hosting capacity to ensure a reliable, efficient, and robust network in a changing and uncertain environment due to the high intermittency that the inclusion of NCRE represents; (ii) DER integration, which involves dealing with large bi-directional power flows on circuits with high DER penetration, which requires more advanced protection and control technologies and operational capabilities. Services are provided in the wholesale market, and there is usually only one buyer, e.g., the distribution grid operator.

Flexibility services, such as demand response management [33,34], aggregation services [35], congestion management [36] and frequency regulation [37] must also be implemented in this phase to ensure security and reliability in service provision; (iii) involves distributed markets, in which transactive energy [38] with new forms of energy transactions [39] such as blockchain [40,41] and Peer-to-Peer (P2P) transactions [42,43] in the retail market are necessary for efficient energy management. The DSO can evolve to provide additional services to make the market viable, such as financial services, clearing, and settlement. At the same time, for DER to offer flexibility services, there must be adequate coordination between the DSO and the Transmission System Operator (TSO) [44].

Figure 2. Stages in the Adoption of DER and Flexibility Services



1 **Modernization of the network and institutional adequacy**

Distribution system planning stage: Includes periodic assessments of network hosting capacity to ensure a reliable, efficient and robust network in a changing and uncertain environment.

Includes the development (still a simplified version) of **standards and procedures** for the interconnection of the DER to the system.

The level of **user adoption** is low.

The increasing impact of randomness and variability implies drastic **changes in system behavior patterns**, how systems are planned, how systems are dispatched, and how energy is managed.

Stochastic models begin to play a key role, in contrast to the deterministic approaches that have traditionally been used.

2 **DER integration**

Bidirectional power flows in circuits with high DER level: Requires more advanced protection and control technologies and operational capabilities to ensure safety and reliability.

The **provision of services** takes place in the wholesale market and there is usually only one buyer, e.g. the distribution system operator.

DER services are available, which enable flexibility in the system

Adoption of DER by users

3 **Distributed markets**

Existence of energy transactions between DER suppliers and peer-to-peer (retail) prosumers through the DSO.

This implies **regulatory changes**, which will allow energy transactions at the retail level throughout the entire distribution system.

Adequate **coordination** between the **DSO** and the **TSO.**

The DSO can evolve to include additional services to make the market viable, such as financial services, clearing and settlement.

This phase implies having a distributed system or at least the complementarity between a distributed system and a centralized system.

Source: Authors' own elaboration based on Thomas [32].

Specifically, this paper focuses on flexibility services that DERs can provide. These resources can offer a wide range of flexibility services that help manage the variability of renewable energy, improve grid resilience, and optimize energy use at the local level. As the energy system transitions toward greater decentralization and higher shares of renewables, these flexibility services become increasingly critical. Key examples include DR, aggregation services, and grid-support functions such as congestion management and frequency regulation via energy storage.

DR is defined as changes in electricity consumption by the user in response to price signals or incentives designed to encourage low consumption during certain periods, primarily during peak hours [30]. DR has been considered one of the primary approaches to resolving network operation limits violations and increasing system flexibility [24]. An aggregator offers the service by combining a group of consumers (such as households, businesses, and industrial users) into a unified electricity purchasing entity, or “virtual consumer,” and by pooling distributed generation resources, thereby reducing the costly power generation and transmission expenses from the primary grid [22,45]. The aggregator can have two roles: a demand aggregator or a generation aggregator. In the last case, the aggregator can negotiate favorable pricing with electricity providers via collective purchases.

Energy storage offers a range of regulated and market-remunerated services that can enhance power system reliability [46]. In the case of grid-scale storage, these technologies can be connected to the grid to store energy and supply power to the grid when necessary, such as at night when solar plants do not generate or during extreme weather events that disrupt the system [47]. Because they can be deployed anywhere and in various sizes, Battery Energy Storage Systems (BESS) are now playing an important role in decentralized energy systems. BESS can be defined as the installation of battery groups, with their corresponding connection, cut-off, and protection equipment, used for the temporary storage of electrical energy and its subsequent delivery to the system [30], which offer complementary services to the power system, enabling the preservation of the quality, reliability, and security of its supply [48,49]. BESS can also provide frequency regulation services to adjust the supply and demand of electricity to maintain a consistent alternating current (AC) frequency [37]. Likewise, EVs are beginning to play a fundamental role in the energy transition, providing grid-scale storage when connected to the grid (vehicle-to-grid) [50].

Moreover, congestion management is the action of alleviating capacity constraints in the power grid, whether at the transmission or distribution level. It arises as a necessity as NCRE and DER integration increase. It is a strategy for using power efficiently without violating system constraints. Congestion management approaches can be classified into three categories: i) direct control, ii) market-based, and iii) price-based methods [36]. Frequency regulation is an essential service for power system balancing, focused on maintaining the system frequency within acceptable limits in the face of deviations [24]. In the context of ancillary services to maintain a stable system frequency, frequency regulation refers to services designed to control and stabilize the power system frequency in the face of variations in energy supply and demand [37].

3. Methodology

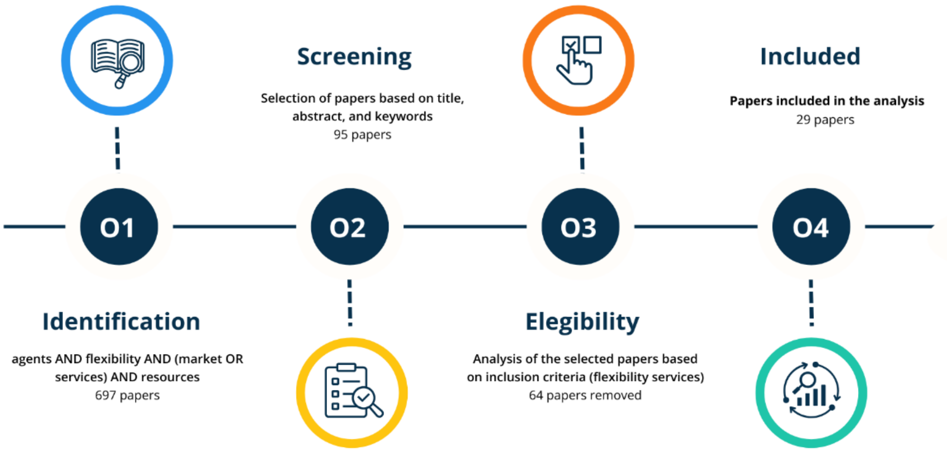
To conduct our systematic literature review, we used the PRISMA methodology [51], which consists of four stages, as shown in Figure 3. For the first stage of identification, we formulated a research question that includes the agents (DSO, aggregator, prosumer, or Energy Community) and resources (Energy Storage Systems, Electric Vehicles, Demand

Response, or capacity) relevant to DERs to provide flexibility services. We included only published articles, reviews, books, or book chapters. The research equation is the following:

> **((DSO OR (Distribution System Operator)) OR aggregator OR (prosumer OR (Energy Community))) AND (electri* OR energy) AND flexibility AND (market or services) AND (((Energy Storage Systems) OR ESS OR EV OR (Electric Vehicle) OR BESS) OR (Demand Response OR DR) OR capacity OR ((Distributed Energy Resources) OR DER)) (Topic) AND Article OR Review OR Book OR Book Chapter (Document Type)**

The database used is Web of Science (WOS), and the research question yielded 697 papers until February 8, 2024. In the second stage of screening, 95 papers were selected based on their titles, abstracts, and keywords. This selection followed the inclusion criteria for papers on flexibility services or markets that DER can provide or enable.

Figure 3. Stages Systematic Literature Review



Source: Own elaboration.

The third stage consists of analyzing the 95 papers screened based on the eligibility criteria: (i) papers on flexibility services that DERs can provide, and (ii) papers that discuss the economic, financial, institutional, technical, or social barriers that DERs face for their deployment in the energy transition.

In line with these criteria, we read the 95 papers and removed 64 that did not comply. As a result, 29 papers passed to the final stage and were included in the analysis.

