

A Transition Perspective on Demand-Side Flexibility in the Integrated Energy System

Insights from the Danish ISGAN Annex 7 Project 2017-2021



The production of this report was supported by the EUDP programme under the Danish Energy Agency, project no. 64017-05203.

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CITATION:

Bergaentzlé, C., S. Bolwig, H. Juhler-Verdoner, K. Kubeczko, X. Liu, K. Nørregaard, J. Rossi, D. Steen, A. Stengel, and A. Wieczorek. 2021. A Transition Perspective on Demand-Side Flexibility in the Integrated Energy System. Insights from The Danish ISGAN Annex 7 Project 2017-2021. UNEP DTU Partnership. Published in September 2021 in Copenhagen.

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Design: Monna Hammershøj Blegvad
Photos: Shutterstock

ISBN: 978-87-93458-03-1

2021

About this report

This paper synthesises insights from three seminars/webinars organised as part of the Danish ISGAN Annex 7 project during 2017-21 (see below). It reviews the academic and policy literature, and draws on the diverse expertise of the authors within transitions management, smart grid, energy-system integration, and flexibility. While the empirical experiences reported on are mainly drawn from Nordic and other European contexts, it is our hope that readers from other regions will also find the insights of relevance.

The International Smart Grids Action Network - ISGAN

The International Smart Grids Action Network (ISGAN) is a Technology Collaboration Programme (TCP) for a Co-operative Programme on smart grids under the International Energy Agency. ISGAN creates a strategic platform to support high-level government attention and action for the accelerated development and deployment of smarter, cleaner electricity grids around the world. See www.iea-isgan.org. The main objective of ISGAN Annex 7 - Smart Grid Transitions is to investigate institutional change associated with smart grid deployment. It uses the framework of transition management to spark international, transdisciplinary research activity in the social sciences supporting policy-makers in the field of smart grids by focusing on the direction and efficiency of the energy system transition. See www.iea-isgan.org/our-work/annex-7.

The Danish ISGAN Annex 7 project

This report is a deliverable of the project Participation in the IEA ISGAN Annex 7 - Smart Grid Transitions, which ran from 2017 to 2021. The project was implemented by the Technical University of Denmark, the Danish Technological Institute and Green Transition

Denmark, in collaboration with the ISGAN Annex 7 Operating Agent and the Danish Intelligent Energy Alliance. It received financial support from the Danish Energy Agency through the EUDP programme. The project aimed to improve understanding among Danish and international stakeholders - industry, government, non-governmental organizations and research - of what policies, institutions, market designs and consumer incentives can help the development and deployment of smart grid technologies, thus providing a clearer vision and greater coherence to the transition to a smart, flexible and sustainable energy system. The project's dissemination activities included three smart grid seminars/webinars: "Smart Grids and Smart Energy Systems for the Low-Carbon Energy Transition, EnergyLab Nordhavn, Copenhagen, 22 October 2018; A Nordic Carbon-Neutral Energy System Enabled by Flexibility and Storage, Webinar, 30 June 2020, and; "Flexibility Services in the Zero-Emission Smart Grid, Webinar, 15 June 2021. See the project site [here](#).

Abstract

The report emphasises the integrated and dynamic aspects of demand-side flexibility (DSF) in the energy system by applying a transition perspective, which highlights the long-term transformative change in the energy system as the result of the interactions of technology with institutions and actors. It identifies barriers and opportunities to the provision of DSF services in the power sub-system as part of an integrated and flexible energy system with new actor roles and new energy technologies and products. We discuss new models for flexibility services that can support the transition to a zero-emission electricity system that builds on strong engagement by all actors.

Executive summary

The transition to a zero-emissions energy system based on high shares of volatile renewable energy resources (RES) depends strongly on the ability to increase the flexibility of energy demand to avoid large imbalances between energy generation and consumption. In the power system, the electrification of transport, heating and industrial process-energy is expected to accentuate the challenges of balancing supply and demand. This is particularly the case for the (local) electricity distribution grid, where distributed energy devices, such as electric vehicles and heat pumps will strain grid infrastructure unevenly, creating instability and local bottlenecks in the grid. Digitalisation is a central enabling factor for controlling and balancing the power system in zero-emission scenarios. However, the power system is increasingly interlinked with other energy sub-systems, notably for heating and transport fuels, but also energy for industrial processes, creating a progressively integrated energy system that places new demands for demand-side flexibility (DSF) beyond just contributing to grid stability and balancing. It also creates new opportunities for private-sector and civil-society actors, e.g. in the provision or aggregation of flexibility, the selling of excess heat, or the production of "green" hydrogen. That said, DSF systems, infrastructures and technologies also carry substantial investment and operating costs and may not pay off in all situations, and they require the generation of new knowledge through research, development and demonstration (RD&D) activities.

The report emphasises the integrated and dynamic aspects of flexibility by applying a transition perspective, which highlights the long-term transformative change in the energy system as the result of the interactions of technology with institutions and actors. It identifies barriers and opportunities to the provision of DSF services in the power sub-system as part of an integrated and flexible energy system with new actor roles and new energy technologies and products. We discuss new models for flexibility services that can support the transition to a zero-emission electricity system that is not just stable and resource-efficient, but that also builds on strong engagement by citizens and consumers, communities, and the private sector. We take a broad view on flexibility by considering the potential contribution of all actor types to DSF, including different types of end-users as well as aggregators of flexibility.

We find that decarbonising our energy system, including balancing the volatile production of RES, relies heavily on the nexus between technologies, institutions

and actors. A focus on the dynamic interplay of these three pillars of the energy transition is important. This is partly because of the rapid technological advances, as demonstrated by the progress made in low-carbon production and data management, but also to take the social dimension of the energy transition into account. Regulators and lawmakers, especially, must design a body of rules that ensures the coordination of all actors in terms of their integration in the electricity value chain and across energy sectors. In the Nord Pool market area, for example, the successive evolution of electricity market rules demonstrate how industry actors are progressively completing the market design to meet the constraints imposed by the rapid growth of wind energy. A key facilitator is a transparent, well-organised and inclusive discussion forum for the sector's stakeholders.

What lays ahead?

Integrate all the actors

While technology makes it technically possible to control all types of decentralised load or production, the human factor must be taken into account to a greater extent. This implies, in particular, a better understanding of what motivates energy users in the context of decarbonisation. The richness of the work done in the behavioural and social sciences, among others, that focuses on the motivations of consumers in their consumption or production of energy is beginning to shed new light supplementing traditional studies in which the consumer is treated as a simple rational agent seeking to maximize her utility. In reality, the effects of communities that build on attitudes, beliefs, etc., reveal an array of important levers to activate consumers that must be better understood and utilised in a smarter way. It is worth emphasising here that the level of automation will be important for the flexibility provision of end users, and that manual solutions conversely are less likely to be successful.

Ensure that regulation does not stand in the way by supporting a competitive, transparent and liquid market

This means abolishing rules that act as a barrier to the participation of actors capable of providing flexibility services and that hinder investment in carbon-free generation or storage. This also requires the establishment of a level playing field between production and flexibility technologies, as well as between energy sources. It also implies the minimization of distortions of efficient prices set by the market and in particular implies a revision of grid tariffs. Finally it implies the protection of precarious consumers for a fair transition.

Data, always more data

The ability to take advantage of new flexibility services will require changes in information flows among grid devices (e.g. through smart meters), as well as innovations in communication and coordination tools and data management systems that increase the observability, predictability and controllability of the grid. These data streams and systems are needed to activate the economic mechanisms that reward consumer flexibility. Two price signals must be provided here: rewards and penalties in relation to congestion in the grid, and signals related to the fluctuating price of electricity on the wholesale market.

Lower the technical barriers to interoperability

Generating more data does not in itself enable a smart grid and DSF. Technical solutions must be replicable to gain wide acceptance in the market, and technical barriers to interoperability will also be barriers to replicability. Such barriers include, for example, the quality and cost of internet services - especially in remote areas, lack of standardised data formats, incompatibility of EV technologies hindering smart charging, high cost of re-sizing grid components to integrate energy surpluses if other balancing controls fail, and physical

limits of residential buildings in accommodating smart grid solutions due e.g. to age or size. Finally, citizens' low smart-grid literacy level, combined with weak economic incentives for flexible consumption, may cause an underinvestment in the capacity to serve the grid rather than just the household.

Thinking out of the box, go hybrid when you need to

The urgency of climate change requires that the full range of options be considered when it comes to developing innovative energy and flexibility solutions. In particular, the activation of certain diffuse flexibility potentials with high added value for society may still not generate a sufficient return on investment for private actors to develop service products to harvest them. Clearly, the climate objective must be placed on the same level as the market objective, while avoiding regulatory lock-ins, for example those hindering the operation of flexibility services by the actors that are best able to provide them. This may give rise to new, hybrid organisations with new types of participation of, and collaboration between, private energy-service providers (e.g. electricity retailers, aggregators, and prosumers) and regulated actors (DSOs, TSOs, and gas and heating network operators).



