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Step-by-step guide for DSOs

A tool to support DSOs

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Authors

Surname	First Name	Beneficiary	e-mail address
Yang	Ying	RISE	ying.yang@ri.se
Tobiasson	Wenche	RISE	wenche.tobiasson@ri.se
Warneryd	Martin	RISE	martin.warneryd@ri.se
Fernqvist	Niklas	RISE	niklas.fernqvist@ri.se

Reviewer

Surname	First Name	Beneficiary	e-mail address
Tiborn	Mats	Spinverse	mats.tiborn@spinverse.com

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List of abbreviations

Abbreviation	Definition
BRP	Balance responsible party
CAPEX	Capital Expenditures
DSO	Distribution System Operator
EV	Electric vehicle
FlexiGrid	Enabling flexibility for future distribution grid
FSP	Flexible Service Provider
GHG	Greenhouse gases
HP	Heat pump
ICT	Information and Communications Technology
IoT	Internet of Things
LEM	Local energy market
LFM	Local flexibility market
LV	Low voltage
MV	Medium voltage
PPF	Power Flow Analysis
TSO	Transmission System Operator

Contents

1. Introduction

1.1 Aim and scope of the work

This report constitutes one of the exploitable results from the FlexiGrid project. As one of the last deliverables, the report will utilise findings, experiences, and lessons learned from throughout the project to produce an accessible report that will support Distribution System Operators (DSOs) that are considering different methods for accessing flexibility in local networks. Whilst a range of methods for accessing flexibility in local markets will be considered, particular focus will be given local energy and flexibility markets.

Understanding the variation of the different drivers, actors may have for providing flexibility services to the electricity grid is crucial for the development of attractive value propositions to unlock flexibility resources.

The report unfolds as a comprehensive guide that transforms the culmination of the groundbreaking FlexiGrid project into a structured narrative that equips DSOs with actionable insights and strategies. The report begins with an introduction that explains the goals of the project and contextualises the need for access to flexibility in local energy grids. The background section addresses the evolution of energy flexibility, the central role of DSOs, and emerging trends in local energy and flexibility markets. In the subsequent methods section, the report describes a multi-faceted approach: a review of project reports, a comprehensive analysis of relevant literature, and the integration of insights from workshops and interviews. These methods are brought together to formulate effective ways for DSOs to access flexibility.

Key findings from the FlexiGrid project form a cornerstone of the report and include identified issues, available grid flexibility, quantified value propositions, and a nuanced understanding of roles, responsibilities, and regulations. The report culminates with conclusions and next steps that summarise the significance of the project, impact on Transmission System Operator (TSOs), recommended strategies, and future research directions. It also provides tailored recommendations for DSO decision-making, enriched by real-world case studies that highlight successful flexibility implementations and shed light on challenges, strategies, and outcomes. The report also provides a guide based on FlexiGrid lessons learned and industry standards, providing DSOs with a guide for navigating the intricacies of local energy and flexibility markets.

1.2 Methodology

The practise of this document for the FlexiGrid undertaking is based on a multi-faceted method that includes an overview of reports and findings from the project itself, an evaluation of applicable published literature, and insights from workshops and interviews. This comprehensive approach ensures that a broad variety of perspectives and empirical evidence are blanketed, supporting to produce an informative and actionable guide that meets the project's objectives.

The foundation of this document is based on a thorough review of the extensive deliverables and reports. This internal analysis serves as a cornerstone which provides a synthesis of the project's progress, outcomes, challenges, and innovations. The key findings, lessons, and breakthroughs that emerge from this review provide an important basis for formulating the report's recommendations and conclusions.

Integrating findings from a wide range of published literature is important to situating the FlexiGrid project within the broader context of energy flexibility, local flexibility/energy markets, and grid management strategies. A review of peer-reviewed academic papers, industry reports, and relevant publications enriches the report's content with established theoretical frameworks, comparative analyses, and empirical studies. This approach promotes a well-rounded perspective that accounts for advances, challenges, and emerging trends in the field. Insights from the published literature lend depth and credibility to the recommendations made in the report.

Collaboration with stakeholders who were directly involved in the FlexiGrid project and its implementation provides an invaluable layer of experiential knowledge. Workshops and interviews conducted with project team members, researchers, engineers, and other relevant participants provide an opportunity to explore nuanced aspects of project implementation. Qualitative data is collected through structured interviews and collaborative workshops, allowing for deeper exploration of insights, experiences, and lessons learned. The perspectives of these participants contribute to practical findings and insights from the field that complement the technical and theoretical underpinnings of the report. To identify what drivers there may be for enabling resources as flexibility services to the electricity grid, we stared in identifying different flexibility resources such as smart energy use, heat pumps (HPs), thermal inertia, and energy storage capacities. Identifying resources was done by desk-top research using web pages, literature and review of several research projects about flexibility. We deliberately excluded resources typically controlled by energy companies, such as hydropower and district heating systems. After listing and sorting the identified resources, we contacted actors who we knew, or assumed, had ownership of these resources, and conducted interviews in one-to-one or focus group settings. The interviewees were clustered into four different categories: Commercial, household, community, and public. The interview data in each category was analysed to identify themes of how different actors perceive the value of their flexibility resource and what motivates them to provide flexibility services.

1.3 Outline of report

The report is organised as follows: Section 2 outlines the background and motivation for DSOs to access flexibility, Section 3 presents the methods for DSOs to access flexibility, Section 4 highlights the key takeaways from FlexiGrid project, and finally Section 5 provides the conclusions and next steps.

2. Background

In the rapidly changing landscape of power distribution, DSOs are at a crucial point where integrating flexibility has become a compelling strategy. Traditionally, DSOs have been tasked with providing reliable power to end users, ensuring grid stability, and minimising interruptions. In the traditional structure of the power grid, most electricity is generated in large and centralised generation facilities and then transported unidirectionally to end users.

However, with the rapid proliferation of renewable energy sources, the growth of distributed generation, the advances in digital technologies, and the increasing complexity of energy consumption patterns with prosumers involvement, the role of DSOs has expanded beyond traditional boundaries. Renewable energy sources such as solar and wind have brought both opportunities and challenges. While these energy sources contribute to sustainability and reduced emissions, their unsteady nature causes fluctuations in the grid, making it increasingly difficult to maintain the delicate balance between supply and demand. The emergence of bidirectional power flows challenges the static design and passive operation of distribution grids. In this context, flexibility becomes an important tool for DSOs to optimise grid operations and adapt to the dynamics of renewable energy integration [1].