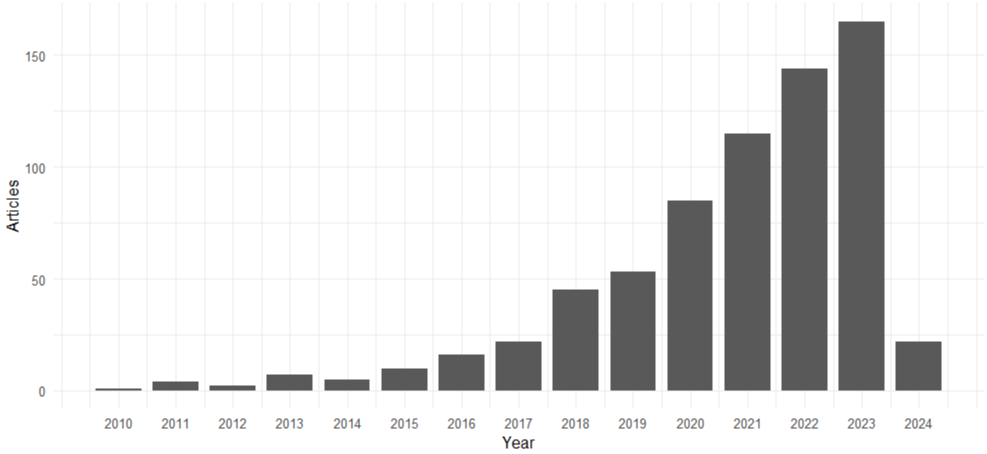
4. Results and Discussion

Following the search equation presented in Section 3, we present a bibliometric analysis of the 697 papers identified by this equation and a summary of the contributions and main results of the 29 final papers selected after applying the eligibility criteria (see Section 4.1). Next, we analyze the selected papers and their contribution to the discussion on the role of DERs as providers of flexibility services (see section 4.2). We then discuss the main barriers to the development of DER and flexibility services (see section 4.3).

4.1 Bibliometric Analysis

Figure 4 shows the annual scientific production of the papers identified by the search equation, restricting the analysis period to 2010 to February 2024, as only one paper was published before this period. On average, 46 papers were published per year, with exponential growth from 2015 onwards. The maximum number of papers published per year was in 2023, with 165 publications, indicating growing interest in the literature on agents and resources relevant to DERs.

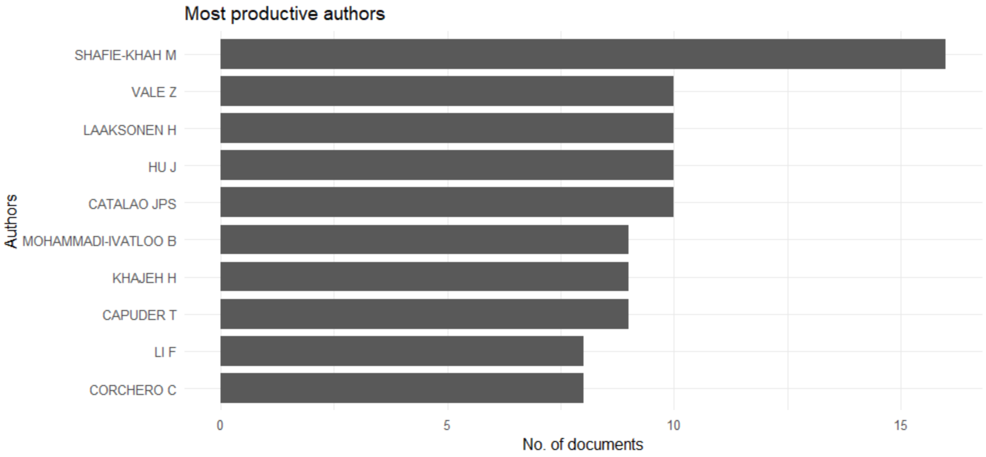
Figure 4. Annual Scientific Production



Source: Own elaboration on the Bibliometrix R package.

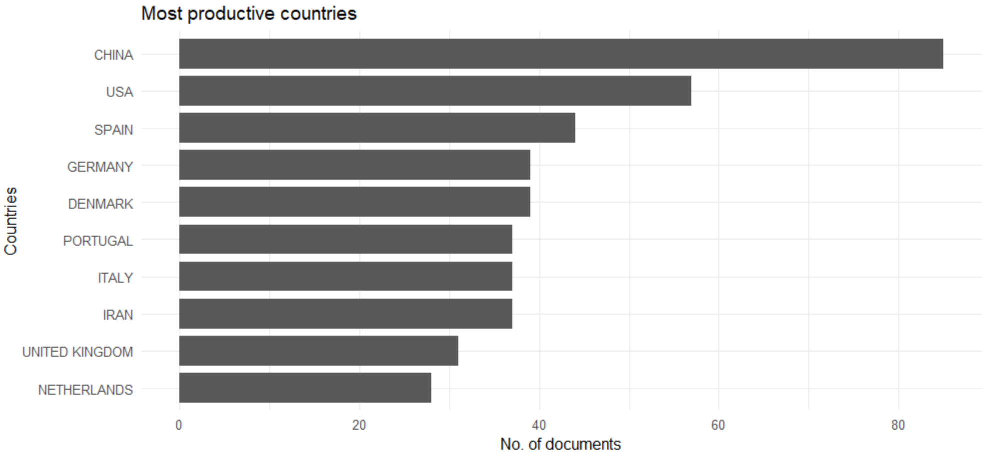
Figure 5 presents the ten most productive authors from the research equation. The author with the highest number of papers published, 16, in the period analyzed. However, none of these authors wrote any of the 29 selected papers. Figure 6 shows the ten most productive countries, with China in first place with 85 published papers, the United States in second place with 57, and Spain in third place with 44. Of these ten most productive countries, six are European, consistent with the fact that Europe is generally more advanced in integrating DER into the electricity system (see Section 4.3). These countries accounted for 434 of the 696 publications found in the search equation from 2010 onwards. Of the 434 publications, 267 were intra-country collaborations (SCP), i.e., 62% of the research was conducted with researchers affiliated with institutions in the same country. In contrast, inter-country collaborations (MCP) accounted for 38% of the output, indicating a lower level of international collaboration in scientific research in the most productive countries.

Figure 5. Most Productive Authors



Source: Own elaboration on the Bibliometrix R package.

Figure 6. Most Productive Countries



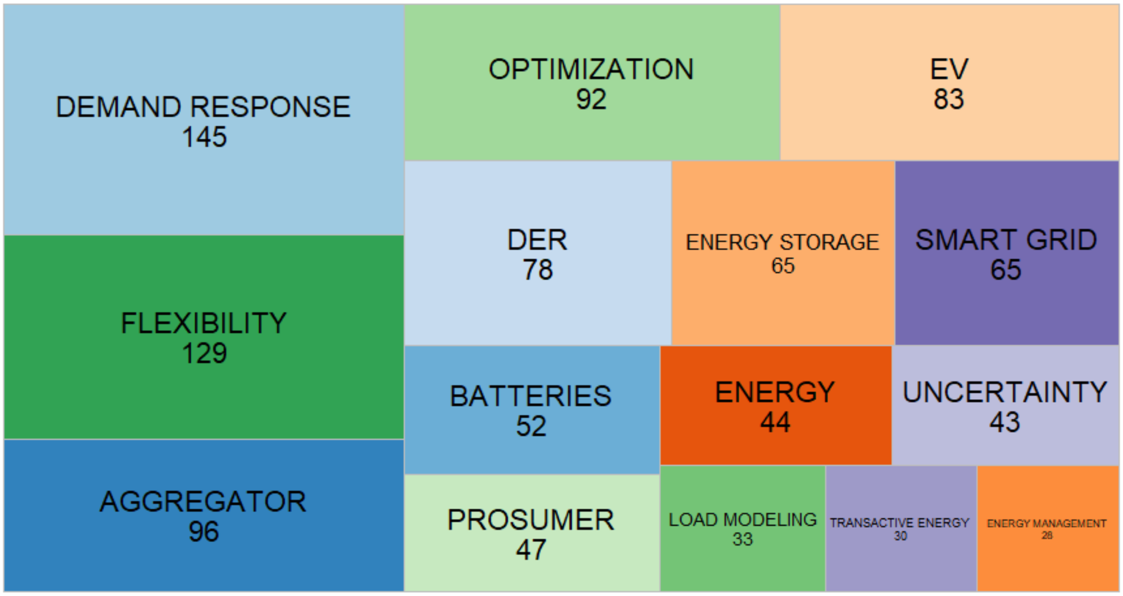
Source: Own elaboration on the Bibliometrix R package.