Table of Contents

1. A transition perspective on flexibility in the energy system	1
1.1 An integrated framework for understanding and promoting flexibility	1
Economy	1
Technology	2
Actors and institutions	2
Socio-technical system	3
1.2 Organisation of this report	4
2. New actors, roles and markets for flexibility services	4
2.1 The rationale for the aggregation of flexibility	4
2.2 New actors and organisational models for flexibility services in the Nordics	4
Denmark	5
Sweden	7
Overall experiences from the Nordics	7
2.3 Prosumers and energy communities as flexibility providers	8
2.4 The changing role of the DSO	8
3. New technologies for enhanced flexibility	9
3.1 Digital tools and data	9
3.2 Data management systems and tools	10
3.3 Short-term storage technologies to balance energy and power (batteries)	10
Battery-related smart grid activities: lessons from the SMILE project ⁸	10
Flexibility provision by electric-vehicle batteries: an energy system-wide perspective	11
3.4 Technical barriers to interoperability in the smart grid	12
A new flexible energy systems lab-set up	12
4. Regulatory changes for activating flexibility	13
4.1 Regulatory frameworks are lagging behind	13
4.2 Regulatory barriers to flexibility and sector coupling	13
4.3 Regulatory barriers to active energy communities	14
4.4 Regulatory barriers to flexible grid management: hybrid models worth exploring?	14
4.5 Regulatory 'sandbox' experiments	15
5. Conclusion	15
5.1 What lays ahead	16
Integrate all the actors	16
Make sure that regulation does not stand in the way	16
Data, always more data	16
Lower the technical barriers to interoperability in the smart grid	16
Thinking out of the box, go hybrid when you need to	16
References	17
Endnotes	21

1. A transition perspective on flexibility in the energy system

The transition to a zero-emissions energy system based on high shares of volatile renewable energy resources (RES) depends strongly on the ability to increase the flexibility of energy demand to avoid large imbalances between energy generation and consumption [1]. In the power system, the electrification of transport, heating and industrial process-energy is expected to accentuate the challenges of balancing supply and demand. This is particularly the case for the (local) electricity distribution grid, where distributed energy devices, especially electric vehicles, heat pumps and boilers, roof-top solar panels and batteries, will strain grid infrastructure unevenly, creating instability and local bottlenecks in the grid [2,3]. Digitalisation is a central enabling factor for controlling and balancing the power system in zero-emission scenarios, a process captured by the concept of the smart grid [16]. However, the power system is increasingly interlinked with other energy sub-systems, notably for heating and transport fuels, but also energy for industrial processes, creating a progressively integrated energy system that places new demands for demand-side flexibility (DSF) beyond just contributing to grid stability and balancing. It also creates new opportunities for private-sector and civil-society actors, e.g. in the provision or aggregation of flexibility, the selling of excess heat, and the production of "green" hydrogen based on clean electricity.

Hence the overall aim of this report is to discuss barriers and opportunities to the provision of DSF services in the power sub-system as part of an integrated and flexible energy system [4] with new actor roles and new energy technologies and products. We will discuss new models for flexibility services that can support the transition to a zero-emission electricity system that is not only stable and resource-efficient, but that also builds on strong and broad engagement by citizens and consumers, communities, and the private sector. The paper takes a broad view on flexibility by considering potential contribution of all actor types to DSF, including different types of end-users as well as aggregators of flexibility. Furthermore, we consider flexible electricity demand in the context of the larger integrated energy system, where energy-system integration is defined as "the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors" [5]. Here we give attention not only to different forms of energy production but also to different types of energy demand and to linking energy supply and demand in an intelligent way.

Finally, the paper emphasises the integrated and dynamic aspects of flexibility by applying a transition perspective, which highlights the long-term transformative change in the energy system as the result of the interactions of economy and technology with institutions and actors (see the next section). The paper is based mainly on experiences from European and Nordic countries, but are deemed to be relevant for other regions as well.

1.1 An integrated framework for understanding and promoting flexibility

The transition to a zero-emission energy system involving significant flexibility will require a holistic or integrated approach that takes into account the interplay of economic, technological and institutional factors, as well as the role of different actors in incentivising, enabling and providing flexibility services. The literature on sustainability transitions highlights the dynamic interplay of so-called socio-technical factors in fostering the transition to clean energy systems, in particular actors, institutions and technologies [6–8]. This socio-technical perspective can be seen as an alternative to (or critique of) the so-called techno-economic analyses that emphasise the interplay of economic and technical factors, often in a static (energy-modelling) framework [9]. Moving towards an integrated framework (Figure 1) focusing on the socio-technical perspective, while also considering aspects such as economic costs and efficiency emphasised by the techno-economic view, below we briefly review the role of economy, technology, actors and institutions in the activation of flexibility services.

Economy

The analysis and promotion of flexibility have often been framed in terms of economic efficiency gains, in particular cost savings. Indeed, DSF can help lower the costs of the energy transition by reducing the need to reinforce the local power grid as a result of changes in energy demand and supply, although the European Commission and national governments do not discourage grid operators to enforce their grid if needed. This would mean avoiding the curtailment of RES in times of surplus production, and limiting the need for storage or reserve-generating capacity during periods of low RES generation. In Denmark, for example, using smart solutions to reduce the need for distribution-grid investments would save about 2 billion euros over the next decade [10,11]. Distributed RES can also replace fossil fuel-based flexibility on the generation side [10]. Here cost-benefit analyses can show what is the most effective solution in a specific situation: on a certain location of the grid this could be a demand-side flexibility service, a bat-

tery or sometimes also grid enforcement. Such techno-economic evaluations are obviously a central element in the provision of flexibility as part of a clean and affordable energy system, and should be integrated with socio-technical analyses of technologies, actors and institutions.

Technology

The role of technology in enabling DSF and energy-system integration has also received a lot of attention from policy, research and the private sector, and digitalisation is widely regarded as a fundamental factor in balancing the power system (see section 3). Digital tools and real-time data streams are needed to activate the economic mechanisms that combine multiple value streams from merely being able to monitor consumption. The most important value streams, which today are driving the business case for the digitalisation of consumption, are energy savings and spot-price optimisation (reducing consumption when the energy price is high). However, integrating volatile energy production and avoiding grid congestion add additional value streams to the business case and create a need to reward consumer flexibility (see section 3.1). Digital data and tools can also help enable greater community participation in the energy system as energy producers or providers of flexibility services. Such an engagement would not just reduce system costs but also distribute revenues over a larger group of actors and increase public support to the transition (see section 2.3). Finally, battery technologies in conjunction with digitalisation can help activate the flexibility potentials of buildings and electric vehicles, providing both short-term storage and balancing services to the grid while increasing citizen participation (see section 3.3).

Actors and institutions

While economy and technology are obviously important drivers or enablers of flexibility and system integration, an excessive focus on them can distract us from addressing important institutional, political and behavioural aspects of the clean energy transition, which may jeopardize or delay the transition and increase its costs to social actors. In this regard, the ISGAN Annex 7 Smart Grid Transitions programme was set up to help address such challenges using a broad transitions management framework and focusing on (the need for) institutional change and social innovation and experimentation, particularly in relation to policies and regulations, firm and consumer behaviour, markets and actor roles, and taking into account the diversity of ISGAN countries [2]. Following this approach, this paper emphasises the role of actors, actor linkages and institutions in providing flexibility services.

Regarding actors, we do not just consider traditional actors, such as distribution system/network operators (DSO/DNO), transmission system operators (TSO) and incumbent energy companies, but rather focus on new actors and new actor roles (for both incumbents and new actors). In a flexibility context, this implies, for example, not seeing end-users or citizens only as energy customers but also as service providers that help grid operators (who are responsible for the power supply) balance supply and demand in the grid through DSF. Prosumers may, moreover, help balance the grid from the supply side, and different actors, including firms and energy communities, may play a role as flexibility aggregators (see section 2.2). Finally, increased flexibility and system integration depend on multiple 'supporting actors' such as ICT and energy technology suppliers, market operators, R&D institutions, and regulators, requiring an even greater need for collaboration and coordination.

Regarding institutions, we need to consider not just how policies and regulation (both within ICT and energy) can enable DSF, but also different market models (enabled by policy), as well informal norms, rules and attitudes affecting the behaviour of actors. Partnerships and looser network structures also form part of the institutional environment. We consider also social and commercial practices here.

Figure 1 below illustrates an integrated approach for analysing and promoting flexibility as a key factor in the transition to a clean energy system. The top part shows, on the left-hand side, the three key elements in the socio-technical system for energy production and consumption, composed of actors, technologies and physical assets, and institutions and practices. The arrows illustrate the interplay of these elements. The right-hand side of the figure (the broad arrows) shows how flexibility services evolve from (are formed by) the socio-technical system in a particular market or area, emphasising that experimentation carried out under place-specific preconditions shapes the nature and mix of flexibility services, implying the possibility of significant variation in dominant models between areas (and time periods). There are dynamic feed-back effects/loops from the flexibility services to the socio-technical system, e.g. when the activation of DSF (e.g. smart EV charging) changes the optimal mix of energy-generating assets (e.g. towards more wind turbine) [12]. The bottom part of the figure provides details of the actors, technologies and institutions in an integrated energy system of potential relevance to flexibility.

