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Review

Opening of Ancillary Service Markets to Distributed Energy Resources: A Review

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Abstract: Electric power systems are moving toward more decentralized models, where energy generation is performed by small and distributed power plants, often from renewables. With the gradual phase out from fossil fuels, however, Distribution Energy Resources (DERs) are expected to take over in the provision of all regulation services required to operate the grid. To this purpose, the opening of national Ancillary Service Markets (ASMs) to DERs is considered an essential passage. In order to allow this transition to happen, current opportunities and barriers to market participation of DERs must be clearly identified. In this work, a comprehensive review is provided of the state-of-the-art of research on DER integration into ASMs. The topic at hand is analyzed from different perspectives. First, the current situation and main trends regarding the reformation processes of national ASMs are analyzed to get a clear picture of the evolutions expected and adjustment required in the future, according to the scientific community. Then, the focus is moved to the strategies to be adopted by aggregators for the effective control and coordination of DERs, exploring the challenges posed by the uncertainties affecting the problem. Coordination schemes between transmission and distribution system operators, and the implications on the grid infrastructure operation and planning, are also investigated. Finally, the review deepens the control capabilities required for DER technologies to perform the needed control actions.

Keywords: aggregator; ancillary service; balancing service provider; distributed energy resources; market models

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1. Introduction

The challenging decarbonization targets set worldwide impose the fast spread of renewable-based electricity generation, usually performed by small power plants, connected to distribution networks and characterized by intermittent and unprogrammable behavior [1]. Traditionally, large generators were in charge of supplying all the regulations required for reliable power system operation; this was usually carried out by conventional (i.e., fossil fuels-based) units offering their services on the market. With the increasing spread of the distributed generation, however, power systems must evolve toward more decentralized architectures where new actors are in charge to perform the control actions required by the grid. This is also a consequence of variability and lack of observability characterizing Distribution Energy Resources (DERs), which implies higher margins of flexibility to ensure a stable and reliable power system operation.

For this purpose, many countries worldwide are opening their electricity markets to DERs, enabling small users to actively supply services to the grid. Dispersed generation, (partially) programmable loads, prosumers, but also new regulating resources, such as Energy Storage Systems (ESSs) and electric vehicles, are involved in this process. Nevertheless, many new challenges are posed by this evolution since proper control strategies are necessary to coordinate the available resources, often intermittent and scarcely controllable, combining their strengths and weaknesses, and making them act as a single dispatchable entity.

National governments are making great efforts in integrating new actors into the existing legislation and market structures [2]. This is the case, in the EU, of the Balancing Service Provider (BSP), or aggregator, defined as the subject that, controlling several energy resources, is enabled to offer the resulting flexibility on the Ancillary Service Market (ASM) [3] (see Figure 1). Therefore, an aggregator usually sets up an agreement with several customers, based on which it can temporarily adjust their power exchange to supply a service to the grid [4]. The flexibility gathered on users is then sold on the market. The aggregator concept sometimes coincides in the literature with the approach known as Virtual Power Plant (VPP). Indeed, grouping different types of resources allows for intelligently managing demand and power generation [5,6], for example, compensating for possible deviations and improving power quality [7]. Finally, the generators and loads in a BSP portfolio have better access both to energy markets, where given amounts of energy are traded between consumers and producers, usually the day ahead, and to ancillary service markets, where grid services are offered by regulating units [8], even close to the real time, thus introducing new economic opportunities for active prosumers [9,10]. The selection of DER resources to include in the VPP is a particularly challenging task, because the BSP must take advantage of the peculiarities of each specific technology and compensate for the relevant lacks. Moreover, as introduced later, national legislations can enforce a minimum bidding size or other performance requirements that must be met by the BSP and relevant DER units' portfolio during the ancillary service provision.

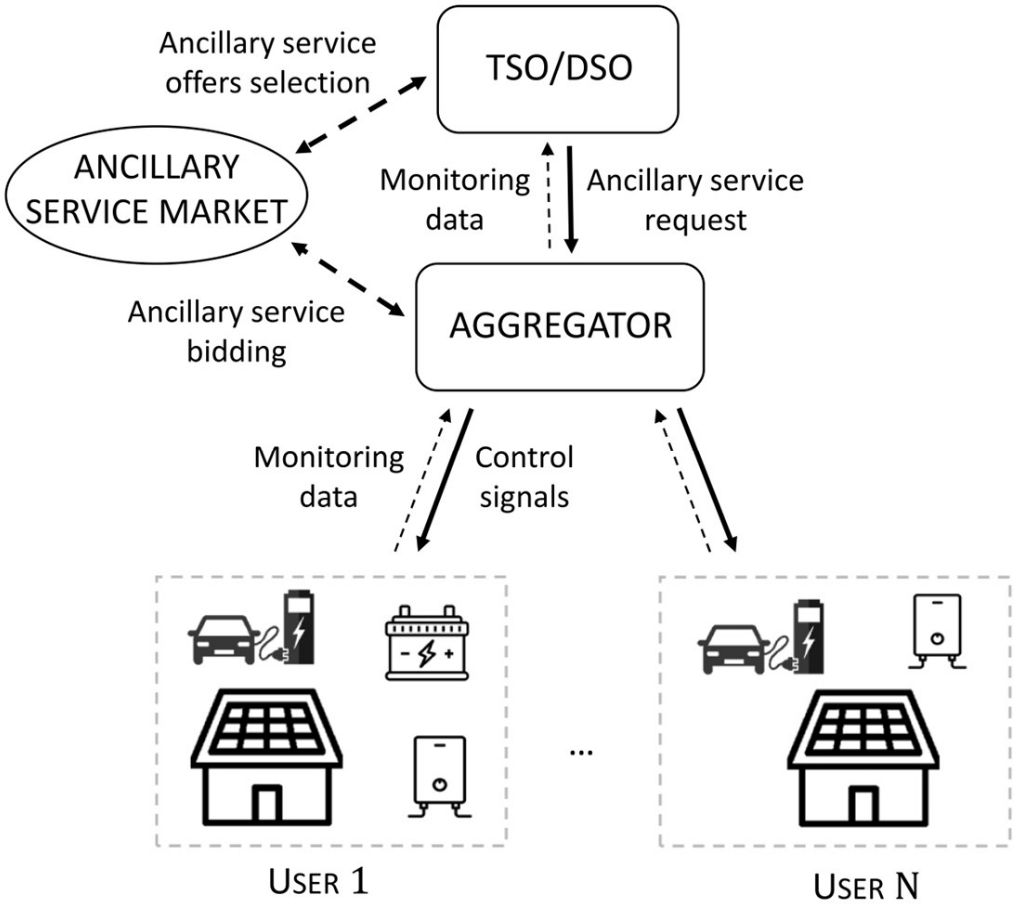

Figure 1. Principle diagram of the aggregator and relevant data flow.

The envisaged evolution concerns the power systems' regulatory and market frameworks as well, which must allow the non-discriminatory participation of all potential flexibility providers, but also support the involvement of those subjects that, for technological or economic reasons, could face barriers in accessing the market. Thus, the market structure, remuneration schemes, and technical requirements of the services offered are further aspects requiring proper investigation.