Figure 7 presents a treemap of the 15 most frequently occurring keywords identified in the literature retrieved through the research query. “Demand Response” emerges as the most prevalent term (145 occurrences), followed by “flexibility” (129) and “aggregator” (96), underscoring the importance of adaptive load management and intermediary agents in modern energy systems. Other high-frequency terms include “optimization” (92), “Electric Vehicles” (EV, 83), and “Distributed Energy Resources” (DER, 78), reflecting a strong research focus on operational efficiency, transportation electrification, and decentralized generation and storage.

Keywords such as “energy storage” (65), “smart grid” (65), “batteries” (52), and “prosumer” (47) highlight technological enablers and the role of active end-users in supporting system flexibility and reliability. Meanwhile, “energy” (44) and “uncertainty” (43) point to central conceptual and modeling challenges, particularly in systems with higher VRE penetration. Additional terms, such as “load modeling” (33), “transactive energy” (30), and “energy management” (28), indicate emerging areas related to demand-side participation, market-based coordination, and operational control strategies.

Overall, the visualization illustrates a tightly interconnected research landscape, with an emphasis on integrating DER, enhancing system flexibility, and developing advanced control, storage, and market mechanisms as VRE penetration deepens.

Figure 7. Treemap of the 15 Most Repeated Keywords



Source: Own elaboration on the Bibliometrix R package.

Finally, Table 1 provides an overview of the 29 selected studies, based on the eligibility criteria, classifying them by methodology and the agent or resource assessed, and discussing the main contributions and results.

Table 1. Overview of Papers Included in the Analysis

Publication	Methodology	Agent or Resource	Contribution	Main Results
Armendáriz et al. [52]	Case study approach	DSO	An approach that involves cooperation between the DSO and the microgrid owner in the investment and planning process to increase the microgrid's installed PV capacity.	Collaboration boosts the value of microgrid investments and enhances service quality. Regulators can support this by raising energy tariffs to reflect the investment lifecycle costs or reducing the PV feed-in's remuneration rate.
Askeland et al. [53]	Game-theoretic framework	DSO	An analysis of a local trading mechanism and its impact on grid tariffs under cost recovery for the DSO within a neighborhood context.	Establishing a neighborhood-based local electricity market offers socio-economic benefits by reducing total costs and enhancing resource coordination. Coordinating flexible assets at the neighborhood level sends effective price signals to reduce peak load, as local market prices reflect capacity scarcity.
Bara & Oprea [54]	Conceptual paper	Energy Community / prosumer / aggregator	Six innovative business models for energy communities (ECs), aggregators, or retailers. The business models reflect the priorities of various EC members, highlighting how financial and environmental benefits can motivate collective action.	Demonstrates a Local Flexibility Market (LFM) and highlights the financial benefits of trading flexibility. Key findings show that when the flexibility price doubles, deficit coverage increases significantly from 62% to 91%, benefiting consumers and retailers.
Barbero et al. [55]	Literature review	Aggregator	Examines barriers and enablers to demand aggregators' participation in balancing markets across four European electricity markets and suggests a new framework to facilitate their involvement.	Technical requirements, such as minimum bid size, offer symmetry, and product resolution, significantly impact demand aggregators' potential earnings in balancing markets.
Barbero et al. [34]	Multicriteria decision process	Aggregator	Introduces an innovative decision matrix to evaluate demand response strategies.	Current energy management systems have technical limitations that must be addressed when developing demand aggregation platforms. Emphasizes the need for a scalable solution to enable active consumer participation in electricity markets.
Cuenca et al. [39]	Case study approach / Literature review	Energy Community	Review of ECs, exploring their technical and economic drivers, existing resources in literature, trading models, price negotiation algorithms, and the benefits they bring to the grid.	DERs in traditional grids introduce uncertainty for system operators, which can be mitigated by clustering resources. The emergence of EC in the electricity sector warrants further research in areas such as flexibility in dispatch, flattening the demand curve, and optimizing network charges.
Degefa et al. [24]	Literature review	Flexibility resources	Reviews key flexibility studies and proposes a comprehensive definition of flexibility and standardized terms for flexibility resources, as well as mapping flexibility resources to ancillary services.	A key issue in the reviewed literature is the significant variation in definitions and classifications of flexible resources and the services they provide.

Eid et al. [29]	Literature review	Prosumer / storage facility / Electric Vehicle	Reviews and classifies existing DERs as flexibility providers, examines trading platforms for DER flexibility in electricity markets, and explores options to incentivize this service.	Emphasizes the need for appropriate signals, such as tariffs and contracts, to enable flexibility. Policies should reduce barriers and establish compensation mechanisms between aggregators and electricity suppliers to support DER aggregation.
Forouli et al. [56]	Literature review	Demand Response	Examines the deployment of demand-side flexibility across various European countries, analyzing best practices and key barriers.	Explores the operation of European electricity markets, the participation of flexibility resources, and proposes approaches to better integrate these assets into the distribution grid.
Good & Mancarella [25]	Quantitative analysis (optimization)	Community Energy System	Introduces a stochastic mixed-integer linear program for community energy systems, factoring in local network constraints.	Shows how the flexibility options facilitate the integration of electric heat pumps into a capacity-constrained smart district, enhancing revenue from multiple markets and services.
Gruber et al. [57]	Quantitative analysis (optimization)	Energy Community	Compares the impacts of optimizing ECs for economic efficiency versus technical resilience. The key contributions include integrating various production and flexibility options into a single EC optimization model with grid constraints and tariffs.	Reveals a trade-off between the flexibility measures needed for EC resilience and their associated costs. Quantifies the subsidies required to incentivize ECs to enhance resilience, positioning it as a valuable grid service.
Hadush & Meeus [44]	Conceptual paper	DSO / TSO	Examines market and grid operation challenges related to various system states and congestion management methods within the European electricity market framework. Explores inter-TSO cooperation and emerging DSO practices.	Effective congestion management requires close DSO-TSO collaboration. Key areas of cooperation, including capacity calculation, joint service procurement, capacity firmness, and market operations, are relevant across TSO-TSO, DSO-TSO, DSO-DSO, and DSO-microgrid collaborations.
Hatziargyriou & Asimakopoulou [58]	Quantitative analysis (optimization)	Aggregator	Presents three core models for integrating DERs into market procedures: direct participation of DERs; management through a monopoly non-profit local EC; and management through price signals by a profit-driven monopoly aggregator.	The analysis shows that using a single intermediary, whether a local EC or aggregator, lowers the System Marginal Price.
Iria & Soares [59]	Quantitative analysis (simulation)	Aggregator / Prosumer	Introduces an “energy-as-a-service” model, where prosumers pay a fixed monthly fee for aggregator services.	The results, based on real Australian prosumer data, reveal that the new business model significantly enhances economic outcomes for both aggregators and prosumers.
Kerscher & Arboleya [35]	Literature review	Aggregator	Reviews aggregator energy management strategies across various DER scenarios and examines the evolving role of aggregators within Europe’s regulatory framework since 2015.	Aggregators acting as suppliers or retailers are well-positioned to enter the market as flexibility contractors, benefiting from simplified market access without the need for a fully developed regulatory framework or standardized remuneration.

