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Aggregators in Digitalised Power Systems

How can Aggregators Improve the TSO-DSO-Customer Coordination in Digitalised Power Systems?

Discussion Paper

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Disclaimer

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List of Acronyms

AI	Artificial Intelligence
AS	Ancillary Service
A2A	Aggregator-to-Aggregator
BEMS	Building Energy Management System
BESS	Battery Energy Storage System
BRP	Balancing Responsible Party
B2B	Business to Business
B2C	Business to Customer
DER	Distributed Energy Resource
DR	Demand Response
DSO	Distribution System Operator
EC	European Commission
EEA	European Economic Area
EEG	Renewable Energy Resource Act
Ei	Energy Market Inspectorate
ESO	European Standardization Organization
EMP	External Market Participant
EMS	Energy Management System
EnWG	Energy Industry Act
EU	European Union
EV	Electric Vehicle
ExDR	Explicit Demand Response
FCR	Frequency Containment Reserve
aFRR	Automatic Frequency Restoration Reserve
mFRR	Manual Frequency Restoration Reserve
RR	Replacement Reserve
GDPR	General Data Protection Regulation
HEMS	Home Energy Management System
ICT	Information and Communication Technology
ISGAN	International Smart Grid Action Network
IT	Information Technology
JRC	Joint Research Center
LV	Low Voltage
MsbG	Metering Point Operation Act
MV	Medium Voltage
NEBEF	Block Exchange Notification of Demand Response
OTC	Over the Counter
P2P	Peer-to-Peer
PV	Photovoltaic

R&D Research and Development
SGAM Smart Grid Architecture Model
SMGW Smart Meter Gateway
TSO Transmission System Operator
VPP Virtual Power Plant

Executive Summary

Utilising untapped Distributed Energy Resources (DERs) potential from customers in the distribution grid necessitates TSO-DSO-Customer coordination. The customers, who consume, store or generate electricity, are gaining importance and have shown attractive potential for ancillary services to power systems. However, customers still face challenges in how to manage and market their flexibility in the energy market and how they can become active customers. Aggregators can facilitate these flexibilities as an intermediary by providing services to different power systems participants, such as Balancing Responsible Partys (BRPs), Transmission System Operators (TSOs), Distribution System Operators (DSOs), but also to other active customers or aggregators. There are existing aggregator services, but the challenges arise on how to accommodate diverse solutions from aggregators to support TSO-DSO coordination and enhance active customer participation. Moreover, the EU regulation has identified the independent aggregator, who is not affiliated to the customer's supplier. Based on that, the regulation allows the customer to have multiple contracts with different market participants without foreclosing the other [1]. However, the independent aggregator has not been fully implemented yet. Each EU member state would need to implement its own national regulatory frameworks to support independent aggregator implementation. This work investigated how aggregators can improve the TSO-DSO-Customer coordination in a digitalised power system by analysing existing policies, their role, possible coordination approaches, and addressing (non-) technical challenges.

This discussion paper identifies the definition and roles of an aggregator along with possible coordination approaches between aggregators, grid operators, active customers, and other market participants using the Smart Grid Architecture Model (SGAM). Based on SGAM, it can be examined how coordination approaches can be realised based on different TSO-DSO coordination (e.g. decentralised or shared markets) and DSO-Customer interactions. The role of the aggregator as an intermediary subject to these coordination approaches and their required interfaces and data exchanges varies with foreseeable technical and non-technical challenges.

Based on the analysed coordination approaches, this discussion paper identifies technical and non-technical challenges for the implementation of aggregator services, which are as follows:

Challenge 1 Interoperability between aggregator and the grid operator coordination

Challenge 2 Interoperability between aggregator and active customer

Challenge 3 Degree of automation

Challenge 4 Implementation of the independent aggregator

Challenge 5 Energy communities and aggregator to aggregator communication

Challenge 6 Cybersecurity preparedness

Challenge 7 Societal factors for behaviour change and customer acceptance

Challenge 8 Data privacy and building trust

Challenge 9 Regulatory framework for increasing system value

Challenge 10 Enhancing knowledge building

From a high-level technical analysis, interoperability can enable freedom of choice for active customers for switching between aggregators' services as well as a seamless integration between aggregators' solutions with other market participants. Smart meter deployment must ensure secure and interoperable data access for other market participants considering customer data privacy. Cybersecurity is essential for providing services to the customer and ensuring their business services in the long term. In addition to the technical challenges, societal aspects should be considered for designing business models and

policy instruments for customer engagement toward consumer behaviour change such as demand response with dynamic pricing. Ensuring trust is key for long-term engagement from active customers. A need for skilled workforces demands education and training programs to update their curricula to support new business services towards the industry's expectations in reality.

Aggregators have the capability to enhance energy community implementation by providing solutions and expertise to manage their energy demand and supply while coordinating with other market participants. The advancement of smart grid technology and policy framework can accelerate aggregator implementation in the power system. Policymakers need to ensure that the regulatory framework supports fair competitiveness, transparency, and freedom of choice for customers toward system value as a whole. Policy instruments supported are essential to accelerate aggregator implementation, especially small entrants to lower market barriers and enhance customer engagement during an early stage of deployment. However, the policy instruments should be monitored and modified for fair competition in the energy market. Moreover, innovative approaches can be tested in demonstration and Research and Development (R&D) projects with temporary regulatory changes and experiments (e.g. regulatory sandboxes), which help to address the technical and non-technical challenges and support needed for the real deployment.

Contents

1 Introduction

1.1 Motivation and Problem Statement

Integrating DERs into the power systems enables opportunities for aggregators to market the untapped flexibility of customers in Low Voltage (LV) and Medium Voltage (MV) grids. In a digitalised power system, Information and Communication Technology (ICT) are in place and therefore an aggregator can integrate these flexibilities for offering established and emerging services to power system actors, such as TSOs, DSOs, and BRPs. Accordingly, an aggregator behaves as an intermediary by managing and coordinating the flexibility of the active customers for other market participants. However, this also poses new challenges for monitoring, controlling, and coordinating these along with other market player's needs.

The provision of flexibility by active customers has to overcome technical barriers in order to realise its full potential, which is necessary not only for aggregators and active customers but also for TSOs, DSOs and their coordination. Low energy prices on energy markets provide incentives for the active customer to shift their flexibilities but simultaneously could create congestions in the grid. Thus, possible coordination approaches between aggregators and other market participants should be investigated, as will be discussed in this work. Moreover, accessing the flexibility is not harmonised and lacks coordination with the grid operator. In some cases, DERs are bound to the proprietary software of the energy product manufacturers (e.g. Battery Energy Storage System (BESS), Photovoltaic (PV) or Electric Vehicle (EV)), which complicates the access for aggregators and grid operators. In these situations, the customer's freedom of choice could be limited. Interoperable solutions with standardized communication protocols could enable plug-and-play solutions and also freedom of choice for the customers to access competitive services. A regulatory framework with a clear definition of the aggregator role should be established in each country to enhance competitiveness, transparency, and societal welfare.

Several studies have investigated the roles of aggregators, but there is still a research gap in coordination approaches between aggregators, grid operators, customers, and other market participants. This discussion paper aims to identify the roles and possible coordination of the aggregators associated with opportunities and key challenges in the digitalised power system. The key challenges from this discussion paper can be further investigated in detail for policy instruments to support aggregator implementations, encourage customer engagement, and increase system value.

1.2 Objective and Context of the Discussion Paper

This report is prepared within the framework of ISGAN working group 6 (https://www.iea-isgan.org/our-work3/wg_6/). The work of working group 6 focuses on establishing a long-term vision for the development of future sustainable power systems. The main objective of this paper is centred around the question: “How can Aggregators Improve the TSO-DSO-Customer Coordination in Digitalised Power Systems?”. Information and data are collected based on existing literature and a questionnaire. This discussion paper, therefore, presents and discusses the different roles of aggregators and various coordination approaches with other market participants. The main challenges are addressed to enhance the need for interoperable coordination and encourage customer engagement in new energy services. Figure 1 positions this work in the ISGAN context.

ISGAN (https://www.iea-isgan.org)
The International Smart Grid Action Network (ISGAN) is a Co-operative program on Smart Grid operating as a Technology Collaboration Programme (TCP) under the International Energy Agency (IEA) and as an initiative of the Clean Energy Ministerial (CEM). ISGAN aims to improve the understanding of smart grid technologies, practices, and systems and to promote adaption of related enabling government policies. ISGAN's vision is to accelerate progress on key aspects of smart grid policy, technology, and related standards through voluntary participation by governments in specific projects and programs.

ISGAN Working Group 6
The main objective of this working group is to establish a long term vision for the development of the future sustainable power systems. This working group focuses on system-related challenges, with emphasis on the technologies, market solutions, and policies which contribute to the development of system solutions.

ISGAN Working Group 6 Focus Transmission and Distribution System Interaction
The main focuses are to address a new role for TSO-DSO-Customer interaction and regulatory requirements.

Discussion Paper on
"How can Aggregators Improve the TSO-DSO-Customer Coordination in Digitalised Power Systems?"

Figure 1: Position of this paper in ISGAN context

The main objective of this discussion paper is to place the role of aggregator in TSO-DSO-Customer coordination and identify key technical and non-technical challenges for aggregator implementation in digitalised power systems. This paper is organized into six sections as follows:

Section 1 introduces aggregators as enablers for service provision in the power system and related research gaps.

Section 2 outlines the background about the definition and regulatory framework of aggregator as well as answers the question on how the transposition of the European Union (EU) directives are currently implemented using the examples Germany, the Netherlands, Sweden, France, and Spain.

Section 3 presents the role of aggregators as intermediaries by explaining how they provide added value for different market participant perspectives, namely TSO, DSO, BRP, and the customer.

Section 4 shows possible approaches on how aggregators and other market participants interact and moreover can be coordinated.

Section 5 addresses key technical and non-technical challenges for aggregator implementation.

Section 6 summarises the main findings of this discussion paper and concludes how aggregators can improve the TSO-DSO-Customer Coordination.

2 Policy and Regulatory Framework

Aggregator services exist with several business models based on existing regulatory frameworks in each country. The EU Directive 2019/944 defines "aggregation" (i.e. action) and “independent aggregator” (i.e. actor) that enables new energy services and players in energy markets [2]. The EU members are mandated to transpose the directive into national law within the deadline defined in the directive, which is normally within two years [3]. A study from the Joint Research Center identifies that 22 out of 26 countries have laws related to aggregators in general, but yet still a low number of countries have a national secondary legislation for definition, market rules, roles, and responsibilities of independent aggregator [1].

This section gives an overview of the definitions for "aggregation" and "aggregator" from literature and moreover describes the "independent aggregator", which is defined in the EU Directive. In addition, the development of EU Directive transposition from selected countries is also presented.

2.1 Policy and Definitions

There are several definitions for aggregators in the literature that aim for a similar interpretation, but the definition of an aggregator depends on the regulation that defines its tasks and responsibilities. Ikäheimo et al. define “an aggregator as a company who acts as an intermediary between electricity end-users and DER owners and the power system participants who wish to serve these end-users or exploit the services provided by these DERs” [4]. Later on, Burger et al. adopted the definition by Ikäheimo et al. and defined aggregation as “[...] the act of grouping distinct agents in a power system (i.e. customers, producers, prosumers, or any mix thereof) to act as a single entity when engaging in power system markets (both wholesale and retail) or selling services to the system operator(s)” [5]. Burger et al. recognise the presence of other definitions and argue that in practice these definitions are subject to the regulations that expand or restrict the roles and activities of the aggregator.

Article 2 of the EU Directive 2019/944 defines aggregation as “aggregation means 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” and an independent aggregator is defined as “a market participant engaged in aggregation who is not affiliated to the customer’s supplier” [2, 6]. Thus, this definition from the EU Directive leads to the differentiation of aggregator, who can either be an integrated aggregator who supplies energy or the independent aggregator who is not responsible as the customer’s energy provider. The differentiation based on the roles is also common in literature [7, 8, 9]. In Section 4 these implementations will be presented by possible interactions and compositions between aggregators and other market participants e.g. DSO, TSO, BRP, customer and with other aggregators based on literature [10, 8, 11].