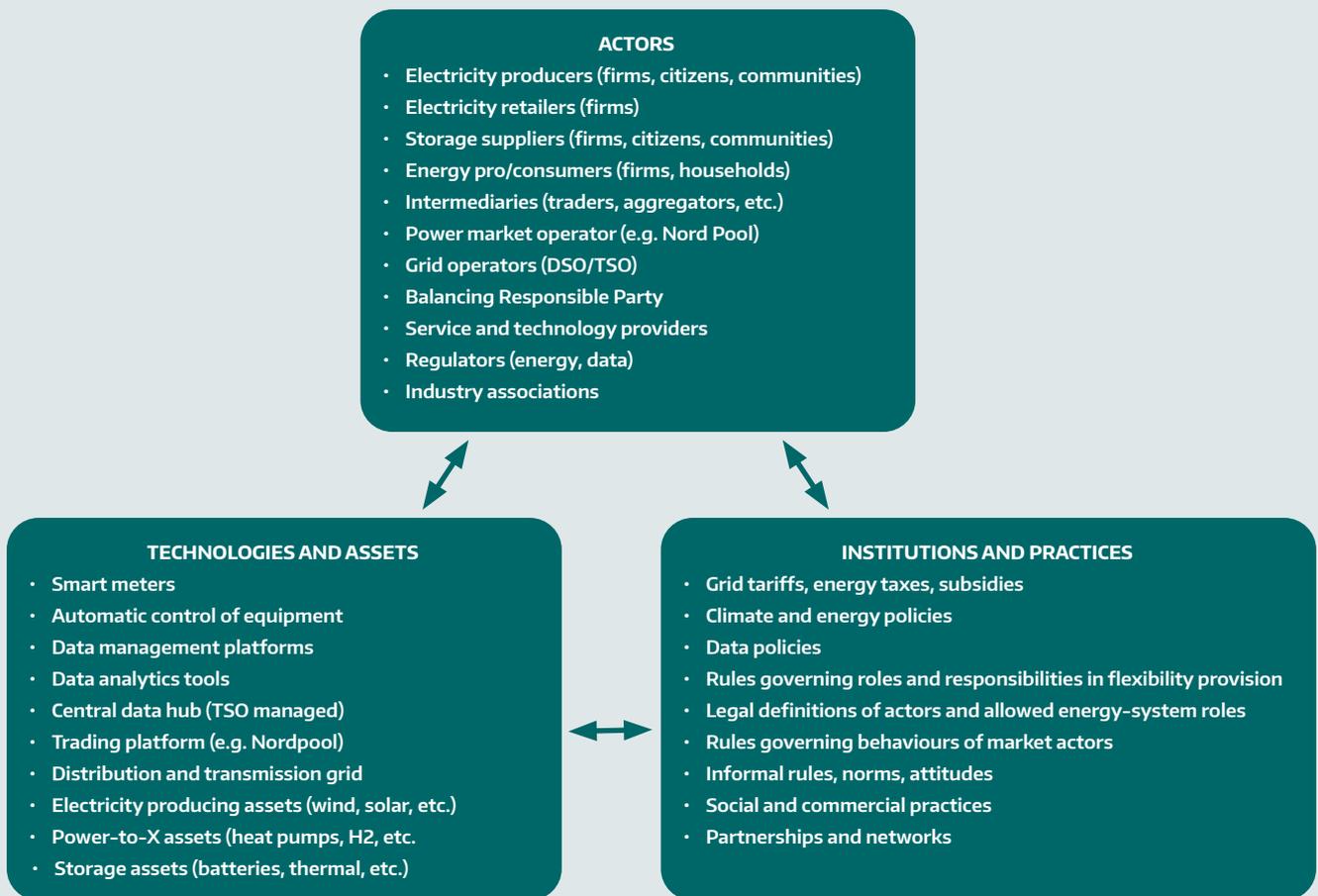
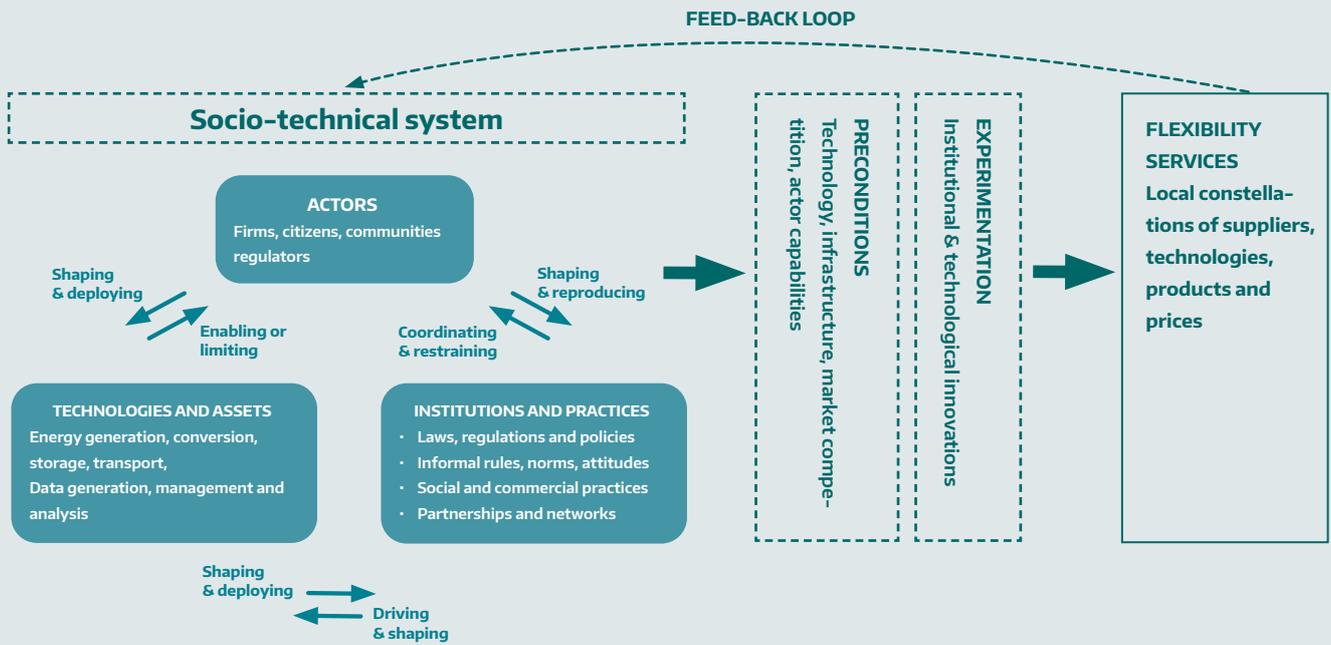


Figure 1. Integrated framework for analysing and promoting flexibility services in the integrated energy system. Source: Inspired by [6,13–15]

1.2 Organisation of this report

With this framework in mind, the remainder of this report is organised as follows. Section 2 discusses new actors, actor roles and markets for flexibility services. It first outlines the rationale for aggregating demand-side flexibility (DSF) from multiple sources, and then presents different organisational models, actors and preconditions for providing DSF services, focusing on the Nordic countries. We then zoom in on the potential of relatively new/niche actors - prosumers and energy communities - as flexibility providers, and finally discussing the changing requirements and role of an incumbent actor - the DSO - in the flexible energy market. Section 3 discusses the technologies, tools and data that are need for enabling and incentivising flexibility services in integrated energy systems, including digital tools, data-management systems and tools, and smart, short-term storage technologies to balance energy and power in the grid. Section 4 addresses the institutional dimension of enhanced flexibility focusing on the regulatory changes needed to activate the different sources of flexibility in electricity markets in a context where these are coupled to the markets for heating and transport energy. We also discuss here specific regulatory barriers to activating flexibility from energy communities, including regulation that hinders the deployment of enabling technologies. The section finally discusses regulatory innovations or 'sandbox' experiments that in recent years have been performed to identify the changes in energy and ICT policies and regulations needed to foster flexibility services. Section 5 presents a short conclusion and identifies avenues for future work on the topic.

2. New actors, roles and markets for flexibility services

2.1 The rationale for the aggregation of flexibility

While large industrial power consumers already provide some flexibility to the grid in many countries, additional consumption flexibility from smaller companies (with e.g. heat pumps or cold stores) as well as households (with e.g. heat pumps, electric heating units, or electric vehicles) is needed in the energy system of the future [16]. The small flexibility potential of each of these consumers means that existing market actors have no incentive to use them as a flexibility service. This has created a role for so-called aggregators, which can pool the flexibilities of small consumers and convert them into power market services for use by the TSO, the DSO, grid companies or the balancing responsible party (BRP) as part of a broader portfolio of services [16]. The advan-

tage is that these products provide reliable flexibility to the market by eliminating the risk of non-delivery inherent in depending on an individual prosumer. At the same time, aggregation may reduce prosumer exposure to the risks involved in participating in the energy market. Advanced control mechanisms of demand-side flexibility from multiple sources such as electric vehicles, heat pumps and buildings can benefit energy consumers financially [10].

2.2 New actors and organisational models for flexibility services in the Nordics

Different organisational models for flexibility services have been developed, involving different actors, cost-benefit structures and complexities. As already mentioned, there is an increasing demand for flexibility, and there are technical developments that make distributed flexibility accessible through aggregation. Yet, how flexibility is accessed specifically, and how the new markets are organized, depend on the existing retail market structures, the existing spread of smart meters and the role of the DSOs. In the Nordics, flexibility services are likely to evolve from relatively favourable preconditions, notably competitive retail markets with multiple competing suppliers, a facilitated supplier switch, the possibility for household electricity prices to reflect varying spot prices and a nearly full roll out of smart meters.

In some other European countries, such as France, a revolution in retail markets is needed since there is a starting situation with strong incumbents, fixed retail prices set by the public authorities still exist along with market-based offers, and the roll out of smart meters faces strong opposition from part of the population. There is therefore no one-size-fits-all when implementing decentralised flexibility markets, and European legislation has the challenge of defining rules that are broad enough to activate flexibility while suiting all types of retail market design. Besides, flexibility needs vary from one country to another. Using the same example, when Denmark benefits from highly responsive distributed-energy resources to adjust to wind generation, France's main flexibility challenge is to improve control of the yearly peak demands when all the electricity plants are running and grid capacities are congested. When organizing and regulating new flexibility markets, there is thus a need to define first the local/national need and preconditions based on the retail market context and the needs of the wholesale market and the DSOs/TSOs, rather than copying solutions from a different setting that may not be transferable.

Below we discuss models and experiences with flexibility services from the Nordic region with a focus on Denmark and Sweden.