Koirala et al. [60]	Literature review	Community Energy System	Introduces the Integrated Community Energy Systems (ICESs) concept as an innovative approach to restructure local energy systems, enabling the integration of DER and the active participation of local communities.	Emphasizes the importance of mapping and balancing the roles of various stakeholders to avoid coordination problems and perverse incentives. ICESs offer the potential to reduce dependence on national energy systems, enhance flexibility, and keep grid investment costs low.
Kubli & Canzi [61]	Case study approach / Quantitative analysis (simulation)	Prosumer / Aggregator	New entrants in flexibility markets may struggle with being “too small to bid,” facing a “technology valley of death.” To overcome this challenge, the authors test strategies such as diversifying revenue streams and offering leasing options.	The findings underscore the importance of integrating various revenue streams for aggregators and eliminating regulations that limit prosumers’ ability to utilize their batteries beyond self-consumption.
Kubli et al. [62]	Qualitative and quantitative empirical analysis	Prosumer	Analyzes 7,216 individual decisions from 902 participants across three main areas of residential energy prosumption: solar PV with storage, electric mobility, and heat pumps.	Finds that current and potential users of electric cars and solar PV systems are more willing to co-create flexibility compared to heat pump users.
Lampropoulos et al. [28]	Case study approach	Aggregator	Explores the emerging business models of aggregator companies in Europe, driven by the need for flexibility in power system operations.	The case study, focusing on residential demand-side resources, demonstrates that aggregator companies can create new value for customers by better integrating wholesale and retail energy markets.
Minniti et al. [27]	Literature review	Local market	Explores how DERs can be leveraged for greater flexibility at the distribution level by establishing a LFM.	LFMs’ design depends on national regulations, system operator needs, the number of stakeholders, and available flexibility. Research should explore the technical, economic, and social factors that determine LFM effectiveness. Success requires enough participants, liquidity, and TSO-DSO coordination.
Montakhabi et al. [63]	Conceptual paper	Prosumer	Examines how prosumers can participate in electricity markets via innovative models, including P2P, community self-consumption, and transactive energy.	Proposes a framework to distinguish market models based on the parties involved (consumers, communities, and grid operators) and the commodities traded (electricity and flexibility).
Neetzow et al. [64]	Quantitative analysis (optimization)	Grids	Evaluates policy schemes to optimize storage use and minimize grid capacity expansion. Using a top-down modeling approach, examines impacts on market prices, storage operations, grid needs, and costs.	Simple feed-in policies, such as uniform grid feed-in limits with compensation for prosumage households, effectively reduce grid demand. However, pursuing complete self-sufficiency is counterproductive, as it limits balancing capabilities and can raise overall system costs.

Soto et al. [43]	Literature review	Prosumer	Reviews P2P energy trading to examine current methodologies, challenges, and areas for future research.	Identifies six key areas of focus for P2P energy trading research: trading platforms; blockchain; game theory; simulation; optimization; and algorithms.
Specht & Madlener [65]	Conceptual paper	Aggregator	Using Osterwalder and Pigneur's business model framework, this study proposes "Energy Supplier 2.0," a concept in which energy suppliers act as aggregators of household-level flexibility energy assets.	The aggregator-based model unlocks new revenue streams, highlights contracting solutions that align the interests of suppliers and customers, and provides policy recommendations to support socially beneficial energy models.
Tang & Wang [66]	Game-theoretic framework	Aggregator	A bi-level optimization framework based on the Stackelberg game determines optimal transactional prices for flexibility services involving an intermediary aggregator to unlock the potential flexibility of buildings.	The case study results reveal that the proposed interactive scheme creates a win-win scenario, increasing aggregator profits by 37.4% and building user profits by 5.6% to 5.9%, while reducing peak demand by 6.3%.
Thomas et al. [46]	Game-theoretic framework	Storage	Introduces a local market framework for allocating Physical Storage Rights (PSRs) as a market product. PSRs, provided by storage owners, enable participants (arbitrageurs, renewable producers, consumers, and prosumers) to access storage.	The case study results indicate that incorporating storage within the energy community can reduce total system costs by nearly 10%. Additionally, the proposed PSR allocation mechanism benefits individual market participants, increasing their revenues by up to 39%.
Torbaghan et al. [67]	Quantitative analysis (simulation)	DSO/ Aggregator / Prosumer	Introduces a market-based framework for trading flexibility in distribution grids, assigning new roles to entities like aggregators and enabling prosumers to participate.	The analysis highlights that the DSO's ability to announce accurate flexibility needs is crucial for market equilibrium. Success depends significantly on precise forecasts of load and DER production.
Valarezo et al. [68]	Literature review	Aggregator / Flexibility market	Performs a comparative analysis of various market and aggregator platforms, highlighting trends in emerging flexibility markets and offering insights into alternative designs for European electricity markets.	The findings show that new market models are technically and economically viable. They foster flexibility from distributed resources by enabling services for DSOs in coordination with TSOs.
Zepter et al. [69]	Quantitative analysis (optimization)	Prosumer / Energy Community	Proposes a framework to integrate prosumer communities into day-ahead and intraday markets, under uncertainties, using a two-stage stochastic programming approach.	The framework emphasizes the value of P2P trading and residential battery storage in enhancing local demand-side flexibility. A study on London residential buildings reveals that P2P trading and battery storage can each reduce electricity bills by 20–30%.

Source: Own elaboration.

4.2 DER and Flexibility Services

The energy transition has involved a profound transformation of the traditionally centralized electricity system towards one with greater participation of NCRE, especially VRE, and DER. The increasing penetration of VRE, such as solar photovoltaic and wind power, challenges the centralized model in meeting the primary goal of energy policy: ensuring a reliable service provision. Therefore, to manage the high uncertainty associated with generation from these energy sources, flexibility services play a fundamental role in electricity markets [24,29,70]. Several of the articles selected in the literature review (see Table 1) consider the importance of DERs as a flexibility resource in the energy transition process for several reasons, as we discuss in this section.

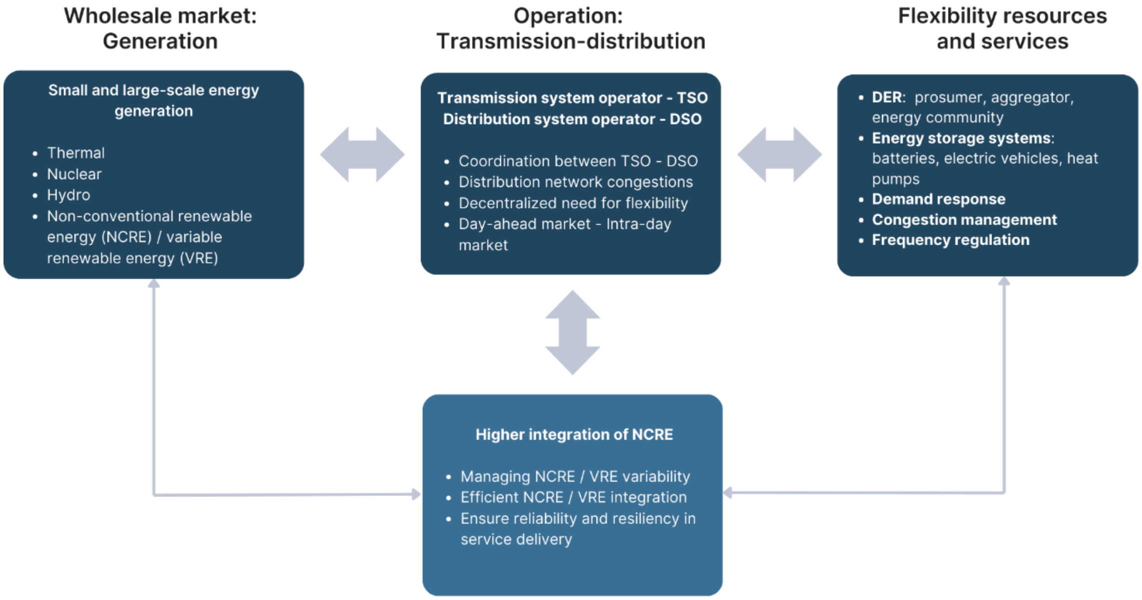
One of the main challenges is the growing integration of VRE, which introduces uncertainty and variability into the energy supply [24,39]. In the same vein, the massive deployment of DER, particularly solar photovoltaic, has introduced new challenges for the operation of distribution and transmission systems. These challenges include voltage variations and imbalances, energy congestion in substation feeders, and reverse power flows, all of which can affect grid reliability [52]. To address these challenges and integrate more photovoltaic capacity and VRE, DSOs play a key role in managing technical issues and ensuring the safe and efficient operation of distribution networks [68]. Moreover, DSOs must adopt technical solutions and make targeted investments to enhance network capacity, enabling the connection of additional DER and increasing hosting capacity [52].