The definitions of aggregator according to the laws can help aggregators to design business models in different markets [12]. Aggregators can benefit from multiple revenues by offering different services to other energy system participants such as Business to Business (B2B) with BRP, TSO, DSO or Business to Customer (B2C) with active customers [13]. The definition and roles of an aggregator should be clearly defined by laws, in which aggregators, particularly new small entrants, are able to perform services.

2.2 Transposition of Article 17 of EU Directive 2019/944

Decarbonisation of energy systems requires a proactive policy framework to enhance new energy services and regulate fair competition and transparency. The European Commission (EC) announced the Clean Energy Package to move away from fossil fuels towards clean energy which consists of four directives and four regulations [14]. The Electricity Directive 2019/944 officially encourages the customers to participate in energy transition as well as utilize their flexibility for the economy of scale i.e. participating in the energy market. Each member state needs to transpose the common principle of an EU Directive into national law for detailed implementation in their countries. Article 17 of EU Directive 2019/944 also outlines the Demand Response (DR) concept in which the regulatory framework should be a transparent, non-discriminatory, and fair rule for market participants including the independent aggregator. This EU Directive opens up new business services for independent aggregators. Furthermore, Article 16 also defines the citizen energy communities and renewable energy communities in which aggregators could play a role for new business services. Small residential customers are hindered from participating in the energy market themselves due to high technical and market requirements that an aggregator could support.

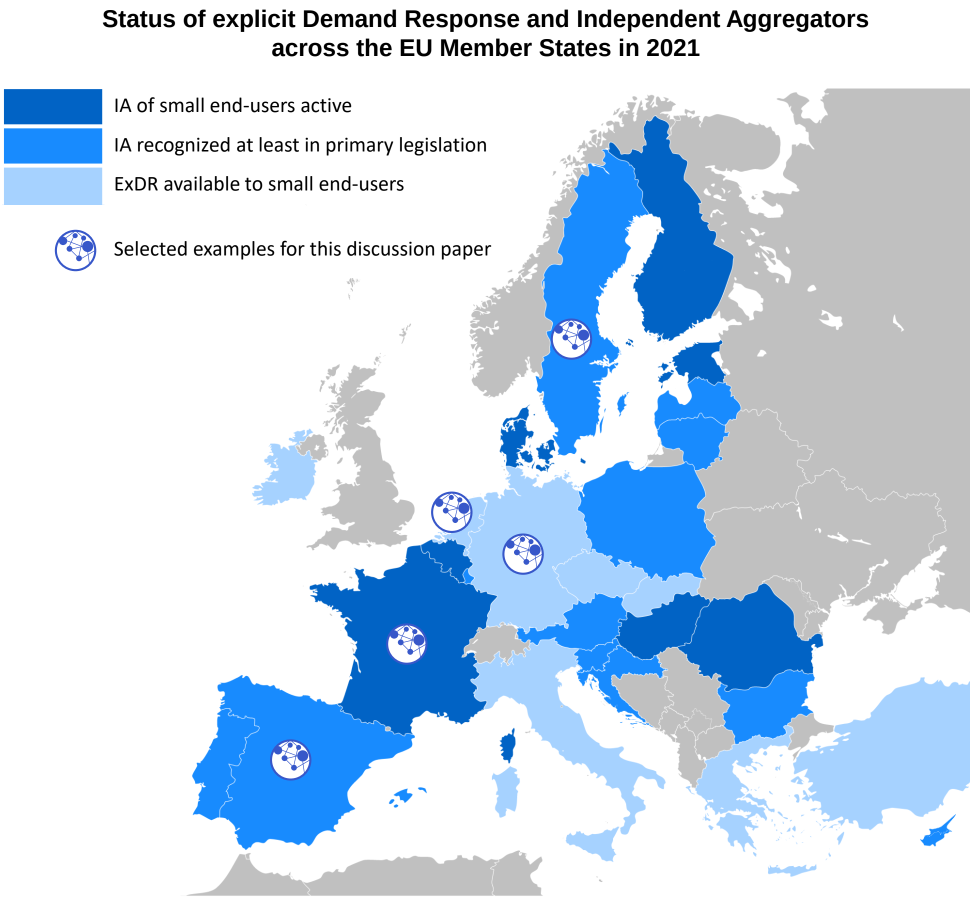


Figure 2: Status of explicit Demand Response (ExDR) and Independent Aggregators (IA) across the EU Member States in 2021 by Joint Research Center (JRC) [1], extended with labels for the countries, which are investigated in this discussion paper.

A study of JRC has shown the current status of Article 17 transposition of EU Directive 2019/944 and the adoption of an independent aggregator in each member state [1]. Figure 2 shows independent aggregators implementation and Explicit Demand Response (ExDR) in the EU member states. It was found that

22 of the 26 member states (light blue) already have demand response legislation in place but only 7 (dark blue colour) implemented independent aggregators of small end-users, who participate in at least one market. The report identified that key enablers for demand response and independent aggregators are regulatory framework, fair and transparent market mechanisms, technical preconditions, business case's viability, advanced smart meter rollout, and awareness of the end-users.

To provide a deeper insight, five examples, which are Germany, the Netherlands, Sweden, France, and Spain, will be presented. The selected countries are examined based on the questionnaire conducted in this study and additional desk research for aggregator policy transposition development.

Germany

To date, Germany has not yet fully transposed the EU Directive 2019/944 to national law [1]. There are two major laws that are relevant for aggregators and DERs: Energy Industry Act (EnWG), and Renewable Energy Resource Act (EEG). Moreover, the two regulation authorities Federal Office for Information Security and the Federal Network Agency define the regulatory framework. The Federal Office for Information Security specifies the smart meter gateway and considers that actors, such as aggregators, aim to access the active customer's flexibility as so-called External Market Participant (EMP). The EMP can either read metering values (being passive) or access the controllable local system in the customer premise (being active). Moreover, this regulation authority determines what belongs to the critical infrastructure and therefore are subject to specific Information Technology (IT) requirements.

Existing German laws and regulations allow aggregators to play a role in the energy market but this could be expanded with active policy and wide adoption of smart meters in which aggregators can gain access to small customers and DERs units [10, 1]. Current implementations show aggregators participating in wholesale and balancing markets as well as their involvement in congestion management [13]. Aggregators, who are qualified in Germany, are able to operate their portfolio with the aim of participating in the German wholesale electricity market. The German wholesale market for electricity is a so-called energy-only market, where only energy but not capacity is traded. Aggregators can help their customers to overcome market entry barriers by providing services to optimize their portfolio with a financial incentive and managing risks that incorporate dynamic prices. Both, day-ahead and intraday spot markets are in the scope of several aggregators in Germany [12].

Besides energy markets, aggregators in Germany are allowed to provide ancillary services and are involved in congestion management. According to EnWG §13 and §14, power system operators are obliged to ensure the security and reliability of their network [15]. A recent regulation called "Redispatch 2.0" stimulates involvement from the distribution level for congestion management with the involvement of aggregators to support DSOs. In EnWG, Germany justifies in §13a that all generation units and storage systems with a nominal power of more than 100 kW or systems that can be remotely controlled by a network operator have to participate in congestion management. Moreover, several aggregators in Germany provide their service in the balancing market.

Recently, the German Bundestag passed the law on the Metering Point Operation Act (MsbG) amendment to restart the digitization of the energy transition (GNDEW) to accelerate the Smart Meter Gateway (SMGW) rollout. It is expected that 95% of all metering points that exceed a certain threshold (e.g. yearly consumption >6.000 kWh or a power plant with a peak power of >7 kW) must be equipped with SMGW by 2032 [16]. The amendment law also specifies lowering the bureaucracy processes and reducing the metering fee for small consumers and plants to a maximum of 20 EUR per year if the consumption is lower than 10.000 kWh per year or the power plant has a nominal power lower than 15 kW. The roadmap to roll out SMGW could accelerate the number of active customers and new energy services offered by aggregators in the future.

The Netherlands

In the Netherlands, smart meter adoption and independent aggregator services are moderate. An existing Dutch Electricity Act 1998 “Gaswet and Elektriciteitswet” does not define the aggregator role but the ongoing development of the new law “nieuwe Energiewelt 1.0” could enhance aggregator roles. It is expected that if a net metering scheme will be phased out by 2025, aggregators could offer alternative solutions for the prosumers [17]. Several IT platforms are being developed by DSO and TSO to integrate aggregators into their business services. Currently, there are initiatives for aggregating flexibility from DERs which are supported by TSOs and DSOs such as Energiekoplopers, GOPACS platform [18, 19]. The GOPACS platform is a flexible platform in the Netherlands owned by TSO TenneT and DSOs [20]. In addition, a number of electric vehicles and charging stations are prominent in the Dutch electricity network which makes aggregator business more attractive for managing congestion by using these potentials [6, 21].

Sweden

A study [1] shows that Sweden has the highest rate of smart meter rollout in the EU. However, an independent aggregator role is still moderate, because all practical details regarding the aggregator’s participation in electricity markets is yet to be determined. For example, the question regarding who in the end shall pay for potential imbalances in connection points, where the aggregator is not the balancing responsible party, is not yet defined. Suggestions for solutions exist, but discussions are ongoing. According to the Electricity Market Directive, Sweden would need to introduce a regulatory framework for independent aggregators no later than 18 months after the Electricity Market Directive was decided in June 2019. The Energy Market Inspectorate (Ei) was commissioned by the government to analyze how the directive should be implemented in Swedish legislation. In a new report in February 2021, Ei submitted proposals to the government on how the EU’s rules on independent aggregation can be implemented in Sweden in accordance with NordREG’s proposal. Ei further assesses and recommends that the Electricity Act needs to be adapted to enable a model for harmonizing Nordic and European markets for aggregating different types of sources considering connection point and financial compensations between parties for the imbalances [22]. Participation of independent aggregators in the energy market is expected to be implemented in the near future.

France

France has a national regulation so-called Code de l’énergie” for independent aggregators in particular a demand response independent aggregator has been in place in France since 2013 [1]. Regulations in France enable aggregators to access all markets such as Frequency Containment Reserve (FCR), Manual Frequency Restoration Reserve (mFRR), Automatic Frequency Restoration Reserve (aFRR), wholesale, and capacity markets [23, 24]. High peak demand is crucial in France because the demand is temperature-sensitive especially in the cold months e.g., November, January and February [25]. Demand response is one of the effective measures for load shedding, which France is one of the most advanced in Europe for developing regulations and infrastructure including smart meter adoption to support demand response implementation [26]. A Block Exchange Notification of Demand Response (NEBEF) is a mechanism that regulates and standardizes coordination between demand response aggregators and suppliers for load reduction without having consent from the suppliers [27, 24, 1].

Flexibility from DERs at the distribution level is promising and could be utilized for congestion management. It should be noted that demand response flexibility in France is in the trial stage in which the past several trial results were disappointing [23, 28]. This is mainly because of unattractive business profit compared to the well-known capacity remuneration mechanism for TSO markets. In addition, the tender design with specific and non-divisible flexibility product, as well as price cap, are considered as the main barriers [28]. As a result, ENEDIS, a DSO responsible for 95% of distribution networks in France, further investigated R&D projects and suggested two use cases for utilizing local flexibility beneficially which are

1) flexibility to facilitate the connection of customers and promote the integration of renewable energy into the grid, and 2) optimise planning and operation of the distribution grid by deploying flexibility [29].

Spain

The Real Decreto Ley 23/2020 introduced an independent aggregator framework in the Spanish Market but yet the secondary law is expected in place in the near future. Recently, the government approved a decree for innovation in the electricity sector which also aims at promoting pilot projects and sandboxes involving aggregation [30]. The current law allows prosumers to supply balancing services but only via suppliers in the energy market. Independent aggregators cannot participate in balancing the market yet. The aggregator business model could be greatly derived from value stacking by providing multiple services. Small customers still face market barriers compared to large customers [1]. Flexibility and demand-side provision for congestion management are not currently established which can limit the profitability of aggregators in Spain. Besides regulation, technical challenges exist for data access from the advanced metering infrastructure that must be standardized, secure, and interoperable. This demands new infrastructures for realization in practice. Reducing the complexity of procedures, ensuring data privacy, and enabling freedom of choice could encourage customer engagement to participate in aggregating services.

