Lecture Notes in Energy 93

Miadreza Shafie-khah
Amin Shokri Gazafroudi *Editors*

Trading in Local Energy Markets and Energy Communities

Concepts, Structures and Technologies

Springer

Lecture Notes in Energy

Volume 93

Lecture Notes in Energy (LNE) is a series that reports on new developments in the study of energy: from science and engineering to the analysis of energy policy. The series' scope includes but is not limited to, renewable and green energy, nuclear, fossil fuels and carbon capture, energy systems, energy storage and harvesting, batteries and fuel cells, power systems, energy efficiency, energy in buildings, energy policy, as well as energy-related topics in economics, management and transportation. Books published in LNE are original and timely and bridge between advanced textbooks and the forefront of research. Readers of LNE include postgraduate students and non-specialist researchers wishing to gain an accessible introduction to a field of research as well as professionals and researchers with a need for an up-to-date reference book on a well-defined topic. The series publishes single- and multi-authored volumes as well as advanced textbooks.

Indexed in Scopus and EI Compendex The Springer Energy board welcomes your book proposal. Please get in touch with the series via Anthony Doyle, Executive Editor, Springer (anthony.doyle@springer.com)

Miadreza Shafie-khah · Amin Shokri Gazafroudi
Editors

Trading in Local Energy Markets and Energy Communities

Concepts, Structures and Technologies

Springer

Editors
Miadreza Shafie-khah
University of Vaasa
Vaasa, Finland

Amin Shokri Gazafroudi
Stromdao GmbH
Mauer, Germany

ISSN 2195-1284 ISSN 2195-1292 (electronic)
Lecture Notes in Energy
ISBN 978-3-031-21401-1 ISBN 978-3-031-21402-8 (eBook)
https://doi.org/10.1007/978-3-031-21402-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Local Energy Markets: From Concepts to Reality

Scot Wheeler, Filiberto Fele, Masaō Ashtine, Thomas Morstyn, David Wallom, and Malcolm McCulloch

1 Introduction

As nations seek to rapidly decarbonise the energy sector to meet national decarbonisation targets, electricity networks are seeing a radical transformation in how they operate, particularly at the local level or 'grid-edge'. Local Energy Markets (LEMs) that facilitate the transaction of power system services between network stakeholders are envisioned as a mechanism to encourage and coordinate active participation within a Smart Local Energy System (SLES) (Charbonnier et al. 2022; Council of European Energy Regulators 2017).

The widespread electrification of the heating and transport sectors, and the increase in decentralised generation technologies, is leading to a dramatic increase in the number of Distributed Energy Resources (DERs). Digitalisation and the growth of smart devices in homes and businesses allow traditionally inflexible primary energy demands to become controllable and therefore flexible.

Scot Wheeler, Filiberto Fele and Masaō Ashtine contributed equally to this work.

S. Wheeler (✉) · F. Fele · M. Ashtine · D. Wallom · M. McCulloch
Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, United Kingdom
e-mail: scot.wheeler@eng.ox.ac.uk

F. Fele
e-mail: filiberto.fele@eng.ox.ac.uk

M. Ashtine
e-mail: masao.ashtine@eng.ox.ac.uk

D. Wallom
e-mail: david.wallom@eng.ox.ac.uk

M. McCulloch
e-mail: malcolm.mcculloch@eng.ox.ac.uk

T. Morstyn
School of Engineering, University of Edinburgh, Robert Stevenson Road, Edinburgh EH9 3FB, United Kingdom
e-mail: thomas.morstyn@ed.ac.uk

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_1

Many local and global benefits can be achieved through the *coordination* of DERs. These include: revenue stacking for DERs, reduced bills, better utilisation of network (contracted) capacity, voltage and network constraints management, reduced energy transport, avoidance (or deferral) of infrastructure upgrades, and system balancing. Most importantly, coordination and cooperation of DERs can yield environmental gains by supporting the penetration of renewable generation, and facilitate social cohesion in the process (Abbas and Chowdhury 2021; Charbonnier et al. 2022; Eid et al. 2016; Pumphrey et al. 2020). Studies on the impact of flexibility and SLES deployment across the national GB system estimate between £1.1bn/yr and £5bn/yr, on the order of 5% of the total annualised system cost (Aunedi et al. 2022; Piclo et al. 2022).

Whilst many smart DER technologies and platforms already exist at high technology readiness level (TRL), whole system integration and demonstration within real-world markets remains limited. The latter require unique sets of stakeholders and communities willing and capable of working together within new and unknown market environments. LEMs require coordination of technology and people: this entails not just economic and technical interaction, but the fostering of legal, digital, data, regulatory and social relationships in the context of energy systems.

This chapter discusses the techno-social learning outputs gained from transforming LEM concepts into real-world implementation through the SLES demonstrator project, Project LEO (Local Energy Oxfordshire) henceforth referred to simply as LEO, based in Oxfordshire, United Kingdom (UK). While some of the activities within LEO are specific to the technical, social and regulatory energy landscape in the UK, many of the concepts are reflected in local energy transitions happening around the globe.

LEO is one of the most ambitious and holistic smart grid trials ever conducted in the UK. Part funded by the Industrial Strategy Challenge Fund's 'Prospering from the Energy Revolution' (PFER) fund (UK Research and Innovation (UKRI) 2022), LEO seeks to understand how new LEMs and improved local engagement can unlock additional societal, financial and environmental value for households, businesses and communities provided by a smarter, more flexible, electricity system (Project LEO 2018). LEO brings together an exceptional set of system stakeholders from the energy industry, local government, community organisations, and academia. By mimicking the requirements of the future electricity system LEO is building an evidence base that will inform future market design.

LEO operates in parallel to the TRANSITION project, led by Scottish and Southern Electricity Networks (SSEN) and funded by the Government's energy regulator in Great Britain, Ofgem (Scottish and Southern Energy Networks (SSEN) 2022). TRANSITION is designing and implementing trials that support the transition from the role of Distribution Network Operator (DNO) to that of Distribution System Operator (DSO). While the exact model of a DSO is still to be agreed by the industry, it reflects the move towards the 'smart-grid' which delivers additional data, monitoring and control systems at the local network level to enable bi-directional energy flow creating a more active and customer led flexible network while maintaining safety and reliability; this is in contrast to traditional DNO activities which largely focuses on infrastructure development and maintenance.