DERs, especially those with storage or demand management capabilities, can compensate for these fluctuations by providing balancing services and maintaining grid stability [29,34,46]. Their inherent flexibility facilitates greater VRE penetration into the system [60,61]. Because they are located close to consumption points, DERs can also help manage congestion in both transmission and distribution networks [29]. In this context, DSOs in the energy transition are evolving into active managers of their networks [53], while facing operational challenges, congestion problems, and voltage limit violations [52]. By leveraging DER flexibility, DSOs can resolve local congestion and defer or avoid costly grid infrastructure upgrades [27].

But perhaps one of the most important aspects of DERs in the energy transition process is their support for system security and reliability. The flexibility they provide is essential for maintaining the resilience and operational stability of the electricity system (see Figure 8). DERs can offer services such as frequency response, operational reserve, and voltage control [60]. Their ability to quickly adjust their consumption or generation in response to system needs helps prevent outages and maintain the quality of supply [24].

Through aggregators, DERs can also pool their capabilities to offer substantial flexibility, overcoming individual participation barriers in ancillary service markets and supplying the services needed for safe system operation. This aggregation not only enhances grid reliability but also creates new market opportunities and revenue streams for DER owners [27,54,58,59,65]. Furthermore, a system with multiple distributed generation points can be more resilient to failures or extreme weather events that could affect large centralized power plants or transmission lines [29]. In such cases, local generation can continue to supply power in nearby areas even if the transmission grid is affected.

Figure 8. Flexibility Services



Source: Own elaboration.

As shown in Figure 8, coordination between DSOs, TSOs, and microgrid owners is also required to improve the voltage control capabilities of the distribution network [44,52]. According to Hadush & Meeus [44], with the energy transition, cooperation between DSOs and TSOs is essential in areas such as congestion management, system service procurement, network capacity calculation, network planning, and information exchange to achieve network efficiency and service reliability. This may involve the application of congestion pricing at the distribution level and coordination schemes, such as centralized markets, local markets, and common markets for DSOs and TSOs, and the coordination of energy market operations at different levels (wholesale and distribution). The creation of new flexibility market platforms to facilitate DSO–TSO coordination remains a significant area of ongoing development [68].

TSOs are beginning to access flexibility resources connected to the distribution network for system balancing. Therefore, given that the DSO can also use these same flexibility resources for congestion management and voltage control in the distribution network, conflicts may arise if actions are not well coordinated. Also, in some markets, DSOs have faced massive connection requests, especially for photovoltaic systems and wind farms, having to opt for smarter mechanisms to connect and release more distributed generation, and are even considering the acquisition of flexibility services to redispatch the system at the distribution level [44].

Likewise, with the growing penetration of VRE and DER, Energy Storage Systems (ESS), considered a subcategory of DER [29] and a flexibility resource, play a crucial role in providing flexibility services to the electricity system, enabling more efficient, flexible, and reliable operation. Given the growing penetration of solar photovoltaic and wind energy, which have unpredictable production patterns, storage can act as a backup, supplying energy when renewable production is low and storing excess when it is high. Therefore, storage can inject energy into the grid at critical times, contributing to supply adequacy and the reliability of the electrical system [29,46].

ESS combined with demand-side management can enhance the self-consumption of photovoltaic-generated electricity and reduce grid imbalance between supply and demand [71]. In this context, by combining behind-the-meter storage with distributed generation such as photovoltaic panels, users can optimize their consumption in response to grid tariffs and electricity price signals. This includes strategies such as peak shaving and load shifting [46]. Local storage is crucial for maximizing the use of on-site renewable energy generation, even for selling it at higher prices, thereby increasing the value of its generation [46].

According to Thomas et al. [46] and Eid et al. [29], ESS can provide a wide range of flexibility services critical to the operation of electrical systems, particularly in the context of DER. ESS contributes to frequency regulation [37] and enables energy time-shifting by storing electricity during periods of low demand or high production and discharging it when demand rises or generation falls. In doing so, it mitigates the variability of renewable energy production and supports the integration of VRES.

Beyond these functions, storage enhances system reliability by providing backup power, supporting grid balancing, and alleviating transmission congestion. It can also increase available supply capacity and reduce the need for long-distance electricity transport. Shared storage further enables peak shaving by discharging during demand peaks, thereby facilitating load shifting.

ESS flexibility extends to EVs, which require aggregation to deliver reliable services in organized markets, as individual units are insufficient. Additionally, storage systems can participate in remunerated and regulated markets, thereby improving both system economics and reliability [46]. Finally, ESS can adjust charging and discharging in response to price signals, contributing to demand response and overall grid stability.

Table 2 summarizes the flexibility services discussed above. It outlines the services that can be delivered through DERs, accompanied by a brief description, key examples of DER technologies, and the markets in which these services can be applied.

Source: Own elaboration.

Flexibility Services that DERs can Offer	Service Description	Key Examples	Markets/Delivery Contexts
Congestion management	Management of network problems or restrictions in the electrical system, such as thermal limitations or overvoltage. This service often requires flexibility resources to be located in a specific geographical position, close to the point of congestion [24].	Flexibility resources located near the network bottleneck. Aggregated demand-side resources [27]. Various types of DERs whose technical characteristics (power capacity, energy capacity, ramp speed) match local needs [24].	Balancing markets [24]. Local flexibility markets (LFM) [68]. Direct services contracted by DSOs [27].
Frequency control	Services such as Frequency Containment Reserve (FCR), Frequency Restoration Reserve with automatic activation (aFRR), Manual Frequency Restoration Reserve (mFRR), and Replacement Reserve (RR), which seek to maintain the frequency of the electrical grid within operational limits, differing in their response times ranging from seconds to hours [24].	Quick response resources, such as flywheels, stationary batteries, and aggregated EVs [56]. Residential loads and continuous loads [29]. Electrical EES in general [56].	Auxiliary services markets, specifically primary, secondary, and tertiary reserve markets [24] and wholesale markets, including reserve markets [35].
Voltage control / Reactive power	Ability to inject or absorb active and reactive power into the grid [24].	Battery Energy Storage Systems [24]. Distributed generation, particularly that located in microgrids connected at low voltage [27]. Resources managed using direct control methods are suitable for this localized service [29].	Ancillary Services Markets, specifically Reactive Power services [29]. Local Markets and services contracted directly by DSOs [27].

System balancing	Modification of generation and/or consumption patterns in response to an external signal (such as a price signal or direct activation) to balance the electricity system [67]. Includes ramp-up and ramp-down adjustments to manage variations and uncertainties in supply and demand for different time scales [24].	Flexible generation units (e.g., cogeneration units, dispatchable biogas plants). Consumption units capable of providing demand response aggregation [29]. Distributed generation based on variable renewable energies in combination with storage [68].	Balancing markets and ancillary services markets [29]. Spot markets, including day-ahead (DA) and intraday (ID) markets. Bulk electricity market [24]. Wholesale market and balance of the portfolio of Balance Responsible Parties (BRP) [35].
Demand Response / Flexible loads	The ability of the demand side to modify its consumption patterns (change the period or level of consumption, or reduce the load) in response to external signals (price or direct activation). This service or capacity is essential to enable the demand side to contribute to system balance and grid constraint management [67].	Loads with differentiated or deferrable duration, e.g., Heating, Ventilation, and Air Conditioning (HVAC) systems, washing machines, dishwashers, clothes dryers, water heaters, space heating, and EVs. Interruptible or reducible loads, e.g., some household appliances, industrial processes [24]. Residential Thermocontrolable Loads (TCLs) [27]. Prosumers and controllable devices (smart appliances, distributed generation sources, storage devices, EVs) [67].	Mechanism or capacity inherent to certain DERs [67], which allows the provision of services in various markets (Ancillary Services, Balancing, spot, capacity, and local markets, services to DSOs/BRPs [24]. Transactions in specific Demand Response programs, which are managed through dynamic price-based mechanisms (e.g., Time-of-Use (TOU) rates, Real-Time Pricing (RTP)) or direct contractual control [29].