In the context outlined, this paper proposes a comprehensive review of the state of the art of the research on DER integration into the ASMs. The topic is analyzed from three different perspectives:

1. Reformation of electricity markets' structure to enable the access of DERs;
2. Control, coordination, and planning strategies for aggregators and network operators;
3. Technological aspects to increase the flexibility of distributed resources.

For each pillar, a literature review has been conducted systematically. With this aim, 63,700 references have been initially selected from the Scopus database as of potential interest. The query has been carried out using a set of keywords broadly covering the topic of interest, such as *virtual power plant*, *distributed energy resources*, *distributed generation*, *aggregator*, etc. The metadata analyzed are relevant to the document title, keywords, year of publication, and abstract. In the database obtained, 56.5% of works are journal papers, 41.4% conference proceedings, and 2.1% book chapters.

In a second stage, for each pillar analyzed, the initial set of references has been filtered through a list of keywords specific to the topic. To limit, as much as possible, unrelated papers, the queries to the database are assembled with logic operators, such as AND/OR, and metadata have been checked to eliminate not relevant results.

2. Reformation of Ancillary Service Market's Structure to Enable the Access of Distributed Energy Resources

In this section, the current European regulatory framework related to the participation of DERs in ASMs is reviewed. Then, the existing literature concerning the reformation process of ASM's structure is presented and discussed.

2.1. State of the Art of European Initiatives for the Opening of Ancillary Service Markets to Distributed Energy Resources

In the new paradigm outlined, many countries worldwide are promoting the opening of their flexibility markets to DERs. This process is well established especially in the EU, where several member states have already adapted their national legislation to better integrate DERs into the markets or are testing, through experimental projects, the feasibility of new market structures [11]. Even if a process of harmonization and standardization is ongoing, aiming at achieving a better integration among national electricity markets, national frameworks still present significant differences (see Table 1).

Table 1. Minimum bidding size required to provide frequency control by DERs in the countries analyzed.

Country	Minimum Bid Size			
	Fast Frequency Response (FFR)	Frequency Containment Reserve (FCR)	Automatic Frequency Restoration Reserve (aFRR)	Manual Frequency Restoration Reserve (mFRR)/Replacement Reserves (RR)
Germany	-	1 MW	1 MW	1 MW
United Kingdom	1 MW	1 MW	-	3 MW
Spain	1 MW	Only large generators	1 MW	1 MW
France	-	1 MW	1 MW	10 MW
Finland	1 MW	0.1 MW	1 MW	10 MW
Denmark	0.3 MW	1 MW (DK1) 0.1 MW (DK2)	1 MW	5 MW
Italy	5 MW	Only large generators	1 MW	1 MW

Regarding Germany, to overcome the technical issues arising from RES spreading, starting from 2018, aggregators have been enabled to provide ancillary services to the power system [12]. To date, all the balancing services, Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), and manual Frequency Restoration Reserve (mFRR), are open to DERs, as long as they fulfill the technical requirements prescribed by the national grid code. Services are procured through daily tenders with 4 h blocks and the minimum bidding size is 1 MW. Furthermore, for mFRR and aFRR, both the available capacity (€/MW) and the energy activated (€/MWh) are paid. However, as emerged in [13], the weak digitalization and data transparency of the German electricity market are limiting the proliferation of DERs' flexibility.

In recent years, the UK regulatory authority (OFGEM) reformed the electricity market to accommodate DERs and RESs [14] and to achieve greater standardization of balancing products. Regarding the ancillary services of potential interest of DERs and aggregators, the dynamic containment (which is a fast dynamic service designed to restore frequency after a significant deviation with full delivery required in 1 s) is tendered on a daily basis and the minimum bid size is 1 MW. Theoretically, all types of DERs can participate but, in practice, the strict technical requirements allow the provision only by batteries. The firm frequency response is open to generators, storage, and demand side response on transmission and distribution networks, with a minimum bidding size of 1 MW. It is procured through pay-as-bid monthly tenders, but to comply with the Clean Energy Package, from April 2023, pay-as-clear daily auctions will be adopted [15]. The short-term operating reserve, which is similar to mFRR in continental Europe, is procured through daily tenders open to DER aggregates having a minimum capacity of 3 MW.

In Spain, non-programmable RESs are eligible to provide aFRR and mFRR and the minimum bidding size for the products has been recently reduced to 1 MW. However, the limited profitability of mFRR and Replacement Reserve (RR) markets, and the absence of a clear regulatory framework for independent BSPs make non-existent the ASM participation of DERs. Indeed, in 2021, the total reserve activated in Spain to provide ancillary services was equal to 2000 GWh and just 1 MWh was by demand-response flexibility [13]. To deal with the scarcity of supply for winter 2022, the national Transmission System Operator (TSO) introduced in October 2022 a new a product similar to a Fast Frequency Response (FFR), having a minimum capacity of 1 MW. However, this is more of an emergency measure rather than a structural change.

In France, DERs are qualified to provide all the balancing services, and the minimum bidding size is between 1 MW for FCR and aFRR and 10 MW for mFRR and RR [16]. Concerning the FCR, the low bidding size and the short product duration (4 h) allows for a large participation of small assets (e.g., heat pumps and electric boilers) and industrial combined heat and power plants. However, non-symmetric bids are not allowed, hindering the participation of flexible loads, such as electric vehicles. Despite that the mFRR and RR products are characterized by high bidding size (10 MW) and the impossibility of aggregating demand and generation in the same pool, the participation of DERs is quite important, reaching 1 GW of mFRR and 500 MW of RR. It is worth noticing that almost 50% of this capacity is provided by demand-side resources, such as industrial loads [17].

Finland has a wide variety of ancillary services, the majority of which are open to all resources. Fast frequency response is fully open to DERs, especially storage systems. The minimum bidding size is relatively low, 1 MW, and the aggregation of demand and generation assets is allowed. These conditions result in the high participation of DERs and storages in the supply of this product. FCR is divided into two different products: Normal Operation (FCR-N) and Disturbances (FCR-D). The first one is a symmetric product having a minimum bidding size of 0.1 MW, while the latter is characterized by non-symmetric bids. Furthermore, aFRR and mFRR products are open to pools of DERs and the bidding size is 1 MW and 10 MW, respectively. In 2022, 630 MW of mFRR capacity have been procured through DERs [13].

Similar to Finland, Denmark, in 2020, introduced the FFR product, which is procured through daily auctions open to all resources, including generation and demand, with a minimum bid size of 0.3 MW. Denmark is subdivided into two synchronous areas: the Western Denmark area (DK1), connected to the central-European countries, and Eastern

Denmark (DK2), synchronized with the Nordic area (e.g., Sweden and Norway). In DK1, the FCR is procured through daily auctions opened to pools of demand and generation with a minimum bidding size of 1 MW. In DK2, the minimum bid size is reduced to 0.1 MW. This ensures an interesting opportunity for DERs, especially electric vehicles, whose participation in the Danish FCR is particularly advanced [18]. aFRR in DK1 is procured through monthly auctions, and multi-technological DER portfolios are allowed. Bids are symmetrical with a minimum size of 1 MW. The participation of DERs in mFRR markets is hindered by the high bid size (5 MW).

