Empowering Energy Markets: Unraveling the Dynamics of Aggregators Relationships in Demand Response Services

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Abstract

This comprehensive review examines the multifaceted relationships involving demand response aggregators within the electricity sector. Focusing on interactions with stakeholders such as electricity suppliers, system operators, distributed energy resources, and flexibility-requesting parties, the paper delves into critical aspects including market dynamics, compensation models, balancing responsibilities, and contractual frameworks. It explores the implications of different aggregator-supplier relationships, considering factors like balance responsibility, transfer of energy, and the rebound effect. The review analyzes the intricacies of aggregator-system operator relationships, including payment mechanisms for system services and the crucial role of data measurement. Additionally, it investigates the varied markets and services in which aggregators participate, ranging from wholesale energy services to congestion management and balancing. The paper highlights the relevance of defining flexibility products attributes such as availability, activation, and market conditions for pooling. Identifying gaps and uncertainties in existing literature, the review underscores the need for further research to enhance our understanding of the evolving role of demand response aggregators in shaping the modern energy landscape.

Keywords: demand response, aggregator, electricity market, compensation models, balancing responsibility, flexibility

1 Introduction

Climate change poses an urgent and critical need to transition towards a sustainable and clean energy system. The International Panel for Climate Change (IPCC) has highlighted the dire consequences of greenhouse gas emissions, predicting a 1.5-degree Celsius temperature increase by 2040 if no action is taken [25]. Addressing this global threat, the United Nations General Assembly introduced the 2030 Agenda, which includes 17 sustainable development goals, with goal 7 focusing on ensuring access to affordable, reliable, sustainable, and modern energy [25]. In line with this agenda, the European Union (EU) has emphasized increasing renewable energy consumption and overall energy efficiency to achieve its energy objectives [25]. The three most recent EU policy strategies have also emphasized promoting local energy production and establishing decentralized and sustainable energy systems [23, 24].

Demand Response is key in adapting energy systems for sustainability, efficiency, and resilience, aligning with global efforts to mitigate climate change and transition towards clean energy. But, what is exactly demand response? The EU defines it as "the change of electricity load by final consumers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bill to sell demand reduction or increase at a price in an organized market [...] whether alone or through aggregation" [26]. In the United States, the Federal Energy Regulatory Commission (FERC) defines DR as "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the prices of electricity over time, or to incentive payments designated to induce lower electricity use at times of high wholesale market prices of when system reliability is jeopardized" [33]. Aghaei et al. [2] defines it as "changes in the consumption of consumers in response to external factors such as electricity prices". The three definitions recognize DR as the adjustment of electricity consumption by end-users in reaction to electricity price fluctuations, incentive payments, or market signals to enhance grid reliability and reduce energy costs.

Agency for Cooperation of Energy Regulators (ACER) and the Council of European Energy Regulators (CEER) categorize DR into two groups [15, 46]: explicit (involves actors actively providing and managing flexible resources to balance electricity supply and demand) and implicit (consumers adjust their electricity consumption in response to changes in electricity prices). DR plays a crucial role in enhancing the safety and reliability of power systems [33]. Both explicit and implicit DR offers benefits such as decreased wholesale electricity prices for all consumers, risk-free opportunities for domestic and small commercial customers to participate in the market, and a potential reduction in the need for power generation investments and mitigate market dominance [7]. It also fosters energy conservation and emission reduction [33].

In 2016, the EU estimated a DR potential of 100 GW, projecting an increase to 160 GW by 2030 [17]. However, only 20 GW were used in 2016 [17]. Gils [27] emphasizes that industries, including steel, cement, pulp and paper, cooling, air conditioning, and washing equipment, possess substantial potential for providing flexibility. His estimation indicates a range of 61 GW to 172 GW for reducible load and from 68 GW to 499 GW for increasable load[27]. Household consumers account for a significant portion of the DR potential, which is expected to grow as more households adopt flexibility-enabling technologies like heat pumps [17].