3 The Role of an Aggregator

An aggregator is seen as an intermediary between other electricity market players. Figure 3 visualises how aggregators are placed among active customers and market players. The contribution of aggregators depends on the services between aggregators and their customers. Aggregators are not limited to only one service per customer but rather have the opportunity to offer multiple services to several energy market participants, which may include other aggregators. Accordingly, aggregators could have more than one business model for different services and customers, which must not violate the conflict of interest for their customers to create an imbalanced energy market on purpose i.e. energy price arbitrage.

In this section, the added value of the aggregator is examined based on the interaction between the aggregator and main market participants, i.e. TSO, DSO, BRP, and customer. The main function of aggregator roles can be seen as bundling of services such as aggregating flexibilities, providing automation, participating in energy markets, and managing risks [12, 31, 32]. For example, an aggregator provides demand response services with attractive incentives to active customers and offers aggregated flexibility to other market participants.

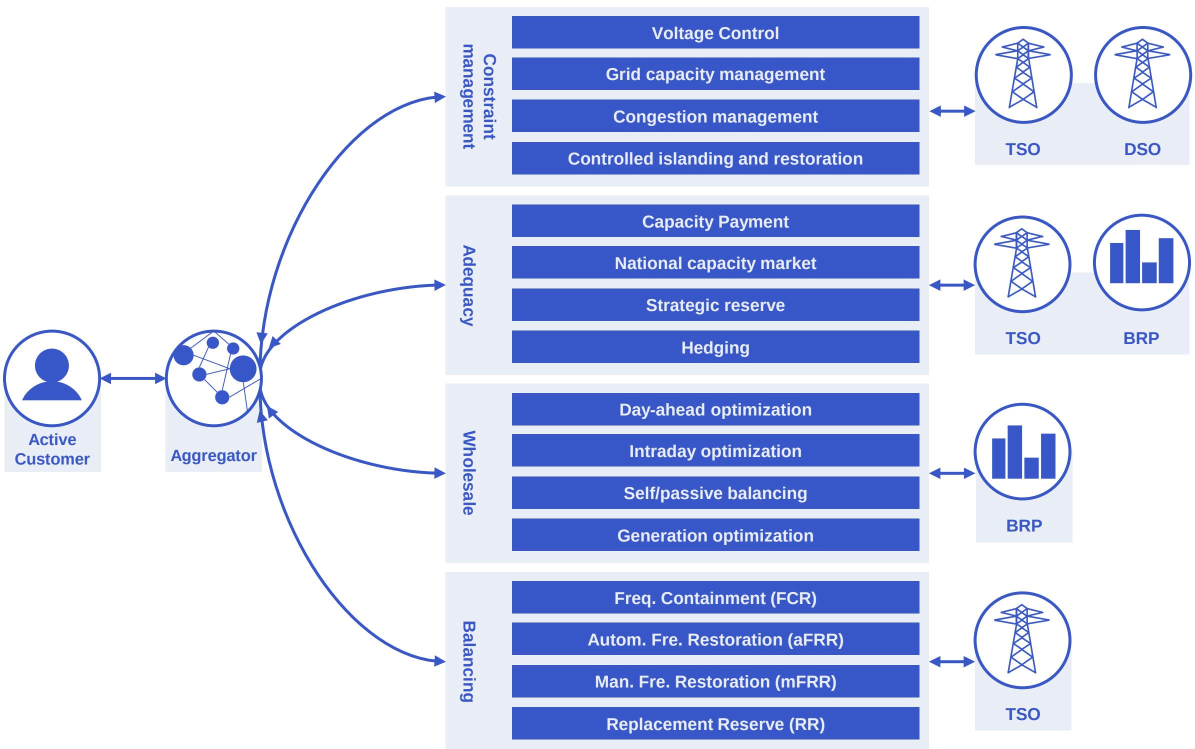


Figure 3: By remunerating the flexibility of the active customer, an aggregator can offer services to the TSO, DSO, BRP, or to other active customers (Figure adopted from [33]).

3.1 Transmission System Operators Perspective

A TSO is mainly responsible for transporting energy at the national and/or regional levels while maintaining the security and stability of the power system. The responsibility of the TSO covers constraint management, adequacy, and balancing, as shown in Figure 3. Aggregators, who offer Ancillary Service (AS) to TSOs, can help grid operation using market solutions, i.e. by participating in the balancing market. There exist not only market-based solutions for AS but also predefined agreements. In both cases, aggregators can offer AS to TSOs (and DSOs) via bilateral contracts or in the energy market [8, 34].

High DERs penetration could pose constraint management challenges to TSOs, where aggregators could assist. An aggregator can provide AS such as providing flexibility to mitigate congestions at the transmission grid. Simultaneously, with more DERs in the distribution grid and fewer bulk generation units at the transmission grid, TSO-DSO coordination is indispensable for TSOs, especially for redispatch. Besides, controlled islanding and restoration rely on TSOs responsibility.

To guarantee long-term system adequacy, TSOs aims for strategic reserves, capacity payment, and capacity markets. Long-term strategic reserves are requested by an authority and are not participating in the energy markets as long as they are not activated by a TSO [33]. Besides, capacity payments and capacity markets exist, which differ in that the capacity payments seek liquidity on the supply side while capacity markets focus more on clearing the expected demand [33]. Thus, aggregators, who aim for long-term service, could assist TSOs in fulfilling their system adequacy responsibilities.

To maintain power system stability, the TSO procures flexibility at the balancing market, in which aggregators can participate. The balancing market differentiates between FCR, aFRR, mFRR, and Replacement Reserve (RR) for mitigating frequency deviations. Depending on the resources in their portfolio, aggregators can qualify for one or more of these services. An example in Germany shows that aggregators provide all three balancing reserve services (e.g. they aggregate resources from BESS to provide FCR [9]). Accordingly, aggregators can compete with other market participants in bidding in the balancing market to obtain profit [10]. Thus, aggregators in the balancing market result in more competition for providing balancing services.

3.2 Distribution System Operator Perspective

Compared to TSOs, DSOs distributes energy at a regional level, taking into account grid constraints. The penetration of DERs in MV and LV networks necessitates DSOs to play a role in constraint management, too. This creates existing and emerging service demands not only for TSOs but also for DSOs. Thus, by aggregating flexibilities from DERs at any voltage level, the aggregator can provide services to both DSOs and TSOs.

The aggregator's involvement in operational planning and operational management facilitates an enhanced constraint management for the DSOs. Thus and as outlined for the TSO, DSOs have to cope with voltage control, grid capacity management, congestion management, and islanding. At the same time, new service opportunities are emerging with the progressive development of DERs [35]. For example, aggregators may also provide voltage control from BESS and rooftop PVs to DSOs. Aggregators cannot only support operational management but also operational planning (e.g. by load and feed-in forecasts). Moreover, flexibility markets could incentivise DSOs to reduce grid reinforcement investments [13]. Without a market-based approach, the aggregator could also act as a service provider by offering access to the Virtual Power Plants (VPPs) and therefore facilitates DSOs to have control opportunities for constraint management (e.g. adapting reactive power).

3.3 Balancing Responsible Party Perspective

BRP is financially responsible for its portfolio imbalance settlement of access points called the balancing group. Each balancing group is assigned to a control area of a TSO, who monitors the frequency as an indicator for the electricity balance and thus for system stability. For maintaining this stability, a BRP is responsible for having a balanced balancing group in the control area of the TSO. A BRP forwards the forecasts for a balanced group and in the event of a measured imbalance that causes frequency deviations, the TSO has to take all measures to maintain the power system's stability. If a BRP causes the imbalance, the TSO charges them or vice versa reimburses if it counters the frequency deviation. Being charged by a TSO for imbalances is an effect of forecast errors or other short-term effects. It has to be noticed that the aggregator can take up the role of a BRP, which will be discussed in the next section.

BRPs are legally bound to have a well-balanced balancing group by buying/selling all necessary energy at the energy market. Depending on the resources within a balancing group, a BRPs either sells or buys energy at the wholesale market. Therefore, aggregators can participate by offering flexibility and energy from their VPP. Consequently, the possible services where the aggregator can assist are day-ahead optimisation, intraday optimisation, self/passive balancing, and generation optimisation as depicted in Figure 3.

The adequacy of the system has already been outlined from the TSO perspective but also BRPs can target system adequacy services. To maintain a balanced portfolio in their balancing group, BRPs not only procure or sell energy on markets, such as day-ahead markets but also hedging is another opportunity to optimise their portfolio via over-the-counter contracts or futures exchanges [33]. Hedging mitigates price risks in the energy market, which occur i.e. when energy scarcity results in high prices. Aggregator could provide flexibility to BRPs by activating flexibility at a specific price level [33].

3.4 Customer Perspective

Passive customer is currently the majority energy customer type that has a great flexibility potential, which could be offered by an aggregator, if they can be encouraged to become an active customer. European Commission defines an active customer as "a final customer, or a group of jointly acting final customers, who consumes or stores electricity generated within its premises located within confined boundaries or, where permitted by a Member State, within other premises, or who sells self-generated electricity or participates in flexibility or energy efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity" [2]. Each country should transpose and design policy instruments to support aggregator services as well as enhance customer engagement to increase the economy of scale.

Currently, customers have limitations in selling their flexibility due to the absence of regulatory frameworks and the underdevelopment of technologies. Technological advancements enable information exchange between customers and other market participants. Aggregators can offer services from downstream to upstream networks such as providing automation solutions, managing customers' portfolios, controlling customers' DERs, and selling flexibility to the market. These emerging new energy services could be achieved if data from smart meters can be accessed and interfaced with other market participant solutions. A regulatory framework and standards are required for interoperable connections between aggregators and also enhance customers' freedom of choice for switching aggregators. Market rules and regulation bodies can ensure transparency and fair competitiveness among aggregators.

Successful energy services to a customer do not only require technology but also an understanding of the customer's need. Customer behaviour interlinks with several factors such as background, knowledge, social norms, and individual preference. An aggregator can encourage passive customers to become active customers by providing expertise in managing their energy portfolio by considering societal factors such as dynamic pricing via demand response program [36, 37].

4 Aggregator Coordination in Digitalised Power Systems

The previous section places the aggregator role in the perspectives of the TSO, DSO, BRPs, and the customer, while highlighting the importance of a digitalised power system. The integration of renewable energies is one of the accelerators for the implementation of digital technologies in power systems [38]. The ongoing digitalisation of the power system facilitates the implementation of smart grids and therefore enables aggregators to provide the described services from the previous section. This section introduces the aggregator implementation model and moreover the SGAM. Afterwards, the role of aggregators can be placed in the context of flexibility coordination with TSOs, DSOs, the active customer, and other aggregators.

4.1 Aggregator's Interaction with Supplier & Balance Responsible Parties

From the energy market perspective, the aggregator's roles can be differentiated by the interaction with the energy supplier and BRP [7, 8, 11, 10, 33]. Figure 4 depicts the aggregator implementation model retrieved from Bignucolo et al. [8], which also refers to the differentiation between independent aggregator and integrated aggregator.

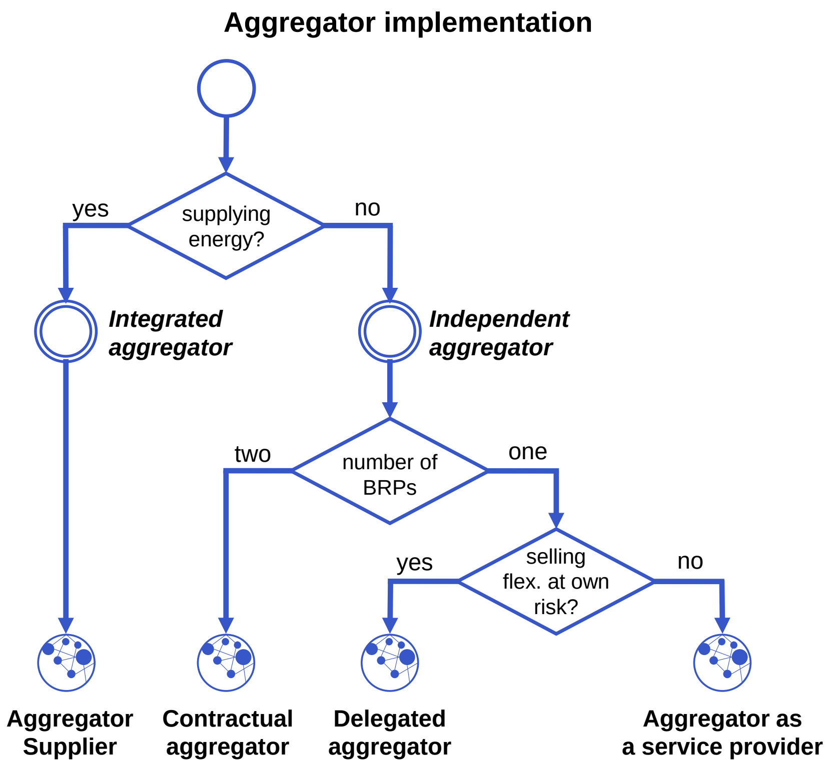


Figure 4: Aggregator implementation models [8].