Regarding the Italian scenario, the participation of aggregators in the ASM is possible since 2017 within experimental initiatives [19]. Different types of pilot projects have been activated to this purpose, exploring how Enabled Virtual Units (Unità Virtuali Abilitate: UVA), involving different DER and RES technologies, can supply services to the transmission system. So far, projects related to UVAP (including production units from programmable and non-programmable units), UVAC (including only load), and UVAM (including a mix of load and generation, energy storage systems and electric vehicles) have been set up [20]. The regulation services that can be provided within the projects are limited to mFRR and RR, and a minimum bid size of 1 MW is considered [21]. A dual remuneration scheme is applied based on both the available capacity (€/MW) and energy activated (€/MWh). More recently, a few other initiatives have been run to enlarge the pool of potential flexibility providers and the number of ancillary services' typologies to be offered. In particular, in 2021, a dedicated project started where enabled virtual units are allowed offering also aFRR [22]. Moreover, with a similar experimental approach, FFR can now be procured as well (however, in this case, a minimum bid size of 5 MW applies) [23]. A better DER integration in the power system also entails greater use of their regulation capabilities at the distribution network level. To this purpose, the Italian Energy Authority also pushed for the launch of pilot initiatives managed by Distribution System Operators (DSOs) focused on the collection of local grid services (i.e., aimed to support the medium and low voltage grid operation) [24].

2.2. Analysis of the Scientific Literature

Despite several national peculiarities, the survey in the previous section highlights a common path of EU member states toward the opening of electricity markets to DERs. In recent years, researchers have also dedicated increasing attention to the topic.

To systematically capture the most significant scientific works in this field, a two-layers approach has been applied to the initial database described in Section 1. Initially, the full database has been filtered to select only documents relevant to the topic covered in the present section. To this purpose, keywords such as *market*, *policy*, and *regulatory* have been used. This way, 5001 works were found. Then, additional queries have been employed to discern the specific topic of the articles: works have been classified according to keywords in Figure 2, which reports also the cardinality of each group. As it is possible to see, *local*, *real-time*, and *incentive* are the most frequently adopted terms, and they, respectively, appear in 23%, 19%, and 18% of the documents. It is worth noticing that the sum of the bins' height (5911) is higher than the total number of articles analyzed (i.e., 5001), since an article can be assigned to several groups. On average, a mutual-overlap value of 15% is found (i.e., 910 articles are allocated to more than one cluster). In some cases, however, the mutual-overlap between two or more clusters is 3 or 4 times higher, indicating that the entries they contain are closely related and can be investigated together.

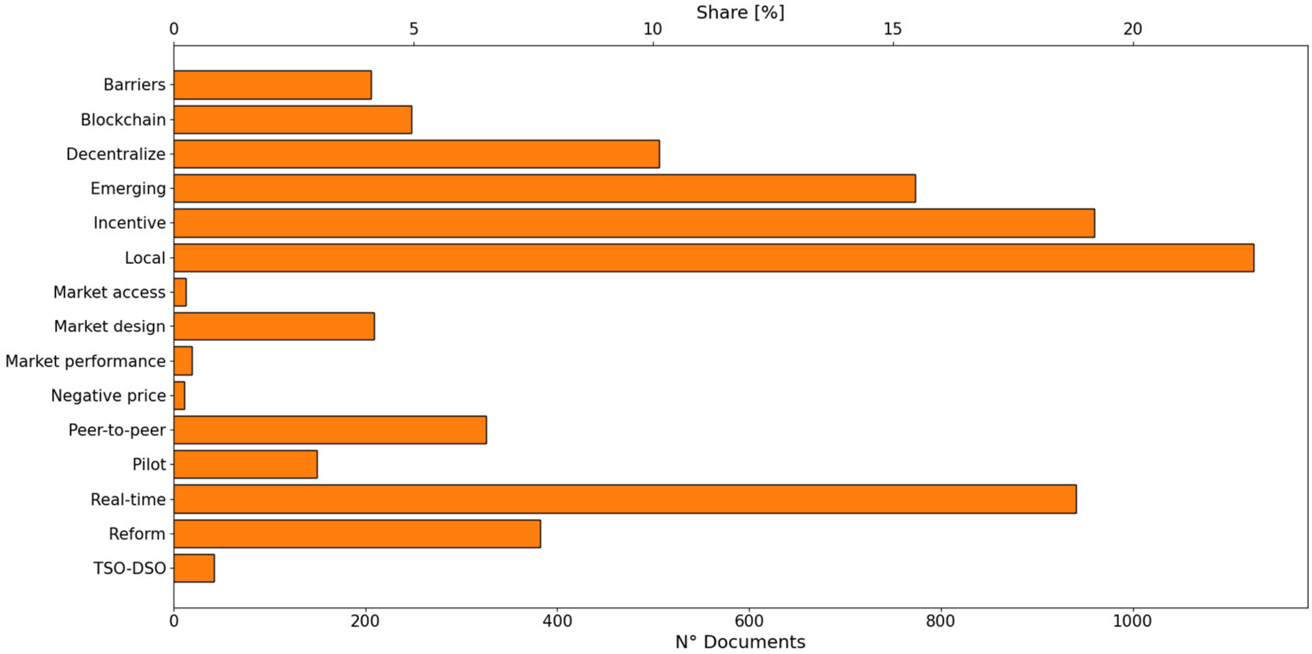

Figure 2. Number of documents including keywords related to the topic of interest (reformation of market structure to enable the access of DERs), both in absolute terms and percentage with respect to the total number of documents.

In particular, three main research areas have been identified:

(i) DERs' impact on the markets, composed of the articles included in the clusters *market access*, *market design*, and *real-time*, having an overlap index of 62%.

(ii) Wholesale market reforms, collecting works with keywords *reform*, *barriers*, or *pilot*. In these groups, out of 380 articles contained in the dataset *reform*, almost 160 are also included in those of *barriers* or *pilot* (50% of overlap).

(iii) Local market design, which is the main subject of the documents covered in datasets *local*, *peer-to-peer*, and *decentralized*. In this case, a mutual-overlap of about 45% is found (i.e., 45% of the documents in the cluster *local* are also present in the *peer-to-peer* or *decentralized* datasets).

The first research area collects works that quantify the impacts of DER portfolios in the electricity markets. In this cluster, the most adopted methodology is based on unit commitment models [25]. However, more recently, approaches based on game theory are implemented [26]. In [27], the participation of DER aggregates in the electricity market is modeled. The authors design a dual clearing mechanism to promote RES production and the market equilibrium is obtained by adopting a co-evolutionary algorithm. In [28], a novel mechanism for the integration of DER pools in the markets is proposed. Dispersed resources receive both energy and capacity payments on the wholesale market to foster their active participation. A comparison with a case study in which DERs do not participate in the market is also provided.

The second identified research path collects works that explore possible reforms to the current regulations to facilitate the DERs integration in the wholesale and balancing markets. For example, the authors in [11] propose a meta-analysis of hundreds of documents to evaluate different regulatory aspects to promote the integration of DERs in the ASM. Among the different evolutions, the possibility to bid asymmetrically, the reduction of the minimum bid size, and the increase of the aggregate procurement perimeter are the most effective ones. The study in [29] underlines the importance of combining different assets and technologies (generation, flexible loads, and storage) in the same VPP to improve the versatility of the BSP's action. According to [30], the reduction of the time between the market's closure and the delivery is beneficial since the uncertainties of the variable resources are largely reduced.