Within this evolving energy landscape, decarbonization, decentralization, and digitalization offer new challenges and opportunities for new actors, such as aggregators [42]. According to Ikäheimo et al. [10], an aggregator is a company that acts as an intermediary between electricity end-users, Distributed Energy Resources (DER) owners, and other power system participants. Their role is to facilitate the provision of services to end-users and the utilization of services provided by DERs [10]. The European Consumer Organization (BEUC) defines an aggregator as an "energy service providers that can adjust the electricity consumption of a group of consumers based on the total demand of the grid" [10]. Additionally, they may operate for consumers who produce their electricity by selling the excess energy they generate [10].

Formally recognized in the EU Clean Energy Package [42], an Independent Aggregator (IA) is a "market participant engaged in aggregation not affiliated with the customer's suppliers" [26]. Aggregation, in this context, is defined as a function performed by an individual or entity combining multiple customer loads or generated electricity for sale, purchase, or auction in any electricity market [26]. When referring to this activity, the EU regulation uses the term "market participant engaged in aggregation" to indicate that aggregation might be combined with other activities [26]. It is worth noticing that while Balancing Responsible Parties (BRP) might align well with this role, Distribution System Operators (DSO) might not be suitable for aggregation responsibilities [38].

The societal benefits of DR outweigh the potential costs, and these services offered by IAs or retailers should prioritize consumers' ability to leverage their flexibility, separate from the sale of electricity itself [6].

Authors suggest that aggregators provide two forms of value in the power system [1, 10, 47]: system value, enhancing economic efficiency and reducing overall system costs while ensuring fair benefits distribution among consumers; and private value, denoting economic benefits for individual agents or specific groups, potentially leading to rent transfers among market actors, not always aligning with the system's broader value.

Muhaimin [38] proposes six value propositions for IAs, encompassing portfolio optimization for balance responsible parties (BRPs), offering DR as regulating reserves in the System Operator's balancing market, trading DR as regulating reserves in the System operator's balancing market, trading DR in organized energy markets, congestion management in distribution and transmission networks, and energy-data based secondary services. In contrast, Okur et al. identify five services for IAs, including trading flexibility in day-ahead and intraday markets, provision of power reserves, internal portfolio balancing, congestion management, and energy-data-based secondary services [39].

Aggregators may enhance energy efficiency and consumer awareness of electricity usage [47]. [36] underscores the importance of compensating consumers for their energy consumption flexibility based on realistic energy savings.

These actors have the potential to transform the energy system by enabling more decentralized and locally owned energy production and demand response, and by providing innovative services to consumers. That said, they also have many other advantages, such as the potential to reduce the need for scheduling reserves under significant renewable energy sources penetration, as they allow renewable energy producers to reduce their imbalances [41]. However, relevant issues still need to be solved, hindering the growth and development of these innovative energy models. In fact, as shown in 1, the number of aggregators widely differs between countries and remains well below the number of suppliers.

Table 1 Number of aggregators, distributors, and suppliers in selected European countries (n.a. means 'non available', as there is no official registry).

Number of...	France	Italy	Portugal	Spain
Suppliers [13, 13, 21]	93	122	48	504
Aggregators [22, 45]	15	30	n.a.	n.a.
Distributors [5, 14, 20, 48]	144	122	11	321

The rest of the paper continues as follows: section 2 presents the methodology used in the paper. Then, the next sections present the challenges of aggregator with other agents: 1) the electricity supplier (section 3), 2) distributed energy resources (section 4), system operators (section 5), and flexibility requesting parties (section 6). Finally, section 7 concludes.

2 Methodology

Based on [3], the provision of flexibility by an independent aggregator may be divided into six phases: preparation/prequalification, plan/forecast, market, activation, monitoring and measurement. In particular, the preparation/prequalification phase involves undergoing technical evaluations to ensure that their resources (like energy storage systems, demand response capabilities, etc.) meet the technical standards required to provide the grid with the services it needs [3]. Then, at the plan/forecast phase, the Flexibility Requesting Party (FRP), which may be a System Operator (SO) or and agent interested in balancing its portfolio, analyzes its portfolio or the electrical grid internally to identify potential or existing issues, such as: balancing issues, congestion issues... [3]. After that, in the market phase, the SO opens a call for the market to provide solutions [3]. In the monitoring phase, once the FRPs have been selected, the SO monitors the grid's real-time conditions. Finally, at the measurement phase, the impact and effectiveness of the deployed services are measured against predefined conditions and agreements [3]. Table 2 summarizes the intervention of each of the agents at each phase.

