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The key role of aggregators in the energy transition under the latest European regulatory framework☆

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ABSTRACT

Future energy systems are reliant on the expansion and management of low-carbon technologies in order to reach climate goals. Impact studies of high-penetration intermittent renewable energy sources and electric vehicle (EV) integration in the distribution networks have demonstrated voltage violation and congestion issues. The role of a clustered coordination of distributed energy resources (DER) with a focus on aggregators is presented in terms of legal and techno-economic aspects. The latest European framework assigns aggregators a fundamental role in energy market liberalisation and DER integration towards carbon–neutral energy systems. Aggregator energy management strategies are examined for different DER scenarios, and analysed in the context of the actual situation of aggregators in Europe. The investigation aims to clearly depict how the new European policies of 2019 envision the future electricity network, in order to reevaluate the role of aggregators taking into account implemented concepts in the current market situation, and the status of aggregator research since 2015 up to date.

1. Introduction

Worldwide there are efforts in decreasing the carbon footprint of, inter alia, economic and energy systems to mitigate climate impacts for a sustainable future. The European Union has formulated common climate goals which are enforced by gradually implemented regulations and directives. Scientific research and the industry have suggested numerous carbon reduction strategies concerning different sectors. 40% of final energy consumption and 36% of GHG emissions in Europe can be ascribed to buildings, making them the largest energy consumers [1]. Together with the transport sector, the European Commission sees large energy efficiency potentials [2]. The high-penetration integration of RES, a possible transport sector electrification, the expansion of DER, including distributed renewable energy sources, and DR are identified strategies to facilitate the defossilisation of this sector. However, these technologies pose new challenges on contemporary electrical networks and markets, dealing with voltage violations and congestion issues resulting from intermittent RE generation and new load peaks from EV charging, for instance (e.g. [3] [4] [5]). To address these problems while further accelerating the zero-carbon-emission-transition, the networks' operation, management, and planning is dependent upon smart strategies involving a holistic systems approach. Traditionally, the distribution network has represented the interface of large producer serving consumers. Since consumer can now simultaneously become new producers (prosumers) and capacity control entities, major transitions are expected at the distribution level (Fig. 2). Although recent EU policies have laid the foundation for non-discriminatory market access, the thorough participation of consumers in the electricity market is at the present time neither legally nor technologically viable in many European countries, and requires new market models [6]7. The bundling and management of small producers or consumers flexibly participating in market activities, is known as the aggregator concept. Concerned parties of the electricity network transition are network users, producers, operators, and in general market players or stakeholders in the energy industry.

This paper reviews the upcoming role of aggregators for implementing and operating DER in European distribution networks. While various studies have investigated particularly the technical and economic challenges and benefits of specific aggregator types, this review provides a holistic picture, including key aspects of the most recent European regulations and directives on energy systems as frame

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Nomenclature

(A) DN	(Active) Distribution Network
(H) EMS	(Home) Energy Management Systems
(I) FL	(In) Flexible Loads
(I) SO	(Independent) System Operator
(P) EV	(Plug-In) Electric Vehicle
ACER	Agency for the Cooperation of Energy Regulators
AS	Ancillary Services
ASP	Aggregator as Service Provider
ASup	Aggregator Supplier
BM	Balancing Market
BRP	Balance Responsible Party
C(C) HP	Combined (Cooling) Heating and Power
CA	Contractual Aggregator
CEEP	Clean Energy for all Europeans Package
D-/TSO	Distribution/Transmission System Operator
DA(M)	Day-Ahead (Market)
DelA	Delegated Aggregator
DER	Distributed Energy Resources
DR(A)	Demand Response (Aggregator)
ESS	Energy Storage Systems (normally battery)
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
GHG	Greenhouse Gas
HP	Heat Pumps
IBDR	Incentive-Based Demand Response
ICT	Information and Communications Technology
IDM	Intraday Market
IndepA	Independent Aggregator
LFM	Local Flexibility Market
MG	Microgrid
MI(L/Q) P	Mixed Integer Linear/Quadratic Programming
MPC	Model Predictive Control
pm	price-maker
pt	price-taker (without market power)
PV	Photovoltaics
P2P	Peer-to-Peer
RE(S)	Renewable Energy (Sources)
RT	Real-Time
SaS	Software as Service
SBSP	Scenario-Based Stochastic Programming
VPP	Virtual Power Plant
WP	Wind Power

conditions.

Moura et al. assess prosumer aggregation concepts and policy impacts, however, their study does not actually include any recent European regulatory framework, such as the CEEP [8]. While they present some business model case studies, the focus is not put on aggregator companies, and there is no aggregator classification. Carreiro et al. and Paterakis et al. examined the European regulatory framework more in detail with focus on the Energy Efficiency Directive of 2012, and a Recommendation (No. 03/2018) by the ACER, which deal with the participation of DR in the energy markets [9]7. The given market overviews provide detailed practical evidence for North America and other non-European countries, while aggregators in Europe are only treated to a limited extent.

The thorough review on aggregators by Okur et al. gives a main classification on concurrent literature on aggregator strategies. However, the assessed strategies are not directly linked to the different possible aggregator stakeholders, missing an aggregator taxonomy for both models from literature and aggregator companies as provided in this review. Barbero et al. present a comprehensive assessment of the European electricity markets in terms of market design and entry barriers, while only a limited overview of the market status with the dispersion of existing aggregator companies is given [10].

The review on the business mechanism of resource aggregators by Lu et al. depicts fundamentals on inter alia potential aggregator products and services such as the enrolment and qualification, information prediction, trading and the settlement process on the electricity market [11]. Even though challenges in the promotion of the resource aggregator are identified, the review does not encompass the broader trends of actual aggregator businesses in Europe, and lacks a classification of aggregator models. Stede et al. propose six functional roles which aggregators can assume, used to further assess empirical findings from industrial DR aggregators in Germany [12]. The conducted survey among aggregators provides interesting insights into their economic value creation and experienced barriers, but at the same time the study focuses on a specific field of aggregation in Germany.

Burger et al. suggest in a comprehensive review the categorisation of the value of aggregation into the fundamental, transitory, and opportunistic value, assessing furthermore system and private value creation [13]. While this strategic approach allows relevant conclusions on potential aggregator designs for the European electricity markets, it lacks the assessment of the most recent European regulatory framework, and the actual aggregator status in the European markets.

In the light of the existing reviews on aggregators in literature, the main contributions of this review are:

a. The assessment of trends in electrical infrastructure development and operation according to EU targets, markets, and system status.

To our knowledge no other journal publication has thoroughly assessed the role of aggregators according to the latest European regulatory framework, including the Electricity Directive and Regulation of 2018. The review answers the questions of whether the aggregator role is well-defined or general on the European level, and whether the dispositions have a significant or minor influence on the jurisdiction of individual Member States.

b. The identification of trends in realisable aggregator designs and business models in practise.

The combined study of status reports, market players, and implemented aggregator concepts in various European countries gives insights on the development status of aggregator business cases and types at present.

c. The taxonomy of relevant literature under a common scheme.

By classifying recent, high-impact journal publications on aggregators under a common scheme, key information on market and network design models are extracted. This review identifies common research approaches and gaps on aggregator models relevant for further research efforts, and potential aggregators.

The following statements will be evaluated in particular in the denoted sections [section X], and discussed in detail in Section 5:

(1) Aggregators will participate as new stakeholders in future energy system operation and electricity market bidding. [Section 2]
(2) The distributed communication control scheme for DER management is advantageous over mere centralised or decentralised coordination [Sections 2 & 3]

(3) Aggregators can be integrated and implemented in European networks and markets. [Section 3]
(4) Aggregators enable individuals to participate in the electricity market in a beneficial way for various involved parties. [Section 4]
(5) Aggregators will facilitate the achievement of climate goals [Section 4]
(6) The development of electrical network infrastructures and associated regulatory provisions ought to consider extensive aggregator concept simulations. [Section 4]
(7) Aggregator coordination can lower the negative impacts of DER on distribution networks [Section 4]

To assess the above-mentioned statements reliably, it does not suffice to review current research publications on the topic only. In particular, the changing regulatory framework can have a significant impact on the market conditions and system development via legal provisions and incentive mechanisms, for instance. The pre-conditions of the energy systems and markets vastly differ among individual European countries. However, the European Union has provided a clear overall picture of the requirements and goals for the energy transition up to the years 2030 and 2050 in the regulations of 2019, which will be depicted comprehensibly hereafter. The study of the current market situation, and more in-depth the diverse aggregator models proposed since 2015 up to date, combined with the legal considerations, allow an extensive reevaluation on the role of aggregators investigated in this work. Aggregators have become a hot topic in recent years with increasing numbers of publications on the regulatory framework, the business environment, and research. The holistic review on these interrelated topics thus helps policy makers, academia, and the industry to stay on top of this rapidly developing concept.

Section 2 will answer the question which role aggregators can take on considering the legal frame conditions. In this section, the traditional electricity network and market principles are depicted as reference for the set goals in the short-, mid-, and long-term regarding the energy industry with particular focus on electricity market design. The European legal documents of 2019 ([1]141516) provide clear guidelines on network access and congestion management, network charges, and distribution system operation, for instance, which are summarised in this section.