The last identified research area involves papers that propose the adoption of local markets, usually managed by DSOs, to enable the participation of prosumers. The increasing interest of the scientific community in this sector is proved both by the number of works in the literature (more than 1200 unique documents) and the fact that on average they have been published in 2020 (almost 68% of them published in the period 2019–2022). On the other hand, the average year of publication of the articles contained in the remaining groups is 2018, and only 55% of them are published after 2019. In the following, some representative articles included in this third research field are reviewed.

Study [31] presents a local ancillary service market managed by a DSO, specifically designed to be easily implemented in the European regulatory framework. In [32] and [33], local peer-to-peer markets are designed to trade electricity among distributed resources. In both cases, neither the network constraints (i.e., voltage profiles or congestion management) nor the possibility to offer ancillary services to the DSO are modeled. Despite that many works conclude that local markets bring benefits for end-users and DSOs [34], some concerns emerged, such as low market liquidity, security, and transparency issues, and price volatility [35]. Furthermore, the participation of DERs in local markets should not inhibit the possibility to bid in the global market managed by the TSO. However, this requires integrated approaches that recognize the increasing potential of DERs to provide both local and system services. For this reason, suitable coordination schemes between the different actors (i.e., DER units, BSPs, DSOs, and TSO) need to be promoted to support the exploitation of DERs' flexibility in each level of the network and the development of consumer-centric market models. In this regard, the following section provides a detailed analysis of the emerging trends on the topic.

3. Control, Coordination, and Planning Strategies for Aggregators and Network Operators

The management of a heterogeneous combination of DER units, dispersed on the territory and characterized by hardly predictable power profiles, is a very challenging task. Therefore, in the literature, great effort has been aimed at the development of tools capable of increasing the programmability of DERs managed by a BSP. This topic is thoroughly discussed in the following. Moreover, the aspects relevant to the optimal strategies for the acquisition of ancillary services by network operators and their integrated operation and planning are also analyzed.

To systematically review the literature's works, an approach very similar to the one described in Section 2 has been adopted. The initial database (containing almost 63,700 unique works) has been filtered through the following keywords: *scheduling*, *optimization*, *dispatch*, *planning*, *bidding*, and *coordination*. These keywords have been selected based on the classification proposed in [36,37], and they have been designated to filter only the works actually related to the topic of interest. Starting from the initial database, 24,171 articles have been chosen and assigned to one or multiple sets. Indeed, as previously discussed, each work can belong to multiple groups since the keywords adopted are not self-exclusive.

From the pool of articles analyzed, more than one-fifth (4923 out of 24,171) deals with the *scheduling* topic. In general, these works propose strategies to manage DER portfolios, considering weather forecast uncertainties [38], network constraints [39], and pollution emissions [40].

About 2500 papers analyze the bidding strategies during market participation. Mainly, these research studies propose strategies to optimize the bidding process on the day-ahead [40], balancing, and reserve markets [41]. Less frequently, the arbitrage opportunities between the day-ahead electricity market and the other markets are assessed [42].

Finally, it is not surprising that a considerably large number of works (16,022 papers) applied optimization algorithms to manage the resources. Profit maximization [43], CO_2

emissions control [44], and ancillary services provision are the objectives mainly investigated. It is worth noticing that almost 2300 works include the provision of grid services as the main scope of the article; in this regard, the most investigated applications are congestion management [45], frequency regulation [46], and voltage control [47].

To extend the proposed analysis and suggest future directions of the literature, the intersections between the different document clusters are analyzed (i.e., works that are simultaneously present in two or more groups). In particular, the diagonal elements in Table 2 represent the total number of works in each group, while the extra-diagonal ones account for works simultaneously included in the two clusters specified by column and row labels. For example, 2081 papers focus on the BSP's bidding strategy, and 35% of them (727) adopt an optimization procedure (see the intersection between the row "bidding" and the column "optimization"). Some examples are references [48,49]. It is worth noticing that 5262 works are focused on the planning phases of a VPP; however, only 96 of them (less than 2%) consider the profit arising from an adequate bidding strategy, see, for example, [50–52]. Therefore, this lack in the literature should be considered in future research.

Table 2. Total number of works in each group (diagonal value) and overlaps between the groups (extra-diagonal value).

	Scheduling	**Bidding**	**Optimization**	**Dispatch**	**Planning**	**Coordination**
Scheduling	4923					
Bidding	312	2501				
Optimization	2222	545	13,432			
Dispatch	851	259	1714	4384		
Planning	335	96	1544	359	4777	
Coordination	303	139	775	325	197	2598

Concerning the algorithms adopted, two approaches are identified: centralized and decentralized architectures.

Around 8200 articles propose centralized approaches to manage DERs. In a centralized architecture, all resources are connected to a single control unit, which gathers all the information available and plans the power exchanges of each DER. On the other hand, in a decentralized system, each DER is equipped with a controller that makes decisions independently after receiving data shared by the other resources. It is undeniable that centralized architectures are capable of achieving greater performances [53]; however, they also present scalability issues, limiting the VPP size to a few hundreds of units [54]. Moreover, the protocols and reliability of the communication channels required to transfer all the information to the centralized unit remain critical aspects [55], as the bandwidth of the communication channel, which can range from tens to hundreds of kB/s, and rapidly grows when new DERs, are connected [56]. The algorithms most frequently adopted to manage and coordinate the DER units in the BSP portfolio are Mixed Integer Linear Programming (MILP) modeling [57], deep reinforcement learning [58], metaheuristics (e.g., genetic and particle swarm algorithms) [59], stochastic and robust optimizations [60], and adaptive control [61]. As mentioned above, the scalability issue is one of the main drawbacks of centralized architecture. However, this issue can be partially overcome through specific algorithms. In [62], an approach is proposed based on a mixed integer non-linear problem to optimize participation in the wholesale energy and reserve markets of a set of units composed of deferable loads, RESs, and battery systems (both ESS and electric vehicles). Despite the complexity of the model, the approach results to be suitable to manage thousands of cars, since a clustering and disaggregation method is specifically designed by the authors.

The systematic review shows that 3000 works adopt a decentralized optimization method. The algorithms used more frequently are alternating direction method on the multiplier [63], computation offloading [64], blockchain (or cloud computing) [65], and distributed robust optimization [66]. For example, in [67], a decentralized architecture, based on a stimulus-response control and reinforcement learning method is proposed to control thousands of DERs (photovoltaic, electric vehicles, and air conditioners). Another representative example of decentralized architecture can be found in [68], where a blockchain model is employed to aggregate several prosumers and provide ancillary services to the power system. The approach captures the technical constraints of the users (e.g., available energy profiles and energy requirements), and remunerates the prosumers that provide the services.

Looking at the resources included in the BSP's portfolio, renewables are the most investigated ones [69,70]. In Figure 3, the number of yearly published articles citing the term *renewable* is shown. As it is possible to see, the total number of works related to this topic is growing considerably over the last 10 years. It is not surprising that a strong correlation exists between the number of these articles (green line) and the number of works dealing with uncertainties. This is shown by the black line in the diagram, which represents the number of published works per year including the term *uncertainty* (or variants), while the orange and blue bars represent the number of articles referring to *stochastic optimization* or *robust optimization* (i.e., the most common approaches to make decisions under uncertainty).