Source: own work elaboration based on Degefa et al. [24], Minniti et al. [27], Eid et al. [29], Kerscher & Arboleya [35], Forouli et al. [56], Torbaghan et al. [67], and Valarezo et al. [68].

Focusing on flexibility services provided on the demand side, DR introduces new solutions in areas that have traditionally been inelastic within centralized systems. Figure 7, as mentioned before, illustrates that DR is the most frequently recurring term in the systematic literature review. DR is an increasingly important concept in modern electricity systems, particularly during the energy transition, that goes beyond simple consumption management, offering significant capabilities for the stability, efficiency, and economy of the electricity grid and microgrids [72]. DR allows generation and/or consumption configurations to be adapted in response to external signals (e.g., price or activation signals), thereby contributing to the stability and security of the energy system [33,56]. The flexibility of DR allows DSOs to seek market products and mechanisms that facilitate more active management and control of the distribution system.

According to Tsybina et al. [72], Forouli et al. [56], and Kuan-Cheng et al. [33], DR can provide direct flexibility services to the system. These services contribute to system stability and network operation through power balancing and frequency control, encompassing frequency response, fast reserve, primary, secondary, and tertiary reserves, as well as demand-side frequency control, high-frequency response, and enhanced frequency response. DR also strengthens reserve services, such as short-term operating reserve, replacement reserve, strategic reserve, and supplemental balancing reserve. Moreover, DR supports congestion management at both transmission and distribution levels, addresses voltage issues, and enables local grid balancing. It enhances the efficiency of renewable energy integration by facilitating the optimal utilization of variable renewable energy. Finally, DR contributes to capacity services that ensure supply adequacy, particularly through participation in capacity markets, thus reinforcing long-term system security.

Likewise, DR, either directly or through aggregators, can participate in a variety of markets and compete with other flexibility resources. These include wholesale markets such as day-ahead and intraday, balancing markets, ancillary services markets, capacity markets, and LFM, which are often operated by DSOs through tenders or online platforms. Additionally, enabling EV participation in demand response requires deploying Advanced Metering Infrastructure (AMI) and developing alternative contracting and pricing methods.

Table 3 summarizes the flexibility services that can be provided through demand response, their service descriptions, key examples of DERs, and the markets in which they can be applied.

Table 3. Flexibility Services that DR can Offer

DR Flexibility Service	Service Description	Key Examples of DER (Devices/Types of Load)	Markets/Delivery Contexts
Frequency regulation	Adjust consumption in response to frequency deviations in the electrical system to maintain grid stability. This may include following variable renewable energy generation, responding to unspecified disturbances or disruptions, responding to system contingencies, or following specific control signals such as droop control. It encompasses primary, secondary, and tertiary (reserve) responses [72].	HVAC systems, water heaters, refrigerators and freezers, pool pumps, TCLs in general, unspecified or interruptible/deferrable loads, fleets or aggregations of devices [72].	Balancing wholesale markets, ancillary services markets [56], and microgrid operation (in island or connected mode) [72].

Balancing (Wholesale market)	Adjust energy consumption to match generation in real time or in short-term markets (DA and ID) to maintain the balance between supply and demand in the wholesale market [56].	Various aggregate loads (residential, commercial, small industrial) and distributed resources [56].	Wholesale energy markets and balancing markets [56].
Capacity provision (Capacity market)	Commit to the availability of power reduction or increase capacity for future periods, ensuring the long-term adequacy of system resources [56].	Load aggregations, industrial and commercial loads, demand response resources [56].	Capacity markets [56].
Network management (distribution level)	Manage the operating conditions of the distribution network, including voltage control and congestion management, by adjusting local demand. This includes local network balancing [56].	Loads connected at the distribution level (residential, commercial, industrial) [56].	LFM/auctions (operated by DSOs), bilateral “flexible connection” agreements, and demand control contracts [56].
Peak reduction / Load management	Reducing electricity demand during periods of peak system load [33] or managing the load profile to comply with established limits or schedules [72]. This may be a specific program or a method to support other services.	Various loads, including interruptible and deferrable loads, households, commercial buildings, and small industrial facilities [56].	Demand response programs, including demand auctions [56], interruptibility contracts, demand turn-up programs [56], and tariffs that incentivize reduction or shift in schedules (implicit DR) [56].
Services for microgrids	They enable stable, reliable, and efficient operation of microgrids, particularly in island mode. This often involves co-optimization with other DERs, including minimizing frequency/ voltage deviations, minimizing active power imbalances, managing load or generation contingencies, and adhering to renewable generation profiles [72].	Various loads within the microgrid [72].	Internal operation of the microgrid (in island mode or connected to the main grid) [72].

Auxiliary services (General category)	A general term that encompasses various services necessary for the safe and reliable operation of the electrical system [72].	Various demand response resource loads and aggregations [56], including HVAC, lighting, EVs, and storage [72].	Auxiliary services markets [56] and microgrids [72].
Capacity deferral	The response to demand may address capacity postponement, for example, investment in networks [55].		Distribution network management [56].

Source: Own elaboration based on Lee et al. [33], Barbero et al. [55], Forouli et al. [56], and Tsybina et al. [72].

As discussed before, aggregators act as intermediaries between DERs and electricity markets, bridging the gap for small-scale resources that, individually, through prosumers, would not have sufficient reliability or capacity to participate [27]. They can offer a variety of flexibility services by combining and managing DERs from multiple customers [35]. In exchange for providing flexibility, customers associated with an aggregator can receive financial benefits, such as savings on their energy bill or other financial incentives [28]. Aggregators can provide the following flexibility services:

- Participation in electricity markets: Aggregators participate in various electricity markets, such as DA and ID markets, and AS. They can participate in bidding for energy and services. Some examples include participation in reserve markets (ancillary services) and balancing markets (real-time market) [34,35,55,59].

- Congestion Management: Aggregators can also contribute to congestion management in distribution and transmission networks with services such as capacity and activation. This is achieved by using the aggregated flexibility to keep networks within their operational limits [62,68].

- Balancing Services: Aggregators can provide balancing services as Balancing Service Providers (BSPs) [28]. This includes services such as the Frequency Containment Reserve (FCR), the Frequency Restoration Reserve with automatic activation (aFRR), the Frequency Restoration Reserve with manual activation (mFRR), and the Replacement Reserves (RR) [68]. In the context of local flexibility markets, aggregators/energy suppliers are flexibility sellers for BRPs and DSOs [67].

- Frequency Regulation: Building flexibility, such as that provided by HVAC systems and dimmable lighting, can be used to provide frequency regulation services in response to grid control signals. Battery capacity can also be allocated to provide this service, as it often offers higher prices [66].

- Operating Reserve Service: In addition to frequency regulation, buildings can offer operating reserve services. This requires rapid load reduction for a limited, short period in response to an urgent request from the power grid, usually in the event of a contingency [66].

- Peak Reduction/Peak Shaving: Aggregators can manage flexibility to reduce peak demand. This helps DSOs manage regional load and can generate additional revenue [61,66].

- Local Grid Congestion Management: Aggregators can manage flexibility to address specific congestion issues in the local grid or at the DSO level [66].

Prosumers have become central to the global energy transition [62,63]. These individuals, often owners of distributed generation systems with renewable sources, represent a potential for energy flexibility that was previously untapped [62]. For prosumers, active participation in the market is driven by a wide range of values that go beyond financial gain, including the pursuit of greater autonomy (self-sufficiency or autarky), contribution to green energy, and a greater sense of agency in the energy transition [63]. The increase in prosumers creates the opportunity for a more decentralized and open electricity grid, improving local energy consumption and generation balance and reducing the vulnerability of the centralized system [43].