Based on the described flexibility provision phases, the remaining four sections of this article analyze the relationship between the agents considered in Table 3 and the independent aggregator. To do so, this article is based on the report [37], adhering to the same methodological framework. It systematically explores the four principal relationships of independent aggregators, encapsulating the essence of the comprehensive

Table 2 Analysis of the involvement of the independent aggregator (IA), the System Operator (SO), the Distributed Energy Resource (DER), the Flexibility Requesting Party (FRP) and the electricity supplier during the different market phases. The market phases have been extracted from [3].

Phase	IA	SO	DER	FRP	Supplier
Preparation/Prequalification	X	X	X		
Plan/Forecast	X			X	
Market clearing	X				X
Activation	X		X	X	X
Monitoring	X	X		X	
Measurement	X	X		X	X

Table 3 Analysis of the interactions between the independent aggregator (IA) and the remaining agents [System Operator (SO), Distributed Energy Resource (DER), Flexibility Requesting Party (FRP) and electricity supplier] during the different market phases. The market phases have been extracted from [3], adding the settlement of the final client, which is not considered a market phase in those documents. The symbols represent the following streams: money (M); energy (E); information (I); and commands/asset control (C). The colors represent the direction of the streams: in green (M), must send or provide something to the aggregator; in orange (M), must receive or take something from the aggregator; in blue (M), may send or provide something to the aggregator; in magenta (M), may receive or take something from the aggregator; and in black (M), may go in any direction.

Phase	Client	SO	DER	FRP	Supplier
Preparation/Prequalification	**I**	**I**	**C**		
Plan/Forecast				**I**	
Market clearing					**M I**
Activation		**I**	**C**		**I**
Monitoring	**E**	**I**	**I**	**E**	
Measurement		**I**			
Settlement	**M**	**M**		**M**	**M**

review accomplished in [37]. By maintaining consistency with the report's methodology, this article ensures a thorough and accurate representation of the research, identifying the complex interconnections of the independent aggregators.

3 Aggregator-Supplier Relationship

While IAs share similarities with electricity suppliers acting as intermediaries for consumers, producers, and the market, their uniqueness lies in economic and energy flows. Table 4 provides a comparative overview of these flows. This section covers the main aspects of the relationship between the aggregator and the supplier.

3.1 Framework of the relationship between aggregators and suppliers

The USEF model categorized the relationship between aggregators and suppliers (actors that supply energy, being supply the "*sale, including the resale, of electricity to customers*" [26]) as contractual or non-contractual [30]. Poplavskaya and de Vries also introduce whether an aggregator's portfolio exceeds a supplier's BRP. It means

Table 4 Comparison between the relationship between the IA and the consumer, and the relationship between the supplier and the consumer.

		From the Independent aggregator	From the Supplier
Power system	Receives	E, S	M
	Takes	M	E
Final customer	Receives	M	E
	Takes	S, E	M

the aggregators have customers associated with multiple BRPs [43]. This scenario fosters competition in the balancing market, stimulates innovation, and benefits from economies of scale. However, managing such a portfolio entails higher optimization costs and increased complexity regarding financial compensation to suppliers [43].

In fact, aggregators exist in jurisdictions such as California and in Germany, but they must have an agreement with the suppliers to interact with a consumer [44]. In other words, they may not interact freely with consumers [44].

3.2 Balance responsibility

Balance responsibility for aggregators involves obligations to maintain their balance positions [30]. The USEF Foundation's framework (USEF model) defines this, emphasizing determining responsibility for aggregator-induced imbalances [30]. The aggregator's relationship with the BRP in the USEF model has two main forms [30]: single BRP or dual BRP. Furthermore, three imbalance compensation models are considered [30]: regulated (mandates compensation with legally defined amounts), contractual (involves bilateral agreements for compensation between the aggregator and suppliers), and no compensation (absence of a specific compensation mechanism).