Chapter III describes the current situation of DER and DR in European electricity markets. This section depicts the available tool-set which aggregators can work with, general system architectures and strategies, as well as possible evaluation criteria, and other players on the market. Further, a summary of status reviews and example projects from the industry illustrate chances and barriers which aggregators face.

Chapter IV reviews different aggregator models to answer the question how they can participate in the future energy and capacity markets. Aggregators may take on different responsibilities, and can be classified accordingly. The research of aggregators over the past five years shows a remarkable variety of different mathematical and business models.

Section 5 discusses the possible impact and relevance of aggregators in the light of the presented review.

Finally, Section 6 concludes the role of aggregators for the implementation and operation of DER in European distribution networks.

2. Regulatory framework on energy systems in the EU

In the 2015 Paris climate conference, the EU and its Member States have committed to limit global warming well below 2°C with reference to pre-industrial levels in the legally binding Paris Agreement [17]. The agreement targets low carbon innovations in all sectors. The transition towards clean energy systems requires particular attention, having a share of two thirds in the current greenhouse gas emissions [18]. For this purpose, the CEEP was driven forth with regulatory proposals and facilitating measures [1]. The CEEP strives for energy efficiency, global leadership in renewable energies (RE) and a fair deal for consumers focusing particularly on the next ten years until 2030 (Fig. 1). Legislative parameters in the package also encompass the design of the electricity market, security of supply and governance rules for a resilient Energy Union. Each country may sovereignly decide on its contribution to the common goals, taking into account the individual conditions and requirements of each Member State. The objectives are recorded in National Energy and Climate Plans (NCEP) for 2021–2030 of each state, and revised by the European Commission to ensure the collective achievement of the Paris Agreement goals.

The Long-Term Climate Neutrality Strategy by the European Commission complements the CEEP with the time horizon on 2050. The maximised deployment of RE with a share of >80% and a fully-integrated internal energy market within an Energy Union are part of the enablers to achieve a climate neutral, fair economy in Europe. Fig. 2 summarizes simplified the envisaged transition of the European electricity network with focus on the residential network connection.

The following subsections present the development goals for the electricity network based on its traditional design and operating principles. The European Electricity Directive and Regulation of 2019 ([14] 15) provide essential requirements for the future electricity network, and are discussed more in detail.

2.1. Traditional electricity network and market principles

The network and market system referred to as traditional state, is dominated by large producers such as nuclear or coal-fired power plants. This vertically integrated electricity system is characterized by a unidirectional power flow. The network infrastructure and its sizing is laid out for this operational mode. The electricity market is dominated by distribution tariffs for either fixed + capacity components or an energy component. The tariff style depends on the country and varies from extremes such as 100% energy component based for households in Romania, to 100% fixed and capacity components based for households in the Netherlands, as well as a combination of the two in other countries [6]. Electricity customers do not participate in the electricity market due to an incomplete regulatory framework, missing suitable business models, and partially technological constraints.

2.2. Future development goals

The development goals are formulated with the time horizon set on the short- to mid-term, referring to the year 2030, and the long-term, viewing the year 2050.

2.2.1. Short- to mid-term state of envisaged energy industry

This traditional system is sought to be replaced by the short- to mid-term state of the envisaged energy industry within an Energy Union. The 2030-goals (Figs. 1 and 2) introduce the combination of many small producers of RE, with ESS, EV integration and regular power plants. DER and DR coordination lead to a bidirectional power flow, which imposes different requirements on the existing infrastructure. New business models, relying on adjusted legal regulations, are aspired to enable electricity customers to participate in the electricity market. The opportunity of new value streams and revenues entails a changing role of DSOs and TSOs in the market [19]. Load control and market

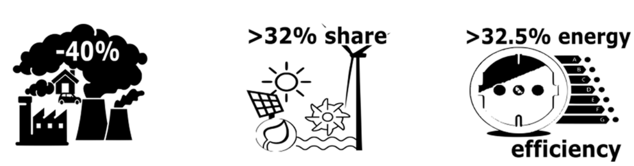

Fig. 1. Principal EU energy targets by 2030.

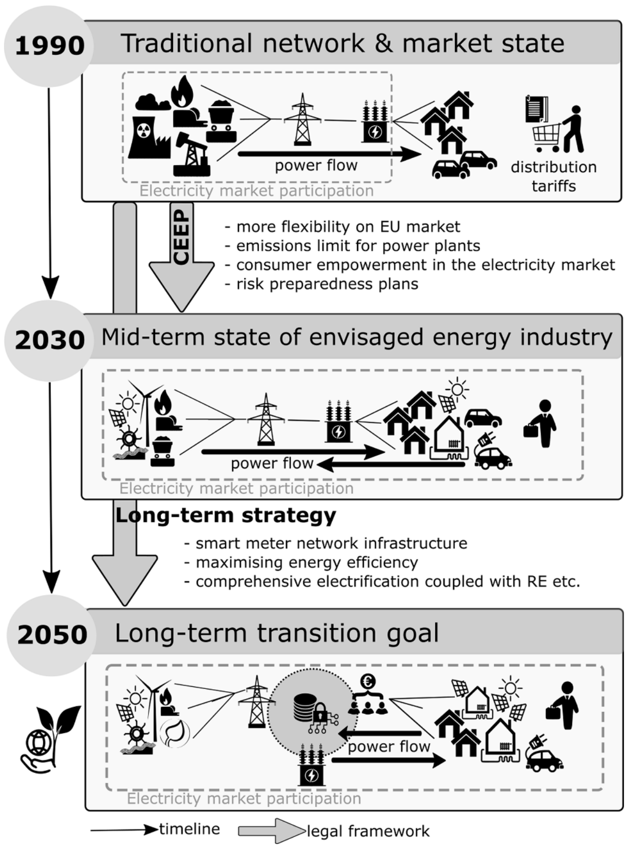

Fig. 2. Simplified overview of the envisaged transition of the EU electricity network with focus on the residential network connection.

participation of customers is enabled particularly through residential RES, ESS, EV and DR flexibility, which needs to be pooled and coordinated by an aggregator, for instance.

2.2.2. Long-term transition goals

The long-term goal of the European Union is to achieve a climate-neutral economy, with the energy industry at its heart. A maximised RE deployment of minimum 80% is thought to contribute to GHG emission reductions between 80–100% compared to 1990-levels. The Energy Union strategy from the Juncker Commission provides the legal and administrative framework for a fully-integrated internal energy market with energy security, solidarity and trust [2]. In particular the collaboration between TSO, DSO, and all other stakeholders involved in the energy industry aims at providing a high-level energy security in Europe. Diverse market participants and asset owners, such as active interacting electricity consumers, participate in a sustainable, fair and transparent market competition considering, however, the data security.

2.3. Key aspects of the European Electricity Directive and Regulation of 2019

The European Electricity Directive and Regulation of 2019 specifically describe favourable design features of the future electricity network and market. The following subsections first describe the fundamental framework set out for the transition of electricity networks and markets, and then depict in particular the regulation for network access and congestion management, the network charges, and the distribution system operation.

2.3.1. Fundamental techno-economic frame-conditions of the transition

The electricity network and market will have to undergo fundamental changes and adjustments in order to host the implementation of low carbon technologies. The required steps and regulations for the transition of the electricity market in particular are contained within the (EU) 2019/943 Electricity Regulation and (EU) 2019/944 Electricity Directive [15]14. The successive main objectives of the regulation are:

- enabling market signals for increased energy efficiency, RES, etc.
- defining fundamental principles for well-functioning integrated electricity markets with e.g. non-discriminatory market access
- fair rules for cross-border electricity exchanges
- a well-functioning & transparent wholesale market

It is noteworthy, that ”market participation of final customers and small enterprises shall be enabled by aggregation of generation from multiple power-generating facilities or load from multiple demand response facilities to provide joint offers on the electricity market and be jointly operated in the electricity system, in accordance with Union competition law”, according to the electricity markets operation principles in Article 3 [15]. Measures for the electricity system decarbonisation - including e.g. enabling RES integration and incentives for energy efficiency - are to be facilitated by appropriate market rules. These rules are to imply the support of demonstration projects of sustainable and secure low-carbon systems. The access to transmission and distribution networks shall be provided to market participants in an objective, transparent and non-discriminatory manner, as valid for subsequent regulation components.

The balance responsibility, including financial obligations due to imbalances, behoves to the market participants or to a contracted balance responsible party (BRP) of the market participant’s choice. Exceptions apply to flagship projects. Balancing energy prices shall be based on marginal pricing (pay-as-cleared) rather than pre-determined contracts for balancing capacity. Therefore, TSOs are required to disclose the current system balance of their scheduling areas with estimated imbalance and balancing energy prices within maximum 30 min.

Further, the day-ahead and intraday markets ought to provide market access to individual or aggregated market participants, making no distinction between inter- or cross-zonal trades (Article 7) [15]. The provision of sufficiently small trading products in the scale of 500 kW or less, targets at the effective participation and integration of DR, ESS, and small-scale RES, considering an imposed imbalance settlement period of 15 min to be complied with by January 2021. This means that the imbalance of the BRP will be calculated for a time unit of 15 min. By January 2025, this period is raised to maximum 30 min, where exemptions may apply.