Flexibility generally refers to as the ability to adjust generation and consumption patterns to a signal in order to provide various grid services [2]. Flexibility is technically defined as a change in power that is activated at a specific time for a specific duration at a specific locational node within the distribution system [2]. Flexibility is used by the network operators to effectively manage peak loads, mitigate congestion, improve overall grid reliability and secure network operation[3]. This approach can not only supports efficient use of existing infrastructure, but also eliminates the need for costly network expansions. Consequently, network operators are able to achieve greater operational efficiency and cost effectiveness, benefiting both themselves and end users. Flexibility is characterised by various attributes such as duration, rate of change, start time and trigger, duration, location, controllability, predictability, time availability, and delivery time.

DSOs that embrace flexibility can optimise the use of distributed energy resources, such as rooftop solar, battery storage systems, and EV charging stations. When used effectively, these resources contribute to grid stability, reduce energy waste, and allow consumers to actively participate in the energy ecosystem. As this background underscores, the path to flexibility is not just an option, but a strategic imperative for DSOs navigating the changing landscape of modern energy distribution.

This underscores the need for a platform or mechanism that allows DSOs to access flexible resources and compensate participating end users. This is where the concept of a flexibility market at the distribution level comes into play, serving as a channel for such interactions. While the idea of incentivising flexibility at the distribution level is not new, terms such as demand response, demand side management, active grid management, and local flexibility/energy markets are closely associated with flexibility markets, albeit with different definitions and applications. The term "flexibility market" in this context encompasses any market-based approach that allows DSOs to access end-user flexibility.

3. Methods for DSOs to access flexibility

In the dynamic landscape of modern energy distribution, DSOs are embracing innovative methods to access flexibility within their networks, ushering in a new era of grid management. These methods, grounded in technological advancements and market-driven strategies, empower DSOs to optimise grid performance, enhance reliability, and accommodate the surge in renewable energy sources and decentralised generation. These methods are categorised in Figure 1 based on two dimensions: 1) more market-based vs. more control-based, and 2) requiring more innovations in technology and business vs. requiring less innovations in technology and business.

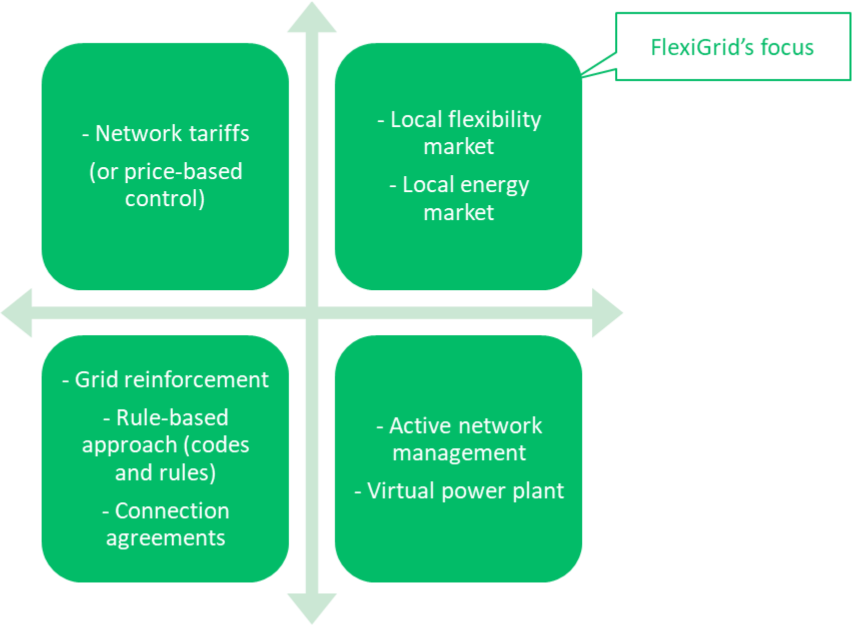


Figure 1. The available methods for DSOs to access flexibility within their networks.

3.1 Rule-based mechanisms

The rule-based mechanism refers to the implementation of technical requirements and grid codes. Rule-based mechanisms offer a systematic and automated approach to accessing flexibility. By implementing predefined protocols based on real-time data and operational conditions, DSOs can dynamically adjust energy flows, curtail demand, and activate distributed resources. These mechanisms facilitate swift decision-making, minimising human intervention and ensuring rapid responses to grid fluctuations.

3.2 Network tariff solutions

The network tariff solutions use the price signals to trigger the activation of flexibility for certain services. Tariff solutions introduce a financial incentive structure to encourage consumer behaviour aligned with grid needs. Time-of-use pricing and dynamic tariffs incentivise end-users to shift their energy consumption patterns to off-peak periods, thereby reducing peak demand and alleviating stress on the grid. DSOs leverage pricing signals to influence demand profiles, optimising resource utilisation and reducing the need for costly infrastructure upgrades.

3.3 Grid reinforcement

Traditional yet effective, grid reinforcement involves physical enhancements to the distribution network. By upgrading transformers, adding new lines, and expanding substation capacities, DSOs increase the network's power handling capabilities. While capital-intensive, this method provides a tangible solution for addressing localised capacity constraints and ensuring reliable energy delivery.

3.4 Connection agreements / bilateral agreements

Collaboration between DSOs and distributed energy resource owners through connection agreements or bilateral contracts yields mutual benefits. These agreements formalise resource sharing and enable DSOs to access flexible assets during peak demand or emergencies. Such arrangements establish a structured framework for cooperation, promoting grid stability and resilience without significant infrastructure modifications.

3.5 Active network management

Leveraging advanced automation and control systems, active network management optimises energy flow within distribution networks. By continuously monitoring grid conditions and utilising real-time data, DSOs dynamically manage voltage levels, reroute energy flows, and harness distributed resources. This real-time adaptability ensures efficient grid performance, mitigating disruptions and enhancing flexibility.

3.6 Virtual power plant

Virtual power plants (VPPs) amalgamate diverse distributed energy resources into a centralised virtual entity, effectively creating a dynamic and responsive energy network. DSOs remotely manage and optimise this virtual aggregation, coordinating resources to balance supply and demand in real-time. VPPs maximise flexibility utilisation, bolster grid stability, and facilitate the seamless integration of renewable energy sources.