The integrated aggregator takes on the role of the supplier and moreover is responsible as the flexibility contractor for the active customer [8]. Accordingly and as the main characteristic, this case would not require a financial settlement with an external energy supplier. It has to be acknowledged, that further distinctions can be made if the aggregator supplier is either responsible as the BRP or not [10, 33]. In the context of this work, however, this implementation model is not further differentiated. The aggregator supplier implementation leads to a one-stop service for the active customer.

Compared to the integrated aggregator, the independent aggregator is not affiliated with the supplier's role. Their interaction with the role BRP and the risk allocation results in three different implementation models. If the aggregator has to assign its own BRP, while the supplier remains its own BRP, the bilateral contract between those leads to the model contractual aggregator. Financial settlements and imbalances, which emerge based on flexibility activation, require information exchanges between both BRPs. However, if the aggregator does not have its own BRP, the aggregator is defined as a delegated aggregator and the supplier is the only BRP, whereby arrangements between both are made. In this case, the aggregator still sells the flexibility at its own risk. Compared to that, the aggregator as a service provider is neither responsible for the energy supply nor for the flexibility trading, and does not take on the role of a balance-responsible party. Instead, the aggregator as a service provider purely offers access to flexibility. An active customer can select different independent aggregators for their resources.

4.2 Smart Grid Architecture Model (SGAM)

To depict the aggregator coordination in the smart grid context, the different approaches can be visualized by the so-called SGAM. SGAM was developed under the EC M/490 Standardization Mandate to European Standardization Organization (ESO) [39]. "The SGAM subsumes different perspectives and methodologies regarding the development and conceptualisation of the Smart Grid [40]. Figure 5 illustrates the SGAM which consists of planes and interoperability layers, that are described below.

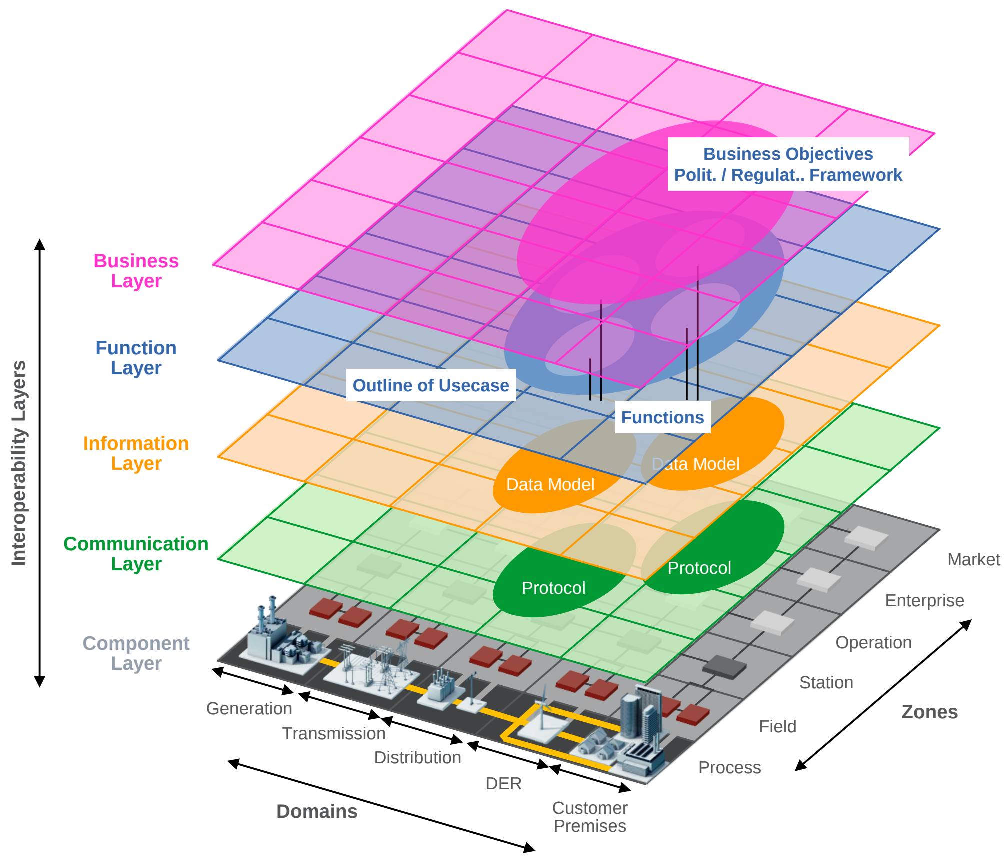


Figure 5: Smart Grid Architecture Model [39].

An SGAM plane spans over the domains and zones of a smart grid system. A domain can be categorized into *Generation*, *Transmission*, *Distribution*, *DER*, and *Customer Premises*. *Generation* covers generation units that are directly connected to the transmission grid such as conventional power plants or large wind farms. Electrical grid infrastructure is divided into *Transmission* and *Distribution* systems. Decentralized energy resources connected to the distribution grid such as small wind, solar farms, and biomass power plants are located in the domain *DER*. *Customer Premises* include commercial, industrial, and home facilities e.g. photovoltaic, electric vehicles, and storage systems. Compared to domains, zones are categorized into *Process*, *Field*, *Station*, *Operation*, *Enterprise* and *Market*. The zones from *Process* to *Operation* are derived from the automation pyramid. Additionally, the zone *Enterprise* includes among others processes and services for companies, while energy markets are located in the zone *Market*.

Five SGAM planes aim to obtain interoperability in smart grid systems. Here, the *Component Layer* represents involved components such as field devices, servers, energy management systems, charging stations, or electric vehicles. On top of the *Component Layer*, the *Communication Layer* illustrates the used protocols for the communication between the systems e.g. a charge point operator can use the open charge point protocol for the communication with electric vehicle supply equipment. Besides defining the protocol, the exchanged data is defined in *Information Layer*. The *Function Layer* depicts functions, services, and their relations from an architectural view [40]. For instance, a charging process will have interactions between the charging point operator and the corresponding electric vehicle user. As the top layer, the *Business Layer* presents among others regulatory and economic structures and policies, business models, and business portfolios as well as business capabilities [40].

4.3 Flexibility Coordination among Aggregator, TSO and DSO

The coordination of power system operators i.e. TSO and DSO can also take into account possible flexibility coordination approaches with aggregators. Although local small flexibilities could be seen as low significance for the TSO at the transmission grid, an aggregator can help TSO (i.e. for congestion management) at lower voltage levels by coordinating the energy supply and demand of its aggregated resources. For this reason, the increasing number of DERs in grid areas of DSOs demand TSO-DSO interaction [41]. Silva et al. [42] present four grid operator coordination approaches, which are transferred to the SGAM as part of this work. Moreover, the aggregator and active customer will be placed in the coordination processes. Figures 6a-6d show the function layer of these four coordination approaches along with an aggregator, who is located in the domain DER, as an intermediary between TSO, DSO, and the active customer.

All coordination approaches represent an aggregator providing services from flexibility procurement over flexibility management to participation in different forms of flexibility markets (global and local). DERs, who are not affiliated directly to the domain of customer premise, can be part of the flexibility portfolio of an aggregator, but will not be depicted for simplicity. Likewise, a meter operator is not depicted, too. Instead, the scope focuses on DERs and flexibilities from customers premises, such as controllable loads, Home Energy Management System (HEMS), Building Energy Management System (BEMS), BESS, PV and EV.

The first coordination setup (M1) consists of a centralized flexibility market in which the TSO procures the available flexibility. An aggregator can offer their aggregated flexibilities from active customer to the TSO by fulfilling existing regulatory and market rules at the transmission grid level i.e. minimum bidding capacity or certificates. Silva et al. acknowledge that the DSO could conduct a pre-qualification process or a validation before flexibility activation, as shown in the light grey box in the distribution domain of the SGAM function layer. However, this coordination approach does not consider DSO constraints on the market level and therefore assumes no physical limitations.

The second model (M2) presents both a local and a global flexibility market in which resources are shared between DSOs and TSOs. In this coordination, the flexibilities are offered at the local DSO

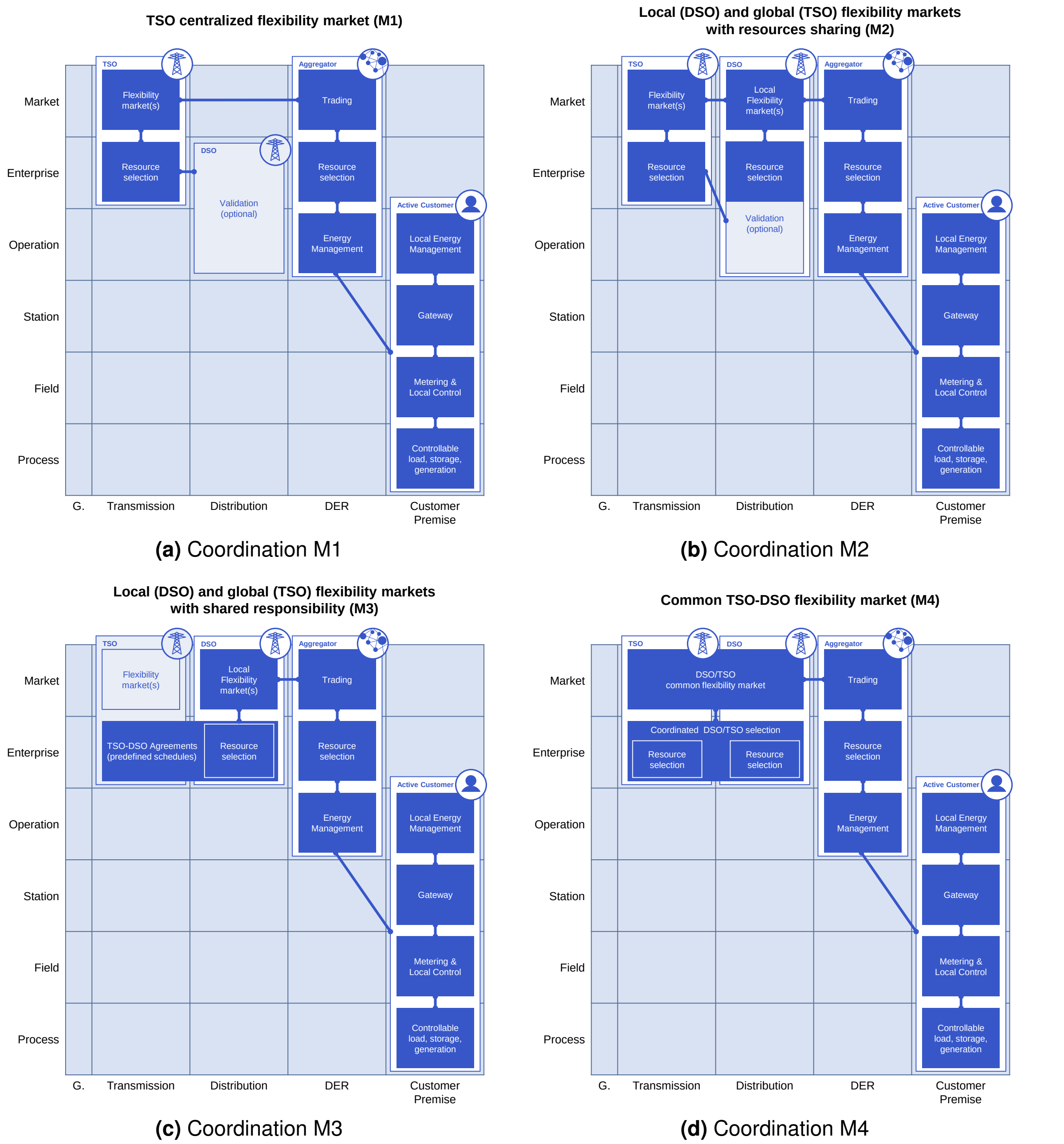


Figure 6: Function Layer of four Basic TSO-DSO Coordination Mechanisms based on Silva et al. [42] (Pre-qualification process and other participants are not displayed).

market. Thus, the DSO procures the flexibility for its own demands, while the remaining flexibilities are offered at TSO market(s), in which the TSO perform their resource selection. Accordingly, the TSO has direct access to the bids for its own optimization. As described for M1, a validation by the DSO may be included in this coordination approach as well.