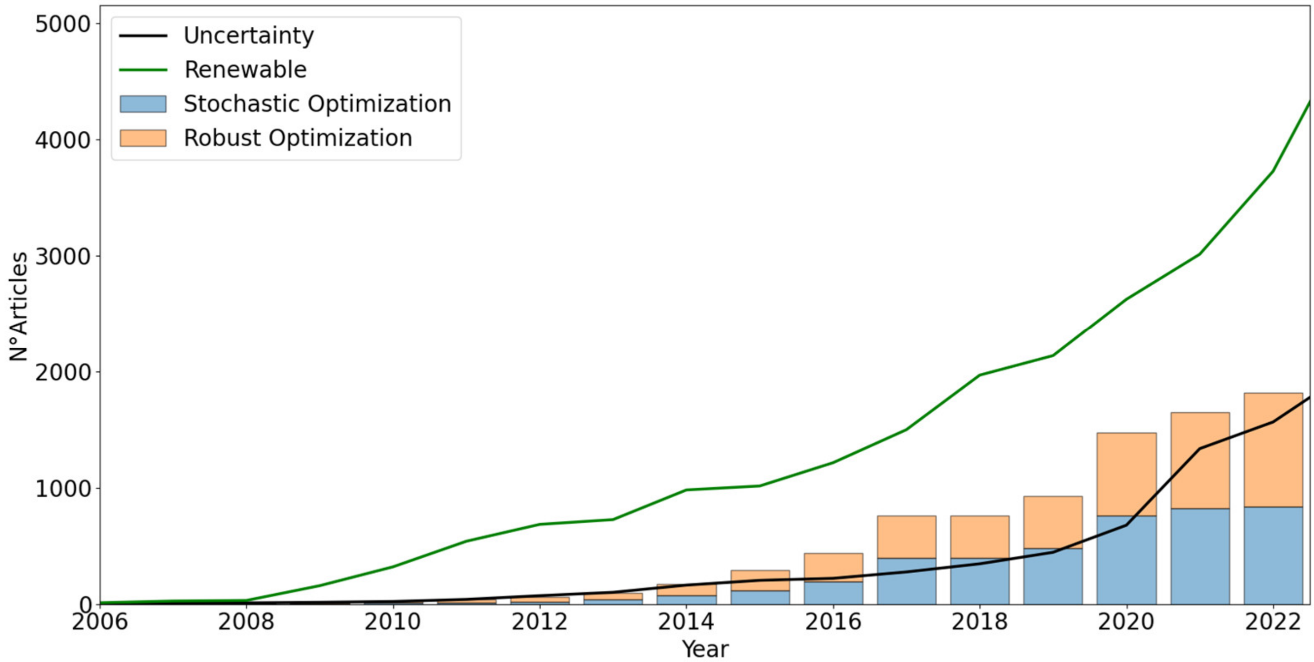

Figure 3. Comparison between the yearly number of articles matching with "renewable" (green line) and "uncertainty" (black line) keywords. The bars represent the number of articles in which "stochastic" or "robust optimization" keywords are present.

The impact of the randomness on the coordinated management of DERs is significant, especially when the RES share is also significant. The authors in [38] estimate that, considering uncertainties during the day-ahead market (DAM), participation allows for reducing operational costs by 6%. This result is achieved by comparing the performances of a two-stage stochastic programming approach with a deterministic MILP model. The test is performed considering a smart parking lot, equipped with charging stations for e-cars, stationary energy storage systems, and PV plants.

Similar considerations are presented in [71], in which the uncertainties of RES generation and market prices are modeled through stochastic scenarios. Furthermore, the influence of the willingness to risk the BSP during market participation is analyzed by adopting the conditional value at the risk metric in the objective function [72]. A similar approach is provided in [73]. Day-ahead uncertainties are also investigated in [74], in which an optimal bidding strategy is proposed for an aggregate of electric vehicles. The real-time performances are evaluated both for a centralized and decentralized approach, and the results are compared. The bidding process on the DAM greatly affects the participation in the ASM, since the commitment resulting from a non-optimal day-ahead scheduling can compromise the capability of the DER units' portfolio of offering services on the ASM. Therefore, several papers explore coordinated bidding strategies aiming at maximizing profits and service provision reliability on both markets. This is the case of [75], in which an optimal bidding strategy is developed for a VPP participating in the day-ahead frequency regulation market and the energy market, or of the study in [76], proposing a formulation applied to an energy community that models the day-ahead and the intraday markets as first- and second-stage decisions, taking into account the offering of reactive power as an ancillary service. In [77], a BESS is considered, which is used by a private owner to maximize its profit while facing price uncertainty. A joint active and reactive power market involving the day ahead and the real-time markets is cleared to determine hourly prices of active and reactive power; then, in a second stage, the robust bidding model aims to maximize the BESS owner's profit, taking into account the prices uncertainty.

In [38,71,73], the uncertainty parameters are modeled by simulating several scenarios, each one characterized by a different outcome of the uncertain parameters. However, this requires modeling, accurately, the stochastic behavior of all factors affecting the problem. To overcome this issue, in [78], a stochastic adaptive robust optimization model is proposed. One of the main advantages of this approach is the possibility to model some of the uncertain parameters through a scenario-based method (similar to the stochastic model), while other uncertainties are modeled by defining confidence bounds and polyhedral uncertainty sets, making the modeling of the uncertain variables less challenging.

Table 3 shows an overview of the literature review performed in this section. From the table, it is evident that most of the decentralized methodologies do not account for RESs and load stochasticity, but they are more suitable to deal with large VPPs. Furthermore, as analyzed in [5], despite that the topic has been investigated in depth in the literature, just in a few cases, the algorithms proposed have been tested in real life.

Table 3. Main research studies regarding the control and coordination strategies for aggregators.

Reference	Method	Resources	Uncertainties
[38]	Centralized Stochastic + rolling horizon optimization	Electric vehicles, PV plants, ESSs	✓
[62]	Decentralized Reinforcement learning control	PV plants, electric vehicles, air conditioners	×
[68]	Decentralized Block-chain model	PV plants, flexible loads, ESSs	×
[62]	Centralized MINL model	Flexible loads, RESs, ESSs, electric vehicles	✓
[79]	Decentralized Nash–Harsanyi bargaining game theory	Power-to-hydrogen, RESs, ESSs, electric loads	✓
[71]	Centralized bi-level stochastic model	Conventional power plants, PV plants, ESSs, demand response	✓
[67]	Centralized Stochastic adaptive robust optimization	Wind and solar plants, ESSs, flexible load	✓

Another aspect covering great interest in the literature is represented by the coordination schemes applicable between the TSOs and DSOs, which should be able to guarantee the effective operation and planning of both transmission and distribution networks, unlocking the DERs potential. For such a reason, the TSO–DSO interface gained increasing attention from researchers in the last years, and extensive literature has been published on the topic.

The author of [80] introduces a thorough framework concerning the optimal operational planning (day-ahead scheduling) and operational management (real-time dispatch) of active distribution systems under uncertainties. A two-stage stochastic programming model is proposed to optimize the scheduled power flows at the TSO–DSO interface and reserved DER flexibility services. Furthermore, the possible grid criticalities (e.g., line congestions, voltage violations, and distribution system balance) are also included in the formulation. Subsequently, the operational management, realized with a predictive real-time dispatch model based on a constantly updated rolling horizon, aims to efficiently activate the available flexibility services to minimize deviations from the committed schedule.