Concerns exist about correcting imbalances caused by aggregators. Voltalis and Baker argue against correcting the suppliers' BRP, content that the aggregator's actions financially offset the suppliers' imbalance [7, 47]. The proposed "perimeter correction" mechanism aims to rectify the supplier's imbalance using the metered energy volume activated by the aggregator [47]. Challenges arise when accurately allocating imbalance and compensation to suppliers, especially when aggregators combine consumers from multiple suppliers [47].

Clear and well-defined guidelines are essential for fairness and effectiveness in balancing responsibility [48]. EURELECTRIC stresses the importance of allocating balancing responsibility for each supply point, ensuring consistent and accurate metering [48]. This approach prevents gaps, overlaps, ambiguities, or discrepancies in balancing responsibility among different actors, facilitating a smooth and efficient balancing process [48].

3.3 Transfer of energy

The sourcing position of a supplier characterizes the equilibrium between energy sold to retail customers and energy acquired from the energy market. In this context, "transfer of energy" denotes *sourcing and selling energy between the aggregator and the supplier* [4].

The sourcing position of a supplier is affected by the flexibility employed by an aggregator, influencing energy sales and requiring additional energy procurement [30]. Additionally, the transfer of energy between the aggregator and supplier plays a vital role in rectifying the sourcing position, establishing prices, and defining settlement procedures [30].

Compensation models for suppliers can be categorized into three types [30]: regulated (a central platform overseen by a third party like a regulator or TSO handles financial transactions and directs payments), contractual (bilateral compensation where the aggregator directly pays the supplier for differences in purchased energy) and corrected (involves the consumer paying the supplier as if flexibility had not been activated, with the aggregator compensating the consumer if necessary).

The regulated model, when managed by a third party, offers aggregator independence but faces criticism for potentially undermining customer savings [47]. Within this model, SEDC suggests that aggregators should compensate suppliers for average costs without additional benefits or losses, emphasizing symmetry in compensation [46]. Furthermore, clearly defined compensation provisions may mitigate disadvantages for suppliers and small consumers [7].

Last, SEDC recommends central management of adjustment mechanisms for the transfer of energy between the aggregator and the supplier to avoid conflicts of interest between the different parties [46].

3.4 Rebound effect on supplier's portfolio

The rebound effect, resulting from DR activation, causes a consumption delay or advancement [4]. This effect varies by charge type; for instance, EVs might exhibit a 100% rebound effect while other appliances may have a 0% rebound effect [4]. Lu et al. show that using electric vehicle aggregators to manage charging uncertainties only delays, not mitigates, uncertainties when recovery occurs within the time horizon [34].

Among the analyzed countries, France is the only country that has considered the rebound effect, particularly its impact on the aggregator's payment to the supplier [4]. However, its analysis does not extend to the effect on the BRP's portfolio, resulting in a lack of best practices for managing the rebound effect [4].

3.5 Information exchange

According to the USEF model, the supplier may provide the following information [30]: activation (which denotes initiating the service from a distributed energy resource) and volumes (which specify the quantity of demand response of flexible resources required by the aggregator).

3.6 Identified gaps

As described in this section, among the gaps in the relationship IA-supplier, first, it is necessary to standardize agreements between aggregators and suppliers to manage portfolio complexity and enhance market competition effectively. Second, it is relevant to define a comprehensive strategy for balancing responsibility, equipped with clear guidelines and fair compensation models to tackle the financial and operational challenges posed by aggregator-induced imbalances. Third, a detailed framework for energy transfer compensation must be defined to align the interests of suppliers, aggregators, and consumers, ensuring equitable compensation for adjustments in energy sourcing. Furthermore, it is necessary to analyze the rebound effect and its implications on the energy market, particularly concerning supplier compensation and balancing responsibilities. Last, improved clarity and efficiency in the information exchange between aggregators and suppliers is crucial for supporting demand response initiatives and flexible resource management. Table 5 summarizes the aspects treated in this section.

Table 5 Different dimensions of the relationship between the aggregator and the supplier.