The third model (M3) depicts shared responsibility between the DSO and TSO. This coordination follows a similar idea of M2 but rather focuses on predefined agreements between the DSO and TSO at the connection points between both grid operators. The DSO selects resources on a local market for their own demands and agreed flexibility profiles. The same as in M2, activated flexibilities may be coordinated between both grid operators to avoid imbalances in the power system.

The last coordination approach (M4) presents a common TSO-DSO flexibility market. This can be done by the DSO and TSO selecting their resources, which can lead to different levels of complexity. Constraints and location information should be incorporated into the selection process e.g. for congestion management. An aggregator can offer flexibility from active customers using their aggregating system to this common flexibility platform.

Coordination approaches between aggregators and other market participants follow the market design and regulatory framework, but the implementation requires a digitalised power system. ICT can improve the reliability of existing systems and can provide interoperability for connecting new systems. Flexible and modular system architectures are recommended for scaling and interfacing different solutions provided by each market participant. Research and development projects are necessary to overcome technical challenges for effective coordination between market participants and market designs.

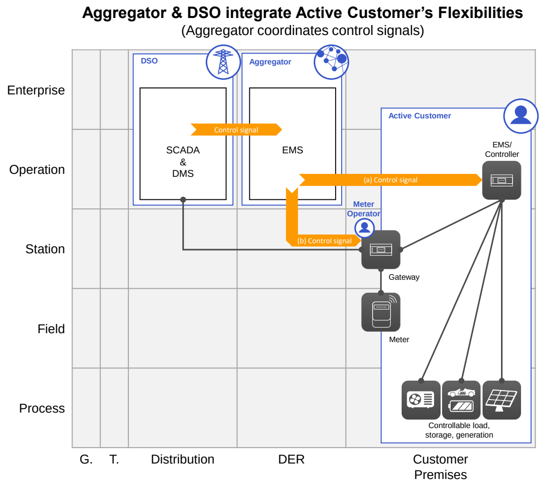
4.4 Aggregators Facilitate Active Customers to Provide Flexibilities

Section 3.4 presented how aggregators create added value to active customers by enabling services and incentivising their flexibility provision. This section will focus on how aggregators can activate flexibilities in the grid area of a DSO. The increasing number of DERs in the distribution grid leads to the demand of DSOs to either activate flexibilities for its own purposes or to monitor the activation by an aggregator to prevent congestions. Therefore both require access to the flexibility of active customers. A technical challenge does not only deal with the complexity of managing energy supply and demand including behind-the-meter components but also integrating proprietary soft- and/or hardware solutions. This section describes different approaches for accessing the active customer's flexibility while considering the DSO during operational planning and management.

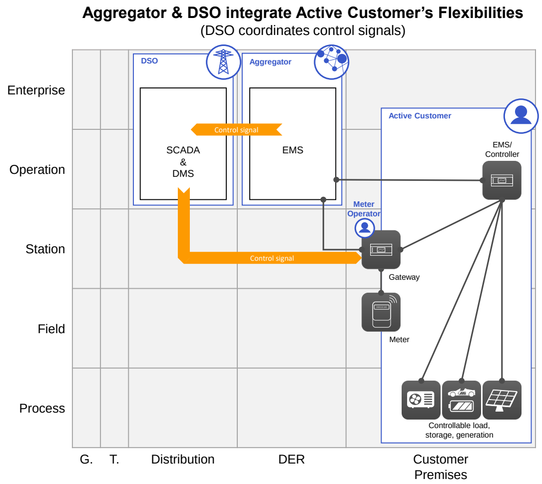
The active customer's flexibilities and their interactions can be managed according to the active customer's preferences. However, it creates different behind-the-meter configurations and moreover leads to different optimisation of resources. To tackle the complexity of behind-the-meter configurations, the DSO can either limit maximum feed-in or consumption of a DER or of the customer's digital grid connection point. The latter relies on an Energy Management System (EMS) in the customer premises that receives digital limitations of the physical connection point from the DSO i.e. an active customer only draws or injects a certain share below the physical maximum. Thus, the way how these limitations are realised can be configured by the active customers in the EMS according to their needs.

Depicted in Figures 7a-7d, four SGAM component layers visualise how an aggregator can have access to flexibilities, taking into account the DSO. These four layers show how coordination can be carried out either by the aggregator, the DSO, the meter operator or by the active customer's EMS. All depicted configurations assume an available smart meter infrastructure at the customer premise. However, for the sake of simplicity, some actors and the corresponding systems of meter operator are excluded in Figures 7a-7d.

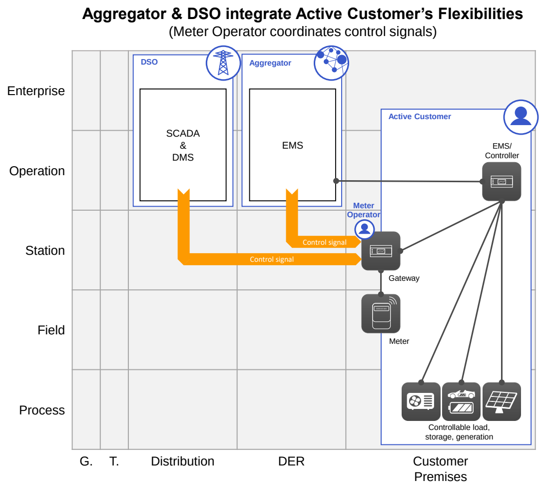
In the first configuration 7a, aggregators have access directly to the resources via proprietary interfaces, which would require a direct information exchange on the operation and enterprise level with the DSO. The DSO has no direct access to the controllable device and therefore requires an interface to the aggregator as shown in Figure 7a. An analysis of different existing aggregators by Poplavskaya et al. [13] pointed out that "Over 85% of the analyzed aggregators use proprietary soft- and/or hardware for VPP operation [...], with 73% of the companies offering it as a white-label solution to other market participants". Moreover, 54% of the analysed aggregators offer platform solutions to utilities and system operators. Aggregator business models exist, which rely on proprietary solutions that have no interface to the DSO. However, utilizing DERs potential for mitigating critical grid states is not possible if a DSO has neither direct control access to the resources nor indirectly via an aggregator platform. Thus, this



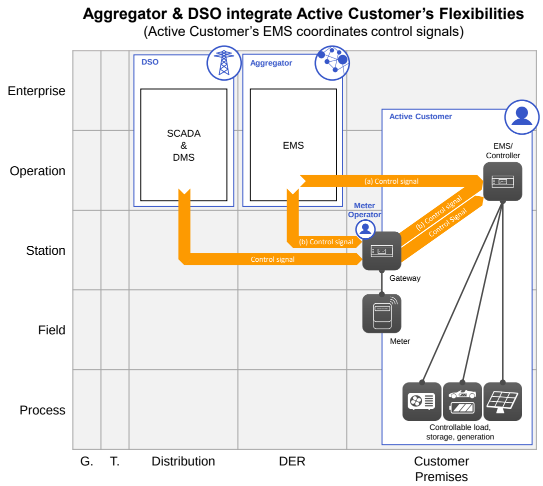
(a) Aggregator coordinates control signals



(b) DSO coordinates control signals



(c) Meter Operator coordinates control signals



(d) EMS coordinates control signals

Figure 7: Four coordination approaches on how aggregator and DSO can integrate and coordinate the active customer's flexibility provision. The most relevant control signals are highlighted in orange. Grey connections are necessary to control, monitor or maintain the flexibility but are not in the foreground for the coordination. For simplicity, the meter operator is visualised purely as a role without the corresponding systems that are necessary for the meter operation.

configuration relies on an interface between the aggregator and DSO in the enterprise/operational zone.

In configuration 7b, only the DSO has access to the flexibilities of the active customer to maintain grid constraints, while an aggregator can send control requests to the DSO. In this configuration, an aggregator has no direct access to the active customer's resources, instead the aggregator forwards control requests to the DSO if they demand flexibilities. After positive validation, the control request will be executed by the DSO. For this coordination approach, the control request has to be forwarded by a DSO, otherwise, the aggregator requires to have access to the flexibilities. This coordination approach ensures that the DSO retains sovereignty of the grid and does not require the aggregator to build up a connection to the active customer. A similar approach can be found in literature [43].

The third configuration (Fig. 7c) relies on a smart meter infrastructure that facilitates multiple actors to have access via a gateway, while the DSO retains the highest control priority. Using a gateway, which is operated by a meter operator, who administrates the access to the flexibilities, requires less interaction between the DSO and aggregator. In this case, the DSO could have the opportunity to set up limited access in critical grid states. As a result, the access by an aggregator depends on the grid status. As mentioned, the meter operator is depicted in a simplified representation without the corresponding systems necessary to realise this approach.

The fourth configuration illustrates the DSO accessing the flexibilities through the smart meter gateway while the aggregator maintains its proprietary solution. Compared to configuration 7b, the aggregator in configuration 7d does not only have access to obtaining measurement data of VPPs, but control signals can be forwarded. Moreover, the interaction between the DSO and aggregator takes place at the resources within the customer premises. The DSO uses the available gateway to intervene in the operation via EMS or at the interface of the flexibilities directly. As in configuration 7c, the DSO in configuration 7d retains a higher priority which has to be implemented at the flexibilities of the active customer. If the DSO has no access, an intervention in critical grid states cannot be realised.

Depending on the coordination approach, extensive and sensitive data exchange could be expected between active customers and other market participants. The exchanged data could contain information about the active customer, which could give insights into their daily lifestyle which leads to privacy concerns e.g. current location of the vehicle, and energy consumption profiles. However, this information could be essential for the VPP operation. Through a smart meter, the DSO can monitor energy consumption, generation, and grid status. Regulation for data privacy and cybersecurity can enhance trust between aggregators and other market participants. In addition, many R&D projects are mainly focusing on the cybersecurity of systems, connections, and components, however, cybersecurity research on human, organization, and societal security is still low [44]. Researches on improving interoperability and technical cybersecurity perspective are important but non-technical cybersecurity should not be neglected.