Denmark

The Danish electricity market has favourable economic, technical and institutional preconditions for developing efficient flexibility services in the forms of a competitive retail market, a wide coverage of smart meters, and well-defined and innovative DSOs. Therefore flexibility services are likely to appear once electricity customers and DSOs see a way to save money by selling and buying flexibility. In this setting, the aggregation of flexibility can be performed by all or any of the actors: retailers that are already aggregating hourly flexibility in the intraday, DSOs balancing between grid investments and buying flexibility, aggregators working with retailers, or independent aggregators.

According to an analysis by Danish electricity stakeholders, there is a need for a suite of aggregation models in view of international differences in regulation, different challenges within the local grids, ICT and markets, given that existing and new actors have different business models [6]. This broad approach, it is argued, will enable a gradual development of flexibility aggregation in the market in concert with required changes in regulation and new digital tools, as well as allow a diversity of actors to function as aggregators [6].

Four basic market models were developed by the Danish Intelligent Energy Alliance, Danish Energy Association, Confederation of Danish Industry and Energinet.dk (the Danish TSO), following the Market Model 2.0 recommendations in 2017 [17]. They involve different flexibility actors and value chains, different levels of organisational and technical complexity, and different regulatory requirements (Figure 1). The models are not mutually exclusive but can be applied across different distribution nets according to local conditions, meaning that a customer has a choice to pick a retailer as an aggregator or an aggregator as a retailer and does not need to pick two companies for delivery. The different models have implications for the kind of role the aggregator assumes in the market and for the conditions under which flexibility and energy supply can be provided by new market actors.

One aim is to lower the entry barriers for new actors compared to the incumbent actors that dominate the energy market today. That said, given the functioning competitive retail market today and engaged DSOs, sup-

port for aggregation should focus on addressing existing barriers to aggregation, rather than pushing new actors into an already competitive market.

The four models are summarised below and illustrated in Figure 2, taking account of developments since 2017.

- In Model 0, the existing energy supplier (and BRP) takes on the aggregator role as a combined service to the consumer¹. This model reduces complexity but may discriminate against independent aggregators that perform aggregation functions cost-effectively. As it also includes energy supply, it does not comply with the European electricity market directive.
- In Model 1, an independent aggregator supplies frequency stabilisation to the TSO, for example, through grid-integrated electric vehicles [7], but does not necessarily supply electricity to the consumer. The small amount of energy involved means that no significant energy imbalance is created, hence there is no need for imbalance settlement, and therefore the model does not require delegating the balance responsibility to a BRP. Removing the requirement to involve a BRP when delivering FCR means lowering the entry barriers for the aggregator and reducing the complexity of the business model.
- In Model 2, the independent aggregator supplies flexibility (but not energy) to e.g. the TSO. Hence an imbalance cost will arise. In the original idea of this model, the balancing responsibility would shift to the partner BRP during the periods when flexibility is activated so that the cost of imbalance falls on the aggregator and the partner BRP. The model has low entry barriers for the aggregator, but high administrative, legal and financial complexities. Hence it was not implemented in Denmark. However, with the implementation of the electricity directive, a somewhat similar model will be implemented where the aggregator has no supply of energy, but the customer's existing BRP is not exposed to an imbalance cost because an energy correction will take place. The regulation supporting this model is under development.
- In Model 3, the aggregator supplies both electricity and flexibility to the consumer as a combined service that can cover multiple markets through a partnership with an electricity supplier/BRP that is different from the customer's original supplier and BRP.²

By sub-metering the supply and flexibility provided through the aggregator, this model does not incur imbalance costs to other actors and is very transparent due to the separation of flexibility and supply of energy, e.g., to the heat pump or electric vehicle (EV) representing a share of the consumer's total energy consumption. So far, this model has required the installation of serial metering points [7] for the flexible units, implying an entry barrier due to the sub-metering and tariff to the DSO. This makes it best suited for large power consumers³. Still, individual heat-pump service providers have applied the serial metering, and the standard terms for DSOs' service when delivering serial meters have been improved⁴. The model is under further development, testing the possibility of using the integrated own meters of e.g. EVs and heat pumps. This would

lower entry barriers by improving the business case and allowing the participation of small consumers. Here, two pilot projects have tested meters integrated into heat pumps (by Neogrid) and EV chargers (by Clever), respectively. If the meters of the equipment and the operator's IT interfaces can be applied to measure and bill consumption on the HPs/EVs, this model can be implemented in the near future. Furthermore, standards on agreement between operators of heat pumps and EVs and the DSO are being developed by the Danish Energy Association, and standard IT interfaces across all Danish DSOs will also have to be developed. Once this is in place, Model 3 may be improved in terms of lowering the costs of aggregator business models, depending on the costs of the IT interface and data validation from own meters.

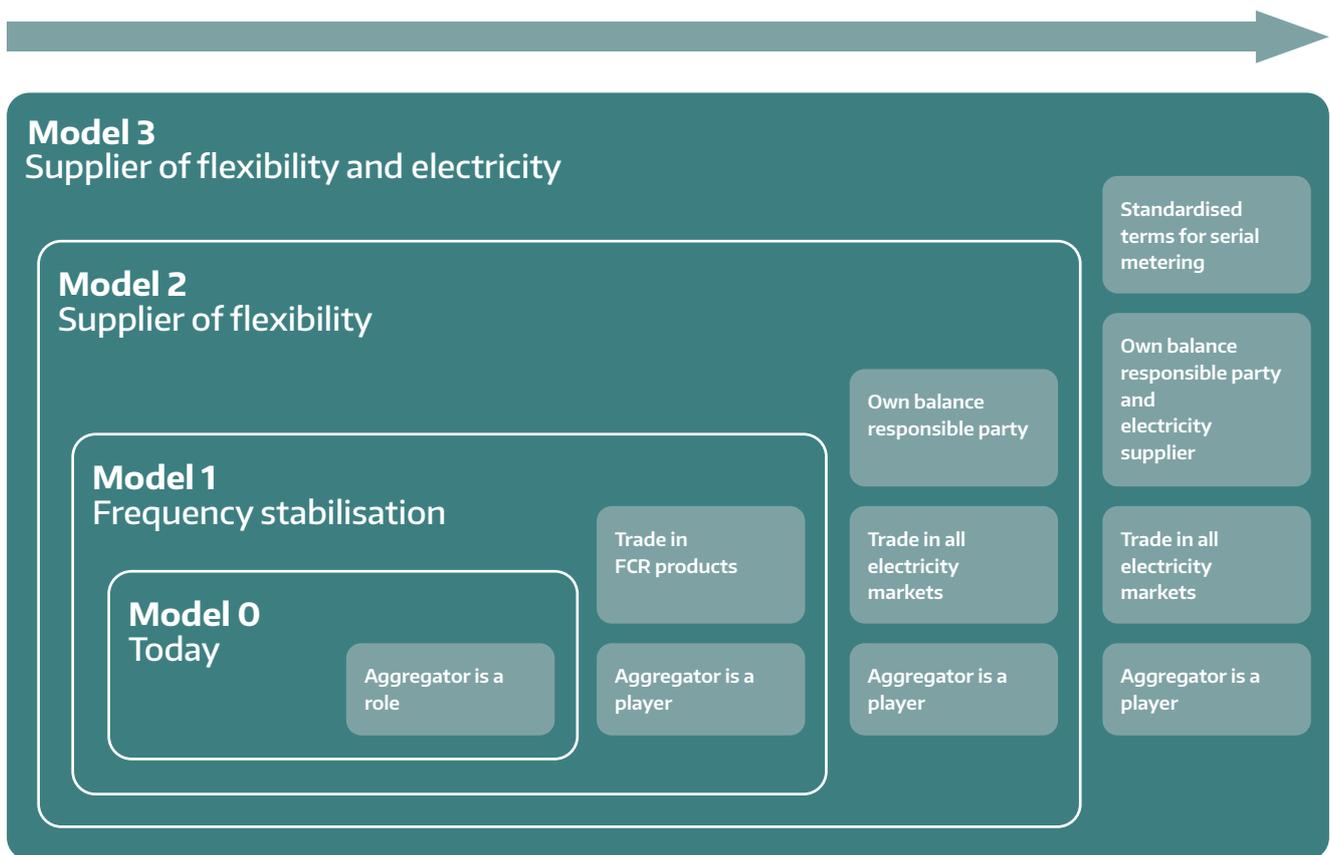


Figure 2. Aggregator market models discussed in Denmark. Source: [16].

The development of the market models and related technologies (section 3) outlined above reveal some progress in the market for demand-side flexibility services in Denmark. The regulation focuses on addressing the barriers to aggregation, including DSO incentives, the use of smart meter data, potential BRP imbalances and the DSO-TSO relationship, rather than on promoting a specific type of actor such as independent aggregator. However, the adaptation of the regulation to fit changing market needs and conditions has been slow, in part because the regulators have caused delays in implementing the results of pilot projects (see above and Box 1) into regulation. This is especially an issue for commercial actors that cannot harvest the benefits of their investments in new technologies and infrastructures (e.g. EV chargers). A recent report by the Danish Energy Agency on Market Model 3.0 [18] provides some grounds for optimism. The report, published in June 2021, provides 13 recommendations and 23 specific suggestions, some of which have already been incorporated into Danish law, for developing the flexible electricity market through this model in order to meet the Danish and European climate and energy objectives.

Box 1.

Aggregation of flexible electric heating units. On the Danish island of Bornholm, the Ecogrid 2.0 project tested the implementation of a local flexibility market that runs in parallel to the wholesale market, involving 800 households with flexible electric heating units (heat pumps or resistive heaters) remotely controlled by an aggregator through ICT (built-in or external) and using smart meters [5]. The experiment showed that 'aggregators are able to reliably shape the load of residential heating units to deliver flexibility services [in the distribution network], despite the presence of large uncertainties' and that such services can act as an insurance policy against rare but consequential network over-loadings and outages [5].