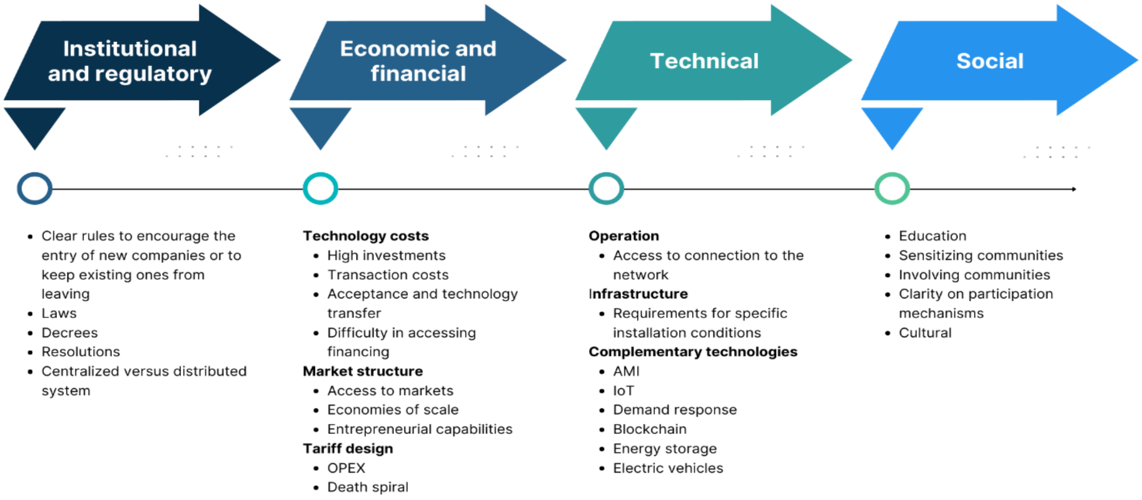
Likewise, energy communities have emerged as a key solution to accelerate the transition to more sustainable energy systems and mitigate climate change [57]. Within ECs, models such as Community Self-Consumption (CSC) and P2P trading enable prosumers to exchange their surplus energy directly with peers, without the need for conventional intermediaries [43,63]. The platform that manages the EC coordinates these operations, using flexibility measures such as BESS and EVs to optimize operations and pursue technical (e.g., maximizing resilience) or economic (e.g., minimizing costs) objectives [57].

P2P trading and local storage generate powerful synergies, which can significantly increase community self-sufficiency and reduce electricity costs for members when combined, by incentivizing internal trading at prices lower than wholesale market prices [69]. However, this active participation requires prosumers to be willing to relinquish some control over their resources, especially in CSC models, where the community manager decides how to use the shared energy and flexibility [63]. The aggregation of flexibility provided by prosumers is vital for CEs or aggregators to reach the minimum bidding size required to compete in reserve power markets [62].

4.3 Barriers to the Development of DER and Flexibility Services

DERs, as key providers of flexibility services in modern energy systems, present challenges to their adoption. These barriers can be grouped into four main categories: institutional and regulatory, economic and financial, technical, and social (see Figure 9). Institutions, understood as the “rules of the game” in a society [73], are fundamental for the functioning of industries and markets, including the energy sector. Consequently, disruptive changes in energy markets, such as the integration of NCRE, new business models, DERs, and flexibility services, must be accompanied by institutional designs and adaptations that facilitate their efficient incorporation [18,74–76]. Markets that have advanced the most in the energy transition, such as Germany, Australia, the United States, and Europe in general, have shown the need for institutional redesigns alongside complementary policies to enable an efficient and resilient energy transition [56,70,77]. With the emergence of flexibility services and markets, regulatory and policy barriers need to be addressed, as the roles and responsibilities of the different actors involved in these markets are not yet clearly defined [68].

Figure 9. Main Barriers to the Development of DER and Flexibility Services



Source: adapted from Patiño Echeverry & García Rendón [30].

Flexibility services, like DERs, are hindered by regulatory and institutional barriers [56,73]. A central challenge is redefining the roles and responsibilities of DSOs and TSOs, while strengthening coordination between them to ensure flexibility is delivered where it creates the most value for the whole system [27,78]. This coordination is crucial for solutions such as congestion management in distribution networks [27,44,56,78]. The EU Clean Energy Package offers a clear example of regulatory progress, encouraging DSOs to procure flexibility services and act as local market facilitators, aggregating DER offers and cooperating with TSOs to determine the available capacity at the TSO-DSO border that can be allocated by the market, allowing DERs to provide valuable services to the grid [44].

Furthermore, the existence of an aggregator and the change in the role of DSOs initially imply a regulatory definition of the role and responsibilities of the aggregator, and the necessary regulatory changes for DSOs in the context of a distributed market to offer services to existing markets. This includes interactions with short-term markets, such as the DA and ID markets for market services, and AS markets for system services [27]. Consequently, regulatory changes are required to facilitate interactions between the wholesale market and other markets necessary for providing real-time service.

As DER penetration grows, DSOs require incentives and regulatory frameworks that enable them to recover the CAPEX and OPEX associated with flexibility procurement, while ensuring a transparent, non-discriminatory, and market-based allocation of services [44,52]. Given DSOs' limited experience in operating markets, neutral entities or independent operators may be needed for prequalification, settlement, and local market operation [68]. DSO remuneration schemes must be revised to encourage end-users to activate flexibility. For example, dynamic network tariffs could incentivize users to be more flexible [27]. Pricing design is crucial for market-based services, such as energy, capacity, and balancing markets; ancillary services; and charges for regulated services, including network and other energy policy costs [60].

Moreover, stronger cooperation between TSOs and DSOs is required in governance, planning, and system operation, particularly for capacity calculation and allocation at the transmission–distribution interface. With the rise of local energy markets, DSO-DSO and DSO–microgrid cooperation could become equally important [44]. To overcome current regulatory barriers and foster innovation, regulatory sandboxes can provide controlled environments for testing new services and products not yet covered by existing regulations [68,79].

From an economic and financial perspective, significant challenges remain despite the progress of renewable technologies. For instance, the Levelized Cost of Electricity (LCOE) for solar photovoltaic has dropped sharply, from 0.445 USD/kWh in 2010 to 0.049 USD/kWh in 2022, making it cheaper than the most competitive fossil fuel option [80] and, on average, the least expensive source of electricity globally by 2020 [81]. Nevertheless, investment, operation, and maintenance, as well as grid connection costs, still represent barriers to large-scale adoption [82,83]. Similarly, tariff structures have lagged behind technological advances. In many markets, the lack of remuneration mechanisms for DERs and the flexibility services they provide discourages their integration, contributing to challenges such as the "death spiral" for prosumers [84] and the "missing money" problem [85,86].