4.5 Aggregators Enable Energy Communities

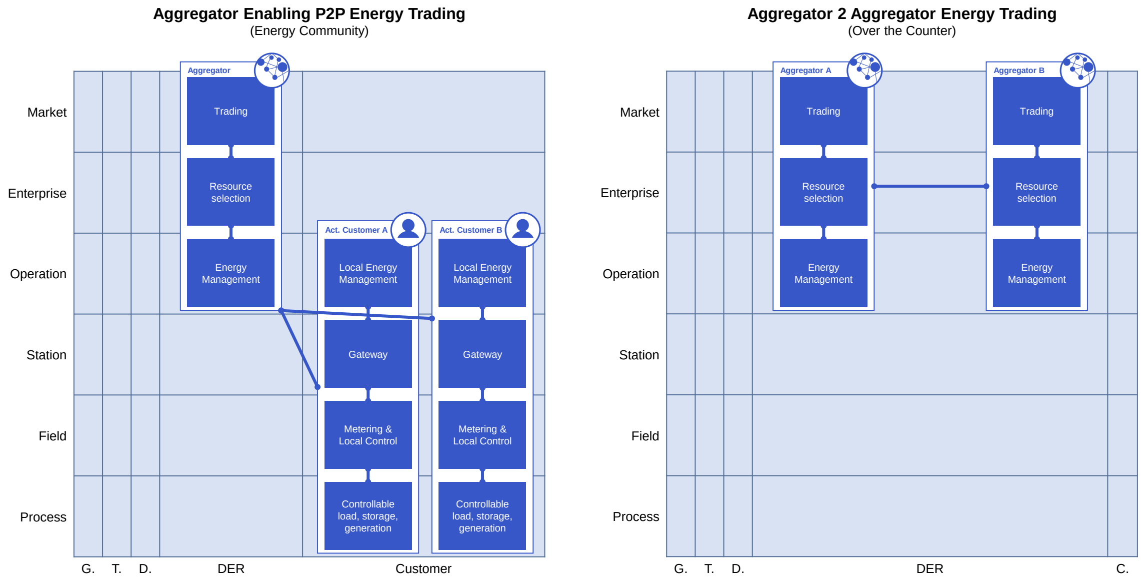
The Clean Energy for All European package, adopted in 2019, has promoted the energy communities concept [14]. In addition, the EU Directive 2019/944 also defines a citizen energy community as a legal entity that:

(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;

(b) has for its primary purpose to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and

(c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;

The EU legislation allows European citizens to participate in energy markets by aggregating their energy resources including renewable energy resources as well as energy demand and flexibility from DERs which could be traded or provided to other members. The EU Directive 2019/944 also specifies that citizen energy communities can provide their flexibilities through a demand response program [2]. However, the legislation points out that the citizen energy community is primarily for local environmental, economic, and societal value rather than generating private financial benefits. The aggregator can aggregate their energy resources and utilize them for community members or shareholders which can be within the same energy community or between energy communities. From this perspective, aggregators could play a role in enhancing energy community and Peer-to-Peer (P2P) deployment. For example, an energy community can also offer trading services among their product's users and at balancing market [45, 46]. This section presents possible coordination between aggregators and other market participants to enable P2P and Aggregator-to-Aggregator (A2A) implementations.



(a) Peer-to-Peer (P2P) trading.

(b) Over the Counter (OTC) trading.

Figure 8: Aggregator trading: Within energy communities (a) and among aggregator (b).

Figure 8a depicts both the local and global energy communities in which a single aggregator could bundle customer A and customer B within the same community. Figure 8b presents A2A trading concept in which an individual aggregator represents their active customer. Thus, A2A energy trading could be realised. Moreover, in both cases, an aggregator can offer the remaining flexibility from their customers to the energy market. Bilateral contracts between two or more aggregators are possible. Multi-agent systems are an example where each aggregator can be represented as an agent for aggregating energy portfolios, optimizing, and trading energy with other market participants. An aggregator increases system value by trading the prosumer's flexibility to the energy market which benefits all stakeholders.

Several P2P energy trading platforms exist in which some platforms also use Artificial Intelligence (AI) and blockchain technologies [47, 46]. Although, there is high-level legislation on P2P but still has not yet been widely implemented due to clear market rules as well as customer acceptance [47]. A financial value proposition is a main driver for customer participation but social awareness could support this business concept sustainably [48, 46]. In addition, interoperable and secure communications between P2P and other ICT platforms of market participants would enhance this business model in practice [46, 49].

5 Challenges

This section summarises technical and non-technical challenges based on the conducted analysis and literature review related to aggregators. The challenges addressed in this study are high-level information that could be further researched to identify solutions to support aggregator roles and enhance customer engagement for new energy services.

5.1 Technical Challenges

Challenge 1: Interoperability between aggregator and the grid operator coordination

Flexibilities from DERs lead to enhancing TSO-DSO coordination, but the role of aggregator and active customer in the coordination is not negligible. The different approaches, which were demonstrated in Chapter 4 outlined how coordination approaches can vary. In order to take advantage of what an aggregator can provide to the power system, grid operators require interoperable connections to various aggregators and/or active customers. With the increasing number of DERs in combination with the amount of DSOs and TSOs across different countries, aggregators have to interface different actors and systems aiming ideally plug and play solutions, otherwise implementation cost could lead to technical barriers for the aggregator to enable flexibilities in grid areas of different DSOs and TSOs. By integrating aggregator into the TSO-DSO coordination, policies should consider that conflicts of interests emerge, when flexibilities are demanded oppositely (e.g. low energy price could lead to aggregator creating incentives for a high demand, which could cause grid congestion for DSOs). This not only raises system stability issues but also the question of which data is required to be exchanged between the actors. Thus, standardisation can facilitate that aggregators can expect the same coordination process with DSOs and TSOs. How to improve the interoperability of digital (ICT) systems in the (electric) energy sector, can be found in another ISGAN discussion paper [50].

Challenge 2: Interoperability between aggregator and active customer

To enable flexible provision of active customers, aggregators require interfaces to the flexibilities as a prerequisite. Proprietary solutions can hinder aggregators from interfacing resources, as implementation costs could exceed the value of available flexibility. Thus as outlined for challenge 1, plug-and-play solutions will reduce technical barriers for aggregators that want to enable the active customer's flexibility provision in combination with services to other market participants. Currently, smart meters are being widely deployed with controllable behind-the-meter resources. A secure and interoperable connection between the aggregator, smart meter, and flexibilities could also enhance trust and willingness to accept from the customers. This means the aggregator must follow regulations and standards for connecting SMGW to ensure a secure and permitted connection. There are existing communication technologies that are behind the meter, such as Modbus, MQTT, EEBUS, ZigBee, WiFi, Bluetooth, and Z-Wave [51, 52]. The main challenge is how to enable freedom of choice to customers for switching between aggregators regardless of solutions provided by the aggregators i.e. preventing vendor lock-in.

Challenge 3: Degree of automation

Technical knowledge on the customer premises cannot be assumed, where not only interoperability but also automation will play a crucial role. Already during the initial phase of installation or commissioning of the flexibilities at the customer premises, technical barriers can emerge, such as interfacing the controllable devices in the customer premises for providing access to the grid operator and aggregator. Moreover, before the operation, an active customer may set up their preferences and priorities, but during operational planning and management of TSOs and DSOs, the aggregator can take over the responsibilities for providing flexibilities (e.g. scheduling the resources). Moreover, automation mechanisms can consider robust fallback options during communication failures. Automation can lack not only on the active customer premises but also in the TSO-DSO coordination. Unified and automated processes for integrating the flexibilities into coordination can overcome this barrier because manual setup processes could hinder aggregators from a cost-efficient integration. As previously mentioned, small flexibilities on their own have less value, which leads to the concept of aggregating them into a VPP and underlines the demand for scalability and automation.

Challenge 4: Implementation of the independent aggregator

To promote the full potential of aggregator implementations, national policies should support the implementation of independent aggregators and take technical challenges into consideration. The European Commission's Joint Research Centre argues that "If the integrated aggregator is enabled to access the market without prior permission from the retailer, as the Directive foresees, this also supports competition on the electricity markets in which the customer should be allowed to have multiple contracts with different market participants without one foreclosing the other." [1]. Thus, multiple aggregators could exist behind the meter, which is not only from the market perspective but also from the TSO and DSO aspect relevant. It could lead to advantages for the TSO-DSO coordination as more aggregators could provide flexibility and at the same time increase the freedom of choice for the active customer. However, the coordination of flexibilities and the demanded control approaches are not yet established. To enable the realisation of the independent aggregator, the ISGAN factsheet can guide how independent aggregators can be implemented [53].

Challenge 5: Energy communities and aggregator to aggregator communication

The European Commission does not only promote independent aggregators but also energy communities, whereby aggregators can either operate energy communities or are part of them. However, local flexibility markets with the participation of aggregators are not yet established. Aggregators can play roles by providing services to market participants in energy markets and over-the-counter agreements between aggregators. For example, a local energy community can incorporate the flexibilities of other aggregators or communities and thus enable aggregator-to-aggregator communication. Interoperability is crucial for software and hardware interfaces between aggregators' solutions as well as with other market participants. Local markets, energy communities, or aggregator-to-aggregator communication raises the question of how TSOs and DSOs are involved in order to maintain grid stability.

Challenge 6: Cybersecurity preparedness

A high number of DERs increases complexities of coordination, but also has to cope with vulnerabilities from cyber attacks. Cyber attacks involve from simple to sophisticated strategies, therefore, proactive defence mechanism improvement and regular vulnerability monitoring are essential elements for aggregator business models to increase trust and secure connections. Cybersecurity must be included in the conceptual design of the aggregator's solution e.g. vulnerability monitoring and associated cybersecurity countermeasures. There are available cybersecurity standards such as IEC 62443, IEC 62351, ISO 27001 that are widely adopted in new solutions, existing operational devices should be able to be upgraded and configured according to the standards. In addition, a European standard for communication and coordination between aggregators and other market participants could help as a guideline for developing technical specifications. Then, aggregator should follow the cybersecurity standard for providing secure services to their customers. Depending on the aggregator's business vision, additional cyber measures can be implemented to increase cyber protection including having cybersecurity officers to address proactive cyber measures. Building a cybersecurity culture in a company is essential for cybersecurity awareness, especially for non-IT employees [54, 55, 56]. In addition, cyber information sharing among market participants is essential to update best practices which requires building trust and cooperation. R&D on cybersecurity are essential to address new regulations and requirements such as security certificates and authentication for the aggregator.

5.2 Non-Technical Challenges

Challenge 7: Societal factors for behaviour change and customer acceptance

Customer behaviour is a dynamic phenomenon, influenced by multiple factors such as social norms, self-awareness, knowledge, incentives, and the type of data. A customer behaviour change can be driven by any combination of these elements. Several research studies have been conducted to examine the impact of social norms and data feedback on consumer behaviour changes in energy consumption. Social norms refer to informal social rules or shared expectations within a specific group regarding appropriate behaviour in certain situations. These norms develop energy practices that have the potential to facilitate consumer behaviour change and embrace the green energy community [57, 58, 59]. Additionally, the appropriateness of energy consumption data can also play a role in inducing changes in consumer behaviour [37, 60, 61]. Moreover, the appropriateness of energy consumption data has the potential to stimulate changes in consumer behaviour such as the granularity of data, frequency of feedback, competitive elements, and the content of the information provided.

Lessons learned from a smart meter deployment have shown misperception of new technologies from the customers which may lead to opposition, particularly regarding privacy concerns [62, 63, 64, 65]. The lessons learned could be considered for designing new energy services. It is essential to investigate customers' willingness to adopt new technologies in order to address their perceptions and raise awareness about the benefits of these new technologies. Demonstration projects, particularly living laboratories, can address significant success factors and societal considerations necessary for successful deployment. To facilitate new aggregator business models, governments can provide support through initiatives like sandboxes or local energy community projects as well as collaborating with other market participants during these demonstration activities.

Challenge 8: Data privacy and building trust

Enhancing trust with customers is an essential factor for new services [12]. As energy consumption profiles have the potential to expose customers' daily activities, data protection becomes imperative for aggregator business models [32]. The ownership and management of customer data raise important questions. In the European Union, the General Data Protection Regulation (GDPR) (2016/679) is a mandatory law governing data protection and privacy in the EU and the European Economic Area (EEA). Aggregator services must adhere to data protection regulations, ensuring transparency in the use of customer data. This is particularly crucial for integrated aggregators who also provide energy supply to prevent conflicts of interest.

Building trust is not solely limited to the relationship between aggregators and customers; it also extends to fostering trust within the aggregator community. This involves sharing information on recent cyber incidents, vulnerabilities, lessons learned, and best practices. A single negative incident can significantly damage an aggregator's reputation and have ripple effects on other aggregators in the market.

Challenge 9: Regulatory framework for increasing system value

A major driving factor behind a new business often revolves around private value by focusing on company profits [66]. Policy and regulatory framework can foster system value which encompasses the economic scale and social welfare benefits. Although the EU has established a policy that supports the role of independent aggregators, each member is demanded to develop its regulatory framework accordingly. Regulatory framework on aggregator can facilitate independent aggregator businesses of aggregator's businesses to achieve economies of scale. A study [10] indicates key factors to maintain aggregator's businesses such as active marketing strategy, adjustment of business model to national regulatory context, creating multiple value streams, strategic partnership, and active participation in shaping policy.