3.7 Market-based approaches

Market-based strategies involve creating mechanisms for trading flexibility services. Demand response programs is a type of platform or arrangement that allows DSOs to access the potentially flexible resources and remunerate the end-users who provide the flexibility. It incentivises consumers to adjust energy consumption during peak periods, reducing strain on the grid. Demand response programs can be naturally integrated within local energy and flexibility market. Local flexibility markets (LFMs) enable participants to exchange flexibility services within localised contexts, fostering a dynamic energy ecosystem. Expanding this concept, local energy markets (LEMs) facilitate the trading of energy and flexibility services within predefined regions.

Local flexibility market [4] [5]

LFMs allow distributed energy sources to provide their demand or production flexibility to grid operations in the form of services. They enable trading of flexibility provided by consumers and generators at the distribution level and provide a support tool for DSOs and a value stream for utilities.

General grid services that can be provided by flexibility markets include peak reduction, voltage control, congestion management, harmonics cancellation, balancing services and frequency control, black start, and controlled islanding.

Three market structures that have been developed and demonstrated the FlexiGrid project, are peer-to-pool, peer-to-peer, and adaptive systems. The peer-to-pool structure is a centralised mechanism that aims to maximise the social welfare of all market participants according to their revealed preferences. The market operator is the consultative actor for managing the market, clearing bids, and conducting settlement. In peer-to-peer structures, trading is decentralised and bilateral. Blockchain is one of the technologies that enable transparent and decentralised payment and smart contracting between buyers and sellers without the need for centralised control. The adaptive system uses both peer-to-pool and peer-to-peer structures and combines them in a larger framework. The adaptive structure adjusts these two different structures according to the need/state of the system through a list of controllable parameters.

The actors considered in the local markets are DSOs, aggregators, end users and market operators. Market structures may differ slightly in terms of actors and their roles. However, from a general perspective, the DSO is the buyer of the flexibility products and is responsible for reliable and secure operation of the distribution network. Aggregators are considered as sellers of the energy or flexibility products. End users can participate directly in the local markets or participate through an aggregator. The market operator is responsible for clearing the market to maximise social welfare and allocates payments according to each market participant's contribution.

The potential cost and revenue streams in a local market for DSOs are further explored. Potential cost streams include costs associated with metering and Information and Communications Technology (ICT)/ Internet of Things (IoT) platforms, administrative and staffing costs for participating in local markets, potential reduction in revenue from electricity tariffs, and lower revenue caps due to Capital Expenditures (CAPEX) deferral/avoidance. Potential revenues (cost reduction revenues) include deferred/avoided capital expenditures, extending the life of assets by not overloading them, lower connection fee payments to the upstream grid owner, savings from avoiding costs associated with operational measures, and potential savings from avoiding curtailment of distributed renewables.

The IoT platform is another important piece of the puzzle for a functioning local market. The IoT platform brings together the different stakeholders involved and facilitates their communication in a secure and user-friendly way. FlexiGrid’s IoT platform was developed based on the concept of Federative System Space concept. This concept allows different demo sites and actors to have their own deployment. The platform facilitates communication between actors by offering common locations for data storage and common functionalities, while providing the opportunity for a certain level of autonomy within the limits of the imposed rules.

Settlement is an important step in the final stages of a market mechanism. Possible options for settlement include currency (national currency or cryptocurrency), blockchain, separate settlement and billing systems, and the use of an existing billing system between market participants. To choose an appropriate settlement option, one must consider the size and number of transactions, the costs associated with a transaction, the payment currency, and legislation.

Local energy market [4]

This market only opens to assets within a limited local area with resources such as distributed generation, storage and demand-side response providers. The sales can be both locally (e.g. through peer-to-peer markets or to local distribution companies) or aggregated and sold further in national-level markets. Local marketplaces can be designed to enable access for consumers, prosumers, aggregators, suppliers, TSOs and DSOs to allow the trade of both energy and flexibility. The functions of such a market can be 1) Network management – purchasing local energy services with the aim of reducing network management costs, or avoiding/deferring network capacity investment. 2) Local portfolio balancing – using local energy marketplace to hedge short-term variation in generation/supply for small-scale asset owners. 3) Local trade – enabling local energy exchange. Table 1 provides the benefits/opportunities and barriers/risks for market participants.

Table 1. Benefits/opportunities and barriers/risks for market participants with local energy markets [4].

Perspective	Benefits/Opportunities	Barriers/Risks
Consumer/ Prosumer	• The higher level of energy independence and source control are often motivators for prosumers to enter into LEMs • Other motivations include reducing greenhouse gases (GHG), reduce costs and become more self-sufficient, all of which is possible to accomplish with LEMs • Strengthening the customers' position and create an active role and more involvement in the electricity market, often connected with P2P trading of electricity • Engagement and active involvement raise awareness of efficient energy usage and provide a better departure point for involvement in innovative demand-side management • Enables aggregated prosumers to engage in wholesale markets, which otherwise would not have been possible • Microgrid design of LEMs enhances the security of supply and lower costs with potential outages • Implementation of LEMs drive further innovation and disruption in the energy sector and make traditional companies develop more consumer-oriented approaches to be able to stay in the competition from the transitioning sector.	• LEM requires active participants and consumers that are not used to these activities • The success depends on the LEM project developer's ability to engage their customers actively – otherwise is the risk of resistance overwhelming • High upfront costs • Split incentive problems with benefits and investments • Difficult to establish secure and transparent local trading platforms • Blockchain technologies have been suggested, but meet challenges with scalability, complexity in technical protocols and implementation with current elements • Preservation of privacy in blockchain-based architectures • Secure data handling and risk for cyberattacks.
DSO/TSO	• LEMs bring prosumer owned distributed resources and can decrease the need to invest in new and reinforced distribution grids due to increased flexibility and balancing of renewable energy sources • Aggregation of both generation and demand from several prosumers can help grid operators to more efficiently balance the grid's demand and supply. • LEMs can efficiently provide support to grid operations • If designed as several microgrids, the LEMs can provide flexibility, reliability and responsiveness to the greater power grid and allow greater integration of DERs	• With a traditional DSO business model, revenues will decrease – comes down to the DSO ability to change the business model and innovate new services and activities to create value for their customers • The interconnection and seamless change between connected and island mode in microgrids are challenging when it comes to voltage and frequency controls. Also, DER synchronisation is part of this with additional complexity from intermittent generation sources • Standardisation issues with interconnections and communication in LEMs are becoming more present as different countries are at various stages in the smart grid roll-out.
Innovation	• Market development for providers in hardware and software solutions for LEMs. Innovations and economic growth	• Some DERs, which play a significant part in LFMs, need further development. Most prominent are storage technologies, where massive R&D is being undertaken, but many solutions are still years away from market implementation.
Regulatory		Many legal barriers exist, due to the traditional market set up and years of evolving legislation in favour of the centralised market model. Barriers can stem from rules regarding: • Who can participate? • Who will operate the market? • What sales and between who can take place?