Characteristic	Possible values
Balance responsibility [30]	Single BRP; Dual BRP
Compensation for imbalances [30]	Regulated; Contractual; None
Compensation for the transfer of energy [30]	Regulated; Contractual; Corrected
Information exchange [30]	Activation; Volumes
Rebound effect [4]	Considered; Not considered

4 Aggregator-Distributed Energy Resource

As presented in Table 6, Broyaux et al. provide a classification of the types of loads based on the type of consumer [9]: industrial (refer to large industrial consumers where the load cannot be shifted to other timeframes, and a single consumer's load is usually sufficient to provide the required service. Supply contracts for industrial consumers are typically signed for many years, simplifying the relationship between the aggregator and supplier), and residential loads (require aggregation to provide a service since a load of each individual residential consumer is usually too small, may also have a rebound effect, and the relationship between the supplier and aggregator becomes more complex because residential consumers are free to change their supplier at any time). In residential-focused IAs, the administrative complexity of managing such loads rises due to the necessity of tracking and managing interactions with various actors [44].

Table 6 Classification of the loads by Broyaux et al. [44].

	Industrial	Residential
Easily changes supplier	No	Yes
Needs to be aggregated	No	Yes
Rebound effect	Not generally	Yes
Smart metering device	Deployed	Might be deployed

Okur et al. provide a comprehensive categorization of household appliances based on their behavior, which is essential for understanding their flexibility potential [39]:

Non-flexible appliances (such as computers, televisions, and lighting, have consumption patterns that are not easily adjusted without causing significant inconvenience to consumers), semi-flexible appliances (washing machines, dryers, and dishwashers, can be shifted or curtailed with prior notification to consumers without causing much inconvenience) and flexible appliances (such as refrigerators, freezers, ventilation systems, fans, and heat pumps, can be shifted or curtailed with short notice without causing any inconvenience).

Based on this characterization of the DERs loads, this section covers the relationship between the aggregators and the DERs. At the end, Table 7 includes the aspects treated in the section.

4.1 Submetering

On the one hand, the split model separates flexibility assets from the rest of the load, installing two meters, one for each kind of asset (controllable and non-controllable) [30]. On the other hand, submetering designates the measuring of energy behind the main metering system of the client [9]. The latter is due to certain aggregators to control interruptible equipment such as heat pumps, electric water heaters, and electric vehicles.

The usage of submetering generates new questions on how to rule its power accuracy and certification requirements, as stringent rules might reduce the viability of many business models [12]. Methods like statistical averaging or measurements help decrease the overall error in equipment, potentially enabling the use of less precise equipment [9].

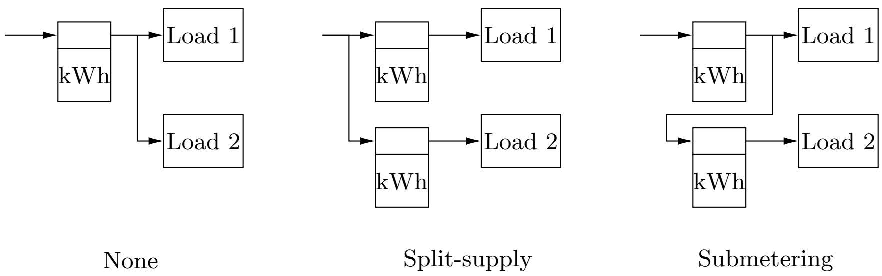

Figure 1 Comparison among the usual meter configuration (left), split-supply (center), and submetering (right), considering that "Load 1" is non-flexible while "Load 2" is flexible and is managed by a given IA. The arrows indicate the energy flow.

4.2 Baseline profile

The baseline profile, a crucial aspect in assessing DER services, is a reference for verifying DER and aggregator performance. It best approximates the power consumption profile without a DR event [30]. Various baseline methodologies exist, including [28, 49]: baseline submitted by the flexibility service provider (the DSO uses a consumption or generation profile provided by the DSP before activation), high X of Y (various criteria can be applied to select certain metered data from the last day, which are then averaged to calculate the baseline profile, including actions such as excluding holidays or selecting only certain days with the highest consumption), meter before/ meter after (it estimates the provision of the service by using the metered value before and after activation), regression methods (multiple data sources allow for calculating a baseline profile for each aggregator), rolling average (it is determined by averaging the metered consumption over a specified number of days, with an option to prioritize the most recent days by applying a window). Lind et al. explore the selection of baseline methodologies, emphasizing the need for tailored, transparent, and accurate methods to accommodate diverse DERs and flexibility services, and calls for further research to refine these methodologies based on market and FSP characteristics [32].