A proactive regulatory framework can support fair competitiveness, transparency, and freedom of choice for customers. A monopoly should be avoided to increase competitiveness and freedom of choice for the customers. Existing large market participants often have a well-known reputation among customers compared to new entrants. Policies can ensure fair competition among all market participants regardless of their scale. Additionally, policy instruments can be employed to support new entrants by reducing market barriers, such as lower fixed fees, network charges, and streamlined permit processes. It is crucial to pay attention to any flaws in market rules to prevent the exploitation of price arbitrage opportunities by any market participants [66]. Regulatory sandboxes can enhance innovative technology that has not yet complied with the existing regulatory requirements. This could help policymakers to understand and foresee potential benefits, and risks as well as appropriate policy instruments to support the implementation [67, 68].

Challenge 10: Enhancing knowledge building

The successful transition to a digitalised power system relies not only on the effective implementation of intelligent technologies and innovative business models but skilled workforce with diverse backgrounds and practical experience in multiple domains. Multidisciplinary education plays a vital role in the digitalised energy system transition and in supporting new business adoption. Therefore, improving education and training programs by incorporating comprehensive curricula that cover both technical and non-technical knowledge is of utmost importance [44, 69].

It is imperative to regularly update education curricula and training programs to enhance the skilled workforce and foster new business models. Given the multidisciplinary nature of the digitalised energy system, students should acquire knowledge that spans multiple domains and understand their interdependence in real-world contexts. Furthermore, the development of curricula should consider the industry's actual expectations and requirements to prepare the right skill sets for their career. Collaboration with industry partners is crucial to provide students with valuable hands-on experiences and expedite the development of innovative solutions. Real-life environment laboratories are essential in creating a realistic environment where students and practitioners can simulate and explore practical and innovative solutions.

6 Conclusion

This work investigated how aggregators can improve the TSO-DSO-Customer coordination in a digitalised power system by analysing existing policies, their role, possible coordination approaches, and addressing (non-)technical challenges. Local flexibilities are not yet fully utilized because active customers face technical and non-technical challenges in marketing their flexibilities. The main motivation for this discussion paper relies on the penetration of DERs, especially at LV and MV systems, that leads to a high flexibility potential that grid operators and market participants can utilise for their operation. Aggregators can enable these flexibilities as an intermediary by providing services to different power system participants, such as BRP, TSO, DSO, and active customers. Thus, this work examined how different coordination approaches can be realised with identified challenges that need to be addressed for supporting and accelerating the development and implementation of aggregators in the TSO-DSO-Customer coordination.

The role of aggregators in different TSO-DSO-Customer coordination approaches revealed technical and non-technical challenges that may hinder aggregator implementation. From a high-level technical analysis, interoperability can enable freedom of choice for active customers in selecting aggregators and their services. Moreover, interoperability promotes the integration of aggregators in the TSO-DSO coordination. The variety of aggregator implementation is not yet fully realised but raises questions on automation, and a high need for interoperability and security. Thus, the limited implementation opportunities for aggregators were shown (e.g. acting as an independent aggregator is not fully established yet). Furthermore, the lack of automation hinders aggregators from accessing the flexibility easily. Cybersecurity is essential for providing services to the customer and ensuring their business services in the long term.

In addition to the technical challenges, societal aspects should be considered for designing business models and policy instruments for customer engagement toward consumer behaviour change such as demand response with dynamic pricing. Ensuring trust is key for long-term engagement from active customers. A need for skilled workforces demands education and training programs to update their curricula to support new business services towards the industry's expectations in reality.

This work concludes, that the full potential of aggregators can help to coordinate the flexibilities and facilitate the active customer to market these. On the European level, the concepts of energy communities and the independent aggregator strengthen the opportunities for active customers, which need to be transposed to the national level. The advancement of smart grid technology and available policy framework enables the full potential of aggregators in the power system. Policymakers should ensure that the regulatory framework supports fair competitiveness, transparency, and freedom of choice for customers toward system value as a whole. Moreover, innovative approaches can be tested in demonstration and R&D projects which help to address the technical and non-technical challenges and support needed for the real deployment.

7 Appendix

ISGAN Annex 6

Aggregator Roles in Digitalized Energy Systems

Integrating prosumer and proactive consumers in the energy market requires an aggregator to play a role in facilitating relevant services. An aggregator can provide services for energy supply, energy demand (i.e. demand response), or both. Therefore, there is an increasing need for a regulatory framework and ICT assistive solutions for better managing intermittent renewable energy and raising awareness of consumer behavior change in energy consumption. This discussion paper aims to address the existing aggregator models from international best practices where the ICT solutions can enhance the coordination between aggregators, TSOs, DSOs, and consumers.

Questionnaire

Please read through the paper table of content at the end of this document and respond to the following questions and send back to jirapa.kamsamrong@offis.de **by 29th July 2022.**

Policy aspect

1. Do you have any regulatory framework for aggregator roles and services in your country? If yes, please specify the country and share the detail with us i.e. link and name of policy/law.

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2. What are the challenges of the existing regulatory frameworks in your country that could limit the aggregator's role in implementing effectively and fairly?

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3. What are the value propositions (from your perspective) of the aggregator roles for power system operations and/or TSO-DSO coordination in terms of system planning, control, and operations?

Technical aspect

4. What are the main technical challenges from your perspective for integrating aggregator services into TSO-DSO coordination? (i.e. smart meter, a software platform, interoperability, standard and protocol, etc)

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5. From your perspective, what are the assistive ICT solutions that we need for enhancing aggregator service?

Social Aspect

6. What are the challenges and key successes for enhancing consumer engagement toward energy consumption behavior change through aggregator services?

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7. From your perspective, what do we need to increase the competitiveness of all aggregators in the market?

Economic Aspect

8. From your perspective, what are the essential incentive schemes for wider adoptions of aggregator services?

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9. What are the business models that would benefit a local energy community? And what are the challenges in implementing these business models?

Recommendation

10. What are the main messages that you think should be conveyed from this paper?

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11. What do we need for R&D to improve the aggregator roles for TSO-DSO coordination?

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12. Please share other comments and any pilot projects or companies related to aggregators in your country. For example local energy communities, demand response, peer-to-peer trading, etc.

Any additional input to improve the paper are very much welcome and appreciated.

Thank you all very much for your cooperation.

ISGAN Annex 6: Dr.-Ing. Jirapa Kamsamrong, **jirapa.kamsamrong@offis.de**

References

[1] European Commission and Joint Research Centre, "Explicit demand response for small end-users and independent aggregators: status, context, enablers and barriers." *Publications Office of the European Union*, 2022. [Online]. Available: https://data.europa.eu/doi/10.2760/625919

[2] European Union, "Directive (eu) 2019/944 of the european parliament and of the council of 5 june 2019 on common rules for the internal market for electricity and amending directive 2012/27/eu," *Official Journal of the European Union*, 2019. [Online]. Available: http://data.europa.eu/eli/dir/2019/944/2022-06-23

[3] ——, "Consolidated version of the treaty on the functioning of the european union part six - institutional and financial provisions title i - institutional provisions chapter 2 - legal acts of the union, adoption procedures and other provisions section 1 - the legal acts of the union article 288 (ex article 249 tec)," 2012. [Online]. Available: http://data.europa.eu/eli/treaty/tfeu_2012/art_288/oj

[4] J. Ikäheimo, C. Evens, and S. Kärkkäinen, "Der aggregator business: the finnish case," *Technical Research Centre of Finland (VTT): Espoo, Finland*, 2010.

[5] S. Burger, J. P. Chaves-Ávila, C. Batlle, and I. J. Pérez-Arriaga, "A review of the value of aggregators in electricity systems," *Renewable and Sustainable Energy Reviews*, vol. 77, pp. 395–405, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032117305191

[6] The Netherlands Authority for Consumers and Markets, "Verkenning naar belemmeringen voor de rol van aggregator," 2019. [Online]. Available: https://www.acm.nl/sites/default/files/documents/2019-04/verkenning-belemmeringen-rol-aggregator.pdf

[7] J. Juffermans, "Aggregators and flexibility in the dutch electricity system," *Industrial Engineering & Innovation Sciences; Eindhoven Univerity of Technology*, 2018. [Online]. Available: https://pure.tue.nl/ws/portalfiles/portal/116531098/

[8] F. Bignucolo, A. Lorenzoni, and J. M. Schwidtal, "End-users aggregation: a review of key elements for future applications," in *2019 16th International Conference on the European Energy Market (EEM)*, 2019, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/8916520

[9] IRENA, "Aggregators innovation landscape brief," *International Renewable Energy Agency, Abu Dhabi*, 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_Aggregators_2019.PDF

[10] K. Poplavskaya and L. De Vries, "A (not so) independent aggregator in the balancing market theory, policy and reality check," in *2018 15th International Conference on the European Energy Market (EEM)*, 2018, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/8469981

[11] S. Kerscher and P. Arboleya, "The key role of aggregators in the energy transition under the latest european regulatory framework," *International Journal of Electrical Power & Energy Systems*, vol. 134, p. 107361, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061521006001

[12] J. Stede, K. Arnold, C. Dufter, G. Holtz, S. von Roon, and J. C. Richstein, "The role of aggregators in facilitating industrial demand response: Evidence from germany," *Energy Policy*, vol. 147, p. 111893, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S030142152030608X

[13] K. Poplavskaya and L. de Vries, "Chapter 5 - aggregators today and tomorrow: from intermediaries to local orchestrators?" in *Behind and Beyond the Meter*, F. Sioshansi, Ed. Academic Press, 2020, pp. 105–135. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128199510000050

[14] European Commission and Directorate-General for Energy, "Clean energy for all europeans," *Publications Office of the European Union*, 2019. [Online]. Available: https://data.europa.eu/doi/10.2833/9937

[15] German Bundestag, "Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftsgesetz - EnWG)," 2022. [Online]. Available: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Standardartikel/energiewirtschaftsgesetz.html

[16] ——, "Gesetzesbeschluss des Deutschen Bundestages, Gesetz zum Neustart der Digitalisierung der Energiewende," 2023. [Online]. Available: https://www.bundesrat.de/SharedDocs/drucksachen/2023/0101-0200/161-23.pdf?__blob=publicationFile&v=1

[17] R. Jetten, "Brief van de minister voor klimaat en energie, tweede kamer, vergaderjaar 2021–2022, 32 813, nr. 1046," 2022.

[18] Liander, "Energiekoplopers2 - de flexibiliteit van huishoudelijk stroomverbruik," 2019. [Online]. Available: https://www.liander.nl/sites/default/files/Eindrapportage%20EnergieKoplopers2.pdf

[19] ENTSO-E, and Frontier Economics Ltd, "Review of flexibility platforms," 2021. [Online]. Available: https://www.entsoe.eu/news/2021/11/10/entso-e-publishes-new-report-on-flexibility-platforms/

[20] GOPACS. (2023) Gopacs - the platform to solve congestion in the electricity grid. [Online]. Available: https://en.gopacs.eu/

[21] J. Dijkhuis, "Strategic market entry for energy aggregator firms in the netherlands," 2021. [Online]. Available: http://resolver.tudelft.nl/uuid:7cea2b7c-2c37-4d73-b211-b7bc3b9fd24d

[22] Swedish Energy Markets Inspectorate, "Oberoende aggregatorer: Förslag till nya regler för att genomföra elmarknadsdirektivet – i enlighet med nordreg:s förslag," 2021.