Sweden

Several ongoing initiatives for local markets exist in Sweden. In Stockholm, the flexibility market Stockholm Flex has been launched, and different market concepts and products have been designed and traded. Similarly, the energy company E.ON has demonstrated another solution for flexibility trading using their market platform Switch. In Gothenburg, a local energy market combining the three energy carriers of heat, cooling and electricity has been developed and demonstrated in the project Fossil-free Energy Districts (FED) [19]. The market was designed to operate with a rolling time-win-

dow of 13 hours, where the market is cleared an hour ahead of the delivery. In this way, issues related to forecasting errors are being reduced. However, for DSOs to ensure that they have the required flexibility a long-term market is vital, especially at an early stage. A similar approach to capacity payments could be one option in a local market. In the European Flexigrid project [20], a long-term, short-term and real-time market framework is proposed to enhance the effective utilization of the local distribution system.

Overall experiences from the Nordics

While Denmark and Sweden are working on their pilot projects and regulations, there are parallel processes going on in the other Nordic countries. There is an interest in coordination from all sides, since the wholesale and balancing markets are integrated and linked across the Nordics, and there are common Nordic services such as eSett for imbalance settlement. There are also enough similarities for retail markets and DSOs, despite national and local differences. The main drivers are flexibility providers that are already active in several Nordic countries and that want to see more harmonized regulation to facilitate their business.

Projects range from DSOs publishing competitive tenders for the provision of local flexibility services to local flexibility markets – the Nodes platform, for example, is active in both Norway and Sweden. The new report Market Design Options for Procurement of Flexibility, published by Nordic Energy Research, provides a comprehensive Nordic overview of DSOs' needs and some of their projects [21]. In these projects, flexibility is offered by traditional providers such as producers and retailers aggregating local resources, but also by aggregators or industry directly.

The Nordic regulators currently discuss the implementation of Article 17 in the Clean Energy Package Directive (2019/944) [22], which allows some flexibility regarding the regulation of independent aggregators. There is a consensus that aggregation is needed and that it does not matter who provides it. Article 17 prohibits discrimination against independent aggregators but at the same time also requires that they are "financially responsible" ⁵, i.e., that they cannot cause costs to BRPs without paying for them. Currently there are two regulatory options used in Europe: full-cost regulation, which tends to favour independent aggregators, since it is close to impossible to calculate costs correctly; and the facilitation of commercial agreements, where the cost basis is regulated (for example, which imbalance must be compensated), but the independent aggregator and the BRP agree bilaterally on the price of the imbalance. A third

solution currently used by the Nordic TSOs is to recalculate the balance of the BRP when an aggregator has activated flexibility resources, so that there is no imbalance for a BRP and hence no cost.

Another question is the relationship between DSOs and TSOs when local flexibility is accessed. While DSOs would be more comfortable if they could reserve local flexibility for their needs, most providers of flexibility object that it does not make sense to offer a resource only on a local market and not on the national market. Therefore DSOs and TSOs need to develop ways to avoid the activation of local flexibility resources solving a national problem for the TSO but causing local congestion and local problems for a DSO. Here no final answer has been found as yet, but several projects have addressed the issue, e.g. SmartNet [23] and CoordiNet [24]. The adoption of demand-side management and the implementation of local markets translate into an increased need and motivation for additional TSO-DSO interaction. In this context, interactions relate to communication, coordination and cooperation between DSOs and TSOs, as well as the regulatory framework under which they operate. The coordination schemes between TSO and DSO are key to establishing operating procedures and the procurement of grid services and to providing increased benefits to each stakeholder within the power system. Different coordination models between the TSOs and DSOs have been proposed for the procurement and activation of the flexibility [25].

2.3 Prosumers and energy communities as flexibility providers

The supply of flexibility services may also become one of the energy communities' business models [26].⁶ Encouraging this would enable prosumers to participate actively in the smart grid, thus increasing acceptance of the energy transition. While traditionally concerned with the production of renewable energy (wind, solar, biogas) in the area of residence of its members, energy communities can actually assume multiple roles in the energy system [7] by being connected to the distribution grid. For example, in Assens in the Netherlands, a local neighbourhood group has experimented with developing a grid-balancing system including storage, as the neighbourhood transformer could no longer manage the load created by the rooftop solar panels ([27], see Box 2). Likewise, in the village of Simris in southern Sweden, a flexibility market in a local grid was developed by the DSO (E.ON) to accommodate the supply of 100% renewable energy from wind turbines and local solar-PV pan-

els, supported by a battery system. Here, residents were engaged to become flexible prosumers, not just by producing renewable energy, but also by having controllable load assets such as heat pumps, water boilers and batteries [28].

Furthermore, recent work highlights how energy communities or individual prosumers across multiple localities (connected via the grid) can be organised in so-called community-based virtual power plants (cVPP) [29] enabled by digital data and tools. cVPP can aggregate members' individual or shared distributed energy resources (including storage) into a coordinated portfolio, thereby providing 'grid support services to grid operators and/or [enabling] energy trading on wholesale markets' [29]. cVPP can also manage members' power consumption into a single community profile, thereby enabling the valorisation of DSF through an aggregator or by assuming the role of aggregator [7]. In this regard, [30] show that, in a so-called transactive energy-based trading framework, prosumers can aggregate and trade in wholesale power markets in an independent manner without relying on a central entity. This model could result in reduced peak load, lower retail prices and higher revenues for both prosumers and end-users. Energy communities may also engage in collective self-consumption at community level (community self-balancing) by coordinating virtually connected shared assets (e.g., solar farms or neighbourhood batteries) and individually owned assets (e.g., roof-top solar PV or EV) [7]. This possibility also applies to situations where the energy community runs as a microgrid or a closed distribution grid (e.g. an urban district), in which case the energy community is connected to the main grid with one connection and can be disconnected from the grid if needed [7].

2.4 The changing role of the DSO

Under the new electricity market rules, the traditional role of the DSO, which includes network planning, development, operation and maintenance, is changing. This was one of the focuses of the UNITED-GRID project [31]. The DSO needs to become an active distribution-system operator and to perform a market-facilitating role giving access to flexibility services in a technology-neutral manner to ensure that the most efficient resources are utilized first. These services can be provided by local market platforms, cost-reflective tariff structures and different forms of market-based procurement in between, such as competitive tenders or combinations thereof, where the DSO could take on different roles such as platform operator or service supplier.

Hence, the DSOs also need to shift their general approach from an engineering to a market-oriented one, where the traditional DSO tasks could turn into a set of DSO market services. Here, the CEER [32] proposes a framework where DSOs may be allowed to perform activities, even if there is a potential for competition under certain conditions or regulatory controls, provided there is a clear justification, possibly based on a cost-benefit analysis. ‘Grey areas’ include energy-efficiency advice, the extent of involvement in flexibility and storage, and engagement with end users.

To improve the functioning of the electricity distribution networks, rapid changes create a need for substantial investment and innovation in smart grid technology and new business models. However, these changes have a high degree of uncertainty and may seem far from how the DSOs operate today.

Moreover, the current regulated income-frameworks provide DSOs with little incentive to increase system operating costs, even if the capital costs are being reduced. Payback periods for innovative investments do not always fit with traditional regulatory payback periods, and the estimated savings for taking advantage of flexibility services will only exceed the cost when the anticipated load growth on the distribution grid becomes more prominent. The ability to take advantage of these services will also vary, and the savings have a high degree of uncertainty and will require changes in information flows, regulatory schemes and operation models [32,33].

Regulation should encourage innovative investments to adopt the most efficient solution. Sometimes the implementation of output-based regulation is seen as a way to promote efficient investments to the benefit of consumers and to tackle the challenges of the DSOs, since it allows the DSO to adjust investment strategies to the targets specified by the regulators in terms of cost efficiency and outputs. However, this also is riskier for the DSOs and complex to monitor, certainly for countries with many small DSOs.

Smart meters will play an important role in the new market design by facilitating consumers in managing their consumption patterns through flexibility, as discussed in Section 3. But DSOs can only access personal data from smart meters if it is necessary to perform other legal obligations, and they should not go beyond the purpose for which these data have been collected. Hence, developing ownership models for technical and user data will become important and still face several

barriers. For example, opting for a central data-hub may solve privacy issues but limits the DSOs’ communication with and understanding of customers and their flexibility assets [34].

In taking up more active system responsibility, the DSO will not only require different choices in network planning and operation, technical data management, the development of new services and consideration of new types of investments. It will also entail establishing new partnerships and end-user relationships in their networks, developing internal competencies and envisaging a future role as an enabling partner for sustainable development within the distribution area. Altogether, the DSO thus remains a key actor for the transition to a clean energy system.

3. New technologies for enhanced flexibility

3.1 Digital tools and data

Digitalisation is a central enabling factor for controlling and balancing the power system in zero-emission scenarios, a process captured by the concept of the ‘smart grid’ [35]. Digital tools and real-time data streams are needed to activate the economic mechanisms that reward consumer flexibility, providing two price signals: rewards and penalties in relation to congestion in the grid, and signals related to the fluctuating price of electricity on the wholesale market. In this context, smart meters providing consumption data on an hourly basis are a fundamental technology allowing consumers to understand and change their consumption behaviour dynamically according to these signals, thereby actively participating in the smart grid [35]. From the point of view of the utility, these data ‘increase the efficiency and the reliability of grid operations, maintenances, and extensions while the share of RES is increasing’ [35]. However, despite an almost complete roll out in Denmark and in many European countries, very few consumers effectively face time-varying prices reflecting market or grid conditions. The main reason for this is a lack of general interest in or perceived benefit from consumers to change their current energy supply contract. Moreover, hourly or real-time data provision is not a requirement of smart meters in the EU (see below).