As Schittekatte et al. explain, the baseline issue for IA might be broken down into two fundamental problems that appear in markets with incomplete information [47]: moral hazard problem (one party is incentivized to take risks or engage in undesirable behavior) and adverse selection problem (one party possesses more information or knowledge about a transaction that the other party). Crampes et al. also focus on those problems, highlighting that customers have private information both on their value for electricity and on their strategic behavior and might have incentives to inflate the baseline [16]. In particular, they refer to a fine to the Maryland Stadium Authority, which artificially inflated its baseline by turning on the light when it was unnecessary [16].

4.3 Pricing and contract types

Lu et al. extensively assessed pricing schemes between aggregators and customers, expanding on He et al.'s work [29]. They identified various pricing schemes, such as [29]: Time of Use (varying rates by time) or Dynamic Pricing (adjusting prices in real-time), or contracts type Fixed Load Capping (setting a consumption limit), Dynamic Load Capping (real-time adjustments based on grid conditions), and Direct Load Control (remote control of specific loads or appliances).

In addition to defining these contract types, the authors provided a taxonomy covering two groups of dimensions [29]: technical and commercial. The former includes dimensions such as [29]: signal form used to communicate DR (price, volume, or control signals), and signal volatility (determines the timeframe and notice given to consumers). The latter encompasses factors such as: price risk (uncertainty of consumer payment), volume risk (uncertainty of available power), complexity (difficulty in understanding and fulfilling obligations), behavior autonomy loss (degree of freedom and privacy sacrificed), and financial compensation (direct or indirect compensation included in the contract). It remains to analyze how the different kinds of contracts of the DER with both the supplier and the aggregate impact the relationship.

4.4 Identified gaps

This section reveals critical gaps in the relationship between the IA and the DER, emphasizing challenges in handling residential load complexities, metering accuracy, baseline profiling, and diverse contract types. The differentiation between industrial and residential loads underscores the need for nuanced strategies to manage the latter's greater administrative complexity and the implications of the rebound effect. Issues related to submetering and meter configurations, such as accuracy and certification, call for developing more refined measurement methodologies. Establishing an accurate baseline profile is identified as crucial, yet challenged by issues like moral hazard and adverse selection that can provoke manipulative behaviors. Lastly, the diverse contract types between aggregators and customers highlight the necessity for a deeper understanding of their effects on the dynamic relationships among DERs and aggregators.

Table 7 Different dimensions of the relationship between the IA and the DER.

Dimension	Possible values
Baseline profile	Submitted by flexibility provider; High X of Y; Meter before / meter after; Regression methods; Rolling average; Other
Kinds of appliances	Non-flexible; Semi-flexible; Flexible
Kinds of contracts	Time of Use; Dynamic Pricing; Fixed Load Capping; Direct Load Control
Metering device in the grid connection point	Smart metering; Conventional metering
Metering scheme	Split supply; Submetering
Types of consumers	Industrial; Residential

5 Aggregator-System Operator Relationship

This section covers the relationship between the aggregator and the SO. Table 9 summarizes the aspects treated in the section. This section does not include the provision of services by the aggregator, which is covered in the next section.

5.1 Payment for imbalances

Balancing markets use two pricing schemes for imbalance settlement [11]: single pricing (uniform price for both purchase and sale, making the price for additional energy supplied and withdrawn the same) and dual pricing (distinct prices for purchase and sale, usually with the purchase price higher than the sale price). Dual pricing incentivizes participants to balance their energy resources and reduce system imbalances [11]. The choice between single and dual pricing systems depends on market design, regulatory policies, and the objectives of system operators or market administrators [35]. Both approaches have their advantages and considerations, and the specific pricing mechanism implemented can vary across jurisdictions and energy markets [35]. Within DR aggregation, dual pricing is seen as a way to create financial value for aggregators [35].