This chapter is organised into two main parts. Section 2 discusses core concepts of LEMs and how they relate to the market designed within Project LEO. Section 3 discusses how these LEM concepts were implemented in a real-world demonstrator project, the agile process developed to manage this, and a discussion around some of the key challenges faced. Finally, conclusions are drawn and a set of recommendations are made.

2 Concepts

LEMs are emerging over alternatives such as direct centralised control or network reinforcement as the favoured mechanism for the coordination of potentially millions of flexible DERs for better network utilisation and local socio-economic and environmental benefit (Council of European Energy Regulators 2017). This section describes some of the key concepts behind LEMs, particularly for the facilitation of local flexibility services within communities and with network operators. Firstly we describe the drivers behind LEMs and the challenges in enabling the 'small and many' to participate. Next we discuss the need for flexibility services, which are important and what opportunities exist to stack revenue streams through integrated markets. Then we introduce the concept of fair and equitable markets before finally discussing the data and digitalisation requirements that are needed to enable LEMs to operate successfully.

2.1 Local Energy Markets: The Main Drivers

Driven by cost reduction of small-scale renewable generation and energy storage, and the electrification of transport and heating/cooling demand impulsed by the *net zero emissions* goal, the electricity sector is becoming more decentralised and local in nature. As the aforementioned technologies populate the edge of the network, grid operators face growing concern with the reliability and resilience of the existing distribution infrastructure.

To ease the deployment of this new fleet of generation assets and loads, a consortium of European energy regulators recognised four mechanisms for enabling grid support from generation and/or demand flexibility in the distribution network (Council of European Energy Regulators 2017): rules based approach, network tariffs, connection agreements, and market based procurement. Within the latter, LEMs have been receiving particular attention as they allow for a competitive service provision from DERs and guarantee the necessary degree of decentralisation (Lezama et al. 2019; Schittekatte and Meeus 2020).

Flexibility can facilitate the penetration of low carbon generation, reduce the effective cost of electricity and its transportation, and accelerate the connection time for new demand and/or generation projects. Supported by the increasing desire and commitment from consumers and communities to cut energy expenditure and associated carbon emissions, a number of pilot projects are currently operating towards the incorporation of DERs in operational energy markets; besides Project LEO, see for example EcoGrid 2.0 (Denmark) (Heinrich et al. 2020), EnergyVille (Belgium),[1] and the various initiatives backed by the USEF foundation across Europe.[2] Important challenges transpire from these trials. In particular, limited local resources and expertise can prevent many potential DERs playing an active role in these markets. It is far from clear how to address the lack of detailed information on (let alone control of) each DER's output. However, this detail is essential to distillate the *value* of their service, on which commercial agreements for the exchange of flexibility services need to be based.

To leverage the population of DERs in impulsing the transition to a smart and sustainable energy system, it is therefore important to steer the design of LEMs in the right direction in a timely manner. In the following section, we discuss in more detail the flexibility products that have emerged to support the aforementioned targets.

2.2 Flexibility—What Services are Important?

In a nutshell, flexibility services consist of (i) a temporary change in the demand or generation profile, or a storage charge/discharge operation, carried out upon request, or (ii) capacity trading, where grid users exchange their contracted import/export rights to temporarily exceed their power limits. Through LEMs, these become a commodity underpinning a more cost-efficient and sustainable network operation. Flexibility services are mainly utilised by:

- The Energy System Operator (ESO) in balancing the electricity system in real-time, e.g., frequency services to manage the imbalance between the level of national demand and the aggregate level of generation.
- The DSO in managing constraints and congestion in the distribution network. The need for this flexibility typically arises as part of the DNO tasks, due the fact that distribution constraints are not adequately taken into account in the existing wholesale and balancing markets (Kok et al. 2019; Schittekatte and Meeus 2020). These services can help prevent the development of a fault on the local network or assist in reinstating the network following a fault. In the long term, the DSO can also leverage flexibility services to avoid investment in new equipment, enable the connection of more renewables to connect to the network and thus support the decarbonisation of heat and transport.

[1] EnergyVille website: https://www.energyville.be/.

[2] USEF website: https://www.usef.energy/implementations/.

- Two or more users establishing a bilateral contract, e.g., trading import and export capacity between sites to enable increased generation or demand in the local area, circumventing lack of infrastructural capacity that would delay (or increase the cost of) development.
- One or more users managing their own price risk behind the meter, e.g., reducing demand when electricity prices are high.

2.2.1 Flexibility Products

Notable products that are procured in LEMs by the ESO are *balancing mechanism*, *dynamic containment* and *short term operating reserve*, dedicated to settling imbalances; *capacity market*, for peak load management; *Optional Downwards Flexibility Management*, developed to cope with exceptionally low demand on the network (as experienced during the COVID-19 pandemic).

With regards to DSO-procured services, the industry has highlighted four relevant flexibility products to manage local congestion and network maintenance (Energy Networks Association 2020a):

- *Sustain* (season ahead, week ahead or day ahead notice): a change in demand or generation over a defined time period to prevent a network going beyond its firm capacity; while this service is mainly used to ease the stress on grid components in correspondence with predictable load peaks, it is also employed in the case of an excess of local generation, producing a too high reverse flow.
- *Secure*, whereby the DNO procures the ability to access a pre-agreed change in input or output based on network conditions; although this service can be procured with large advance, it is designed to respond to *pre-fault* conditions (e.g., to avoid a cascading failure); as such, the service provider must be capable of responding with short notice (∼4-h notice for planned maintenance).
- *Dynamic* (30-min notice), whereby the DNO procures the ability to access an agreed change in output following a network failure (*post-fault*); this service is designed to relieve the stress on the network while the system is being restored to normal operation.
- *Restore*: following a loss of supply, the DNO instructs a utility provider to either remain off supply, or to reconnect with lower demand, or to reconnect and supply generation to support increased and faster load restoration under depleted network conditions.

Peer-to-peer (P2P) services differ conceptually from the aforementioned ones in that they transcend the operational boundaries of DNOs into those of DSOs. In particular, while P2P services are typically defined as bilateral contracts between independent parties (network customers, albeit subject to the DSO's approval), they do contribute to a virtual expansion of the local network capacity, and in the long term, to deferral of infrastructure maintenance and/or upgrade cost (Klyapovskiy et al. 2019; Spiliotis et al. 2016). Notable examples of P2P services are:

- *Exceeding maximum import/export capacity*: the maximum import (export) capacity is the upper limit on the total load (generation) from a given customer. These limits are established as part of contractual agreement with the network operator. One network customer (either generator or load) can temporarily restrict its power allowance and sell this nominal difference to another party so they can increase their power exchange by the same amount. Typically, it is required that the partners are connected at the same point of the grid (e.g., primary or secondary substation).
- *Offsetting*: This service consists in matching local increase in demand with local increase in generation at an agreed time (or a decrease in generation (load) with an increase in generation (load) elsewhere). This produces a 'net zero' change, cancelling out the impact on the network and allowing more energy to be generated and used.