The authors in [81] propose a novel TSO–DSO coordination method that aims to optimally procure ancillary services from DERs. The three-step approach consists of (i) the provision of active-power flexibility by the DSOs, (ii) procurement of active power by the TSO, and (iii) optimal re-dispatch of existing flexible resources by DSOs to maintain the committed active-power schedule at their TSO–DSO interface. The method is based on two deterministic multi-period alternate current security-constrained optimal power flows at the TSO level and DSO level. The procedure, formulated as a non-linear programming problem, allows for guaranteeing the N-1 security criterion on the transmission grid.

The author of [82] presents a cost-based TSO–DSO coordination model to quantify the value of local flexibility services and analyzes its impact on the transmission grid expansion and the system operation. The model's objective is to minimize the overall cost of transmission investments and procured flexibility. This is achieved by using a bilevel optimization criterion where the power exchanges on all connected grid interfaces are controlled. The authors in [83], instead, present a hierarchical planning framework for distribution and transmission in a coordinated manner. Uncertainties that affect the load profiles and line contingencies are modeled, and a flexibility provision from loads and ESSs is used to accommodate more renewable energy.

4. Technological Aspects Related to the Provision of Flexibility by Distributed Energy Resources

The integration of DERs in the ancillary services markets requires a clear identification of the regulation services actually needed by the system and control capabilities that can be offered by dispersed units. Regarding the latter point, it is also essential to invest in research and development to remove the technological barriers preventing effective participation in the market of different DER technologies.

In this regard, it is of primary interest to investigate which are the technological aspects that, according to the current literature, must be taken into account. In particular, many papers provide definitions of flexibility [84,85]; nowadays, many of these are outdated, and some important criteria are missing to clearly state what flexibility means for electric power systems and DERs. The authors in [86] tried to fill this gap by suggesting an updated definition of flexible DER (fDER): any type of technology can be involved, both on the user and grid sides, even with a limited duration of activation (between seconds to several hours); however, the response to an external need must be guaranteed, i.e., flexible resources should activate to satisfy a request of an external subject (e.g., the TSO) for front-of-the-meter services. Therefore, DERs using their regulation capabilities just to provide benefits to the user (behind-the-meter-services) cannot be considered as flexible resources (from the TSO/DSO's point of view).

To find the research studies available in the literature that deal with technological aspects of fDERs, the initial database has been filtered using keywords related to the most common DER technologies (Figure 4). This way, a dataset of 55,648 works has been obtained. It is worth noticing that, in Figure 4, most of the works are related to the keywords *photovoltaic*, *wind*, *storage systems*, *electric vehicles*, and, *demand response* (with more than

6000 works each), while *biogas*, *biofuel*, and, *combined heat and power* represent a minority. As for the previous classification in Section 2, the sum of the bins' height exceeds the total number of articles analyzed, since each article can be associated with multiple clusters.

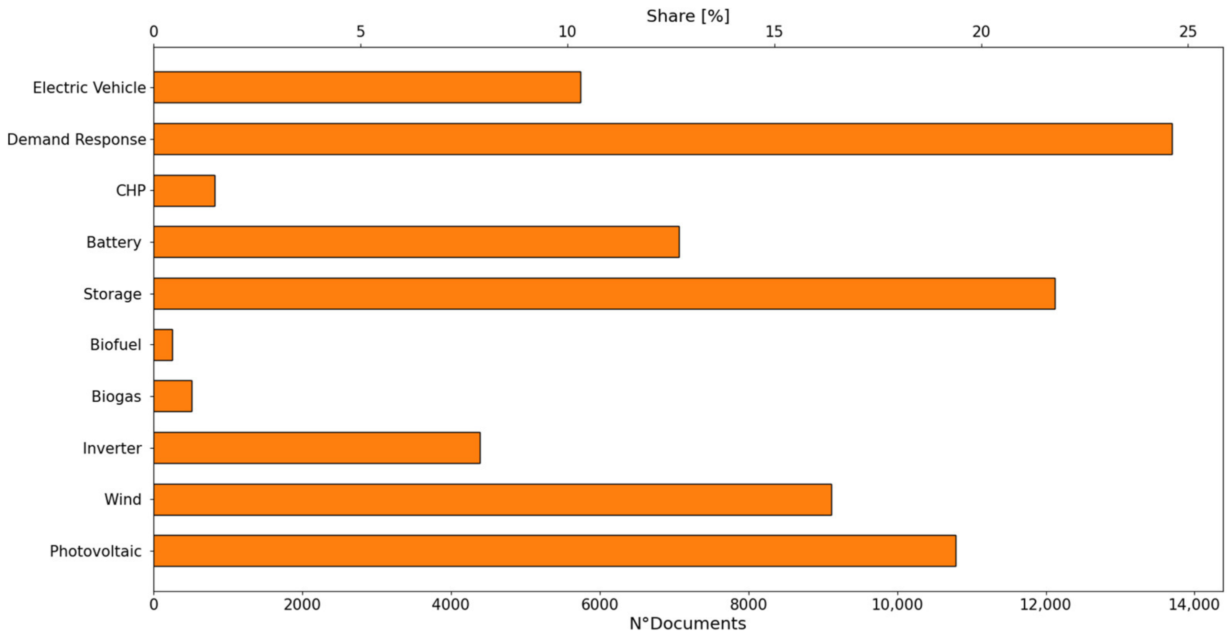

Figure 4. Number of articles, including keywords, related to the topic of interest (technological aspects related to the provision of flexibility by DERs), both in absolute terms and percentage with respect to the total number of documents.

Starting from this classification, in Section 4.1, an overview is provided about the flexible resources more explored in the literature, as well as their applications and technical limitations. Then, in Section 4.2, a classification of fDERs, according to specific technical indexes and trends, is reported; finally, in Section 4.3, the existing communication technologies to coordinate DER units are described together with relevant issues.

4.1. Literature on Flexible Distributed Energy Resource Technologies

Ancillary services supplied by fDERs can be divided into transmission system-oriented (e.g., reactive power support and frequency regulation) and distribution system-oriented (e.g., voltage control and congestion management) [87]. The suitability of the flexible resource in delivering a specific service depends upon the characteristics and the technical constraints of the resource itself (e.g., time response, power/energy capacity, and recovery period) [86].

The spread of generation from renewables is widely recognized as a possible solution to environmental challenges [88]. Many national grid codes worldwide recently introduced prescriptions for distributed and small-sized power units that require the possibility for the TSO and DSO of delivering power setpoint signals to adjust, dynamically, their active and reactive power [89]. The response time to these setpoint signals, especially for inverter-based units (e.g., PV), is generally fast [90,91]. In [92], a methodology is presented to determine the RESs' parameters of the power/frequency droop curves to ensure specific frequency regulation characteristics for the transmission system, while in [93], a droop-based voltage regulation is proposed to minimize the reactive power consumption and line losses. Nevertheless, the main limitation of production from RES, such as PV systems and wind turbines, is related to their stochastic and intermittent nature [94], which may lead to abnormal frequency deviations and dynamic stability issues [95]. In [96], the major technical limits related to solar and wind power plants are discussed, and a new imbalance mitigation strategy is introduced. In [97], a novel configuration to implement on PV panels with the aim to increase flexibility of the power exchanges of a building is presented.