		• Are DSOs incentivised to use demand response over infrastructure investments? • Can inverters run in island mode, and how are the regulations for bi-directional energy flows at the stated point of common coupling? • Taxation rules for local energy generation and sharing • The absence of regulations may cause long administration processes and uncertainties • Building parallel networks which may cause conflicts of interest between DSO and prosumers. • Definitions of LEM and DER in legislations. • Treatment of OPEX vs CAPEX

4. Key takeaways from FlexiGrid

In examining the key lessons from this transformative initiative, we unravel a web of critical questions, the potential of flexibility, the value it brings to grid operations, and the complicated roles, responsibilities, and regulations that govern its implementation. These insights chart a path forward for DSOs by identifying strategies to unlock grid flexibility, improve resilience, and promote the transition to a sustainable energy ecosystem.

4.1 Identify the issue to be resolved

In recent times, noteworthy shifts within distribution networks, including the widespread proliferation of distributed generation and the increasing electrification of transportation, have induced alterations in power flow patterns. The existing static configuration and passive operational mode of grid infrastructure have proven insufficient to accommodate the escalating presence of distributed generation and the resultant transformation in network operations, particularly with the emergence of bidirectional power flow. DSOs are confronted with a burgeoning array of operational challenges engendered by these developments. These challenges stem from the surging penetration of renewable energy sources, coupled with the unpredictable demands introduced by Electric vehicles (EVs) and HPs. The principal operational challenges manifest as capacity constraints during peak loads, congestion phenomena, and voltage control anomalies [4] [6]. For example, the organic escalation in peak energy consumption leads to impedance-related constraints, both in terms of voltage and current, across the electricity distribution infrastructure. Furthermore, the injection of reverse power from PV installations has the potential to strain medium-voltage to low-voltage (MV/LV) transformers, thereby exacerbating network stress. Moreover, the substantial reliance on renewable energy resources exacerbates the vulnerability to sudden meteorological shifts, precipitating network instability. This transition is concurrently imposing a considerable jeopardy to both energy supply security and the economic viability of energy expenditures [7] [8].

Within this project, the focus lies on the development and demonstration of peak reduction strategies, voltage control mechanisms, and congestion management methodologies. Conversely, the undertaking assigns a relatively lower priority to pursuits such as harmonics cancellation, load balancing, frequency regulation, black start capabilities, and controlled islanding. This prioritisation stems from limitations inherent to the demonstration site and the availability of requisite measurement and control systems therein.

Capacity challenges and peak load issues are acutely accentuated by the escalating number of end-users and the ongoing trend of electrification. This strain becomes particularly pronounced during peak periods when energy demand reaches its zenith, potentially leading to grid instability and voltage fluctuations. The capacity challenges stem from the need to accommodate these escalating demands without compromising the reliability and quality of electricity supply. Addressing these challenges requires innovative strategies, including demand response programs, grid optimisation techniques, and the integration of distributed energy resources. By proactively managing peak loads and enhancing capacity, the power grid can navigate the peaks and valleys of energy demand while ensuring uninterrupted and high-quality service delivery to consumers and businesses alike.

The assimilation of RES into distribution networks introduces the potential for congestion quandaries, wherein the electricity supply surpasses network capacity or consumption exceeds generation. The imperative, therefore, is the optimisation of grid hosting capacity without compromising the security and quality of electricity delivery. To this end, congestion management emerges as an indispensable tool for network capacity planning. The judicious deployment of flexibility, harnessed from distributed generators or consumers, presents a viable solution to local grid constraints. This approach allows the deferral of network reinforcements until the cost-effectiveness of flexibility services outweighs network expansion. Congestion management strategies can be tailored for real-time intervention or long-term planning horizons [8].

Voltage control and frequency deviation challenges are repercussions of the inherent intermittency of renewable energy sources like solar and wind power. These fluctuations in electricity generation exert corresponding fluctuations in grid voltage. Grid codes, which dictate voltage and frequency standards, mandate DSO compliance to ensure optimal distribution network operation. Coordination between grid monitoring and DERs enables DSOs to effectively deploy the latter for voltage regulation and power loss mitigation.

DSOs are best placed to identify and analyse the need for flexibility within the local networks based on the particular issues that are present. The need, magnitude, and particular issue to be resolved will inform the DSO how to proceed with utilising local flexibility in network operation.

4.2 Flexibility available in the network

The optimal method for accessing flexibility for local network operation will depend on the amount of available flexibility and the number of flexibility providers. There are a number of technical solutions, discussed below, that can support the DSO to accurately and reliably identify the available flexibility and the different flexibility providers.

4.2.1 Network observability [8]

Flexibility has emerged as a viable and cost-effective solution for modern grid management. However, the efficient procurement and dispatching of flexibility resources necessitate a commensurate enhancement in monitoring capabilities by DSOs. The optimisation of grid observability holds the potential to bolster the provision of flexibility services.

Enhancement of network observability unfolds through the exploration of measurement data and the application of advanced data analytic models, notably employing physics-aware neural network structures. This approach facilitates the equitable allocation of computational resources, crucial for the effective deployment of distribution state estimation algorithms.

Simultaneously, the FlexiGrid project has introduced sophisticated methodologies to identify impending risks across diverse strata of the distribution network. These risk assessments span various temporal horizons, encompassing phases from scheduling to real-time operation. Leveraging novel probabilistic techniques and data-driven distributed algorithms, the project envisages the prediction of network security breaches by amalgamating dynamic pricing, meteorological conditions, and end-user behaviour.