Among the plethora of possible definitions—and variations thereof, tailored to specific system hierarchy—of flexibility products, there is still a debate over their standardisation. Indeed, a major argument in favour of it is the attainment of price transparency and a sufficient level of liquidity in the markets. Furthermore, a standard implementation of the requested services can potentially facilitate the coordination between ESO and DSOs, and among different DSOs that procure these services over the same platform (see, for example, the Piclo Flex market platform involving all DSOs operating in the UK (Stanley et al. 2019)).

However, product standardisation may conflict with the specific needs of DSOs, which may vary drastically from context to context. Moreover, a market based on a standardised definition of flexibility will make it more difficult to distinguish—and accordingly reward—the offers from the various providers. For example, the emissions associated with the delivery might not be considered among the nominal features of a standard flexibility service, therefore missing the opportunity of incentivising offers prioritising this factor (Schittekatte and Meeus 2020).

2.2.2 Energy Versus Power

A fundamental classification regards the way flexibility is quantified, where services are categorised as either *baseline* or *capacity limitation* ones (Heinrich et al. 2021).

In the first case, the flexibility provider is asked (e.g., by the DSO) to deviate from a typical power profile (the so called baseline) to achieve a desired modulation of the grid load. Therefore, baseline services are akin to *energy* trades in existing wholesale (and other ESO-procured) markets. However, important challenges hamper the quantification of a baseline: in fact, the typical population of customers in the distribution network does not consist of dispatchable assets, and as a consequence the definition of a baseline services has to rely necessarily on an estimated reference power profile.

In the second case, the flexibility service is directly defined as an import/export cap on the asset's exchange of *power* with the grid. Clearly, the latter method can benefit from a much straightforward implementation, as the service definition relies on an absolute value (the capacity limit) versus a relative one (the baseline). Nonetheless, while in theory both concepts can yield equivalent outcomes, there is no clear-cut preference in the observed practice of LEMs so far, where the choice appears to be context-dependent. We will discuss this matter further in latter sections; for more details, we refer the reader to (Energy Networks Association (ENA) 2022; Rossetto 2018; Ziras et al. 2021).

We conclude with a perspective from a lower layer of the grid operation. The introduction of real-time metering has driven a transition from energy-oriented billing (e.g., based on energy generated or consumed in a half hour) to power-oriented (based on energy generated or consumed at intervals of minutes, or fractions of them). Settlement periods of the order of a few minutes—now technically possible—can transform how markets operate, as well as the landscape of exchanged products and services.

2.3 Enabling the Small and Many: Routes to Market

Delivering net zero carbon targets will require a transformation in the scale of active participation at the local level, using flexibility within the low voltage network from end users: the grid edge (Origami Energy, The Low Carbon Hub 2021). This will create opportunities to realise the currently dormant potential of millions of DERs in small and medium enterprises, public organisations and domestic premises to support the flexibility needs of the grid. These opportunities will, in turn, support the development of low carbon technologies (LCTs) and help the process of electrification of major infrastructures and the penetration of renewable generation. To enable the participation of DERs in flexibility markets and exploit their full potential in the delivery of the net zero targets, a number of challenges must be resolved. Among these are the attainment of societal participation and an attractive and fair commercial environment (Tushar et al. 2019). Underpinning both is the difficulty of estimating the true value of flexibility: in all markets currently in operation, the rewards to flexibility providers only partially reflect the benefits delivered to the whole system.

2.3.1 Technical Challenges

The technical challenges amount to the DER controllability (i.e., capability of regulating the power input/output and interfacing with market platform), and to the verification of the service delivery (by, e.g., dedicated physical metering or numerical data-based disaggregation methods).

The majority of households are expected to be equipped with smart appliances by the end of the next two decades, facilitating the manipulation and optimisation of the energy use. Moreover, manufacturers have embraced the Internet of Things (IoT) paradigm, whereby connectivity is embedded into appliances (Spanó et al. 2015). This shift in industry-standard solutions for automation aligns with the need of monitoring, controlling and coordinating the DERs energy use, and will underpin both the aggregated delivery of flexibility and its formal verification (Azizi et al. 2022). Nonetheless, to accommodate the number, geographical spread and heterogeneity of DERs, a distributed hierarchy will need to be in place, ranging from households to district, regional and national levels—thus spanning both the grid's distribution and transmission levels. The coordination across layers can be supervised by the DSO in collaboration with the ESO; alternatively, this can be provided by a third-party coordinator or supplier of bundled services to the ESO/DSO in a secure and reliable way (Energy Networks Association 2018).

Another challenge is associated with minimum flexibility requirements, typically set in order to participate in the LEMs. While this varies by market, minimum levels considered in currently operating flexibility markets exclude the vast majority of potential providers from participating (unless they can combine their flexibility with others). Further specifications are typically set on response time (from receipt of a utilisation instruction) and on ramping time (once a utilisation instruction becomes active), minimum sustainable duration period for the flexibility service, and point of connection to the local grid.

2.3.2 Regulatory Challenges

These challenges relate to the regulations on the interoperability of small-scale DERs and the grid at distribution level. New standards can be imposed from governmental and industrial actions to attain attractive financial margins for each DER owner, by reducing the entry cost to flexibility markets and facilitating the participation to smaller scale DERs. In particular, communities should be enabled to provide their members a fair access to flexibility, and to interact with the network as a collective with low transaction costs. Universal standards also help ensure interoperability of hardware and software to maximise ease of integration.

In working in synergy with communities, local authorities will be key to ensuring that flexibility is fairly rewarded. It is important to create a framework that unlocks the contribution of the population of small-scale DERs towards a decarbonised and secure energy supply, where incentives are distributed in a way that encourages further investment in other LCTs. At the same time, the vital role that energy efficiency plays in delivering the net zero targets should be recognised and considered on parity with other LCTs. Facilitating upgrades on the existing housing stock has indeed a clear potential to contribute to the local and national energy system in terms of flexibility at the residential level (Jazaeri et al. 2020).