Incumbent upon further premises, generating installations based on RES or such utilising high-efficiency cogeneration are prioritised during electricity dispatching provided that the national electricity system can be operated securely (Article 12). Redispatched resources range from generation, ESS and DR, underlying market-based mechanisms and financial compensation with exceptions only under special circumstances. However, the balancing energy price shall neither be based upon balancing energy bids used for redispatching, nor on pre-determined contracts, but instead on independent marginal pricing (Article 6 & 13). Concerning the maintenance of reliability and safety, TSO and DSO are obliged to ensure the transmission of electricity from RES or high-efficiency cogeneration with minimum possible redispatching, in particular downward redispatching, as well as sufficient network flexibility. Derogations may occur if more economically efficient network planning can be transparently demonstrated, for instance.

2.3.2. Network access and congestion management

The EU suggests the zonal management of congestions between network areas rather than a nodal concept. Bidding zones shall be organized in such a way that boarder zones comprise the structural congestions in the transmission network observed in the long-term. Maximal economic efficiency and cross-zonal trading are intended to be crucial factors for the bidding zone configuration in the Union, concurrently always respecting the security of supply. Identified structural congestions shall be encountered by action plans with a tangible timetable for improvement measures, whilst increasing cross-zonal trade capacity annually until reaching a defined minimum capacity.

Non-discriminatory market-based solutions are suggested to resolve present network congestion problems, falling back upon transaction curtailment procedures only in emergency situations. Coordinated capacity calculation is supposed to be executed by regional coordination centers following the guidelines in the CEEP and using data from TSOs (Article 16 (3)). Capacity allocation may occur concurrently through explicit capacity auctions or implicit auctions for capacity and energy. The free, secondary trade of capacity is supposed to be available to all market participants with the consent of the TSO. No limit shall be placed upon the volume of interconnection capacity for solving congestion issues inside the bidding zone or for managing internal flows. Article 32 of the Electricity Directive furthermore stresses the importance of Member States incentivising flexibility services to DSO, also for congestion management, to increase distribution network efficiency [14].

2.3.3. Network charges

Network charges and price signals shall neither favour production connected at distribution level nor at transmission level, but instead foster overall system efficiency. In the same way, the regulations postulate neutral network charges for energy storage or aggregation, and in particular a non-discriminated use of self-generation, self-consumption or participation in DR. The aforementioned may also serve resource adequacy. To support individual transactions, no specific network charge shall be placed upon cross-zonal trading of electricity. The implementation of smart metering systems allows for time-differentiated network tariffs, considering cost-efficient network operation. Regulatory authorities may provide incentives to DSOs to increase network efficiency, supporting a development towards smart or neural grids based on energy efficiency and flexibility, for instance. A best practice report on transmission and distribution tariff methodology published by ACER and the Council of European Energy Regulators contains, inter alia, suggestions on the producer tariff to final customer tariff ratio or time-differentiated tariffs, and is strongly recommended to be considered by regulatory authorities [20] [21].

2.3.4. Distribution system operation

A European Distribution System Operation entity (EU DSO entity) will be the central contact point, to take on tasks such as the contribution towards the digitalisation of distribution systems and the support of the development of data management, cyber security and data protection for the collective of European distribution networks, for instance (Article 55) [15]. Furthermore, there shall be an exchange of information and data between DSOs and TSOs for the cost-efficient, secure and reliable network development and operation, considering demand side response and the performance of generation assets. The integral implementation of the Electricity Regulation in Europe shall be facilitated by common network codes and guidelines, concerning e.g. the reactive power and power flow management, or protection equipment and schemes.

3. DER and DR in European electricity markets

Having analysed the European key targets for the energy transition in Section 2, the following subsections will provide a basic description of the available DER tool set, their management strategies and evaluation criteria considering the relevant market mechanisms and actors, and depict the state-of-the-art of DER integration into European electricity markets.

3.1. Basic description of the prevalent playground

To give a thorough overview of the market situation, the following subsections include the available distributed asset types, their general control and communication strategies, and possible metrics to assess the former, as well as a description of participating traditional stakeholders and their key objectives.

3.1.1. DER assets

DER assets include, for instance, ESS, PEV, heat pumps, combined heat and power systems (CHP), rooftop PV, among which some of the former mentioned may serve as controllable loads providing DR services [22]2324. Washing machines, dishwasher, or heating are shiftable, or curtailable loads, respectively, possibly available for DR [11]. The development tends to an increase in RE penetration in power systems, as well as a higher transport electrification and efficient heating facilities [25]. Most small DER assets are connected on distribution grid level with significant impact on the power systems' planning and operation.

3.1.2. General system architectures and strategies

Considering the interdisciplinary character of the problem, overall strategies for DER integration and control can be classified into (1) the geographical distribution of the system resources, (2) the control algorithm distribution and its interactions, and (3) the ICT platform as suggested by Han et al. [24]. The control scheme with particular focus on communication can be subdivided into the following categories [22] 2324:

S1 Centralised	one central controller choosing set-points for local actuation
S2 Decentralised	independent local control execution without communication between agents
S3 Distributed	multiple communicating agents
- Vertical	existing hierarchy among agents
- Horizontal	symmetrical responsibilities of agents

Historically, the centralised communication scheme has been prevalent in power system optimisation and control, dealing with mainly large producers [10]. The data collection and analysis is executed by a single control element which facilitates behavior interpretation and system maintenance, but also creates a major reliance of system functioning on a single entity. Fairness among agents is guaranteed since no information isolation takes place [24]. With an increasing number of agents from small DER with intermittent or flexible availability, the decentralised and distributed approaches can provide a relief for the central information processing by distributing computational tasks and communication to different agents pursuing real-time control [22]. While the decentralised scheme offers basic resilience by not depending on extensive communication infrastructures, it lacks relevant system state information which achieves optimal results and fairness for the entire system. The extreme example of a fully distributed control strategy is the peer-to-peer (P2P) communication. All agents can take control actions autonomously while exchanging information through the P2P network, which further avoids a single point of failure in the system. Liu et al. present a distributed algorithm to manage the energy exchange between cooperating MG, demonstrating cost reductions of grid operation [26].

3.1.3. Performance metrics and market overview

Adequate performance metrics facilitate the assessment of system architectures or control strategies and may include the ease of implement, scalability, maintainability, operational transparency, optimality and accuracy, resilience, maturity, or business models with regard to the European electricity market [24]27. The main market places of the electricity wholesale market in Europe can majorly be distinguished by the time of notification before operation as presented in Table 1.

The ISO conducts the market clearing for the capacity reserves together with the DAM, or immediately after, such that sufficient capacities are guaranteed during RT operation in case of large, unexpected deviations from the predicted energy flows [28]. The frequency containment (FCR) and frequency restoration reserves (FRR) fall in the

Table 1
Features of the main European electricity market places.

Trading mechanism	Abbr.	Time before operation	Traded entity
Day-ahead market	DAM	24–48 h	energy
Intraday market	IDM	1–24 h	energy
Balancing market	BM	13 min - 2 h (tertiary reserves)	energy &/or capacity
Secondary reserves	FRR	< 15 min (automatic)	capacity
Primary reserves	FCR	< 30 s (automatic)	capacity

category of ancillary services (AS). AS could potentially make use of EVs, residential or continuous loads, ESS, or further electrical heating and CHP units as suited DER types for electric flexibility [29]. The IDM and DAM belong to the spot market energy trading, which may access aggregated loads and generation. The BM, also referred to as real-time market (RTM), allows energy trading closest to actual power delivery, balancing the production and consumption which deviates from the previous market clearings.

3.1.4. Relevant traditional wholesale electricity market stakeholders and their revenues

The main electricity market stakeholders include the system or grid operators, producers, retailers, and consumers (Fig. 3). Each of the stakeholders participating in the market bidding may take the role of the BRP, which is required on each grid access point, and has the financial responsibility for its imbalances in the electricity market [15]. The grid usage tariffs charged by the system operators are mostly defined by the National Regulatory Authorities of individual Member States and are incumbent upon transparent and rather predictable and long-term regulations by the jurisdictions [20].

3.2. Status of DER and DR implementation in Europe

Both, status reviews, including specific identified barriers, as well as practical examples from businesses and implemented research projects in the industry, are considered below to provide an overall picture of the actual status of DER and DR implementation in Europe.