Two specific methods are presented. Firstly, a physical-based approach was developed and validated within an actual distribution system at the Chalmers University campus network. Substantiated by simulation results showcasing accurate estimations of voltage magnitudes and angles, the method's efficacy is poised for further validation at the Chalmers campus demonstration site. Secondly, a data-driven state estimation technique was devised, utilising the system's physical connectivity as a blueprint for layer interconnection. This approach exhibited promising results in tests conducted on the IEEE 123 bus system.

Moreover, a congestion forecasting tool predicated on Power Flow Analysis (PPF) has been unveiled, meticulously accounting for uncertainties attributed to PV systems and conventional loads. The tool's salient feature lies in its ability to visually depict network congestion through cumulative probability assessment of key congestion indicators, encompassing node voltage deviation, branch overload, and transformer load. These insights empower DSOs to discern and analyse network congestion, thus facilitating appropriate interventions to manage potential network bottlenecks.

The confluence of improved grid observability, physics-driven estimation, data-oriented methodologies, and congestion forecasting tools augments the capacity of DSOs to efficiently harness flexibility, thereby propelling the power grid towards heightened stability, resilience, and adaptability.

4.2.2 Grid reconfiguration [9]

In the realm of grid management, the effective handling of various operational scenarios is of paramount importance. Two distinct scenarios warrant our attention: non-contingency operation with a high concentration of DERs and contingency operation during stress events. Each scenario presents unique challenges and demands tailored solutions to ensure the stability and resilience of the grid.

In situations where the grid operates within normal parameters, yet accommodates a significant proportion of DERs, specific issues such as voltage rise and transformer overloading become prominent. To address these challenges, a strategic approach involves the introduction of community-based self-adaptive control mechanisms. By engaging customers as active participants, the DSO can tap into their PV inverters' control capabilities. Customers, in turn, can dynamically adjust their PV inverter control set points to counteract voltage rise and transformer overloading. This collaborative approach leverages the distributed nature of DERs to enhance grid stability while also allowing customers to contribute positively to grid management. If voltage-related issues persist, a supplementary measure entails the utilisation of a network reconfiguration algorithm. This algorithm, based on real-time voltage data and current network conditions, intelligently reconfigures the network to mitigate voltage rise concerns and optimise loss reduction.

In scenarios marked by contingencies, where the system experiences stress due to faults or the loss of critical elements, an advanced model predictive control strategy offers a robust response. This strategy encompasses the orchestration of load tap changers and DERs within distribution grids to maintain optimal voltage profiles. The efficacy of this strategy is evident in its rapid response to disturbances, effectively restoring voltage levels and mitigating potential disruptions. Moreover, in cases of severe disturbances that may trigger cascading events and precipitate system-wide blackouts, fault-initiated islanding emerges as a proactive defence. By intentionally isolating a portion of the grid to form an autonomous microgrid, this strategy safeguards critical sections of the network from the cascading effects of disturbances. Furthermore, the proposed control mechanism incorporates a seamless resynchronisation feature, enabling the microgrid to smoothly reintegrate with the main grid once the fault is rectified.

In both non-contingency and contingency scenarios, the overarching aim is to optimise grid performance and resilience. By embracing innovative approaches, such as community-based engagement, network reconfiguration algorithms, and advanced predictive control, DSOs can navigate the complexities of evolving energy landscapes while ensuring reliable and efficient energy distribution. These strategies underscore a proactive stance towards grid management, minimising risks and enhancing the overall operational efficiency of the power system.

4.2.3 Optimal allocation and dispatch of flexibility [10]

In the pursuit of refining the allocation and dispatch of flexibility resources, a series of innovative algorithms and models have been introduced, each catering to distinct aspects of grid management and technical optimisation. There are three types of algorithms and models that were involved in FlexiGrid project: direct self-adaptive control algorithm for PV inverters, indirect optimisation-based control algorithm for flexibility offers, and bi-level optimisation model for local flexibility allocation and dispatch.

Addressing the intricate challenges of transformer overloading and voltage rise, a direct self-adaptive control algorithm emerges as a potent solution. This algorithm, working in tandem with PV inverters, dynamically computes and dispatches optimal setpoints. The core objective is to rectify transformer overloading and voltage rise concerns, thereby fostering a harmonious equilibrium within the grid. By enabling PV inverters to autonomously adjust their operations based on real-time grid conditions, this algorithm infuses an intelligent responsiveness into the distribution network. This not only mitigates technical anomalies but also augments the efficiency and stability of the grid.

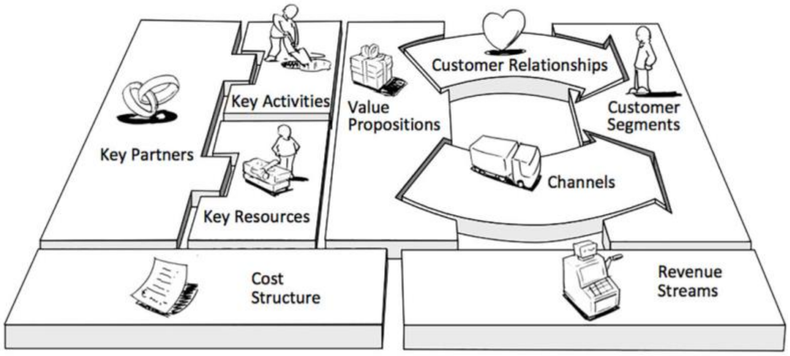
Embedded within the grid orchestration framework, an indirect optimisation-based control algorithm assumes a pivotal role in facilitating the selection of optimal flexibility offers. Aligned with the DSO’s mission to uphold technical requisites and minimise energy costs, this algorithm operates as a sophisticated decision-support system. Through intricate optimisation routines, it systematically evaluates a spectrum of flexibility proposals and assesses their viability against stringent technical criteria. This judicious evaluation culminates in the identification of flexibility offers that seamlessly balance the technical integrity of the grid with the imperative of cost-effectiveness, thereby steering the grid towards an optimal equilibrium.

The intricate interplay of technical and economic considerations is encapsulated within a bi-level optimisation model, tailored specifically for local flexibility allocation and dispatch. Operating as a holistic framework, this model empowers the DSO to wield a nuanced approach in harnessing available flexibility from Flexible Service Providers (FSPs) interconnected across the distribution grid. The model's upper level is devoted to meticulously allocating the technically and economically viable flexibility resources sourced from FSPs, optimising their deployment to bolster grid stability. Simultaneously, the model's lower level delineates an optimal pricing mechanism, balancing the interests of both flexibility procurers and FSPs. By intricately intertwining technical feasibility with economic rationality, this bi-level model embodies a harmonised approach to realising grid potential while fostering a symbiotic relationship between stakeholders.