5.2 Data measuring

Unlike a traditional metering system, a smart metering system is an "electronic system capable of measuring electricity flow in and out of the grid, offering more detailed information than a conventional meter, and facilitating data transmission for information, monitoring, and control via electronic communication" [26]. High-resolution smart metering systems are essential for effectively utilizing distributed energy resources to provide electrical services [48]. That said, in places such as California, the only requirement to provide flexibility is to have a smart metering device [44]. In the European context, even if some countries, such as France, Italy, and Spain, decided to fully roll out smart meters, others did not roll out smart-metering devices or chose to do it selectively [50]. Table 8 compares different European countries regarding the deployment of smart meters and their resolution. Submeters or dedicated metering devices may complement both conventional or smart meters and obtain more granular measurements of specific devices.

Table 8 Smart meter roll-out and time resolution of selected European countries.

	France	Italy	Portugal	Lithuania	Spain	Sweden
Household consumers with smart [19]	90,0%	98,5%	52,0%	89%	99,6%	100%
Time resolution [min.] [18]	30 (10)	15	15	60 (15)	60 (15)	60 (15)
Time-of-use with timely price differentiation [19]	Yes	Yes	Yes	Yes	Yes	No
Real-time or hourly energy pricing [19]	Yes	No	No	No	Yes	Yes
Remote control of consumption [19]	Yes	No	No	No	No	Yes
Critical peak pricing [19]	Yes	No	No	No	No	No

5.3 Identified gaps

On the one side, it remains to analyze more precisely how dual pricing provides more value for aggregators and how that impacts system imbalance. On the other hand, it remains to be studied how precise the smart meters must be. Furthermore, even it remains to analyze if it is possible to provide flexibility and how to measure its provision in case the DER does not have a smart meter. To do so might increase flexibility usage in countries where the roll-out of smart-meters is low.

Table 9 Different dimensions of the relationship between the aggregator and the system operator.

Dimension	Possible values
Pricing of system services	Single pricing; Dual pricing
Type of meter	Smart meter; Conventional meter; Submeter

6 Aggregator-Flexibility Requesting Parties Relationship

This final section on aggregators explores their connection with flexibility requesting parties (FRP). We examine three aspects of this relationship: market types, product definitions, and pooling conditions.

6.1 Market types and operational coordination

The aggregator's power sales span diverse markets and services, as outlined in the USEF model [30]. These include Wholesale Energy Services (involving bulk electricity transactions), Constraint Management (optimizing grid operations), Balancing (ensuring power system stability), and Adequacy (securing reliable generation capacity) [30].

While Constraint Management and Balancing address distinct operational aspects of the power system, EURELECTRIC notes that the same resources can fulfill both flexibility service requirements, being complementary [48]. It also indicates that coordinating both of those services is vital for safe operations, supply security, and fair access to flexibility markets [48]. It also argues that a centralized platform for pooling flexibility resources is proposed for effective coordination and enhanced stakeholder collaboration [48].

Ideally, including consumers in balancing should boost efficiency and welfare, as it allows them to respond to these fluctuations [16]. However, the benefits are less certain if consumers behave strategically and withhold private information about their electricity needs [16]. That said, Crampes et al. show that under such conditions of information asymmetry, allowing consumer participation might actually reduce welfare [16]. This occurs as suppliers offer less efficient contracts upfront to limit the costs of accommodating private consumer information [16]. The negative impact on welfare is more pronounced when the gains from increased post-contractual efficiency are low and the distortions from private information are high [16].

6.2 Product definitions

The USEF model outlines flexibility delivery with two key attributes [31]: availability (ensuring ample flexibility at the specified time, with payment tied to meeting requirements) and activation (controlling assets for flexibility, remunerated based on provided volume and performance). Certain characteristics of those products such as minimum bid size, number of activations, symmetrical products, notification time, duration of delivery, measuring frequency, tender period, and clearing method all play a role in determining the feasibility and participation of DR [8, 35].