3.2.1. Status reviews and identified barriers

The Joint Research Center (JRC) Science for Policy published reports on the status of DR and distribution system operators in EU member states in 2016 and 2018, respectively. DSOs mainly serve residential customers and small businesses and may in the future interact with a new actor, the demand response aggregator (DRA), to implement DER and DR in the electricity market [30]. There is no uniform structure of DSOs in Europe with major deviations in inter alia number, size, governance, and average distribution tariffs even within member states, and DR is offered by few of the reviewed DSOs [6]. While consumer profits were mainly observed for the service of heating and cooling consumption flexibility, some DSOs partially utilise demand side management in the case of constrained networks. There are still major regulatory, technical and economical barriers for the role of a DRA integrating consumer participation in flexible markets (Fig. 4) [10]. Furthermore, Lampropoulos et al. mention social barriers considering the acceptance of measures and technologies [31]. A market agent has to demonstrate in advance that it can fulfill all requested technical requirements to the TSO in order to get permission to provide ancillary services. It is essential that this prequalification can be provided at the pooled DRA level, instead of at the customer level for the individual assets. The direct access of consumers' assets without requiring special permissions through the BRP or retailers, is seen as an enabler for aggregator operation [10]. The minimum bid size, symmetry of the offer, and product resolution significantly influence the DRA's income. Small bid sizes and shared activation among customers enable the DRA to participate in the bidding process with a smaller number of customers and available assets, and therefore the chance of revenues is increased. Sufficient reaction time for the control of the flexibility source decreases problems of communication delay between the DRA and the consumers and lowers the need for expansive automation in the short-term [10]12. The investment responsibility for smart meter and software infrastructure enabling automated processes is not resolved [8]. When the flexibility offer provides upward and downward regulation, it is considered symmetric [10]. Asymmetry in the bidding offer allows an aggregator the grouping of mere production assets to participate in the bid, for instance. If symmetry is required, this aggregator type would be excluded from the bidding process as it might not be able to provide balancing in the case of network overloads. Since the availability of flexible loads is determined by the customers' comfort levels, there is a natural restriction to the maximum activation duration of assets. Generally, shorter activation periods are advantageous to increase the DRA participation. Similarly, tender periods with at least daily auctions enable the DRA to make more prompt and possibly accurate predictions on the clients' behavior and facilitate participation in the bidding process. Unfavorable conditions resulting from a still centralised market orientation are also prevalent in countries open to DRA, such as France and England. Thus, for fully unbundling new market competition and regulation services provided by DER and DR through a DRA the mentioned barriers yet need to be overcome.

3.2.2. Example projects and customer services from the industry

Despite the mentioned challenges, some European companies or system operators provide customer services for DER integration or use DER for balancing their own portfolio as summarised in Table 2. Eneco CrowdNett in the Netherlands offers grid services from aggregating home batteries, for instance [32]. The German company Energy & meteo systems acts on the DAM and IDM through a VPP [33]. The German RheinEnergie is an example of a utility resuming the role of a VPP for municipal utilities, industry, or other major customers [34]. The BalancePower GmbH enables operating reserves, DSM, direct trading and further services to suppliers, DSO, TSO, or BRP [35]. Centrica Business Solutions is another stakeholder selling energy optimisation solutions

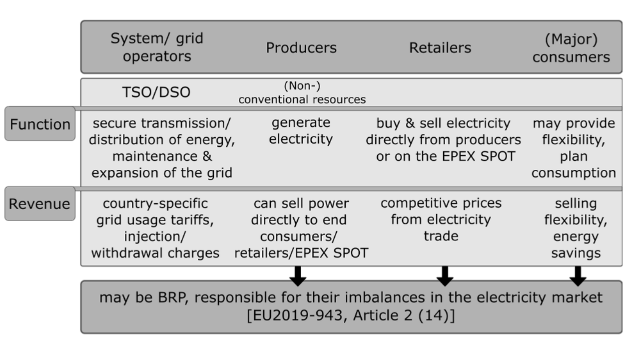

Fig. 3. Main traditional stakeholders on the European electricity market, their functions and revenues.

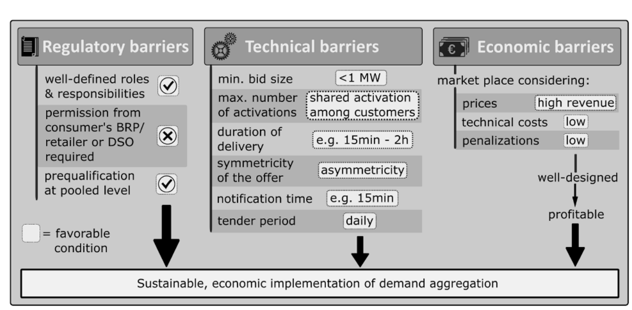

Fig. 4. Barriers for DRA implementation and favorable conditions. (referring to [25,10]).

Table 2
Companies providing aggregator (enabling) services in Europe assessed according to the functional roles presented by Stede et al. [12]. For the companies offering software-as-service (SaS) solutions, the customer type and functional roles are filled in according to the direct potential of aggregator services enabled by the software.

Company	Ctry.	Aggr./ SaS	Resid./ Major Customer	Functional Roles				
								
VERBUND AG	AT	ASup	MC	✓	✓	(✓)	✓	✓
Next Kraftwerke	BE	VPP	MC	✓	✓	✓	✓	✓
Hive Power	CH	SaS	RC,MC	✓	✓	✓		✓
BalancePower GmbH	DE	IndepA	MC	✓	✓	✓	✓	
BayWa r.e. GmbH	DE	IndepA	MC	✓	✓	✓	✓	✓
Energy & meteo systems	DE	VPP	MC	✓	✓	(✓)	✓	
GreenCom Networks	DE	SaS	RC,MC	✓	✓	✓	(✓)	✓
gridX	DE	IndepA	RC,MC	✓	✓	✓		
RheinEnergie	DE	ASup	MC	✓	✓	(✓)	✓	✓
Venios GmbH	DE	SaS	MC	✓	✓	(✓)		✓
Plexigrid	ES	SaS	RC,MC	✓	✓	✓		✓
SEAM Group	FI	IndepA	MC	✓	✓	✓	✓	✓
Voltalis	FR	IndepA	RC,MC	✓	✓	✓	✓	
Eneco CrowdNett	NL	ASup	RC,MC	✓	✓	✓	✓	✓
GreenFlux	NL	SaS	MC	✓	✓	✓		✓
ICT	NL	SaS	RC,MC	✓	✓	✓		(✓)
Peeeks BV	NL	SaS	RC	✓	✓	✓		(✓)
Sympower	NL	IndepA	MC	✓	✓	✓	✓	
EmbriQ	NO	SaS	MC	✓	✓	✓		✓
Entelios	NO	ASup	MC	✓	✓	(✓)	✓	✓
eSmart Systems	NO	SaS	MC	✓	✓	✓		✓
GridBeyond	IE/UK	IndepA	MC	✓	✓	✓	✓	
Centrica plc	UK	ASup	MC	✓	✓	✓	✓	✓
Flextricity	UK	ASup	RC,MC	✓	✓	✓	✓	✓
Kaluza	UK	IndepA	RC,MC	✓	✓	✓	✓	✓
Opus One Solutions	UK	SaS	MC	✓	✓	✓		✓
Smarter Grid Solutions	UK	SaS	RC,MC	✓	✓	✓	✓	✓

 Identification of flexibility potential

 Realisation of potentials

 Automation

 Wholsale electricity market participation

 Bundling of services (aggr./supplier/BRP)

such as DSM, DR, or software-as-service (SaS) solutions for clients to launch their own VPP [36]. The Norwegian provider Entelios (Agder Energi), as well as the Austrian VERBUND Power Pool are energy suppliers who incorporate DR solutions, and aggregation for large consumers or DG owners through a VPP [37]38. Next Kraftwerke is a VPP operator and power trader acting on the wholesale market (including all reserve markets), providing market access, balancing group and portfolio management with various software solutions [39]. Flextricity in the UK offers a wide range of services reaching from frequency response, balancing mechanisms, and DNO services, to EV and smart homes RT optimisation services, for instance [40]. The Finnish SEAM Group provides energy optimisation services via inter alia DR with focus on customers from industry and commerce [41]. Voltalis is a major aggregation platform in France designed for residential, and medium- to small-scale commerce and industry, offering the free installation, maintenance and operation of smart home devices enabling customer savings in exchange for the market profits gained [42]. Further companies such as the Dutch Peeeks or GreenFlux offer cloud-based platforms and software to third parties for monitoring, and controlling of DER in general or specialised assets such as EV, respectively [43]44.

Table 2 shows that the vast majority of aggregator services currently focuses on large customers only, rather than targeting residential customers as well. This trend can be explained by several arguments [11] 12:

- Existing infrastructures: the diffusion of basic EMS in the industry, for instance, facilitates the identification of DR potentials.
- Forecasting: the baseline electricity consumption in the industry tends to be rather predictable due to commonly planned consumption profiles, and applicable large-scale RES forecasting models exist.
- Data privacy: non-disclosure agreements are already a common practise in industrial collaborations.

All of the reviewed companies execute the functional aggregator roles of identifying and realising flexibility potentials, including in most cases the automation of required processes. Only a quarter of the companies - those in the role of independent aggregators - does not provide service bundling, whereas the rest of the presented companies integrate the aggregator and supplier or BRP role, for instance. More than half of the aggregator companies directly engage in the wholesale electricity market bidding. As Stede et al. mention many of the industrial clients are large enough to participate in the wholesale electricity market themselves, but choose to collaborate with an aggregator due to, amongst others, financial hurdles involved with ICT infrastructures[12].

As these examples show, a variety of companies sell software products or direct aggregation services to benefit from the market potential and cost savings of DER activation.

Further pilot projects exemplify aggregator market opportunities for flexibility activation and DER integration services. The project Ecogrid 2.0 by the Danish Energy Association has investigated on the control and management of electric heating and heat pumps [45]. The European eDREAM project is a consortium of various companies investigating on DER integration and aggregator solutions [46]. The system operator Fingrid runs an aggregation pilot project focusing on the balancing energy market [47]. Alongside these examples of European electricity market stakeholders moving forward DER integration, the new business opportunities available in this sector may increase significantly.