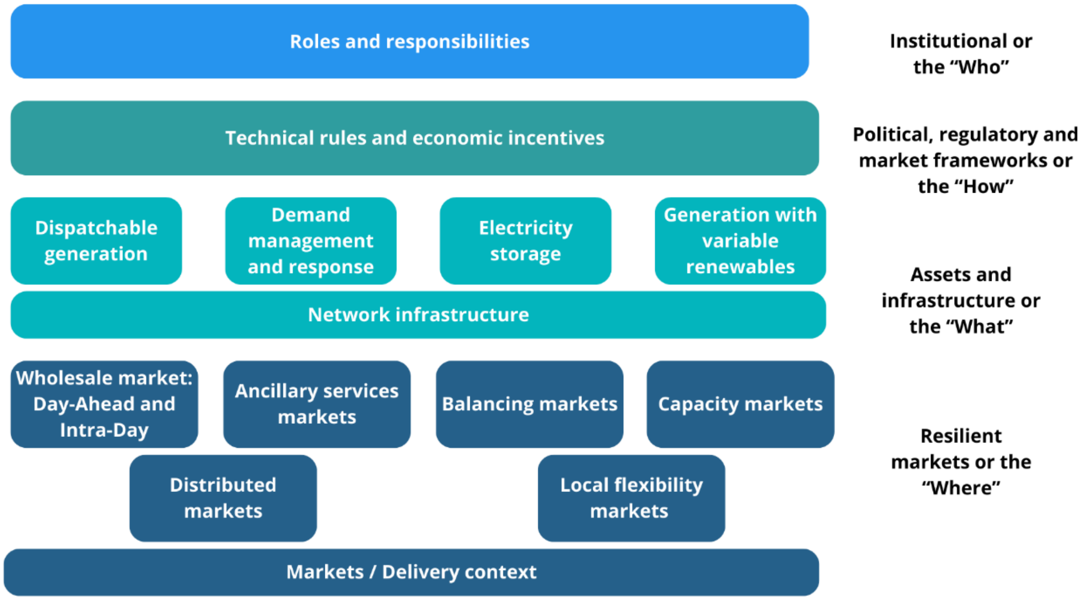
Furthermore, the economics of flexibility resources are shaped by capital expenditures (CAPEX) and operational expenditures (OPEX), which directly influence investment and deployment decisions [24]. Techno-economic assessments are therefore critical to evaluate cost-effectiveness under different operational and market conditions, particularly given expectations of rising OPEX due to the costs of procuring flexibility [68].

Technical barriers are equally significant, particularly regarding access to and modernization of grid infrastructure. Challenges include securing reliable and affordable network connections [64,87,88] and ensuring that buildings and other sites have the necessary structural conditions for renewable installations, such as PV panels [89,90]. Beyond infrastructure, a modernized grid architecture and economic dispatch mechanisms are necessary to ensure reliability and efficiency in increasingly uncertain operating environments [32]. Complementary technologies also play a crucial role in addressing technical barriers. AMI, demand response programs [91,92], Internet of Things (IoT), blockchain [93], ESS [37,49], and EVs [78] all provide critical support for the integration and optimal operation of DERs and flexibility services. Additionally, policy schemes that enhance the grid utilization of DERs (in prosumage households) can lower overall grid demand and reduce the need for capacity expansion [64].

Finally, social barriers remain a substantial obstacle to the expansion of DERs and flexibility services, especially in the deployment of energy communities and other local renewable initiatives. As Tarpani et al. [74] emphasize, communities need not only technical knowledge but also social engagement and motivation to support energy transition projects. Information campaigns and participatory approaches are crucial for highlighting the environmental and economic benefits of renewables, strengthening local ownership, and enhancing public trust [94]. Without this social dimension, even well-designed technical and regulatory measures may fall short in achieving widespread adoption.

In sum, the barriers to the development of DERs and flexibility services must be understood as multidimensional and interconnected. Institutional and regulatory aspects define the “who” by clarifying roles and responsibilities; political, regulatory, and market frameworks determine the “how” through technical rules and economic incentives; assets and infrastructures such as dispatchable generation, demand response, storage, and renewables represent the “what”; and resilient market structures, from wholesale to local flexibility markets, define the “where.” As illustrated in Figure 10, overcoming these barriers requires coordinated action across all dimensions, ensuring that institutional arrangements, regulatory frameworks, infrastructures, and market mechanisms evolve together to enable a flexible, efficient, and socially inclusive integration of DERs as flexibility providers in the electricity system.

Figure 10. Factors Relevant to the Flexibility of an Electrical System



Source: own elaboration, adapted from IEA [95].

5. Conclusions and Future Work

The integration of flexibility services into the electricity system depends not only on the physical resources that can adapt their injection or consumption patterns, such as generation, demand response, and energy storage, but also on the existence of adequate facilitators at the regulatory, market, and technological levels. Dispatchable plants, demand-side participation, and storage systems have demonstrated their technical capacity to contribute to system balance. Still, without regulatory clarity and well-designed markets, their full potential remains underutilized. The challenge is therefore twofold: ensuring that technical flexibility can be mobilized when needed, and creating institutional and economic conditions that allow these services to be properly valued and remunerated.

From a regulatory perspective, significant adjustments are required to achieve the complementarity between centralized and distributed systems. Historically, electricity markets have been structured as natural monopolies, especially in transmission and distribution. In the context of the energy transition, this structure must evolve to incorporate distributed resources through transparent, predictable, and innovation-oriented regulations. Regulatory sandboxes can play a transitional role, allowing experimentation with new models in controlled environments. Ultimately, regulation should be dynamic and flexible, enabling market participants to anticipate and adapt to future needs.

On the economic side, incentives must be designed to encourage investment, innovation, and the deployment of flexibility services. Rather than relying on punitive measures, it is more effective to stimulate demand-side participation and business model innovation through targeted incentives, dynamic tariff structures, and clear remuneration mechanisms for flexibility. This requires designing frameworks that not only recover CAPEX and OPEX but also send consistent long-term price signals to investors and system participants.

Markets should provide economic signals and mechanisms for owners of flexibility resources to offer their capabilities to the system. The existence and design of appropriate markets, such as ancillary services, balancing markets, capacity markets, and local flexibility markets, are key to harnessing the technical potential of these flexibility resources. But it is not enough to have flexible technical resources; it is equally important to have market designs that allow these services to be mobilized and remunerated. Once all potential participants are enabled, local flexibility markets should be established, in which each system actor (aggregators, DSOs, and BRPs) can trade their flexibility for different purposes (grid-oriented and market-oriented).

Technical barriers, particularly access to the grid, remain a major obstacle. Network operators often lack the capacity to accommodate all connection requests, creating bottlenecks that limit the deployment of renewable and distributed resources. Strengthening coordination between TSOs and DSOs is essential to optimizing flexibility allocation and ensuring efficient system operation. At the same time, the emergence of transactive energy models presents opportunities for greater efficiency in resource coordination, but it also raises challenges related to cybersecurity, interoperability, and governance of decentralized platforms.

In this context, and based on our systematic literature review, future work on DERs as providers of flexibility services should focus on closing critical research gaps. First, it is unclear how flexibility and non-flexibility resources can coexist within grids where reliability and security of supply remain paramount. Co-simulation approaches that integrate technical and economic perspectives at both operational and planning levels are necessary to address this issue. Second, as power flows in distribution networks become more complex, assessing their impact on network performance and designing mitigation strategies will be essential. Third, new trading algorithms must be developed to enable flexibility markets that are efficient, transparent, and compatible with network constraints. Finally, as investment in distributed resources grows, new strategies for resource allocation are required, considering both technical efficiency and the governance challenges posed by sharing-economy principles.

In conclusion, the consolidation of a distributed market and flexibility markets depends on aligning technical capacity, regulatory innovation, and economic incentives within a coherent framework. Only then can DER contribute to system resilience, reliability, and sustainability, while also providing clear and stable signals to investors, communities, and market actors.

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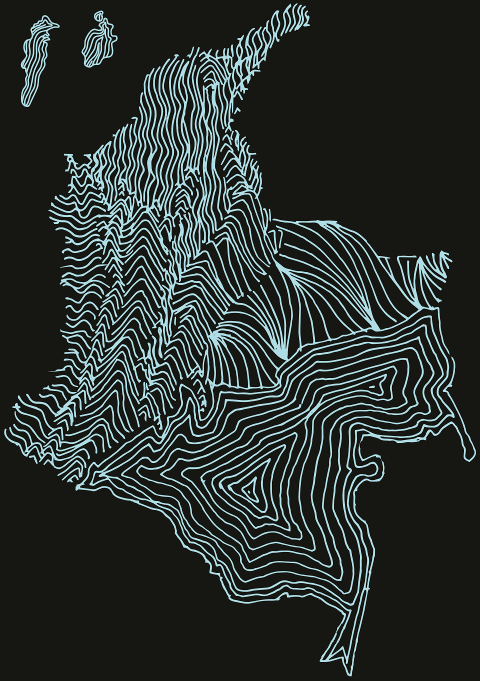

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