Demand Response (DR) is another promising way of supplying flexibility services to the power system: it involves consumers who are incentivized to reduce or shift their electricity consumption during times of high demand. The response time of DR strategies greatly varies, depending on the loads and consumers involved: small loads can react faster than thermal conventional units [98]. In particular, different designs of DR programs have been proposed in the literature, characterized by different objectives, load involvement levels, and decision variables. A comprehensive review of DR programs is provided in [99], while [98] describes different control strategies for optimizing DR programs, such as direct control, real-time pricing, and critical peak pricing. However, it should be noted that the application of DR programs as a flexibility source faces various challenges, such as the need of changing electric consumption patterns [100,101]; moreover, conventional meters and non-variable billing policies are not adequate for implementing time-varying tariffs. Smart meters, secure and reliable communication infrastructures, and responsive loads must be available [102].

ESSs are a valuable source of flexibility for power systems. Specifically, they are considered promising solutions to provide fast frequency reserve due to their fast response times and high reliability [103]. In [104], the results of a simulation study on the application of ESSs for providing FFR are reported in two different scenarios, referring to the current situation and a 2040 projection. In [105], the main technical limitations of ESSs are analyzed, focusing on the challenges of their participation in the ASM. Even if pumped hydro storage still represents the highest amount of total storage capacity worldwide [106], smaller ESSs are becoming more popular: these are often based on electrochemical technologies, Batteries Energy Storage System (BESS), but also ultracapacitors, and flywheels [107]. BESSs are, today, the most promising type of ESSs, both for stationary and portable applications, given their fast dynamics and increasing lifetime. The strong interest in BESSs is also highlighted by the meta-analysis carried out in the present work: more than half of the documents analyzed that contain *storage* as a keyword, also specifically include the term *battery*. For the majority of BESS-related technologies, however, the development is still in progress [108]. A good trade-off in terms of cost, performance, and technology maturity is represented by lithium-ion batteries (Li-Ion) [109]. The attention toward this technology is also proved by the fact that, out of 7068 works related to BESSs found in the review analysis, 491 works contain also *Li-Ion* as a keyword, while just 192 mention at least one of the other electrochemical technologies (e.g., *Pb-A*, *Ni-Cd*, and *ZnBr*).

In the literature of recent years, an increasing focus can be observed on the use of the storage capacity of electric vehicles to perform grid services [110]. In particular, most papers consider a bidirectional power exchange between the car and the network by the Vehicle to Grid (V2G) technology, which allows the user to sell the energy stored in the battery pack of the vehicle to the grid [111]. Out of 5744 works related to electric mobility, 628 papers also present *vehicle to grid* as a keyword. The feasibility of V2G technologies and their potential contribution in the ASM have been explored in [20], while in [112], their participation in flexible services is discussed by varying e-car's battery capacity, and user's charging and driving habits.

4.2. Literature on Technical Indexes of Flexible Distributed Energy Resources

The sheer existence of fDERs is not sufficient to fully exploit their potentialities: enablers (i.e., electric market structures and regulatory grid codes [113]) are key factors for taking advantage of them. This section introduces an overview of fDERs technical characteristics impacting the ancillary service provision. In particular, as proposed in [114], both quantitative and control characteristics are considered.

Focusing on DER participation in the wholesale market, the quantitative characteristics have been defined in [115] by taking into account three indices: ramping rate, power capacity, and energy capacity.

The ramping rate is defined as the maximum change in the power output per unit of time, depending on the DER's internal dynamics. Usually, it is limited to a maximum ramping rate value that differs depending on the country: in [105], a comprehensive review about this parameter is provided according to national grid codes. In [116,117], the compliance of real PV power plants with the technical requirements established in the new Spanish grid code is evaluated; both papers suggest the practical applicability and compliance of the aggregated PV units with the considered prescriptions. However, in the literature, the computation of the ramping rate is not uniquely defined, and several calculation methods are proposed: in [118], it is obtained as the change in the output power between two successive time instances; in [119], it is obtained as the difference between the maximum and the minimum values measured during a specific time window; while in [120], it is obtained as the difference between consecutive boxcar averaged values whose width is a specific time window. In the latter, the ramp ratings of different BESSs are also evaluated.

The power output refers to the minimum and maximum power that can be provided by any flexible resource, specified both in active and reactive power [121]. Additionally, some papers introduce the direction of the regulation, depending on the flexible service required, such as a net increase in power output (e.g., increase in generation injection or decrease in power consumption), or vice versa [88,122]. Not all fDERs can provide regulation in both directions: for example, ESSs can both absorb and inject active power, while DR typically just reduces power demand [123].

The energy capacity concerns the maximum fuel or energy supply of a power source, and it is calculated as the upper time integral limit of the power output. It is an important parameter especially for ESSs: even if sometimes it can be considered virtually endless (as for large pumped hydro storages), for most ESS technologies this limit is finite [124]. In addition, after the activation period, the flexible resources often need to restore their energy status, drawing active power from the electric network; this process is called rebound effect, and it is common to all the fDERs having a finite energy output, but also to DR [125].

In general, in the ASM, high-capacity flexible resources provide energy-related services (e.g., tertiary and balancing regulations, and congestion resolution), while low-capacity flexible resources provide power-related services (e.g., primary control, and fast reserve) [91].

In addition, some studies, such as [115,126], include the response time as an additional technical index of flexibility, describing how fast an fDER reacts to an activation signal by the enabler. For example, large thermal generation units have slow time responses compared to BESSs; in contrast, BESSs can change their output quickly, but are limited in their energy and power capacities; in the case of DR and dispersed generation, it is worth noticing that the actual response time and power capacity depend greatly on the type of loads and distributed units involved.

The main bibliographic resources discussing the provision of grid services by the different DER technologies are reported in Table 4.

Table 4. Literature review about the applicability of different DER technologies to the specific grid service.

Orientation	Ancillary Service	Dispersed Generation	Demand Response	Energy Storage	Electric Vehicles
DSO	Voltage Regulation	[93,127,128]	[101,129]	[128,130,131]	[132]
DSO	Voltage Unbalance Mitigation	[133,134]	No	[135]	[136]
DSO	Congestion Management	[137]	[138–140]	[141,142]	[143]
DSO	Power Smoothing	[144,145]	[146,147]	[148]	[110]
TSO	Reactive Power Support	[149,150]	No	[151]	[152]
TSO	Inertial Response	[153–155]	No	[156,157]	[158,159]
TSO	Power Smoothing for grid stability	[116,160]	No	[161,162]	[163]
TSO	Frequency Response	[92,154]	[155,164]	[165]	[166,167]

Regarding the control characteristics of fDERs, two different approaches exist to collect the required grid services from dispersed resources: direct and indirect control [86]. In the first case, resources are primarily controlled through price signals, and DSOs or TSOs do not have direct control over availability or reaction time [121]. On the other hand, the second scheme assumes that fDERs respond to external control signals provided by enablers. The control approach is different according to the application: in the ASM, flexible resources are direct-controlled, while in the day-ahead market, the indirect approach can be useful for changing user patterns.