2.3.3 Commercial and Social Challenges

If reducing barriers to market entry and transaction costs will allow small-scale DERs direct market access, leveraging meaningful flexibility services from these will require a critical mass that can only be achieved by aggregation. Energy communities can support social aggregators who provide collective benefit and mutual sharing of the rewards, while ensuring a reliable and transparent delivery of flexibility. Importantly, communities can alleviate the contractual responsibility of individual owners of DERs, increasing the trust of system operators and promoting the creation of a broader set of flexibility services.

Standard solutions like *direct load control* (DLC) can be used to leverage flexible assets, by explicitly incorporating their scheduling in power flow calculations, whereby decisions about flexibility are driven by grid state (Correa-Florez et al. 2020). This approach relies on the assumption that the DSO and the DER come to an agreement. DLC agreements are commonly reflected in more mature flexibility and aggregation markets involving large industrial and commercial customers; however, they can often exclude real-world scenarios in the public and residential building sectors (Cardoso et al. 2020). Indeed, where public buildings are concerned, key aspects around demand-side response (DSR) for flexibility services raise very different constraints compared to those imposed to providers from the industrial and commercial sectors (Ofgem 2016). These issues include separate asset ownership (key stakeholders may not be decision-makers in an asset's operation), misaligned interests in asset/building management, and privacy constraints that conflict with commercially-sensitive data.

2.4 Integrated Markets

This section considers the interaction of different flexibility services and highlights where revenues can be stacked across different time periods. In current flexibility markets, the value for flexibility paid to the DER does not typically reflect the full benefit delivered to the grid. Analyses carried out in the UK context have revealed that the value offered in some markets is insufficient to attract investment in new capacity as well as flexibility at the levels required, which will put the security of power systems under pressure in the medium term (Scottish and Southern Electricity Networks 2019).

2.4.1 Revenue Streams and Stacked Service Provision

As discussed in Sect. 2.2, the main income streams for flexibility services are made available through ESO- and DSO-procured services, and P2P-type bilateral agreements. Further revenue streams—generally reserved to large-scale DERs—are related with transmission and distribution charge minimisation (see, e.g., National

Grid ESO 2022; Scottish and Southern Electricity Networks 2022a), and direct wholesale trading (possibly through third party aggregators).

In general, however, the estimation of the possible revenue for a given DER is not trivial. This is mainly due to the fact that the reward assigned to a flexibility service can be inherently volatile (this is the case, for example, for the ESO's wholesale trading and balancing mechanism services). Indeed, many externalities—including market liquidity, local grid constraints, weather perturbation on flexibility levels—can affect the LEM's settlement across different layers (Tao et al. 2020; Vespermann et al. 2021). Predicting a nominal price for these services is challenging as the bidding strategy is often determined at the day ahead stage (if not with larger advance, as common with many DSO-procured services, see Sect. 4). In the future, datasets relative to historical flexibility market operations can help in achieving a more precise prediction of the performance of a given DER class (Fele and Margellos 2021). However, the amount and quality of currently available data is insufficient to ensure adequate financial security for the DER manager; this is especially true for specific newly introduced flexibility services in the context of P2P trading. It is worth mentioning that this in turn has implications on the side of the flexibility procurer—hence on the general network performance and reliability—, as it may lack too the necessary information to carry out an optimal selection of providers for the required services.

A number of factors should be considered when determining the business case for determining the viability and enabling DERs to deliver flexibility services:

- the priority assigned to the provision of flexibility services versus the primary purpose of the DER;
- the ability of the DER to deliver *stacked* flexibility services to increase income;
- the operational impact and costs of delivering these services;
- the costs of enabling the DER to deliver flexibility services: this can include equipping the DER with remote monitoring and actuation technology.

The technical ability of a DER to deliver multiple flexibility services at the same time or during adjacent periods, allows the DER owner to bid on a stack of products (or combine them with wholesale trading) and realise a higher price (Energy Networks Association 2020b). The ability of flexibility providers to differentiate their bids depending on whether flexibility is traded locally or centrally is key to the development of sufficiently liquid markets. Indeed, selling at specific grid locations may be risky, since flexibility is typically needed locally only a few hundred hours a year.

For this reason, the availability of a common market platform can bring significant advantages, enabling the maximisation of the scope of flexibility services outside the local network boundaries (Lopes 2021). Establishing an efficient coordination between ESO and DSOs is critical to ensure ESO- and DSO-procured services do not have opposite impacts (e.g., a ESO service creates a constraint locally that triggers procurement of a DSO-service), and finally to enhance the value of flexibility across all layers of the grid (ENTSO-E et al. 2019; Le Cadre et al. 2019). Such a coordination is already possible (at least up to a certain degree) with some of the currently operating flexibility platforms (Schittekatte and Meeus 2020; Stanley et al. 2019).

2.4.2 Challenges Due to Uncertainty on Delivery and Coalitions of DERs

The flexibility output of some classes of DERs may be subject to uncertainty (e.g., some DERs can be highly sensitive to weather). This can have a significant impact on the financial performance of these DERs, unless the markets can offer specific mechanisms to deal with this challenge; see, e.g., Vespermann et al. (2021), Laur et al. (2020). In practice, the value flexibility is paid out on the market decreases as a conservative amount is commonly procured to offset the uncertainty of delivery. Similarly, on the providers' side of the market, aggregators that utilise pools of DERs with low or unreliable flexibility have to factor this risk and contract with more flexibility than needed to avoid contractual penalties. Ultimately, such compensation on both sides can significantly decrease the value of flexibility and could reduce the attractiveness of such markets for new participants.

Establishing cooperative clusters of DERs can help address these issues (Fele et al. 2017; Han et al. 2021; Morstyn et al. 2018). A group of DERs can be used collectively to deliver a flexibility service where some could provide the initial speed of response and initial period of delivery (e.g., a battery which is energy limited and cannot deliver a long duration service) whilst others could either extend the duration or the capacity associated with the service (e.g., an industrial demand process which could not provide the service alone due to significant response delay, a plugged-in EV fleet could be used to fill in gaps in the delivery profile).

2.5 Fair and Equitable Markets

If mass participation within LEMs is a requirement, organisations, communities, and individuals need to engage with LEMs and become active participants (Tushar et al. 2019). Any system considered fair and ethical is more likely to be met with social and political approval and therefore succeed (Fleurbaey et al. 2014). System transitions inevitably lead to winners and losers based on an individual's attributes and ability to participate in the new system (Savelli and Morstyn 2021).