4. Aggregator models

Having depicted the current market situation, and DER and DR integration in Section 3, the following subsections will first define and classify aggregators, and then use this classification to assess research publications on aggregator models of 2015 up until 2021.

4.1. Aggregator definition and classification according to their responsibilities

The EU 2019/944 Electricity Directive defines aggregation as a ”function performed by a natural or legal person who combines multiple customer loads or generated electricity for sale, purchase or auction in any electricity market” [14]. The stakeholder engaged in aggregation may interact differently with upstream and downstream parties of the electricity market and can be classified accordingly [48]49. The integrated aggregator type supplies energy to prosumers whilst offering flexibility contracts, holding the entire balancing responsibility (Fig. 5). The independent aggregator does not supply energy to the prosumer, and may need to assign its own BRP as a contractual aggregator (CA). Market participants can contract a BRP of their choice, who can be an energy supplier or trader, a producer, or a major customer. In the case of a CA, there are two BRP - e.g. supplier and aggregator - on the same connection point, requiring a bilateral contract for imbalance settlement. If the aggregator is not a BRP, but still sells prosumer flexibility at its own risk to the electricity markets, TSO, or BRP, it acts as a delegated aggregator with consistent compensations that are agreed on between the BRP and the aggregator. Finally, an aggregator may not sell the prosumer flexibility at its own risk, but only provide a flexibility activation service to a third party, acting as a service provider aggregator. Large prosumers from the service sector or industry can also take on the role of an aggregator for their portfolio management. However, this prosumer as aggregator will presumably still interact with other stakeholders on the electricity market, and is thus not classified individually. Xiao et al. suggest a price-maker ASup who holds contracts with prosumers with HEMS which are controlled by the aggregator for bidding in the energy and regulation markets [50]. Wang et al. propose a CA who uses a robust optimisation-based model for DAM and RTM bidding and scheduling, considering in particular the uncertainty of customer price responsive load [51]. Asrari et al. present a DelA of EV and DG units contributing to congestion relief via DA bidding, while the DSO takes administrative actions for market and network support with focus on severe congestions [52]. In the framework proposed by Dadashi et al., an ASP offers flexibility activation to an electricity retailer who covers its energy requirements through the DAM, RTM and forwards bilateral contracts [53].

Wang et al. (2015) classify the role of the aggregator according to its collecting objects into production, demand, and commercial aggregators [25]. The production aggregator enables economies of scale for market access by grouping small generators, mostly in the role of an independent aggregator. Prosumers with storage and/or production capacity can interact with other market players, e.g. retailers or DSOs, through the demand aggregator. The commercial aggregator may be balance responsible, supplying energy and buying locally generated electricity. Since the responsibilities of the aggregator agent are not clearly defined under this aggregator classification (Fig. 5), we will focus on the aggregator scheme with ASup, CA, DelA, and ASP.

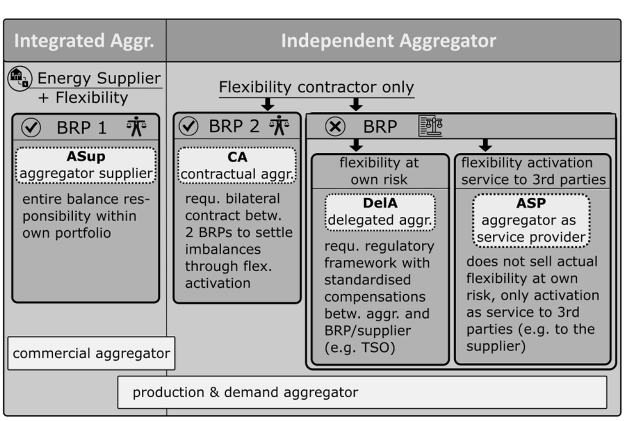

Fig. 5. Classification of aggregator types according to interactions with downstream parties of the electricity market and collecting objects.

Various studies investigate the concept of peer-to-peer energy trading for DER integration in the electricity networks [54]5556. Similarly to the above described aggregators framework, prosumers can benefit from energy trading through their flexible resources and DG. However, the concept is based upon direct prosumer interactions via an appropriate market and transaction platform, and thus does not comply with the above aggregator definition. The P2P-trading framework is hence not further investigated here.

4.2. Operational aggregators studies

Recent studies on aggregators have majorly focused on the independent aggregator type over an aggregator supplier with the entire balance responsibility. This might be due to the broader business opportunities for market participants taking the role of an independent aggregator. The most common types of DER present in around half of the reviewed publications include PV, FL, and ESS, followed by EV and WP (see Table 3). Selected studies further investigate conventional DG, HP, C(C)HP and fuel cells as flexibility assets in the mix. Almost all mentioned publications consider aggregator operations on the DAM, around half on the RTM, and less than a fifth on the IDM and reserve markets. The most popular model for describing the suggested aggregator market implementation is the stochastic bi-level OptMod formulated as MILP, with a notable focus on economic optimisation and considerations. Bi-level optimisation can be formulated as a hierarchical game, where a follower creates optimal decisions to his objective function, which is influenced by the selection of the leader, and upon which the leader minimises his own objective function [57]. An example for the upper-level problem (leader) is the optimisation of the strategic aggregator bidding, who considers the outcome of the lower-level (follower) representing the market clearing process, as depicted in [50]. In almost three quarters of the publications the optimisation aims at maximising the aggregator’s profits, or minimising its operational costs, respectively. Other mentioned objectives include the minimisation of system imbalance, or the resulting maximisation of social welfare, the customer payment minimisation, and the maximisation of RE consumption, for instance.

Fig. 6 summarises the main stated reasons for the study executions and uniqueness of the models presented in the reviewed publications. The bullet points are clustered into common categories such as the market and network, or the aggregator actuation and DER-related questions. Only few studies have focused on prosumer-related topics of cost reductions and privacy preservation. Adequate uncertainty representation has been investigated in all three categories, e.g. the uncertainty of prosumer reliability, the uncertainty in DR forecasting, or the uncertainty of the market clearing. While Asrari or Koraki et al. put a particular focus on system security and alleviation of congested feeders in their modeling approaches, Wang et al. (2019) and Contreras-Ocaña et al. centre the fair benefit allocation and sharing DER for system welfare, for instance [52]585960. Hashemi et al. further introduce an incentive and regulatory scheme for the DSO-aggregator interaction, and depict in particular financial-technical interactions between the aggregator and customers [61]. The investigated network types include islanded, residential or large-scale MG, as well as distribution networks of inter alia 4-, 6-, 25-, 33-, 34-, 118-, and 136-buses. The number of interacting prosumers or households reaches from as little as four up to

Table 3
Main features of concurrent aggregators' (aggr.) studies.