Enabling prosumer participation in the smart grid, moreover, depends on the installation of serial metering points at each production facility [7], which, however, comes with significant costs. As DSOs and TSOs in, for example, Denmark are aware of this challenge, build-

ing on the results of pilot tests, it has been decided that future operators of, for example, EVs and heat pumps should be allowed to use their own meters instead of serial meters to bill the consumer behind the main meter. The development of ICT interfaces and operator agreements is the next step in realising this goal.

3.2 Data management systems and tools

The ability to take advantage of new flexibility services will require changes in information flows among grid devices (e.g. through smart meters), as well as innovations in communication and coordination tools and data management systems that increase the observability, predictability and controllability of the grid, including at lower voltage levels. Advanced distribution management systems can help the DSO optimise and secure the grid in real-time with advanced automated solutions, as well as anticipate future situations by using forecasting methods. These solutions can improve efficiency, reliability and productivity and reduce system losses but can also be used for market facilitation, including the development of flexibility services.

Smart grids collect vast amounts of data to make themselves smart, including through smart meters, home area networks, etc. Big data⁷ potentially allow utilities, aggregators and other energy-system actors to do things they have never been able to do before, including enabling and motivating flexibility through various mechanisms and service products, building on a better understanding of consumer behaviour, the active management of consumption and generation, and monitoring downtime and power outages. The data can be turned into information through advanced analytics, then into insights, and finally into action plans. Due to the nature of big data, the distribution and real-time constraint requirements, smart grid data require complex treatment, such as the use of sophisticated tools, a reliable data management platform and advanced analytical algorithms, which poses major challenges. Most actors are currently not able to exploit big data fully due to a lack of technology, infrastructure, or expertise in data-processing and management.

Big-data technologies are a good opportunity for utilities to introduce new methodologies, evaluation models and applications and to improve data management in smart grids. The big-data life-cycle consists of five phases: data sources, data integration, data storage, data analysis and data visualisation [36]. Big-data analysis is the most important phase of the life-cycle because it can help make the grid smarter, more efficient and more cost-effective. Each phase of the life-cycle has its own tools and technologies.

In this area, Denmark has a head start, with an ecosystem of actors committed to making electricity data available and at testing new flexibility products with high added value. The ongoing digitalisation of energy systems based on the DataHub (and most recently, the Green Energy Hub) provided by the Danish TSO Energinet and the concentration of smart grid assets constitute a strong digital foundation for leading test and demonstration facilities. Examples of relevant projects in Denmark are the Flexible Energy Denmark [37] and CITIES [38] projects, which stand out in their composition and scope, as they go beyond the electricity sector by addressing flexibility synergies across energy systems and establishing the required link between digital and energy worlds. This digitalisation of energy is also conducive to the development of new actors located at the junction of these sectors, such as Center Denmark [39], which brings together energy data from several DSOs and living labs in a digital hub and makes it available for testing new solutions and advanced business models.

While it is clear that market actors are ready and organised and that the technological solutions are already mature or will soon become so, the major challenge remains that of regulation (see section 4), which must catch up, as well as consumer behaviour, which needs to adapt to the challenge of flexible consumption.

3.3 Short-term storage technologies to balance energy and power (batteries)

Battery-related smart grid activities: lessons from the SMILE project⁸

The European Smart Island Energy System - SMILE project [40] has implemented different demand-side flexibility measures and management systems on the Islands of Madeira (PT), Orkney (GB) and Samsø (DK) with and without storage for both heating and electricity. The DSF solutions are not based on central controls or any sort of flexibility market but focus primarily on local economic optimisation. While final conclusions are not yet available, the impression is that most DSF solutions and battery energy storage systems (BESS) have some advantages. A single test-site with a BESS at a local substation (distribution transformer) used for phase and day/night balancing of PV and consumption proved that BESS can be used to postpone investments in grid reinforcement. SMILE has also analysed regulations and standards and in this context also recorded some of the barriers experienced during the installation and operation of the pilot sites.

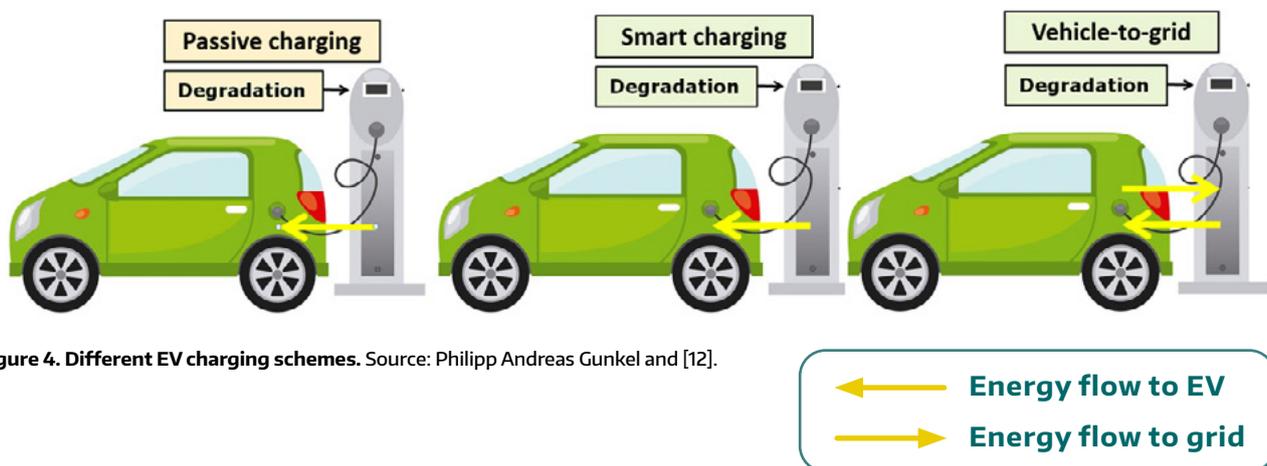


Figure 4. Different EV charging schemes. Source: Philipp Andreas Gunkel and [12].

One of the principal but not clearly visible barriers restricting implementation of flexibility services is the current supply-focused topology of the electric grid, both physically and conceptually. The grid only requires minor adaptations to support the distribution of power in both directions, but the grid management regime must be changed from "supplying central generated energy to electric consumption" to "distributing energy services between all grid-connected installations". Many grid codes are still modelled in accordance with the classic concept, where the central generation is responsible for providing stability and voltage quality. The classic thinking attempts to shift responsibility for stability to the new distributed renewable generation as central generation is phased out (Figure 3). Consumers and prosumers are mostly seen as a challenge rather than an asset that can contribute to stability through flexibility measures such as storage.

Flexibility provision by electric-vehicle batteries: an energy system-wide perspective

With the electrification of personal mobility, attention has been directed to the increase in energy demand and the potentially large peak effects of charging electric vehicles (EV) if done in a passive way [12,41]. Conversely, the smart integration of electric vehicles may offer significant benefits for the flexible energy system. The study by [12] investigated alternative charging strategies for electric vehicles in Europe offering various degrees of flexibility: passive charging, smart charging and vehicle-to-grid (Figure 4).⁹ It compared this flexibility and its overall energy-system effects with the flexibility offered by interconnections, using an energy-system model for Northern Europe. The results showed that the flexibility enabled by the three EV-charging schemes generated efficiency gains across the entire energy system, translating into lower costs, a higher share of variable renewable

energy resources, and lower CO₂ emissions [12]. Notable mechanisms behind this overall effect were:

- A virtuous dynamic is activated when linking flexible EVs to wind penetration: the greater flexibility created by EVs accelerates the penetration of wind energy, which in turn further improves the competitiveness of electricity as a fuel for cars.
- It is important for RE integration patterns that EV charging is enabled: if charging is possible only during the hours when cars are normally parked at home, then less solar PV is needed, while charging also at work means a better utilization of power from solar PV and hence higher shares in the system.
- There are important substitution effects between competing technologies: flexible EV charging from a critical mass of electric vehicles calls into question the competitiveness of stationary batteries.
- Substitution effects also have knock-on effects outside the electricity sector: EV flexibility competes directly with power-to-heat technologies (heat pumps, but also electric boilers), which are replaced by biomass-fuelled boilers. Yet the latter effect is likely to be reduced with rising biomass prices as a result of the increasing demand for biofuels in aviation and on-road freight.

It is important to note that the study does not account for distribution-system costs (due to their high complexity) and therefore only provides potentials from the perspective of day-ahead markets and does not consider relevant potentials and revenue streams in balancing and frequency markets.

3.4 Technical barriers to interoperability in the smart grid

Smart grid solutions must be replicable to gain wide acceptance in the market. Technical barriers to interoperability will also be barriers to replicability. Some of the technical barriers identified in the SMILE project are listed below:

- Access to stable internet connection is a dominant issue for many practical demonstrations. The cost and quality of internet service will in reality limit smart cloud solutions. Broadband/4G is not an alternative to cabled internet since it is limited or non-existent outside populated areas. Even smart grid technology providers can be reluctant to visit remote areas.
- Data may often be available, but different data formats often restrict communications between technology providers. Finding applicable standards is a practical challenge that can result in a lack of interoperability.
- Limits to smart charging of EVs. Many EV-charging points are incompatible with the Open Charge Point Protocol (OCPP) 1.6. There are issues with implementation and cyber security. Additional data access to vehicle on-board diagnostics (OBD) ports in EVs for advanced charge planning for fleets is becoming more complicated and may disappear altogether in the future unless regulation addresses this problem.
- It is hard for citizens to make informed energy decisions with low literacy in terms of distributed energy generation and energy efficacy. With few or no incentives for smart grids, the technologies installed may just meet the home's requirements without consideration of the rest of the grid or system.
- If the control mechanism of the smart grid fails, grid reinforcements will be needed somewhere to support the grid. The integration of energy surplus in the public grid will imply the costs of the re-sizing of components (lines/cables, transformers, etc.). Technical grid compliance differs from country to country, so it is difficult to design systems that can be used everywhere.
- Many houses wanting to exploit smart grid solutions and storage are not suited to domestic-scale solutions due to the age of the building, low insulation levels, or a lack of space.