The notion of a *just transition* concerns the overcoming risks of unfairness and leaving the vulnerable behind. It has been acknowledged by many key stakeholders at the centre of the energy transition that energy justice must be applied to the planning, implementation and assessment of any aspect of the transition (Carley and Konisky 2020). Energy justice has three core concepts: *Distributional justice*, ensuring any benefits and burdens are distributed across the population without some receiving an inordinate share or being denied access to participation; *Procedural justice*, ensuring decision-making process is fair, equitable and inclusive to all who may wish to participate; *Recognition justice*, an understanding of historic and ongoing inequalities.

How does this apply to LEMs and smart DERs at the grid edge? The Centre for Sustainable Energy produced a report on this, funded by some UK based DNOs. It concluded that for a market-led approach, interventions from regulators and policy makers will be required to secure inclusive participation and a 'safety-net' for anyone left behind. Whilst market commissioners are unlikely to be able to ensure fairly distributed participation alone, there are steps centred around transparency that will assist in delivering market equity (Centre for Sustainable Energy 2022).

Without starting entirely from a clean slate, energy networks and network users will have inherent non-uniformities, embedded both spatially and temporally, which determine the types of network services that are required to decarbonise in the most cost-effective way. Likewise, participants and DERs will differ in their capability to participate and compete to deliver energy and flexibility services within a market. For example, DERs with a high degree of uncertainty, perhaps due to being heavily weather dependent, or inexperienced market actors, are likely to find it much harder to produce firm capacity forecasts ahead of service periods (particularly season/month ahead) compared to more conventional storage technologies. This could translate to such DERs being underpaid or undervalued in their service offering. Therefore, the design and operation of competitive flexibility markets needs careful consideration and testing to ensure equitable principles are delivered.

It is necessary to make a clear distinction between energy *equity* and *equality*; it is not about offering the same thing, but what is right for the participants' own circumstances to take part. To be an ethical system, it needs to engage participants through honest and transparent communication with the market rules, and clear and understandable benefits of participating. LEO has developed an ethical framework to support the delivery of SLES trials which includes the following principles: (1) Collaborative design, (2) Inclusive offering, (3) Fair distribution of benefits and costs, (4) Minimise risk, (5) Informed consent, (6) Respect and (7) Data fairness (Huggins 2022).

Translating these concepts to a fair and equitable implementation of a LEM has three main components. Firstly, through collaboration itself, the market should be designed with input from multiple stakeholders. This includes energy industry actors, academia, local authorities and representation of community energy groups. The LEM architecture can be adjusted through multiple trial period iterations which allows feedback from participants to be taken on board, and multiple market mechanisms and value propositions to be tested.

Secondly, the LEM should be an open marketplace that can offer multiple access opportunities to local network flexibility, peer-to-peer capacity and energy, and national balancing markets, tailored to specific market actor types or DERs (CGI et al. 2022; Schittekatte and Meeus 2020). Central to this is some form of Neutral Market Facilitator (NMF) platform through which coordination with the DSO is achieved. Crucially, the NMF integrates with third party market platforms, aggregators and other independent intermediaries so bespoke services and value stacking across multiple markets can be offered to meet participants needs (ENTSO-E et al. 2019); this approach is currently followed by Project LEO.

Finally, multiple routes to market should be tested for the DNO-procured flexibility services. These range according to the degree of competition—informed both by market liquidity but also participants' appetite for risk—the length of the ahead-of-time procurement period and the ability to weight bids across availability (£/MW/h paid whether called upon or not) and utilisation (£/MWh paid for the energy delivered). For competitive and liquid market nodes, this includes a fully competitive auction or fixed price contract (fixed price contracts are based slightly below the average competitive market settlement price to reflect extra risk being taken by the DNO) while for non-competitive market nodes, price ceilings are in place. Market stimulation packages (MSPs) offer an alternative route to encourage new DERs and market actors into the market that might require some capital support to become 'flex-ready' (Scottish and Southern Electricity Networks 2022b). Initially, services will be procured in season ahead, week ahead and day ahead auctions but some studies believe continuous market clearing might be more suitable for early LEMs with low levels of liquidity (Kok et al. 2019; Prat et al. 2021).

While these market mechanisms are designed to reduce barriers for a range of participant types, a balance must be struck between multiple offerings versus both the market complexity (that may discourage smaller, non-traditional market participants) and cost of implementation.

2.6 Social Aggregation: The Community Side

One of the pillars supporting the long term sustainability of the future SLES will be the communities of active participants from the grid edge. To ensure social desirability, it is therefore important to align business plans for LEMs with the sustainable development objectives of local communities (Low Carbon Hub 2022; Tushar et al. 2019).

In particular, LEMs should foster the development of new products and services that can enable a smart and sustainable operation of the grid edge, for example, maximising the connection of embedded renewable energy and incentivising the electrification of heat and transport as well as efficiency improvement interventions. Functional LEMs are expected to deliver positive returns on the individuals and organisations that are the fabric of energy communities (Savelli and Morstyn 2021). Through the mediation of *social aggregators*, these can achieve the democratisation of mid-scale DERs ownership (e.g., solar parks, local hydro power plants) and access ad-hoc discounts and feed-in tariffs for community members (Low Carbon Hub and Origami Energy 2021).

Importantly, the social aggregator can provide small-scale DERs with low levels of flexibility a viable access route to LEMs. It can avoid owners needing to understand the market rules, and release them from the burden of participation. The social aggregator can provide market access on a not-for-profit basis using agreed shared-risk principles.

It is worth pointing out that this role requires a certain set of skills to interface with rapidly evolving LEMs. While this might currently lie out of the scope of most currently operating citizen communities, some larger co-operatives are taking action to reach this goal; an example of the latter is the Low Carbon Hub in Oxfordshire, UK, with the creation of the technical (behind the meter, P2P) and commercial (interfacing with external LEMs) aggregation platform *People's Power Station* (Low Carbon Hub 2022).

2.7 Data and Digitalisation

Energy markets and the mere provision of energy services are inextricably tied to the data streams that enable them. Transmission services have always utilised data for grid balancing services, peak management, short-/long-term operating reserves, and for financial settlement within very liquid and competitive markets. However, the role of data at the grid edge is gradually morphing from one of network stability and monitoring, to unlocking greater levels of flexibility as least-regret investments become more attractive in the short-term. Smart systems, which buffer these short-term needs, can only be defined as such when the proper data layers and communication streams are in place for the provision of services that transcend high-level network operations. Data underpin the ability of LEMs and their agents to create local ecosystems for the mutual benefit of all stakeholders involved. The focus of this section will be on the rapidly evolving domain of distribution services, highlighting particular guidance for data management within LEMs and flexibility services.