Year, Ref., Aggr./ control	Considered DER/ agents	Market focus/ business model	Applied model/ algorithm	Main result	Case study? (detail)
2021 [65] IndepA, pm	WP, ESS, EV, conventional DG, FL	Energy & frequency regulation markets; focus: VPP profit maximisation	Deep learning-based approach for uncertainties; MILP problem	Bi-directional long short-term memory network outperforms other forecasting methods, yielding higher profits for the VPP	Yes (designed)
2020 [50] ASup	PV, FL	Energy & regulation markets	Stochastic bi-level OptMod for strategic prosumer aggregation, transformed into MILP	Large-scale aggregated prosumers can yield system-wide benefits with strategically acting aggr.	Yes (Australia)
2020 [51] CA, pt	WP, PV, BES	DAM & RTM; focus: maximising aggr.'s profit	Robust OptMod (max–min problem), solved via 2-stage relaxation algorithm	Customers' price responsive load and its uncertainty significant for reasonable pt DER aggr. strategies and profits	Yes (US, 200 resid., upscaled)
2020 [66] CA, pm	WP, gas-/oil-fired generation, heating loads with high thermal inertia	DAM, (IDM); focus: maximisation of aggr. operating profit	Bi-level OptMod (Stackelberg & Nash Bargaining Game) with scenario-based stochastic programming for uncertainty of expected DAM clearing	Attainable profits in DAM decrease with less controllable DR resources, & more risk-averse aggr., however well-functioning and liquid IDM yields operating profit for aggr.	Yes (Belgium)
2020 [67] CA	PV, thermal & electro-chemical ESS	DAM & LFM; focus: minimising aggr. operation costs	MILP problem and adjustable Robust OptMod (ARO) including uncertainties	Expected operational costs decrease with robust approach considering participation in multiple markets and uncertainties from energy prices, PV production, & load; the level of robustness determines the remuneration of flexibility	Yes (designed)
2020 [68] CA, pt	WP, EV, FL	DAM & regulation markets; foci: aggr. profit maximisation & customer payment minimisation	Regret-based stochastic bi-level model	Aggr. tends to more risk-averse energy biddings, yielding fairer customer prices, compared to SBSP approach with more down regulation market participation	Yes (designed)
2020 [52] DelA	WP, PV, EV, diesel-engine DG	DAM	Defined objective functions solved by GAMS & nonlinear solver of CONOPT	DA congestion management scheme demonstrates that overloaded feeders can be alleviated via DG/EV aggregator contributions	Yes (136-bus DN)
2020 [53] ASP	PV, WP, FL	(DAM), RTM, forward bilateral contracts	2-stage stochastic bi-level programming for short-term decision-making by the electricity retailer considering DRA & self-production RES	Retailer's profit increases through the presence of DR programs and local RES by 39% in the deterministic, and 44.5% in the stochastic model	Yes (designed)
2020 [69] IndepA	PV, ESS, FL	DAM; focus: maximisation of aggr. profit, while reducing customer electricity bills	Battery degradation model incorporated in SG resource allocation problem, solved via parallel processing technique in 3 phases (initial run, estimation, validation)	Reverse power flows from resid. PV generation decrease aggr. profits, whereas installing ESS leads to an increase; market conditions of 2017 do not compensate ESS investment costs, but additional profits from AS through ESS are possible	Yes (US)
2020 [70] IndepA	EV, HP	DAM; focus: maximisation of aggr. profits	ADMM-based algorithm to solve MILP model of market clearing; MIQP for aggr. bidding	Market clearing strategy provides privacy preservation; particular consideration of energy payback hour and power	Yes (4-bus DN)
2020 [71] IndepA	FL	DAM	Support vector machine (SVM) forecasting of DR capacity for IBDR	SVM suitable for stable forecasting, where principle component analysis assists in processing redundant information of features	Yes (US)
2020 [72] IndepA	EV	DAM; focus: aggr. profit maximisation	Stochastic OptMod incorporating uncertainties from electricity market & EV charging	Difference of day-ahead and RT price significantly influences bidding strategy; EV strategy with centralised protocol management mode experiences greater price sensitivity compared to decentralised	Yes (China)
2019 [73] ASup, pt	PV, HP, FL	DAM & RTM; focus: minimise positive + negative imbalances of the aggr.	MPC OptMod	Aggr. individual imbalances reduced by up to 30% via model (beneficial for power system), but high dependency on solar generation forecasts, and no financial benefits for aggr. from reductions	Yes (Netherlands)
2019 [59] ASup, pt	PV, ESS	Energy & capacity markets; focus: peak shaving & load balance	Asymmetric Nash bargaining model for benefit allocation, decentralized algorithm based on ADMM	Sharing energy scheme outperforms both traditional price-fixed energy trading & bidding-based centralized market	Yes (US, large consumers)
2019 [74] CA	WP, controllable μ-generator, ESS, FL	RTM; focus: minimising aggr. cost	Stochastic dual dynamic programming (SDDP) applicable to multi-stage uncertainty model	SDDP achieves better trade-off betw. solution effic. & computational performance, which is particularly relevant for longer operating horizons	Yes (designed)
	PEV		2-stage stochastic OptMod as MILP		

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Table 3 (*continued*)

Year, Ref., Aggr./ control	Considered DER/ agents	Market focus/ business model	Applied model/ algorithm	Main result	Case study? (detail)
2019 [61] CA		DAM, AS & RT markets; focus: maximising aggr.'s daily profit		Coordinated PEV charging scheme benefits the aggr. and reduces customers' bills by >75%; applying regulatory policies further improve grid operation	Yes (IEEE 34-node feeder)
2019 [75] CA, pt	PV, EV (V2G), FL thermal capacity, IFL	DAM & secondary reserve markets; focus: minimising net cost of aggr.	2-stage stochastic OptMod	Proposed dual bidding strategy reduces participants' cost compared to inflexible & single market stages	Yes (Iberia/ Portugal)
2019 [76] IndepA	PV, EV, FL	DAM & secondary reserve markets; focus: minimising net cost of aggr.	2-level hierarchical MPC, 1-deterministic OptMod for operating point & flexibility, 2-controller adjusting operating point of each FL within range	MPC enabling arbitrage between markets during RT stage always satisfying prosumer preferences	Yes (Portugal)
2019 [77] CA	PV, dispatchable units (not specif.), ESS, EV, FL, IFL	Wholesale/DAM & LFM	2-stage stochastic OptMod; scenario generation by Monte Carlo simulation using probability distribution function	The local market benefits rise with accurate forecasts & high diversity of traders in the market; assumption of pt consumers (instead of pm) are a key limitation of the study	Yes (25-bus MG)
2019 [62] CA	FL	DAM & BM	Information-gap decision theory based bi-level model for self-scheduling, transformed to single-level (MINLP)	Lowest robustness when accounting for uncertainties of both market prices & consumers' behavior, with lower aggr. risk for DAM participation, thus avoiding BM bidding	Yes (Australia)
2019 [60] DelA	ESS	Wholesale electricity market; focus: aggr. profit maximisation in socially optimal manner	Nash Bargaining Theory for cooperative equilibrium between aggr. & ESS, with Pareto-optimality of supply/demand bids	Rational aggr. of ESS always benefits the system, and acts socially optimal under non-uniform pricing scheme for market power mitigation	No
2019 [78] DelA	ESS, EV	BM; focus: maximising aggr.' operational profits in IDM & BM	Network-constrained transactive energy framework	Transactive approach admissible for prosumer flexibility activation, conserving user privacy, actively solving distrib. grid line congestion & V violation problems	Yes (Danish LV DN)
2019 [79] ASP	PV, WP, ESS, EV, FL (AC, thermostatic loads)	RT market with DER agents & ADN agent; focus: maximizing RE consumption & minimizing power imbalance of ADN	Monte Carlo simulation for DG output; Interactive benefit prioritization principle, & multi-objective OptMod to solve contradictory objection between DER agents & ADN agent	Agent-based coordination operation strategy for ADN can reduce power imbalance, increase profit margins for ESS & flexible load agents + encourage RE consumption	Yes (33-bus system)
2019 [80] IndepA	PV, ESS, EV, thermal loads, (I) FL	Focus: minimizing total cost of purchasing energy from the grid	Dantzig-Wolfe decomposition & column generation to integrate any resource which can be formulated within MILP	Centralized MILP intractable for large systems; can be implemented in decentralized fashion which is technology agnostic and highly scalable	Yes (Canada)
2019 [81] IndepA	PV, ESS, EV	Energy markets; focus: maximisation of aggr. profit	MINLP model, solved in GAMS	Robust OptMod can minimize daily market accounts for energy market with an EV aggr.	Yes
2019 [82] IndepA	WP, conventional DG, FL	DAM & regulation markets; focus: profit maximisation of VPP & minimisation of emissions	Bi-level multi-objective OptMod into MILP	Profit and emission simulation more reasonable in 2-objective case compared to single-objective OptMod	Yes (IEEE test syst.)
2019 [83] IndepA	FL	Wholesale energy market; focus: aggr. cost minimisation	Subgradient-based disaggregation algorithm based on zonotopic sets	Quantitative description and pricing of flexible energy systems based on zonotopic sets for economically optimal & fair distribution of aggregate-level signals	No
2019 [84] IndepA	PV, CCHP syst., FL	DAM; focus: 1-minimizing annual capital + operating costs of CCHP & 2-minimizing aggr. annual consumption expense	2-stage model for DR program of multi-energy systems (MES), with LinDistFlow & quantity regulation method for DEN & DHCN	DER planning influences equipment configuration (e.g. ESS capacity) in MES with improved economy of investment & operation; precise nodal energy price from flow-tracing method reflects the spatial–temporal price variance in CCHP syst. and may support end user participation in DR	Yes (China)
2018 [85] ASup, pt	PV, EV, FL	DAM; focus: minimising aggr. net cost in RT	2-stage stochastic OptMod for demand & supply bids, & MPC for aggregated FL in RT	Incorporating FL uncertainty increases model robustness, reducing the aggr. net cost compared to inflexible/ deterministic approaches; more available DER increase aggr. savings	Yes (Portugal)
2018 [64] CA	PEV, FL	DAM (pt), RTM (pm); focus: 1-maximising aggr. profit, 2-minimising RTM clearing cost operated by SO	Bilevel stochastic OptMod as MILP	Notification time for DR execution, contract granularity and aggr. location significantly influence the value of DR programs	Yes (designed)
2018 [58] CA	PV, WP, CHP, ESS (el. & thermal storage,	DAM & IDM (service centric VPP); focus: minimizing		Mutual benefit in electricity market environment with uniform marginal	

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Table 3 (*continued*)