Direct-controlled resources are usually managed with a centralized approach [87,168], where a central controller delivers the required setpoint to all the regulating units involved [169]. Conversely, with a decentralized control, each flexible resource is governed by its own local controller, and set points are determined based on local measurements [170]: each controller is not entirely aware of the status of system-wide variables nor actions taken by other controllers. Table 5 shows the main advantages and disadvantages related to both approaches. The control strategy to be adopted on the single DER (remote-controlled or local) is strictly correlated with the control and coordination algorithms implemented at the TSO/DSO/aggregator level (see Section 2).

Table 5. Advantages and disadvantages of centralized and decentralized control strategies.

Control Strategy	Advantages	Disadvantages
Centralized (remote-controlled) [171]	Simplicity of management. Greater predictability of the system behavior. Greater efficiency, as the central entity can make decisions more quickly and accurately than many distributed entities.	Strongly dependent on the availability and reliability of the central entity. Poor fault tolerance. Less flexibility, as the central entity cannot always adapt to changing conditions in the distributed system.
Decentralized (local) [172]	Greater fault tolerance. Greater flexibility, as distributed entities can adapt to changing conditions in the system. Greater scalability, as it is possible to add new entities without having to modify the existing system.	Greater complexity of management. Less predictability of system behavior. Less efficiency, as decisions can be made less quickly and accurately than a central entity.

4.3. Literature on Data Handling for Distributed Energy Resource Management

In the centralized approach, the DER coordinated operation is made possible by information and communication technologies [173], which can be used to deliver signals to dispersed units and to collect measurements and information regarding the status of each component. On this topic, data handling becomes crucial for the opening of ASMs: DER management requires more data availability by the new market participants, such as VPPs or aggregators, while respecting confidentiality laws and customers' privacy [174]. Moreover, data processing is time-critical, especially where balancing or system services rely on DER's responses to control signals [175]. National grid codes establish the basic framework regarding the data required for operating the system: in some countries, such as Italy, a centralized power plant controller has been introduced to enable communication between the TSO, DSO, aggregators, and dispersed units [176,177]. A similar device is foreseen also to activate a communication channel with the charger of public and private electric vehicles.

In addition, proper data handling should be implemented to coordinate TSOs' and DSOs' needs in terms of information exchange for operational planning purposes, real-time operations [178], and to fulfill their tasks in the market [179]. Given the difficulty and cost to obtain real-time information from small-scale DERs [180], in the literature, several papers discuss different data handling strategies to improve TSO–DSO coordination. The author of [181] provides an overview of the developments made so far by five EU H2020 projects regarding data exchange architectures for TSO–DSO coordination: SmartNet, CoordiNet, TDX-Assist, INTERRFACE, and EU-Sysflex. Among the different coordination schemes investigated, the decentralized common TSO–DSO market model is considered the most challenging from the data transfer point of view. For real-time market and meter data exchanges, publish–subscribe protocols were, in general, conveniently implemented by all the demos. In [182], cloud computing techniques are investigated, concerning information and data exchange between TSOs, DSOs, and other actors or participants; it highlights that the TSO and DSO can benefit from utilizing cloud-computing platforms for exchanging information and data. Furthermore, using client-server mechanisms, i.e., request-response, is found appropriate for communicating synchronous market processes and grid data. The authors in [183] propose and evaluate a novel "business use case" methodology, based on the categorization of the IEC 62913-1 standard, which defines the necessary information and data that have to be exchanged between the TSO and DSO in order to exploit the DSO-connected resources for an overall system-balancing purpose. Finally, geographic routing [184], considering the physical location of nodes of the electric system as the basis for routing decisions, is identified in the literature as a useful approach to improve the efficiency and reliability of the network.

5. Conclusions

This study aimed to provide a comprehensive literature review regarding all the main aspects to consider for the effective distributed energy resources integration in the power system operation through the opening of national ancillary services markets.

The quali-quantitative analysis performed clearly showed the multi-faceted nature of the issue at hand, which makes close the collaboration between academia and industry essential to achieve the needed evolutions. In this process, a few different key topics are involved.

Legislations and policies must be updated and revised to support the active inclusion of all flexible DER technologies. The review analysis highlighted that this process is already ongoing in many countries in the EU, even if the approaches and solutions adopted are still far to be harmonized. A focal aspect in the discussion is represented by the minimum bidding size and other technical requirements applicable to DERs during the service provision (e.g., symmetric or non-symmetric products): if not properly defined, prerequisites can act as barriers to the feasibility and profitability of DERs' participation in the market. The interest and efforts of the scientific community on the topic have grown rapidly, especially in very recent years, mainly toward decentralized market structures. In the new paradigm, the TSO no longer operates as a single central counterpart in collecting (usually on large generators) the ancillary services needed by the power system, but the DSOs can also acquire services beneficial for the reliability and efficiency of the distribution grid.

Techniques and numerical methodologies to make DER units programmable and dispatchable, facing the intrinsic technical limits of relevant technologies, are another branch of the scientific and technological development impacted by the change. Aggregation and coordination of many single DERs with different (even complementary) characteristics is the solution commonly adopted to achieve the minimum level of controllability needed to access the ASM. To this purpose, most of the efforts are being directed at developing strategies to be adopted by balancing service providers to optimize the behavior of users distributed on a given territory, coping with all the uncertainties involved in the problem. In this regard, centralized architectures taking advantage of stochastic programming are one of the solutions most widely adopted, even if the computational complexity of the problem can suggest relying on alternative methods (e.g., decentralized optimization strategies). Scientific developments must also involve the control and coordination strategies for network operators, since, with the DERs spreading, the procedures usually adopted to identify possible issues on the electrical grid and select the ancillary services to collect could be no longer valid.

Research on how to increase the control capabilities of DERs to perform the control actions requested by the TSO or DSO is another key element for making the provision of flexibility services by DERs viable. Even if all DER technologies are involved in this process, inverter-based generators and especially electrochemical energy storage systems are covering the greatest interest. The fast dynamics and reliability in following the requested setpoints are some of the main advantages of batteries, even if the limited provision duration and costs are also factors to be carefully considered. Finally, dispatching DER units over the territory requires suitable communication and control infrastructures, where data handling must be performed respecting customers' privacy issues and guaranteeing high reliability, but also limiting the data exchange among all actors involved.

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Abbreviations

ASM	Ancillary Service Market
aFRR	Automatic Frequency Restoration Reserve
BESS	Batteries Energy Storage System
BSP	Balancing Service Provider
DAM	Day-Ahead Market
DER	Distributed Energy Resources
DR	Demand Response
DSO	Distribution System Operator
FCR	Frequency Containment Reserve
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal Operation
fDER	Flexible DER
ESS	Energy Storage System
FFR	Fast Frequency Response
mFRR	manual Frequency Restoration Reserve
MILP	Mixed-Integer Linear Programming
PV	PhotoVoltaic
RES	Renewable Energy Source
RR	Replacement Reserve
TSO	Transmission System Operator
UVA	Unità Virtuale Abilitata (Enabled Virtual Unit)
UVAC	Unità Virtuale Abilitata di Consumo (Load Enabled Virtual Unit)
UVAM	Unità Virtuale Abilitata Mista (Mixed Enabled Virtual Unit)
UVAP	Unità Virtuale Abilitata di Produzione (Production Enabled Virtual Unit)
V2G	Vehicle-To-Grid
VPP	Virtual Power Plant

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