Net-zero objectives at a national level are futile without structured digitisation at local scales that open networks to increased participation, services, and liquidity. Data innovation and investments play key connections across national-local boundaries and increased data ingestion will accelerate the transition of DNOs to DSOs, in particular, their ability to model and forecast network operations. This has been long recognised by agencies such as ElectraLink which stated that 40% of total renewable electricity generation falls under the regional DNOs, at the grid edge, rather than at the level of the transmission grid—highlighting the importance of increased data transparency at the distribution level (ElectraLink 2016). Flexibility has been a fixture of the energy landscape across the world during the last decade (Lopes 2021), but where local-scale provision from a diverse array of assets is concerned, the grid edge requires significant levels of data investment and governance. Increased connectivity and flexibility demand a level of dynamism whereby assets no longer act in silos, but the network aims for whole system optimisation versus data being used simply for monitoring and network stability.

There is little question on the importance of increased data visibility within networks and the added benefits to LEMs. The grid-edge has already moved beyond any doubt in this regard with homes, generation assets, and transport all becoming much 'smarter' in their collective operations and function (Vigurs et al. 2022). The question then remains around the barriers to connecting rapidly evolving assets within a historically inert grid to accelerate local energy transitions.

Data transparency across the grid however allows networks to better forecast local demand, and subsequently, provide more symbiotic advancements of energy provision.

There are three main bottlenecks which we posit are essential to unlocking the value of data for LEMs. These impingement points are centered around access, management, and validation as described below:

- **Access**: This layer is at the core of data value for network operations within LEMs. Simply put, if data cannot be accessed at levels that match the need of local network services, there will be little to no innovation at this scale. Asset owners and operators need to consider increased data monitoring and storage at the grid edge from where many other services can flow. It is not only the fundamental access to data that is needed, but the access (through both hardware and software) to real-time data streams with appropriate Application Programming Interfaces (APIs) for increased connectivity. Electric vehicle (EV) and vehicle-to-grid (V2G) services for instance will require instantaneous access to network data for decision making, scheduling, and operations. Access cannot be limited to just end-users, but must enable other smart systems that require interfacing with the network. Furthermore, access to long-term data is proving increasingly more important for forecasting and validation. DSR services are another example where real-time communications with assets are required. These services, historically functioning for ESO-procured balancing services in a number of markets in the UK, Europe and the US, must adapt for flexibility at the local level as long-term data are needed to validate services with appropriate levels of forecasting (Rossetto 2018).
- **Management**: Data need to be managed, not only through qualified/automated personnel/systems, but with increasingly standardised methods of privacy protection, aggregation, storage, and metadata. This particular data core is complex across a multi-stakeholder approach to LEMs as each agent within the overall system is aiming to optimise their own data and management needs. However, a critical point of open and standardised data protocols is key to unlocking many data barriers. In the UK, there has been considerable lack of a unified effort amongst DNOs where data management is concerned and standardisation is lacking (Energy Systems Catapult 2021). Many reports by the Energy Systems Catapult (Catapult 2021; Energy Systems Catapult 2021) and EnergyREV (Chitchyan 2021; Maidment et al. 2020; Morris and McArthur 2021; Verba et al. 2022; Vigurs et al. 2022) have touched on these issues to a large degree and it is clear that SLES need to become more open and transparent with data.
- **Validation**: Finally, with the inner two core data layers in place, the right systems are available for the effective validation of local services on the network. Data need to be open (where appropriate for network innovation as seen through projects like

Fig. 1 Three main data cores proposed for supporting flexibility services and local energy markets

OpenLV[3] and Western Power Distribution's (WPD)[4] stewardship in data access and portals), transparent with clear provenance (aggregation, pre-processing treatment, missing data and post-processing cleaning etc.), temporally sufficient with appropriate resolutions to invoke validation at differing scales (high-resolution data are not always needed depending on the application for instance), and of substantial quality to ensure solid footholds of analysis where validation is concerned.

From Fig. 1 we can see the main aspects of data access, management, and validation that are needed to remove barriers for LEMs. These high-level categories are certainly not the boundaries of data concerns within a SLES but highlight key areas of focus. Where access is concerned, the grid edge needs to be 'armed' (a term used to describe the process of readying assets or smart systems to participate in proposed services) to allow for effective bidirectional data streams. Data must shift from access with function of monitoring and case-specific assessment to access for real-time services to enable flexibility and dynamic responses to local markets. Arming of assets retrospectively will demand a high level of resources and DNOs and aggregators must play an increasing role in facilitating this to ensure a level playing field for smaller agents (Scottish and Southern Electricity Networks 2022b).

For management, system-wide standardisation at the utility-scale is needed for data management best practices to filter down at the local levels (Energy Systems Catapult 2021); one can also argue that top-level standardisation needs to be guided by local learnings. Translating these practices to grid edge can be guided by the 15 FAIR (Findable, Accessible, Interoperable, Reusable) data principles (Wilkinson et al.

[3] OpenLV Portal: https://openlv.net/.

[4] Western Power Distribution's Connected Data Portal: https://connecteddata.westernpower.co.uk/.

2016) which are seen as a cross-disciplinary approach to data management. For local flexibility, data and their management systems will play a large role in the automation and scheduling of services (reducing marginal costs), with qualified personnel needed before full system maturation. Management also brings many questions around data custodians and proprietors, particularly for privacy and personal data. As SLESs are effectively 'crowdsourcing' energy data, there needs to be management around the protection of sensitive information.

Validation will require aspects of the data cores listed above but with a further level of specifications to ensure that services and markets benefit from trusted analysis. This data core does not have clearly defined roadblocks as those seen in data access, and issues centre more around the application of data processes in network validation. Thus, moving from access to validation, we see a shift in so-called blockers to more guiding measures for system enabling. For instance, *baselining*, prominent in the literature where domestic DSR application is concerned (Rossetto 2018; Ziras et al. 2021), presents a good use-case to highlight common data issues in validating network services. Where local systems are at play, baselining is an important step in grounding the day-to-day operations of a DER in order to confidently quantify benefits provided to the network during service provision (even before, to schedule said services). Commonly overlooked specifications of data such as the percentage of missing/corrupted values and the overall dataset length (for timeseries data) are often preliminary stumbling blocks for validating flexibility services as statistical and technical limitations are imposed. These issues fare better in low-capacity trading, but when capacities in orders of magnitude far greater are up for financial settlement, data quality cannot be trivialised. Validation is also key to ensure the fair scheduling and settlement of services, limiting data manipulation for commercial gain, and ensuring that reliable assets are rewarded by DSOs in a SLES.