In integrating these cutting-edge algorithms and models, the realm of optimal flexibility allocation and dispatch is significantly augmented. Technical integrity, energy efficiency, and economic pragmatism converge to underpin the resilient and adaptive fabric of modern grid management.

4.3 Value of flexibility

Having understood the needs of the grid and what flexibility can provide to solve these grid issues, it is time to start thinking how to do this in practice. One of the most important things is how to access the various flexibility resources which we have presented several different market solutions for. However, flexibility agreements and markets are primarily designed to cater to a financial value for providing flexibility. Yet, the profitability of providing flexibility services depends on a variety of factors, including, for example, the alternative costs of upholding a resource for providing flexibility services. For an actor such as a property owner who owns HPs, the profitability of providing these HPs for flexibility may be relatively low compared to the risk of jeopardising indoor climate and dissatisfying tenants. In addition, despite increasing flexibility needs in the electric grid, most resource owners are just fine without engaging in flexibility trading. So, beyond understanding how local flexibility resources can be utilised and controlled, we also need to understand what motivates the owners of these resources to leverage them and provide flexibility services to the electricity grid. In a business model language this would apply to the different value propositions that are communicated to the potential customers, see the middle box in the Osterwalder business model canvas in Figure 2.



Adapted from "Business Model Generation", Alexander Osterwalder, Wiley 2012.
www.businessmodelgeneration.com

Figure 2. Osterwalder business model canvas.

Behind these value propositions lies a value logic which need to be connected to the customers desired values. Figure 3 from Brown et al [11] display this connection and add a third dimension of governance.

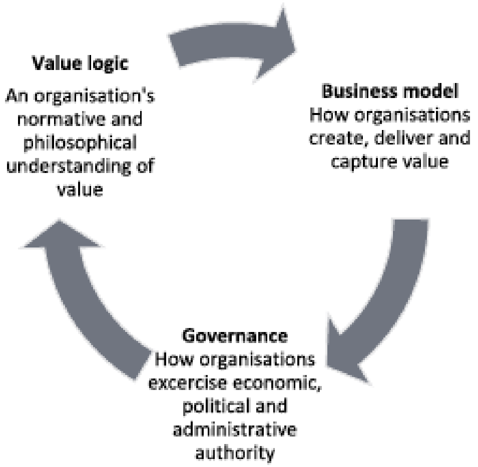


Figure 3. The relationship between, business models, governance and value logics.

In the FlexiGrid project we dug deeper into the underlying value logics that potentially can include or exclude a flexibility resource from being utilised on the grid and found that despite potentially high alternative costs and low or uncertain financial benefits, some actors still choose to participate in flexibility trading because they believe that other values are realised. Hence, engaging in providing flexibility services to the electricity grid can feel rewarding for actors, as they can contribute to renewable energy production, energy resilience and social benefits. To leverage actors who choose to participate in a flexibility market, we therefore developed a value model highlighting the motivational factors actors have for providing flexibility services to the electricity grid. This value model can be used as a departure for developing new and most likely cross sectoral value models.

4.3.1. Value model for flexibility resources

In essence, actors are driven by different value ideals. Owners of one and the same type of flexibility resource can thus have different reasons for engaging in flexibility services for the electricity grid. In the FlexiGrid project we identified four categories of actors owning flexibility resources: commercial, household, community and public[1]. Among these actors, many different drivers were found and in the value model they are divided into an inside focus and an outside focus.
With an outside focus, resource owners tend to engage in flexibility services for realising values that are connected to improving or supporting the energy system and values relating to social empowerment and justice. The following values and drivers are typical for an outside focus (Table 2).

Table 2. Outside focused values and drivers for utilising resources as flexibility services

Value	***Driver***
Urbanisation	Combating energy congestion allowing for regional development
Sustainability	Combating climate change
Sufficiency	Prudent use of resources

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[1] As we deliberately excluded flexibility resources such as hydropower and district heating systems from this study, energy companies are not included among these categories of actors.

Robustness	Strengthening the energy system
Empowerment	Take ownership of the situation
Responsibility	Consequences for others
Benevolence	Fairness of distribution of costs and benefits between groups
Inspirational	Encourage others to become engaged

In contrast, with an inside focus, some flexibility resource owners tend to prioritise profitability and control, and values relating to build identity and image in sustainability transitions. The following themes are typically for an inside focus (Table 3).

Table 3. Inside focused values and drivers for utilising resources as flexibility services.

Value	***Driver***
Identity	Strengthen the self-perception
Predictability	Reduced uncertainty
Frontrunner	Take leadership and act as an influencer
Sharing	Reducing own responsibility and risk exposure
Growth	Enabled increased energy use
Profitability	Increased income or reduced costs
Self-sufficiency	Energy independence

It is worth noting that these categories are not mutually exclusive – what one actor may perceive as beneficial for its own can also be considered a value for others. For example, a general market expansion is often seen as beneficial from both an internal and external perspective. However, actors typically tend to prioritise what is most important to them along these two categories. In Table 4, we summarise how each owner category tend to prioritise values associated with providing flexibility services.

Table 4. Prioritised values for providing flexibility services in each owner category.

Owner category	***Commercial***	***Household***	***Community***	***Public***
Focus				
Outside focus	• Responsibility	• Sustainability • Benevolence	• Sustainability • Sufficiency • Empowerment	• Urbanisation • Sustainability • Robustness • Empowerment • Inspirational
Inside focus	• Profitability • Growth • Frontrunner • Predictability	• Self-sufficiency • Sharing	• Sharing • Identity	• Frontrunner • Identity

To illustrate what role different prioritised values can play let us consider two different actors, a public school, and a private property owner. Both have decided to make available their HPs for flexibility services. The public school has decided to engage in flexibility services because they find it important to support climate mitigation and regional energy system benefits. They also want to inspire others to do the same. The private property owner, on the other hand, has decided to engage in flexibility services because they find it important to enhance their buildings environmental performance. The property owner also wants to demonstrate to the tenants that they take environmental responsibility and be recognised as a frontrunner in sustainable transitions.