Year, Ref., Aggr./ control	Considered DER/ agents	Market focus/ business model	Applied model/ algorithm	Main result	Case study? (detail)
	pumped-hydro), el. & thermal FL	overall cost over IDM scheduling horizon	Stochastic dispatch, objective function for DAM market involvement	energy price through agreements between network operator & VPP	Yes (CIGRE MV European benchmark)
2018 [86] CA	PV, WP, diesel generators, ESS, EV, FL (water & space heaters)	DAM, IDM, BM; focus: minimizing aggr. operation cost	MILP problem	Development of LFM with smart energy service provider platform	Yes + lab testing of software
2018 [63] CA	PV, WP, CHP, thermal & el. ESS, auxiliary boiler	Wholesale market; focus: 1-maximizing multi-energy players' profits, 2-maximising LFM profit + social welfare in ISO market clearing	Bi-level decision making problem into single level MILP	Multi-energy players to aggregate set of local energy systems & participate in wholesale electricity market	Yes (designed)
2018 [87] DelA, pt	PV, thermal & electro-chemical ESS	DAM; focus: minimizing operational costs	ARO, incl. uncertainty in energy prices, PV, & load, + explicit representation of battery degradation; Pareto-optimality theory to detect best robust solutions	Average cost & risk reduction compared to deterministic solution demonstrated	Yes (Portugal, MG)
2018 [88] DelA	(I) FL	DAM & RTM; focus: 1-minimising DSO minus-profit, 2-minimising aggr. minus-profit	One-leader multi-follower bi-level model; primal–dual approach	Proposed model for proactive DSO making optimal procurement with aggregator-based DR resources in RT trading framework	Yes (33-bus DN)
2018 [89] ASP	WP, FL	DAM; utility minimises operation cost, aggr. maximises net income, customer maximises social welfare	Multiobjective opt. with artificial immune algorithm leading to Pareto optimal set to maximise the minimum improvement in utility, aggr., and customer objectives	Utility can reduce generation cost, DR aggr. profits from DR service, customers can save money on their electricity bill	Yes (UK)
2017 [90] CA, pt	PV, WP, PEV, ESS	DAM & RTM	Multiple stochastic scenarios for risk-averse optimal bidding strategy based on CVaR theory, compared to traditional SBSP approaches	Risk-averse model effectively reduces DA energy procurement costs & related decision risks, with particular computational advantages of the CVaR strategy	Yes (US)
2017 [91] DelA	thermal & electro-chemical ESS	DAM; focus: maximising aggr. profits	Game-theoretic model; Competition without limitation, & Stackelberg competition	Payoffs in regulated (Stackelberg) games were generally decreased compared to purer competition without limitation and scheduling of price-sensitive water heaters increased DR aggregators' payoffs	Yes (Hawaii)
2016 [92] CA, pt	EV	DA energy & regulation reserve markets; focus: maximisation of aggr. profits considering EV battery degradation costs	Monte Carlo for probability estimation of offer/bid acceptance & deployment	Reserve market more profitable for aggr. as battery degradation does not incur from obtained capacity revenue for regulation provision + add. revenue for RT deployment, with potential for significant cost reductions for power system operation	Yes (US IEEE RTS-96)
2016 [93] CA/ DelA	Thermal units, WP, EV	DAM & ASM; focus: 1-maximising aggr. CVaR, 2-minimising total system operation cost	Stochastic OptMod as MILP with linearized constraints in prime-dual formulation, solved via progressive hedging algorithm	Regulation services may constitute large part of aggr. profit, using CVaR for effective risk management	Yes (6-bus/ IEEE 118-bus)
2016 [94] Undefined, pm	PV, air source HP, ESS	DAM, focus: maximising aggr. profit	Stochastic & deterministic OptMod as MILP	Market price change is related to the aggr. size, affecting costs of buying energy & the profit of selling energy at a wholesale level, whereas the stochastic pm model is more robust to price changes	Yes (Spain)
2015 [95] CA, pt	WP, fuel cells, micro turbines, diesel-generators, ESS, FL	DAM & RTM; focus: maximising aggr. profit & risk mitigation	2-stage scenario-based stochastic programming approach (Monte Carlo simulation with Latin Hypercube Sampling technique for scenario generation)	Trade-off: maximising expected profit & risk of low profits using conditional value at risk (CVaR) approach; Deployment of load curtailment & shifting contracts provides benefits for MG-aggr. & customers	Yes (designed)
2015 [96] DelA	EV, HP	DAM	Distribution locational marginal pricing through quadratic programming (QP)	Equivalence of centralized DSO optimization & decentralized aggr. optimization with QP formulation proven, ensuring expected aggr. behavior to DSO	Yes (Denmark, 4-bus DN)
2015 [97] IndepA	(I) FL (extendable by DG, EV, thermal loads)	DAM; focus: optimizing aggr. profit	Genetic algorithm; heuristic optimization methods since problem is considered mostly NP-complete	Customer pricing structure with near RT choice of electricity supplier in fully deregulated market scenario with heuristic framework benefits all parties involved	Yes (designed)

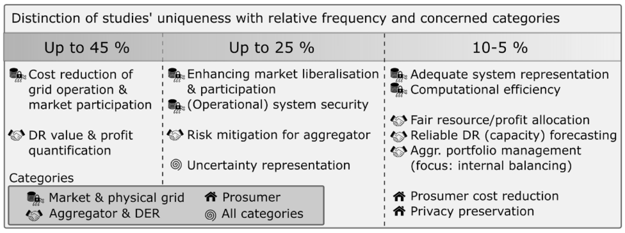

Fig. 6. The reasons for the stated uniqueness and major foci of the individual models from the reviewed publications sorted according to their relative frequency and marked by their common objective category.

140,000.

Most studies suggested further research related to market-specific representations, the aggregators' behavior, stakeholder interactions or system-specific configurations as presented in Fig. 7. Vahid-Ghavidel et al. propose long-term contracts and markets in the aggregator's self-scheduling model for future research [62]. Yazdani et al. identify the impact of the changing gas prices on the aggregator's behavior, as well as other strategic stakeholders in an oligopolistic market as open questions for prospective investigations [63]. Both Wang et al. (2020) and Henriquez et al. name the uncertainty of prosumers' price responsive load, and the prosumers' influence on the DR portfolio as relevant topics for further study [51]64. Diverse publications depict how aggregators can integrate DER and what impact they may have on the presented systems. The following discussion concludes the role of aggregators regarding the presented European framework, and state-of-the-art of DER in the electricity markets, potential strategies and business models.

5. Discussion

The study's key aspects comprise the role of aggregators regarding European policies, the prevailing implementation and operation of DER, and potential aggregator operation in particular in European DN. The following hypotheses will be discussed considering the legal conditions presented in Section 2, the state-of-the-art DER integration in European

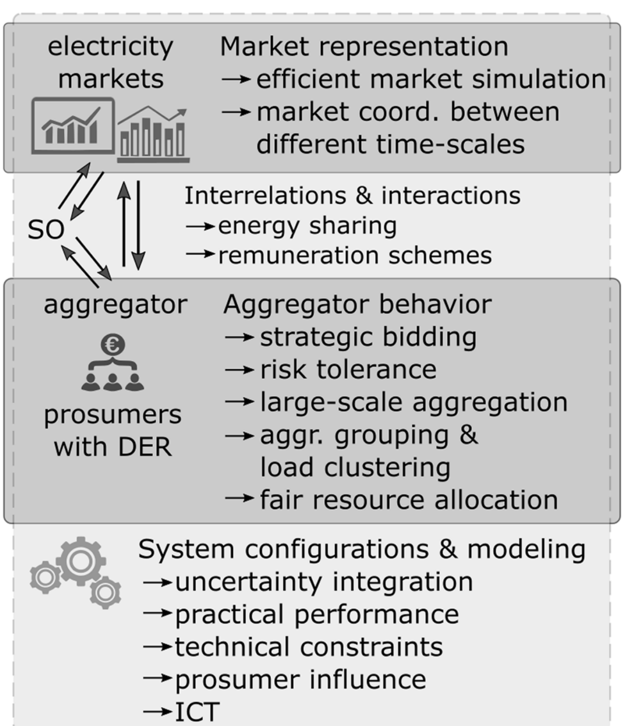

Fig. 7. General topics for future research mentioned in studied publications.

electricity markets from Section 3, and the studied aggregator concepts and impacts from Section 4.

(1) Aggregators will participate as new stakeholders in future energy system operation and electricity market bidding.

Bearing in mind that the worldwide commitment to limit the human impact on climate change has been widely expressed and agreed on, it can be assumed that low carbon technologies will emerge further. Concomitant with the increase in intermittent RE generation comes the requirement for adequate control mechanisms and strategies such as DSM and DR to ensure system reliability. The absence of strategies for the integration of high-penetration RES in the traditional networks has demonstrated grid congestion and voltage violation issues in a significant number of studies. Furthermore, the aspired liberalisation of the energy markets necessitates new business models for flexibility activation and DG integration via e.g. aggregation of many small prosumers and other stakeholders. Small prosumers do not possess sufficient capacities for market bidding and may lack the knowledge of market interactions [10]7. The integrated or independent aggregator enables this interaction between prosumers and the market. In a similar vein, the European authorities have defined aggregation as an enabler for prosumer market participation. The CEEP explicitly states that trading opportunities should be available to all market participants, provided that system security is assured. The European regulatory framework specifies how the electricity market and network ought to function in the future, including due dates for the implementation of market conditions, such as the imbalance settlement period. Examples from research and industry (as from Sections 3 and 4) demonstrate how aggregators can be a sustainable part of current and future energy systems, further promoting the integration of volatile DER into a reliable network. Therefore, aggregators will likely play a part in future energy system operation.

(2) The distributed communication control scheme for DER management is advantageous over mere centralised or decentralised coordination.