A new flexible energy systems lab-set up

The Danish Technological Institute has established a lab dedicated to smart energy, where it is possible to setup combinations of physical components and in-the-loop simulation to test the interoperability, connectivity, power quality etc. of smart-energy components and systems. Being able to simulate frequency or voltage issues on a grid with other real components can be useful to prove conformity to future applications.

GRID SERVICES Danish focus	Central power plants (being phased out)	Decentral power plants (CHP) (closing or change to back-up)	Wind turbines on land	Wind turbines on sea	Interconnectors VSC	Interconnectors HVDC	Synchronous compensators	FACTS components (Statcom and SVC)	DC/AC inverter generation	Consumption Balancing (Demand Side Management)	Battery Storage System MW-class	Battery Storage System kW-class domestic, V2G etc.)
	MW (Energy)											limited energy size
MW (Power)												limited inverter size
Mvar (Reactive power)		Local only										Local only
Volt (voltage)		Local only	Local only									Local only
MVA (short circuit power)		Local only									limited inverter size	limited inverter size
Inertia		Local only									limited energy size	limited energy size
Hz (frequency)											limited energy size	limited energy size
Black Start (from dead rid)						Skagerak 4 only						

Figure 3.4 New and old measures versus grid services. In Denmark, central power plants are being phased out and decentral CHP being challenged by wind and PV. The new smart grid measures are often referred to as challenges rather than part of the solution. However, there is a new specific Danish grid code for battery storage systems. Source: Danish Technological Institute.

4. Regulatory changes for activating flexibility

4.1 Regulatory frameworks are lagging behind

The development of the smart grid in a zero-emissions energy system depends on regulatory frameworks that support viable business models for flexibility services, including the use of digital data collected by the utilities for activating flexible consumption by end-users [42].

In many countries, existing laws and regulations are lagging behind in stimulating the development of new models of flexibility services. At the European level, the texts that govern the roll-out of smart meters emphasise the need to provide consumers with better information on their consumption in order to promote awareness of energy efficiency, not flexibility [43].¹⁰ In this context, the DSO, or the private suppliers in charge of installing smart meters, have the choice of determining the reading time step according to the information they wish to collect and the economic benefits they foresee. The third legislative package of 2009 further stresses the relationship between time steps and economic benefits by establishing that the roll-out of smart meters must be subject to a positive cost-benefit analysis.

Beyond this technical backbone for active and integrated energy systems, there is a clear disconnect between the sophistication of market designs following the boom in renewables and the regulatory frameworks that apply at the distribution-grid level, which have hardly evolved since the reforms opening up the electricity market. The case of EV flexibility discussed above exemplifies how current regulations hinder the utilization of flexibility. In particular, restrictions regarding market entry, such as minimum bid size or outdated technical standards, limit EVs in offering their flexibility to the market [12,44]. Hence, today new innovative regulation models must be explored and evaluated to activate the missing link for a full use of all flexibility potentials, thus bringing us closer to reaching our deep decarbonization targets at an affordable cost.

This also applies to Denmark, for which it is estimated that only one-third of the emission reduction target will be met in the current policy and regulatory set up [45]. Nevertheless, Denmark has two key assets inherited from past energy policies that can be used to accelerate decarbonisation, provided the right set of regulatory incentives is implemented: its district heating system, which is one of the most advanced in the world; and its long history of consumers' involvement in the energy sphere, discussed in turn below.

4.2 Regulatory barriers to flexibility and sector coupling: the discriminatory effect of current grid tariffs

Among the necessary regulatory changes for grid operators is the revision of grid tariff design to support the efforts undertaken by market actors regarding flexibility, for example, of EVs and heat pumps, and sector coupling [46,47]. In the Nordics, this regulatory change is part of the Nordic region-wide coordination strategy for energy decarbonisation, which calls for a holistic approach to regulation to break with the “silo” view and accelerate electrification, especially in the (district) heating and transport sectors. The strategy further reflects wider consideration undertaken at the EU level among policy-makers and the industry [48–50]. Currently, the dominant grid tariff design builds on a fee charged per unit of energy (kWh) consumed which adds up to the energy price and masks flexibility signals. The adaptation of current tariff design that allows market signals to become detectable has given rise to multiple studies estimating the missing flexibility resulting from volumetric tariffs. These studies have focused in particular on estimating the flexibility potential at the interface between district heating and electricity since about half of the heat demand of Nordic and Danish households (except in Norway) is supplied by district heating. The studies demonstrate that current tariffs substantially hinder investment in flexible P2H technology by discriminating against electricity for heat generation [51–53], usually at the benefit of biomass in inflexible heat-only boilers [52,54]. Switching from current volumetric tariffs to a capacity-based tariff would trigger 25% additional P2H capacity and 5 to 15% more heat storage in Nordic district heating in 2050. By means of a ratchet effect, the adoption of new tariffs may trigger 3% to 5% more Nordic wind capacity in 2050, or 19 TWh to 22 TWh additional electricity generated, capable of contributing to the decarbonisation of neighbouring countries [55].

In Denmark the tariff has already evolved to incorporate time differentiation to reflect the use of the grid throughout the day and night (time-of-use design). Discussion of the so-called Tariff Model 3.0 is ongoing to tackle geographical differentiation further in the future, which will involve lower tariffs for consumption close to local production, as well as more generally wherever the network is not congested.

4.3 Regulatory barriers to active energy communities

The effective participation of energy communities in green, flexible energy systems requires significant changes in regulation and in the broader governance of energy systems.¹¹

In 2018, the EU agreed on an enabling framework for energy communities as part of a reworking of the Renewable Energy Directive which requires developing, implementing and rolling out business models that broaden the capital participation of consumers [56]. An energy community is a legal entity that may engage in multiple forms of energy generation and flexibility services locally, provided to its members or to third-party shareholders. This new form of actor therefore entails a clear legal definition that delineates the boundaries of its own activities and those of other existing actors, such as DSOs and aggregators. However, this definition has not yet been fully established.

The ongoing discussion in Denmark on how to transpose this text very much relates to the Danish cooperative tradition, which has influenced the formation of electricity distribution systems, district heating and the earliest deployment of wind projects. Energy ownership structures are not regulated in a dedicated act but rather refer to multiple acts establishing the governance model of companies and cooperatives (e.g., Lov om visse erhvervsdrivende virksomheder) and of heat supply (Varmeforsyningsloven).

Two questions thus require further investigation: whether the traditional cooperative model with limited liability is suitable for future Danish energy communities; and to what extent are the responsibilities of actors in the context of local markets well defined. Today the regulatory rules that govern the distribution of roles and responsibilities in the activation and operation of specific flexibility solutions locally have not yet been fully established, which results in the inaction of stakeholders, as discussed below.

Finally, to take off, energy communities will have to rely on advanced communication tools capable of metering energy flows, automatically controlling the equipment to optimise clean energy use and flexibility, and tracking the exchange of services for efficient price settlement and billing. However, regulation may hinder the technical development of such advanced management tools. Indeed, the three European cVPP studied by [29] were also constrained by existing rules, for example, prohibiting peer-to-peer trade, high administrative burdens and

the demand for costly technological requirements, such as investing in a flexibility asset that is better suited for large actors such as data centres or district heating. This created a gap between the (significant) role envisaged by the energy communities and the (minor) role 'assigned' to them by the incumbent energy regime [29].

4.4 Regulatory barriers to flexible grid management: hybrid models worth exploring?

Advances in tariff design are a progressive step that must be accompanied by innovative regulations for the active management of distributed energy resources (DER) on networks to limit their integration costs for society. DER involve significant investment and financial risks for DSOs and ultimately TSOs. The estimated grid investment cost to meet the deep decarbonisation ambitions in Europe are estimated at € Billion 400 [57] and € billion 4 in Denmark in 2030 and 2040 respectively. As noted above, half this cost can be avoided in Denmark by appropriate regulation fostering flexibility [5]. This issue is clearly outlined in the Green Deal as a way to provide incentives that can reduce system costs and support an affordable transition.

In Denmark, the rules and frameworks that underpin the DSO's acquisition of flexibility services must take place in a transparent, non-discriminatory and market-based way, given that flexibility has the same value for the power system, irrespective of how it is provided or by whom [16]. Here, efforts are underway to develop market design further not just for DSO flexibility but also for balancing services and for engaging new market actors within the Tariff Model 3.0. DSOs are also allowed to explore non-market-based methods, such as interruptible agreements for the procurement of flexibility, if no market actor is able to deliver the service. In practice, however, DSOs receive limited incentives for active flow management, which may ultimately affect their ability to lower grid costs. Besides, there exist several grey areas within the EU regarding the role and responsibility of DSOs in activating flexibility. Notably, EU directives are silent on the need for coordination to exploit flexibility with energy communities and at the district level, for instance, over heat and gas coupling. Fundamental policy questions exist about the appropriateness of using grid-users' funds for what is otherwise a competitive service [58,59]. However, the imperative of climate action suggests that there is a need for systematic assessments of the consumer benefits of different modes of business models for flexibility that under certain conditions could support a more active role for DSOs.