This example shows that different owners of one and the same type of flexibility resource, in this case HPs, can have different reasons for engaging in flexibility services for the electricity grid. The school is primarily driven by values associated to an outside focus, while the private property owner, in our example, is driven by an inside focus. Despite this, many flexibility resources, such as HPs in buildings, are often regarded as one single type of flexibility resource with all its technical possibilities and obstacles.

To summarise, understanding the variation in the different drivers that motivate actors to provide flexibility services to the electricity grid is as crucial to consider as the technical aspects when designing an attractive value proposition. Adding non-financial values to the financial benefits can attract more actors to engage in the flexibility market. To develop attractive value propositions that encourage actors to engage in the flexibility market, there are thus three key questions (also found in the BM canvas) that need to be considered:

(1) What type of actor is addressed?
(2) What type of value proposition would encourage this actor to engage in the flexibility market?
(3) What key partner(s) do we need to collaborate with to provide this value proposition?

With the help of the above tables, it should be possible to develop attractive value propositions, considering the three questions.

4.4 Roles, responsibilities, and regulation

Following assessment and evaluation of the need for flexibility, the amount of flexibility available and the potential value of flexibility, it is important to identify the options that are possible within current regulation and legislation. Areas to consider include roles, responsibilities and relevant regulations, which are discussed further, below.

4.4.1 Roles and responsibilities [5]

There are different actors with different roles and responsibilities in the local markets. Understanding the roles and responsibilities of these actors and their business models play an important role in a better mechanism design and a more successful implementation. In this section, the potential stakeholders and their roles are presented. Moreover, to initiate the work on the business models, the potential related cost and revenue streams of the DSOs, as one of the main stakeholders in the local markets, are discussed.

These potential stakeholders in the local markets include DSOs, aggregators, market operator, balance responsible parties, and end-users (prosumers, passive, or responsive). The roles and responsibilities of these actors may be slightly different in different market designs. The roles and responsibilities of these are explained below.

- Balance responsible party (BRP): also known as retailers and load-serving-entities. A BRP is an entity which serves in the electricity market as a representative for a certain and predefined group of loads. The BRP forecasts the consumption size of its constituents, to be incorporated in the operation optimisation plans. In the likely scenario where the actual consumption size deviates from the forecasted amount, the BRP is responsible to correct the deviation by filling the energy deficit / selling the energy surplus through bilateral agreements, or pay penalties to cover this deviation. The BRP can represent any type and number of customers, i.e., passive non-responsive consumers, responsive consumers, and prosumers. When BRPs detect a deviation between their load forecast and actual load, BRPs may procure flexibility from other BRPs, aggregators or small sized DERs.

- Aggregators: An entity which represents a large number of responsive consumers and/or prosumers. Aggregators acquire and consolidate flexibility from small consumers and prosumers to sell it in the electricity market. The aggregator negotiates on behalf of its constituents to trade flexibility or even energy. The aggregator issues commands to its subscribers (responsive consumers and prosumers) to adjust their energy levels exchange, such that the aggregated portfolio delivers the flexibility agreements held by the aggregator. Aggregators can act as BRPs for their clients.

- DSO: The authority which owns the distribution grid and holds the responsibility to preserve the grid by conducting the necessary maintenance, making expansion and reinforcement projects, and operating the grid components such as on load tap changers, line-drop compensators and capacitor banks. The DSO procures flexibility from other stakeholders for the purpose of resolving congestions and deferring network investments.

- Market operator: The entity which applies the market mechanisms, acting as the auctioneer in different auctions. In classical power systems, this role was assumed by the grid operator itself. However, future decentralised markets may allow for operators of different grid-levels or regions to compete for flexibility, therefore, it becomes necessary for a 3rd non-partisan entity to take this role.

From the entities defined above, the building-blocks and end-users in the distribution system can be classified into three types:

- Prosumers: end-users and customers who have generation sources in excess of their own consumption size, such that they are able to inject some energy into the grid. Prosumers may also own energy storage devices such that they can benefit from differences in electricity prices, or demand on flexibility. Prosumers can participate directly in the peer-to-peer market, or under the umbrella of an aggregator in any market.

- Responsive consumers: consumers who adjust their consumption level in response to price signals, or command signals to fulfil their commitment and subscription to an incentive program. Examples include rescheduling the charging of EVs or rescheduling some intermittent loads such as washing machines and cookers. Such responsive consumers can participate in peer-to-peer markets as buyers of energy, or sellers of up-flexibility. They can also participate under the umbrella of an aggregator in any market.

- Passive consumers: classical end-users who neither react to any price signals, nor flexibility requests, or inject positive energy into the grid, either. Such consumers choose to forfeit the benefits of engaging in such market interactions, at the cost of paying a fixed above-average tariff. Passive consumers are treated as fixed or inelastic load, and do not engage in any trades.

4.4.2 Regulations

The landscape of LFMs hinges on a decisive factor - the legislative framework established at the EU level. Currently, a notable void exists in regulations governing LFMs, a deficiency that looms as a significant impediment. The paramount goal in crafting these markets is to engender trading rules that foster healthy competition, thwart market power abuse, and ensure equitable trading practices. While fundamental principles can be outlined at the EU level, the nuanced regulatory tapestry concerning flexibility access and utilisation should be calibrated to reflect distinct national norms within Member States. A judicious balance must be struck, mindful that overly intricate regulations could stifle the innovation vital for the evolution of LFMs.

On one trajectory, establishing overarching principles either at the EU or national level may streamline access to flexible assets, enhance market liquidity, and uphold the core tenets of non-discrimination and fairness intrinsic to EU electricity market legislation. The anticipation of relatively robust EU rules is spurred by the diverse market structures that pervade the EU's member nations. However, the potency of the regulatory framework hinges on its completeness, encompassing multifaceted dimensions rather than omitting certain facets prematurely. These regulations will inevitably evolve over time, mirroring the maturation of the LFMs.

In this landscape, DSOs emerge as pivotal stakeholders, both procurers and purchasers of flexibility provisions. Simultaneously, their status as regulated monopolies underscores the need for meticulous scrutiny. A delicate equilibrium must be maintained, ensuring that DSO activities neither impede competition nor distort the market's equilibrium. Striking this balance is imperative to preserve fair market dynamics and equitable opportunities for all participants.