The European Energy Union strives for maximising economic efficiency and fostering cross-zonal trading, considering in particular the overall system efficiency. Decentralised coordination may yield locally optimal solutions, providing system resilience, data privacy, and high scalability at DER integration. However, the lack of system state information hampers finding the system-wide optimum solution [22]. A centralised controller can target at optimising the entire integrated power system, but majorly relies on a single entity for system functioning and faces heavy computational burdens. As expressed by Morstyn et al., distributed control strategies can be perceived as compromise between central and decentral control [98].

The case study conducted by Arefifar et al. shows that collective energy management at system level procures higher benefits and lower system losses, compared to performing the optimisation for the individual MGs [99]. The investigation by Carvallo et al. yields similar results, remarking that centralised decisions can lead to significant cost reductions [100]. Molzahn et al. emphasise the potential advantages of distributed algorithms over centralised ones, such as the improved cyber security, system robustness, and potential computational superiority regarding maximum problem size and solution speed [23]. Han et al. highlight the design flexibility in weighting trade-offs such as optimality vs. scalability, or fairness vs. privacy, and state that the implementation of a transactive energy framework relies on distributed architectures [24].

To achieve an optimised overall system efficiency as pursued by the European Energy Union, variations of distributed communication control schemes of DER appear favourable.

(3) Aggregators can be integrated and implemented in European networks and markets.

The late 90s and early 2000s marked the turnaround for the energy market liberalisation in Europe. The power partition of the former energy monopolists, along with the broad grid access to diverse stakeholders, positively affects policies that support RE [101]. The latest European policies as presented in Section 2, pursue a thorough energy market deregulation, fostering aggregator and prosumer market participation. The expansion of decentral RES/DER creates new management requirements and business opportunities [13]11. Diverse possible aggregator roles and responsibilities as from Fig. 5 and Table 3 enable aggregator actuation in different country preconditions.

The multitude of aggregator examples in Europe (Section 3.2.2) demonstrates that economic value creation from aggregation is possible at the current state, despite yet remaining regulatory, economic and technical barriers as described in [10]1231102 for different aggregate levels. Kubli & Canzi identify the starting phase as particularly critical for flexibility service business development and propose strategies to overcome this phase [103]. The JRC Report of 2016 on the DR status in the EU Member States classified the existing country-specific regulations into group one to three, with very little DR engagement (e.g. Croatia, Bulgaria, Portugal, Spain), to enacted DR reforms enabling DR and independent aggregation (e.g. Belgium, France, Ireland, UK), respectively [30]. While changes to this status over the past five years can be assumed, the CEEP and the long-term strategy are expected to set the ball rolling further. The Spanish national commission on markets and competition (CNMC) has enacted a resolution at the end of 2019, which formulates equal conditions for balancing service providers possessing generation, DR, or storage assets (Article 1), and enables the aggregation of generation assets for system balance services within further specified frame conditions (Article 2), for instance [104]. Numerous countries, such as Finland, Germany, and Ireland, are conducting fundamental regulatory revisions in the early stages [7]. Harmonising the heterogeneous national regulations on the electricity market design potentially poses further challenges for implementing the European Energy Union concept in the future. However, the integration of aggregators in most European energy markets is likely.

(4) Aggregators enable individuals to participate in the electricity market in a beneficial way for various involved parties.

Owing to market entry criteria, such as the minimum resource bid size, direct market participation is currently not viable for residential and small commercial consumers/prosumers [7]. An aggregator can unleash these flexibility potentials and create private, as well as system value, in terms of the economic wellbeing of particular agents, or economic efficiency of the entire power system, respectively [13]. The VPP operating mechanism presented by Yin et al. consists of prosumer aggregation only, and shows that all participating prosumers profit from this cooperation [105]. More competitors in the market may also result in more competitive prices, which benefits the system value. According to Moura & Brito grid operators can benefit from aggregation due to the improved matching between DG and consumption [8]. Jeddi et al. remark that appropriate DER integration can decrease requirements for substation upgrading or power line expansion [106]. At the same time, the dispersion of DG may lead to new DSO/TSO tasks of guaranteeing supply security in the role of active system managers, including possible increases in operational costs. Contreras-Ocaña et al. and Burger et al. remark that a monopolist aggregator, for instance, may create private value from aggregation at the expense of optimal system efficiency [60]13. Given the former superiority and competencies of large energy utilities in traditional centralised energy production, their potential rejection towards RE policies is allegeable [101]. Since the transition to carbon–neutral, sustainable energy systems is an inevitable constituent of climate action, there are a number of industries, that will have to reorganise their business concepts. Overall, the aggregator models presented in Table 3 almost entirely demonstrate private and system value created through the operating aggregator.

(5) Aggregators will facilitate the achievement of climate goals.

The achievement of climate goals is coupled with the defossilisation of the energy industry, foregrounding RES and DER, for instance. The reviewed literature has shown that aggregators can potentially diminish negative impacts of these resources on the electricity network, fostering their diffusion (e.g. [79]). Khan et al. show that a suitable energy management strategy in a multi-energy generation grid can effectively decrease pollutant emissions [107]. Hyun et al. have specifically investigated the environmental impact of DR market bidding, which is a potential service provided by aggregators [108]64. The small but statistically significant improvement in terms of CO_2 and particulate matter mitigation supports the concept implementation, requiring, however, further research verification. Paterakis et al. have emphasised the potential of DR in improving the integration of intermittent RE generation [7]. By fostering the DER integration in electricity networks, aggregators may indirectly support the achievement of climate goals.

(6) The development of electrical network infrastructures and associated regulatory provisions ought to consider extensive aggregator concept simulations.

The electricity network as it has functioned over the past century is experiencing its first major transformation in order to accommodate the zero-carbon-emission-transition. Design questions arise on how to accomplish non-discriminatory energy trade with high penetration of RES, and challenging load profiles, considering the additional transport sector electrification and rising energy demand. Pan et al. demonstrated that the planning for the full exploitation of customer RE and DR can affect the asset configuration in the energy system, e.g. the system's capacity expansion via ESS [84]. While the DER management system presented in Horowitz et al. could mitigate voltage and thermal overloads, the study showed that this management scheme for a high penetration of PV assets only, leads to high levels of curtailment, resulting in a lower profitability of these systems [109]. The study conducted by Henríquez et al. identifies the notification time for contract execution or contract granularity, for instance, as factors influencing the DR value, and which thus should be considered for market design [64]. Okur et al. conclude that internal imbalance reductions via DR do not yield any financial benefits for the aggregator [73]. Since this activity is beneficial for the system's operation, incentives may support the desired behaviour. Hashemi et al. proposed incentive and regulatory policies for EV penetration levels >50% to encounter possible issues with the security of grid operation [61]. These and further studies demonstrate the necessity of concept testing, in order to develop suitable regulations and targets to promote an efficient system-wide optimisation.

(7) Aggregator coordination can lower the negative impacts of DER on distribution networks.

High-penetration intermittent RES and EV can have a significant impact on DN. Aggregators activate unengaged agents (DER owners, particularly in the residential sector) and use their flexibility or capacity for value creation via electricity service market participation. The available resources, e.g. DG and flexible assets, are coordinated according to a major objective, such as the economic optimisation of the aggregator's profits. Since the market prices often reflect the network status in terms of peak loads, the aggregator operation can coordinate and manage DER, making for improved system conditions. The inherent or fundamental value creation of aggregation by upscaling and diversifying DER (economies of scale & scope), can mitigate DER impact on the respective network, particularly with higher penetrations of DER [13]. Smart DER management performed by aggregators can alleviate overloaded feeders, and resolve congestions, for instance [52].

6. Conclusion and future research

Aggregators are agents who bundle and manage distributed energy resources and their flexibilities to create value from an optimised electricity service market participation. European policies, such as the Clean Energy for all Europeans Package, establish the foundation for the net-zero-emission energy transition, defining in particular framework directives for the redesign of the traditional electricity market operation. By targeting the liberalisation of the electricity market access recorded in the (EU) 2019/943 Electricity Regulation and the (EU) 2019/944 Electricity Directive, aggregators will be legally enabled to offer their services as new, independent stakeholders in the European markets, as presented in detail in Section 2. The status of the liberalisation and distributed energy resource integration varies significantly between the individual member states, including the structure and tariff scheme of distribution system operators. Accordingly, aggregators face various regulatory, technical, and economic barriers as described in Section 3, and encounter broad business opportunities for service provision in countries like England or France, or very limited market access in Bulgaria or Croatia, for instance. Aggregators can assume different responsibilities concerning the supply of energy, provision of flexibility, and interaction with other stakeholders depicted in Section 4. In the short-term, aggregators with an integral role as that of a supplier or retailer are more likely to start a business as a flexibility contractor, as they are granted with easier market access, and do not require the in-depth elaboration of a regulatory framework with remuneration standards. However, there is a business opportunity for software management solutions which can be provided to the established stakeholders. The independent aggregator is likely to enable more specialised products and services, once the regulatory barriers are further lowered, as their presence in respective countries already shows.

Owing to the versatile problem statement, future investigation on the role of aggregators, as presented in the literature, can be subdivided into the categories of the aggregator behaviour, the particular interactions with other stakeholders, the general realistic electricity market representation, and overall system modeling design questions. Since the electricity market redesign is in the formation phase, it is indispensable to study and define the responsibilities of market stakeholders in such a way, that non-discriminatory market access is enabled, respecting the system-wide optimisation of resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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