[23] USEF, "White paper: Flexibility deployment in europe," 2023. [Online]. Available: https://www.usef.energy/app/uploads/2021/03/08032021-White-paper-Flexibility-Deployment-in-Europe-version-1.0-3.pdf

[24] R. Bray and B. Woodman, "Barriers to independent aggregators in europe," 2019. [Online]. Available: https://ore.exeter.ac.uk/repository/bitstream/handle/10871/40134/Barriers%20to%20Independent%20Aggregators%20in%20Europe.pdf?sequence=1&isAllowed=y

[25] ENTSOE, "Winter outlook 2020-2021 summer review 2020," 2020. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/sdc-documents/seasonal/WOR2020/201130_Winter%20Outlook%202020-2021_Report.pdf

[26] Nordic Energy Research, "The regulation of independent aggregators with a focus on compensation mechanisms," 2022. [Online]. Available: https://www.nordicenergy.org/article/the-regulation-of-independent-aggregators/

[27] RTE, "Participate in the nebef mechanism," 2023. [Online]. Available: https://www.services-rte.com/files/live/sites/services-rte/files/pdf/NEBEF/2023.07%20R%c3%a8gles%20SI%20NEBEF%203.4.1.pdf

[28] European Commission and Joint Research Centre, *Local electricity flexibility markets in Europe.* Publications Office, 2022. [Online]. Available: https://data.europa.eu/doi/10.2760/9977

[29] Enedis, "Flexibilities to enhance the energy transition and the performance of the distribution network," 2020. [Online]. Available: https://www.enedis.fr/sites/default/files/documents/pdf/flexibilities-enhance-energy-transition-performance-distribution-network.pdf

[30] BOE, "Real decreto 568/2022, de 11 de julio, por el que se establece el marco general del banco de pruebas regulatorio para el fomento de la investigación y la innovación en el sector eléctrico." 2022. [Online]. Available: https://www.boe.es/buscar/pdf/2022/BOE-A-2022-11511-consolidado.pdf

[31] P. Olivella-Rosell, P. Lloret-Gallego, Í. Munné-Collado, R. Villafafila-Robles, A. Sumper, S. Ø. Ottessen, J. Rajasekharan, and B. A. Bremdal, "Local flexibility market design for aggregators providing multiple flexibility services at distribution network level," *Energies*, vol. 11, no. 4, p. 822, 2018. [Online]. Available: https://www.mdpi.com/1996-1073/11/4/822

[32] C. Eid, P. Codani, Y. Chen, Y. Perez, and R. Hakvoort, "Aggregation of demand side flexibility in a smart grid: A review for european market design," in *2015 12th International Conference on the European Energy Market (EEM)*, 2015, pp. 1–5. [Online]. Available: https://ieeexplore.ieee.org/document/7216712

[33] The Universal Smart Energy Framework (USEF), "The framework explained," 2021. [Online]. Available: https://www.usef.energy/news-events/publications/

[34] P. Betancourt-Paulino, H. R. Chamorro, M. Soleimani, F. Gonzalez-Longatt, V. K. Sood, and W. Martinez, "On the perspective of grid architecture model with high TSO-DSO interaction," *IET Energy Syst Integration*, vol. 3, no. 1, pp. 1–12, Mar. 2021.

[35] K. Oureilidis, K.-N. Malamaki, K. Gallos, A. Tsitsimelis, C. Dikaiakos, S. Gkavanoudis, M. Cvetkovic, J. M. Mauricio, J. M. Maza Ortega, J. L. M. Ramos, G. Papaioannou, and C. Demoulias, "Ancillary services market design in distribution networks: Review and identification of barriers," *Energies*, vol. 13, no. 4, 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/4/917

[36] B. R. Alexander, "Dynamic pricing? not so fast! a residential consumer perspective," *The Electricity Journal*, vol. 23, no. 6, pp. 39–49, 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1040619010001417

[37] A. Faruqui, D. Harris, and R. Hledik, "Unlocking the €53 billion savings from smart meters in the eu: How increasing the adoption of dynamic tariffs could make or break the eu's smart grid investment," *Energy Policy*, vol. 38, no. 10, pp. 6222–6231, 2010, the socio-economic transition towards a hydrogen economy - findings from European research, with regular papers. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421510004738

[38] P. Palensky and F. Kupzog, "Smart grids," *Annual Review of Environment and Resources*, vol. 38, pp. 201–226, 2013. [Online]. Available: https://www.annualreviews.org/doi/pdf/10.1146/annurev-environ-031312-102947

[39] Smart Grid Mandate, "Standardization mandate to european standardisation organisations (esos) to support european smart grid deployment," *European Commission: Brussels, Belgium*, 2011. [Online]. Available: https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/m490_smart-grids_mandate.pdf

[40] M. Gottschalk, M. Uslar, and C. Delfs, "The smart grid architecture model–sgam," *The use case and smart grid architecture model approach: the IEC 62559-2 use case template and the SGAM applied in various domains*, pp. 41–61, 2017.

[41] M. Stefan, A. Zegers, and F. Kupzog, "Ict aspects of tso-dso interaction data exchange and ict requirements along organizational interaction between tso and dso," *ISGAN Discussion Papers*, 10 2018. [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2019/02/ISGAN_DiscussionPaper_ICTAspectsOfTSODSOInteraction_2019.pdf

[42] R. Silva, E. Alves, R. Ferreira, J. Villar, and C. Gouveia, "Characterization of tso and dso grid system services and tso-dso basic coordination mechanisms in the current decarbonization context," *Energies*, vol. 14, no. 15, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/15/4451

[43] VDE FNN, "Gesamtkonzept zur Steuerung mit intelligenten Messsystemen," 2022. [Online]. Available: https://www.vde.com/resource/blob/2199366/c0105f2fb4cdc5e8a6f9a97467db64d6/gesamtkonzept-steuerung-pdf-data.pdf

[44] B. Siemers, S. Attarha, J. Kamsamrong, M. Brand, M. Valliou, R. Pirta-Dreimane, J. Grabis, N. Kunicina, M. Mekkanen, T. Vartiainen, and S. Lehnhoff, "Modern trends and skill gaps of cyber security in smart grid : Invited paper," in *IEEE EUROCON 2021 - 19th International Conference on Smart Technologies*. IEEE, Jul. 2021. [Online]. Available: https://doi.org/10.1109/eurocon52738.2021.9535632

[45] J. Barnes, P. Hansen, S. Darby, S. Sommer, and A. M., "Newcomers summary case study report:the sonnencommunity. newcomers project," 2022.

[46] International Renewable Energy Agency (IRENA), "Innovation landscape brief: Peer-to-peer electricity trading," 2020.

[47] A. Nadeem, "A survey on peer-to-peer energy trading for local communities: Challenges, applications, and enabling technologies," *Frontiers in Computer Science*, vol. 4, Sep. 2022. [Online]. Available: https://doi.org/10.3389/fcomp.2022.1008504

[48] M. Karami and R. Madlener, "Business models for peer-to-peer energy trading in germany based on households' beliefs and preferences," 2021.

[49] W. X. Wu, G. Quezada, E. Schleiger, A. Bratanova, P. Graham, and B. Spak, "The future of peer-to-peer trading of distributed renewable energy," 2019.

[50] J. Schütz, M. Uslar, J. Meister, and J. Köhlke, "How to improve the interoperability of digital (ict) systems in the energy sector," *ISGAN Discussion Papers*, 09 2020. [Online]. Available: https://www.iea-isgan.org/how-to-improve-the-interoperability-of-digital-ict-systems-in-the-energy-sector/

[51] International Energy Agency (IEA), "There's more to buildings than meets the eye: They hold a key to net zero emissions," 2023. [Online]. Available: https://www.iea.org/commentaries/there-s-more-to-buildings-than-meets-the-eye-they-hold-a-key-to-net-zero-emissions

[52] K. T. Ponds, A. Arefi, A. Sayigh, and G. Ledwich, "Aggregator of demand response for renewable integration and customer engagement: Strengths, weaknesses, opportunities, and threats," *Energies*, vol. 11, no. 9, 2018. [Online]. Available: https://www.mdpi.com/1996-1073/11/9/2391

[53] S. Gruen, "How independent aggregators can be implemented in sweden," *ISGAN Factsheet*, 11 2021. [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2022/06/WG9-Indepdendent-aggregators-Sweden.pdf

[54] G. Culot, F. Fattori, M. Podrecca, and M. Sartor, "Addressing industry 4.0 cybersecurity challenges," *IEEE Engineering Management Review*, vol. 47, no. 3, pp. 79–86, 2019.

[55] A. da Veiga, L. V. Astakhova, A. Botha, and M. Herselman, "Defining organisational information security culture—perspectives from academia and industry," *Computers & Security*, vol. 92, p. 101713, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0167404820300018

[56] European Union Agency For Network and Information Security, "Cybersecurity culture guidelines: Behavioural aspects of cybersecurity," 2018. [Online]. Available: https://www.enisa.europa.eu/publications/cybersecurity-culture-guidelines-behavioural-aspects-of-cybersecurity

[57] H. Allcott, "Social norms and energy conservation," *Journal of Public Economics*, vol. 95, no. 9, pp. 1082–1095, 2011, special Issue: The Role of Firms in Tax Systems. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0047272711000478

[58] J. Bonan, C. Cattaneo, G. d'Adda, and M. Tavoni, "The interaction of descriptive and injunctive social norms in promoting energy conservation," *Nature Energy*, vol. 5, no. 11, pp. 900–909, Nov. 2020. [Online]. Available: https://doi.org/10.1038/s41560-020-00719-z

[59] G. P. Verbong, S. Beemsterboer, and F. Sengers, “Smart grids or smart users? involving users in developing a low carbon electricity economy,” *Energy Policy*, vol. 52, pp. 117–125, 2013, special Section: Transition Pathways to a Low Carbon Economy. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421512004004

[60] T. Hargreaves, M. Nye, and J. Burgess, “Keeping energy visible? exploring how householders interact with feedback from smart energy monitors in the longer term,” *Energy Policy*, vol. 52, pp. 126–134, 2013, special Section: Transition Pathways to a Low Carbon Economy. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421512002327

[61] J. Carroll, S. Lyons, and E. Denny, “Reducing household electricity demand through smart metering: The role of improved information about energy saving,” *Energy Economics*, vol. 45, pp. 234–243, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140988314001649

[62] D. N. yin Mah, J. M. van der Vleuten, P. Hills, and J. Tao, “Consumer perceptions of smart grid development: Results of a hong kong survey and policy implications,” *Energy Policy*, vol. 49, pp. 204–216, 2012, special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421512004685

[63] T. Krishnamurti, D. Schwartz, A. Davis, B. Fischhoff, W. B. de Bruin, L. Lave, and J. Wang, “Preparing for smart grid technologies: A behavioral decision research approach to understanding consumer expectations about smart meters,” *Energy Policy*, vol. 41, pp. 790–797, 2012, modeling Transport (Energy) Demand and Policies. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421511009244

[64] S. Döbelt, M. Jung, M. Busch, and M. Tscheligi, “Consumers’ privacy concerns and implications for a privacy preserving smart grid architecture—results of an austrian study,” *Energy Research & Social Science*, vol. 9, pp. 137–145, 2015, special Issue on Smart Grids and the Social Sciences. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214629615300451

[65] J. Naus, G. Spaargaren, B. J. van Vliet, and H. M. van der Horst, “Smart grids, information flows and emerging domestic energy practices,” *Energy Policy*, vol. 68, pp. 436–446, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0301421514000755

[66] Massachusetts Institute of Technology, “Utility of the future,” 2016. [Online]. Available: https://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf

[67] A. An, D. Bauknecht, I. Gianinoni, J. Heeter, N. Kerkhof-Damen, O. Pascoe, U. Peyker, and K. Poplavskaya, “Innovative regulatory approaches with focus on experimental sandboxes casebook,” *International Smart Grid Action Network (ISGAN) Annex 2*, May 2019. [Online]. Available: https://www.iea-isgan.org/wp-content/uploads/2019/05/ISGAN-Casebook-%E2%80%9CInnovative-Regulatory-Approaches-with-Focus-on-Experimental-Sandboxes%E2%80%9D.pdf

[68] BMWi, “Making space for innovation: The handbook for regulatory sandboxes,” *Federal Ministry for Economic Affairs and Energy (BMWi)*, 2019. [Online]. Available: https://www.bmwk.de/Redaktion/EN/Publikationen/Digitale-Welt/handbook-regulatory-sandboxes.pdf?__blob=publicationFile&v=2

[69] B. Eltahawy, M. Valliou, J. Kamsamrong, A. Romanovs, T. Vartiainen, and M. Mekkanen, “Towards a massive open online course for cybersecurity in smart grids – a roadmap strategy,” in *2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2022, pp. 1–6.