EU legislation, in its evolutionary trajectory, is poised to accommodate not just emerging actors - aggregators, citizen energy communities, and market operators - but also to redefine roles held by established entities such as DSOs and BRPs. Anchoring flexibility product and service design within the framework of established electricity markets, like the wholesale and balancing markets, is a logical step. Yet, future regulations must mirror the distinctiveness of these flexibility-driven offerings and their underlying objectives. This underscores the imperative for well-regulated contractual agreements, transparent bidding processes, streamlined billing, and efficient market settlements.

As the LFM matures, robust infrastructure serves as its bedrock. A robust smart metering ecosystem and accessible energy storage solutions are instrumental in bolstering the market's evolutionary trajectory. Equally critical is the underpinning of data exchange and communication, marked by sufficiency and stringent data security aligned with EU directives to safeguard customer interests.

In the realm of LFMs, the regulatory fabric woven by EU legislation is pivotal, sculpting a dynamic landscape that nurtures innovation, promotes equitable opportunities, and ensures the integrity of market dynamics.

4.5 Comparing viable solutions

D6.4 [12] outlines and utilises a qualitative and quantitative assessment framework to assess and compare LFM and LEM. The qualitative assessment includes regulatory, technical, cultural aspects. A recent conference paper [13] takes a step further by including additional methods of accessing flexibility, some of which are outlined in section 3 of this report, in the discussion and assessment. The framework for qualitative comparison can be applied in individual cases and could therefore be utilised by DSOs when trying to establish the best option for including flexibility in the operation of local electricity networks.

In general, the assessment finds that LEMs are more complex and challenging compared to LFMs, particularly from a regulatory aspect. Introducing LEMs would require a complete overhaul of the electricity market, whilst LFMs can be designed to operate within the current framework. Other options, such as bilateral contracts or agreements could be acquired through some kind of market process and could therefore act as a starting point for DSOs accessing flexibility through a market-based approach. If successful, the market can be allowed to mature over time, attracting more actors to participate, and move more towards continuous trade. This process is illustrated in Figure 4 [14].

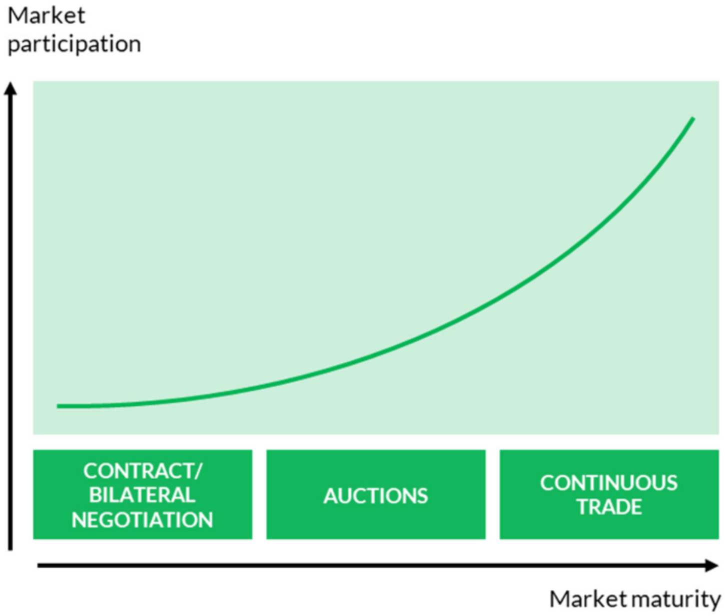

Figure 4. Market participation and maturity.

5. Conclusions and next steps

In culmination, our exploration of LFMs within the FlexiGrid project unveils a multifaceted landscape characterised by dynamic stakeholders, evolving regulatory frameworks, and the promise of resilient energy systems. The significance of these markets reverberates across diverse facets, from grid stability and energy optimisation to consumer empowerment and sustainability. As we draw our current discourse to a close, the following conclusions and next steps emerge as essential guideposts in harnessing the potential of LFMs:

(1) Regulatory foundations and harmonisation

The legislative bedrock at the EU level serves as a foundational pillar, shaping the contours of LFMs. A nuanced approach is paramount, wherein fundamental principles are established at the EU level, while intricate regulations concerning access and utilisation of flexibilities flex to accommodate diverse national norms. Striking this balance ensures an ecosystem that fosters fair competition, upholds non-discrimination, and drives innovation.

(2) Stakeholder symbiosis and collaboration

The ecosystem of LFMs thrives on collaboration among an array of stakeholders, from DSOs and aggregators to responsive consumers and prosumers. Nurturing a symbiotic relationship among these entities is indispensable. Transparency, equity, and a vigilant regulatory eye ensure that DSOs, while being key flexibility purchasers, do not unduly distort market dynamics.

(3) Innovation and flexibility design

Flexibility, the cornerstone of these markets, necessitates careful design that reflects the uniqueness of its offerings and the broader energy landscape. Adapting the design of flexibility products and services to align with existing electricity markets, while acknowledging their distinctive attributes, forms a strategic approach. This approach catalyses a market ecosystem capable of accommodating emerging actors and fostering seamless transactions.

(4) Infrastructure and data security imperatives

As LFMs burgeon, robust infrastructure underpins their viability. Smart metering systems and accessible energy storage solutions emerge as crucial enablers, amplifying market potential. Alongside, the seamless exchange of data and communication must be fortified, adhering to stringent EU data security protocols to ensure customer protection.

(5) Next steps

With these conclusions as our compass, the next steps on the journey of LFMs beckon. Collaborative efforts at the EU and national levels to establish comprehensive regulatory frameworks remain pivotal. Nurturing innovation and engaging stakeholders in shaping market dynamics are imperative in realising the full potential of these markets. Additionally, investments in infrastructure, particularly smart metering systems and energy storage solutions, are poised to be catalysts in steering these markets toward maturation.

Identifying the appropriate solution for individual DSOs will require individual assessment to outline and specify the requirements and optimal solution given each particular circumstance.

Ultimately, our exploration within the FlexiGrid project lays the groundwork for a future marked by adaptable energy systems, empowered consumers, and sustainable energy landscapes. The road ahead is illuminated by the promise of LFMs, guided by regulatory wisdom, stakeholder collaboration, and the unwavering pursuit of energy efficiency and resilience.

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