Beyond the main data cores presented here, an increasingly digitised energy system must also have the necessary frameworks to ensure overall system resilience and security. SLES data transfers require communication streams that are not overly-linear in design as to avoid 'weakest-link' points of failure that can disrupt entire services, or in worst-case scenarios, expose the network and users to malicious attacks. Users, asset owners, aggregators, and DSOs all need confidence in the system when many complex business models inherently rely on their functioning. Moving to partially/fully digital systems shifts risk to one where many actors can be disrupted. Data resilience also means that in very liquidated flexibility markets, DSOs have a clear understanding on reliability at the grid edge, leading to better scheduling and frequently successful flexibility services based on critical market reliance indices.

Data need innovative yet standardised management with resilience weaved into all planning. Data, however, must not only consider function with a SLES, but wider system purpose that mutually benefits relevant stakeholders. In the road to robust data structures in SLESs and LEMs, data must also enable fair participation among energy actors to ensure that competitive advantages operate within equitable ecosystems. Though beyond the scope of this chapter, data communications must themselves be held up to net-zero targets where the embodied energy of increased data networks and traffic are assessed to truly achieve 'smart' design.

3 Real-World Experience: Translating Concepts Into Reality

For innovative change to take hold within a system, quickly and at scale, stakeholders and participants need confidence and engagement in the new concepts being proposed. Demonstrator projects test new concepts within real-world environments (or as near as possible to real-world while maintaining the safety and security of customers) to build an evidence base of what works well and uncover the barriers that may restrict acceptance.

In this section, we discuss the trial approach developed for asset participation in LEO market trials, alongside some of the insights (both successes and failures) that have arisen in the first three years of the four-year project. The first phase of trials, called the Minimum Viable System (MVS) trials, focused on initial market design and single asset activation, and ran approximately from month 6 to month 18. The second phase of trials, referred to as the MVS Programme and Smoke Tests, added more structure and complexity to asset trials and began market integration tests, running approximately from months 18 to 32. Finally, the full market trials, which are testing whole system operation across three trial periods, runs through to the end of the project at 48 months. At time of writing (38 months since the start of the project), LEO has completed the first of three full market trial periods.

Project LEO is far more than just a LEM demonstrator project, with a great deal of community engagement, policy and regulatory activity that is beyond the scope of this chapter. Readers are encouraged to visit the LEO website[5] for continuous updates on activity across the whole project.

3.1 *Learn by Doing: The Agile Approach*

LEMs require the local interaction and operation of multiple stakeholders, energy resources, digital platforms, and business models, in new ways not previously demonstrated or necessarily designed for. Due to the nature of a fast-moving energy transition happening in an ever-increasing digital space, we took inspiration from agile approaches (Ghezzi and Cavallo 2020), particularly that of *Lean Startup*—a concept popular with entrepreneurs, allowing for agile innovation of business models through fast feedback loops that have led to 'build-measure-learn' approaches to growing startups (Ries 2011).

At the heart of early LEO trials was MVS, a concept akin to that of the Minimum Viable Product within lean theory; the difference being it is applied to whole-system integration rather than a single component. An MVS should represent the minimum set of participants and processes that are required in order to test a new process or asset use case. In doing so, new value can be identified and confirmed at a small, quick scale, before significant investment in time, money and user relations are committed.

[5] Project LEO website: https://project-leo.co.uk/.

The full *Lean Ecosystem Transition* approach used within LEO is summarised in Fig. 2 and described as follows: The societal need is the technical delivery of flexibility as per the proposed DSO flexibility market (versus current DNO operations). This need inspires a hypothesis, or Theory of Change, as to how best to deliver flexibility; this process could be a modification to an already established procedure or an entirely new one. Hypotheses are translated into trial objectives which lead to MVS trials being run. Through the collection of data during a trial, processes and Key Performance Indices (KPIs) are measured and analysed to enable new learnings to be generated. These can lead to a better understanding of the requirement—which in the extreme case could indicate a false need and therefore the opportunity to stop a particular avenue of exploration—or an adaption of the hypothesis proposed, both of which inform future iterations (Ashtine et al. 2021).

This agile approach was extremely effective in the early stages of the project. It helped break-down the final goal of a very complex (and at that stage mostly unknown) technical system and market process, into more manageable problems and components. A series of MVS trials were run on LEO partners' DERs of varying types (including battery storage, demand side response, micro-hydro generation and vehicle-to-grid). The majority of these DERs had not previously been used for flexibility services or were operated by non-traditional market actors (with little to no experience of flexibility or wider energy market participation). These trials started to identify the capabilities (or lack thereof) of the DERs, digital platforms for monitoring and communication, and market participants; this was crucial to direct the focus of development where it was most required for the market to become operational. The MVSs also provided the use case to begin developing the full end-to-end process for market operation. A set of reports summarising outputs of the early MVS trials are available through the Project LEO website (Origami Energy 2022; Wheeler 2022a, 2022b; Wheeler and Ashtine 2022a, 2022b; Wheeler et al. 2022).