A key point to remember is that there is a need for a better alignment of price signals between market prices that reveal flexibility needs and for network prices that reveal grid investment needs. Between these two signals lies a legal and regulatory framework that sometimes puts a hold on flexibility and takes us away from implementation of the least expensive solution. The new flexibility potentials linked to sector coupling, local markets and energy communities driven by smart-grid technologies that have emerged over the last decade require a rethink of those regulatory frameworks that limit their activation and a systematic evaluation of new ones. Regulators are now seizing this opportunity by testing new enabling frameworks designed to maximise flexibility and zero-carbon technology uptake, notably through so-called 'sandbox' experiments, discussed in the next section.

4.5 Regulatory 'sandbox' experiments

Regulatory innovations or 'sandboxes' have in recent years pointed to the changes in energy and ICT laws and regulations that are needed to develop efficient, effective and fair models for the provision of flexibility in the smart grid. These real-world experiments, in which the authorities grant temporary exemptions from regulation, are based on interventions in regulatory frameworks such as energy law, derogations, tariffs (exemptions), building regulations, or other framework conditions and thus require involvement by a broad range of stakeholders [60]. While rules have often limited the scope of such experiments, many countries, especially in the OECD, are now allowing more room for experimentation [60]. Sandbox experiments on flexibility services for grid stability have in recent years been carried out in countries such as Australia, Germany, Italy, the Netherlands and the United Kingdom [60,61]. They have identified important regulatory barriers and related recommendations regarding the activation of flexibility services. In Italy, the responsibility to operate charging stations was extended to the DSO and funded through the tariff according to schemes designed, monitored and evaluated by the regulator. In the Netherlands, a menu of derogation to unbundling were defined for energy communities to operate as flexibility providers before EU legislation allowed for it. In the UK, peer-to-peer exemptions were granted to the suppliers to also activate energy communities. These experiments allowed innovative and tailored regulations and resulted in high learning capabilities for regulatory agencies that are likely to drive further changes in European countries.

Box 2.

Experimenting with community-based grid-balancing facing regulatory constraints: the "Houtlaan Minder op de Meter" project

Houtlaan is a neighbourhood of 136 detached houses in Assen in the Netherlands. In 2017, a working group was established in Houtlaan to reduce the community's CO2 footprint. This group is exploring how it can meet the government's objective of 50% reduction of CO2 by 2030 in its neighbourhood through a combination of private rooftop solar PV, electric vehicles and heat pumps. In October 2020, the group received an experimentation grant to develop a grid-balancing system, including storage, as the neighbourhood transformer was encountering problems managing the load created by the solar panels. This system should provide day/night as well as seasonal balancing services, but its success depends on the introduction of a flexible pricing system for storage. At the moment, the lack of a follow-up to the experimentation decree is severely hindering the experiment, as it heavily depends on similar regulations to allow for peer-to-peer supply. A tax regulation that doubles the tax on storage is another key barrier. Source: [27].

5. Conclusion

The efforts needed to decarbonise our energy rely heavily on the nexus between technologies, institutions, and actors (citizens, consumers, communities, firms, and regulators). These three pillars of the energy transition are constantly interacting and evolving. A focus on this dynamic interplay is important, partly because of the rapid technological advances, as demonstrated by the progress made in low-carbon production and data management, but also to take the social dimension of the energy transition into account. In between, regulators and lawmakers must design a body of rules that ensures the coordination of all actors in terms of their integration in the electricity value chain and across energy sectors, to balance the volatile production of renewable energy resources.

In the Nord Pool market area, for example, the successive evolution of electricity market rules demonstrate how industry players are progressively completing the market design to meet the constraints imposed by the rapid growth of wind energy. A key facilitator is a transparent, well-organised and inclusive discussion forum for the sector's stakeholders. A well-functioning market is, of course, necessary, but alone it will not be sufficient.

That said, DSF systems, infrastructures and technologies also carry substantial investment and operating costs and may not pay off in all situations, and they require the development new knowledge through RD&D activities, as this report clearly shows.

5.1 What lays ahead

Integrate all the actors

While technology makes it technically possible to control all types of decentralised load or production, the human factor must be taken into account to a greater extent. This implies, in particular, a better understanding of what motivates energy users in the context of decarbonisation. The richness of the work done in the behavioural and social sciences, among others, that focuses on the motivations of people in their consumption or production of energy, is beginning to shed new light supplementing traditional studies in which the consumer is treated as a simple rational agent seeking to maximize her utility. In reality, the effects of communities that build on attitudes, beliefs, etc., reveal an array of important levers to activate consumers that must be better understood and utilised in a smarter way. It is worth emphasising here that the level of automation will be important for the flexibility provision of end users, and that manual solutions conversely are less likely to be successful.

Make sure that regulation does not stand in the way

How? By supporting a competitive, transparent and liquid market. This means abolishing rules that act as a barrier to the participation of actors capable of providing flexibility services and that hinder investment in carbon-free generation or storage. This also requires the establishment of a level playing field between production and flexibility technologies, as well as between energy sources. It also implies the minimization of distortions of efficient prices set by the market and in particular implies a revision of grid tariffs. Finally, it implies the protection of precarious consumers for a fair transition.

Data, always more data

The ability to take advantage of new flexibility services will require changes in information flows among grid devices (e.g. through smart meters), as well as innovations in communication and coordination tools and data management systems that increase the observability, predictability and controllability of the grid. These data streams and systems are needed to activate the economic mechanisms that reward consumer flexibility. Two price signals must be provided here: rewards and penalties in relation to congestion in the grid, and signals related to the fluctuating price of electricity on the wholesale market.

Lower the technical barriers to interoperability in the smart grid

Generating more data does not in itself enable a smart grid and DSF. Technical solutions must be replicable to gain wide acceptance in the market, and technical barriers to interoperability will also be barriers to replicability. Such barriers include, for example, the quality and cost of internet services - especially in remote areas, lack of standardised data formats, incompatibility of EV technologies hindering smart charging, high cost of re-sizing grid components to integrate energy surpluses if other balancing controls fail, and physical limits of residential buildings in accommodating smart grid solutions due e.g. to age or size. Finally, citizens' low smart-grid literacy level, combined with weak economic incentives for flexible consumption, may cause an underinvestment in the capacity to serve the grid rather than just the household.

Thinking out of the box, go hybrid when you need to

The urgency of climate change requires that the full range of options be considered when it comes to developing innovative energy and flexibility solutions. In particular, the activation of certain diffuse flexibility potentials with high added value for society may still not generate a sufficient return on investment for private actors to develop service products to harvest them. Clearly, the climate objective must be placed on the same level as the market objective, while regulatory lock-ins must be avoided that would hinder, for example, the operation of flexibility services by certain actors when they are best able to drive them. This may give rise to new, hybrid organisations with new types of participation of, and collaboration between, private energy-service providers (e.g. electricity retailers, aggregators, prosumers, energy communities) and regulated actors (DSOs, TSOs, gas and heating network operators).

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Endnotes

¹ Balancing responsible parties (BRP) or actors are firms that buy and/or sell power in the power market (e.g. Nord Pool) on behalf of power suppliers and producers [16]. A firm can be balancing responsible for consumption, production and/or trade. The BRPs are financially responsible to the TSO for imbalances between the expected and realised production and consumption over each 24-hour period of operation of the market.

² The split supply may be induced by a heat service on subscription or an EV supply with flexibility service where the FCR income is split between the aggregator and consumer, so the additional benefit is lower investment costs for the heat pump and access to EV-flex-income.

³ Such as large buildings, data centres, cold storage facilities and industries using electricity as a processing energy.

⁴ These improved terms include service criteria about numbers of days till the delivery of the serial meter and registration in the data hub.

⁵ The full quote is "an obligation on market participants engaged in aggregation to be financially responsible for the imbalances that they cause in the electricity system" [62].

⁶ These include citizen energy communities (CEC) and renewable energy communities (REC).

⁷ Big data can be defined as (1) a large volume of data sets, but it actually includes other characteristics, including (2) variety in presenting different data formats, (3) velocity to meet speed requirements, (4) value to provide the ability to extract information from data, (5) variability to provide a concept of data inconsistency and (6) veracity to work on data reliability [63].

⁸ Another project addressing this topic is FlexPlan [64], which aims at establishing a new grid-planning methodology considering the opportunity to introduce new storage and flexibility resources in electricity transmission and distribution grids as an alternative to building new grid elements.

⁹ Many other projects and initiatives have addressed this topic. In the context of ISGAN, the "Clean Energy Ministerial Horizontal Accelerator for Power System Integration of Electric Vehicle (EV) Infrastructure is an innovative new mechanism strengthening the collaboration and capitalising on the synergies between four CEM work streams involving the International Smart Grid Action Network (ISGAN), 21st Century Power Partnership (21CPP), the Electric Vehicle Initiative (EVI) and the Power System Flexibility (PSF) Campaign" [65].

¹⁰ The text was contained in Article 13 of the EU Directive 2006/32/EC [43]. The law was industry-driven and aimed to replace existing analogue meters with grid operators as customers, who were not interested in energy management applications beyond their established way of thinking.

¹¹ The EU Directive on common rules for the internal electricity market ((EU) 2019/944) includes "new rules that enable active consumer participation, individually or through citizen energy communities, in all markets, either by generating, consuming, sharing or selling electricity, or by providing flexibility services through demand-response and storage. The directive aims to improve the uptake of energy communities and make it easier for citizens to integrate efficiently in the electricity system, as active participants." [66].