An appropriate definition of these products, that considers the characteristics of DR, is emphasized as an essential aspect by SEDC and EURELECTRIC [46, 48]. In particular, they highlight the need for compatible and fair market rules that consider the features of aggregated DR and generation [46, 48].

In the United States, FERC Order 745 indicates that DR should be given a "just and reasonable" compensation comparable to that of traditional generation sources when providing a comparable benefit [40]. By saying that, the Order prioritizes the same product definitions and compensation for DR and electricity production [40].

6.3 Pooling conditions

The USEF framework suggests two flexibility market participation options based on service provision [30]: unit-level (flexibility offered at each individual unit or customer) or portfolio-level (flexibility provided from a set of flexible assets without specifying them in advance). Additionally, the framework defines two ways of fixing balance responsibility in resource pools [30]: fixed and dynamic. In the fixed approach, the aggregator is responsible for balancing all flexible assets in the pool, regardless of whether they were activated during the delivery or not [30]. In the dynamic approach, the aggregator is only responsible for the flexible assets activated during the delivery [30]. Implementing dynamic pooling presents certain challenges as it complicates the verification of flexibility activation, requires adjustments in the affected suppliers' perimeters, and increases the potential for gaming, thereby reducing transparency [30]. USEF recommends that flexibility services should be provided at the pool level, while baselines and measurements should be conducted at the unit or resource level [30]. Furthermore, the aggregator should provide information after the fact about the resources that have been utilized to ensure accurate settlement [30].

6.4 Identified gaps

This analysis identifies significant gaps for the integration of aggregated DR within electricity markets, both participating individually and as part of aggregators, emphasizing the need for coordinated services across diverse markets to ensure safety, security, and fair access (revenue stacking, bid forwarding...). It also points out the necessity for precise flexibility product definitions that reflect DR characteristics and accommodate essential attributes, aiming to establish equitable market rules for all flexibility providers by ensuring that the requesting SO needs are fulfilled. Moreover, it underlines the complexities and challenges associated with dynamic pooling strategies, particularly the verification of flexibility activations and adjustments in supplier perimeters, which could impact market transparency. Even if these gaps are shared both by single DR units and by aggregators, the latter introduces complexity due to technological differences. Addressing these gaps is crucial for advancing DR integration and fostering a competitive, innovative, and consumer-engaged energy landscape.

Table 10 summarizes the dimensions covered in this section.

7 Conclusion

In conclusion, this comprehensive review delves into the intricate web of relationships involving DR aggregators in the electricity sector. Each relationship is multifaceted, from their interactions with energy suppliers, SOs, and FRP to the nuanced dynamics with distributed energy resources. The exploration identified critical aspects such as market structures, compensation models, baseline profiles, and pooling strategies.

Table 10 Different dimensions of the relationship between the FRP.

Dimension	Possible values
Aggregation in market participation	Unit-level; Portfolio-level
Market types	Wholesale energy; Constraint management; Balancing; Adequacy
Product types	Availability; Activation
Product characteristics	Bid size; Number of activations; Symmetrical bid; Notification time; Duration of delivery; Measuring frequency; Tender period; Clearing method
Balance responsibility in resource pools	Fixed; Dynamic

Key findings highlight the ongoing debates around compensation mechanisms, balance responsibility, and the need for transparent guidelines in the DR ecosystem.

One of the pivotal revelations pertains to the ongoing discourse on compensation mechanisms, the allocation of balance responsibilities, and the pressing need for unambiguous operational guidelines within the DR domain. Specifically, the paper emphasizes prioritizing the resolution of dynamic and portfolio-level aggregation strategies—areas marked by significant analytical gaps that merit immediate and focused research attention.

A priority is to direct future research towards developing more sophisticated compensation models, clarifying the frameworks for balance responsibility, and overcoming the challenges associated with dynamic pooling strategies. Such focused inquiries are essential for advancing the integration of DR services in a way that is both equitable and conducive to the sustainable evolution of the energy landscape.

Funding

This work received funding from the European Union's HORIZON Innovation Actions under grant agreement No 101075438 (BeFlexible project).

Declarations

- The authors declare that they have no conflict of interest.

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