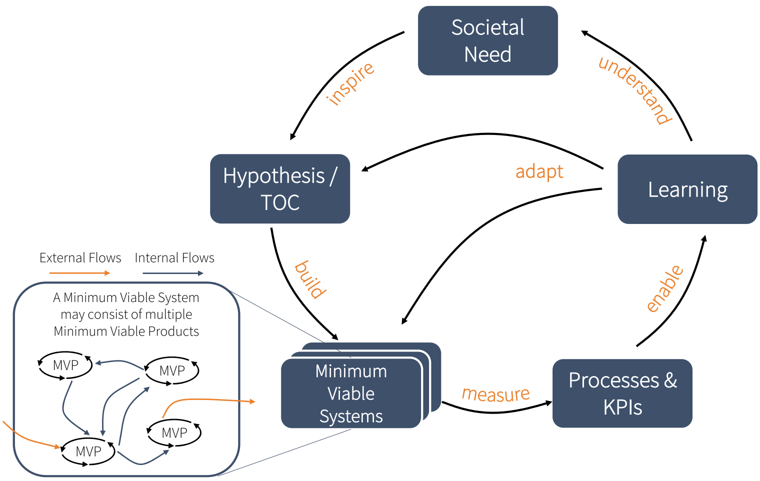


Fig. 2 The lean ecosystem transition approach developed and utilised in project LEO

As the project progressed, several challenges arose with an entirely agile project management approach:

- Firstly, more effort than was initially envisaged was required to enable existing DERs to deliver services in an easily controllable way, and for the project consortium to understand the flexibility services. See Sect. 3.3 for further discussion on this.
- Secondly, some core digital platforms such as the NMF were delayed. While manual proxy workarounds allowed other parts of the end-to-end process to be tested within the wider market context, progress was restricted for other components of the market, particularly external platform integration.
- Thirdly, limited personnel resource and the challenge of assigning responsibility across multi-organisational teams meant the iterative development of key interlinkages between market components and organisations, that are critical to a whole-system approach to LEMs, was hampered. On occasion where partners did take a leading role in developing shared market processes, significant progress could be made in a short period. An example of this is the Commercial MVS run by Origami Energy which tested DER and participant preferences for different time-ahead auctions, the ability to baseline and the settlement processes (Origami Energy 2022).
- Finally, to be compatible with the external audit of deliverables and project monitoring as required by the funding body, time-based milestones were linked strongly with development of high-cost physical DERs. This removed emphasis from the agile development of the digital systems and market mechanisms. However, overall the slightly modified approach described below, led to more frequent trials and an enriched coordinated approach.

What became known within the project as the 'MVS Programme', applies a more classic Waterfall Project Management structure to the MVS trials whereby particular steps must be completed (or at least started) as per a pre-planned timeframe. The MVS Programme was coordinated by Origami Energy and the University of Oxford. The steps themselves describe the objective of the trial and therefore simplify trial design and lead to similar development work across all assets (Wheeler 2022a). The steps broadly increase in service complexity and market integration, but do not strictly need to be executed in sequence; these are described in Table 1. For an experienced asset and market participant, multiple if not all could be achieved in one trial. The result was a much higher frequency of trials being run across all assets with a logical progression of asset capability. However, the programme became very asset centric with less attention on whole system integration or service design within the second year of the project. Following the introduction of the NMF in year three, full market trials are now focusing on whole-system operation of the LEM. The MVS Programme proved itself as a useful approach for enabling new DERs and supporting inexperienced market participants and remains a tool within the project for on-boarding within the market.

Table 1 Key stages within Project LEO's MVS Programme to support enabling new assets and service providers technical participation in the LEM

MVS step	Description
Asset parameters	Through dispatch of the asset, determine the technical characteristics[a] for the asset
Service allocation	Through dispatch of the asset, determine the service allocation per asset
Manual dispatch	A manual dispatch instruction is issued to manually start the asset, resulting in the successful manual delivery of flexibility
Automated dispatch	An automated dispatch instruction (e.g., via a control platform or schedule) is issued to automatically (or remotely) start the asset, resulting in the automated delivery of flexibility
Service test	The technical qualification of the asset. The asset performs the requested flexibility service for the specified time
Availability declarations	The service provider declares asset availability and resulting changes of availability are received by the DSO or market place
Manual service	A manual instruction from the service buyer triggers a manual dispatch to deliver a service, resulting in the manual delivery of the service[b]
Manual service/Automatic delivery	A manual instruction from the service buyer triggers a manual dispatch to deliver a service, resulting in the automated/remote delivery of the service
Semi automated service	A manual instruction from the service buyer triggers an automated dispatch to deliver a service, resulting in the automated/remote delivery of the service
NMF availability	The NMF and other external market platforms are made available
Automated service	An automated instruction from the service buyer triggers an automated dispatch to deliver a service, resulting in the automated/remote delivery of the service
Automated multi-service	An automated instruction from the service buyer triggers an automated dispatch of multiple assets to deliver a service, resulting in the automated/remote delivery of the service within a simulated constraint
Automated multi-service (real constraint)	An automated instruction from the service buyer triggers an automated dispatch of multiple assets to deliver a service, resulting in the automated/remote delivery of the service within a constrained area of the network
Asset monitoring	Data collection from the asset during delivery of a flexibility service test to determine whether the service was delivered as instructed
Network monitoring	Data collection from the network constraint during delivery of a flexibility service test to determine whether the service was delivered as instructed

[a]Eleven service parameters were identified to characterise the technical operation of the asset including: ramp time, minimum and maximum flexibility capacity and time before next use (Wheeler 2022a)
[b]Instruction denotes the message sent from the market to the service provider to deliver a service. Dispatch denotes the instruction sent from the service provider (which could be an aggregator) to the asset to deliver as service. Delivery is the action of the asset during the service window

3.2 Market Process

For a LEM to function successfully, the full end-to-end process and market rules for delivering market services must be well established and understood by all market participants. This extends beyond just the technical delivery of services and includes registration, legal agreements, market operation (including auctions), verification and settlement. Figure 3 shows a simplification of the combined DSO procured and DSO enabled full end-to-end process developed for the LEM being tested within LEO.

Relative timings for each step may differ depending on the particular market service being arranged. *Registration* of the service provider and asset with the DSO and market platforms needs to happen well in advance, between 2 and 6 months before participation. It requires the signing of the Flexibility Services Agreement (FSA), P2P term sheet and platform terms. *Identify Need* (P2P and DSO) can happen season ahead up to the week or day before the service window depending on service and must allow time for the DSO to run Power Flow Analysis (PSA) during the *Trial Pre-approval* stage to ensure no issues may arise on the network.

Requests for services are published on the market platforms alongside potential stimuli packages to encourage or support greater market participation in the *Publish Stimuli and Requests* step. Service providers are then able to *Respond to Request* which—depending on the service type, market liquidity and market competition—may proceed via an auction mechanism or fixed price at the set time-ahead period; currently only season ahead, week ahead or day ahead are being tested. Next there is the *Assess and Qualify* stage where the requester of the service (either DSO or peer) assesses offers before selecting services based on a particular criteria. In the early trials this is simply based on price, but other criteria such as historic reliability and carbon impact will be explored. The provider is notified of selection during the *Select and Notify* step and should be available to deliver the service if instructed.

Following a final *Approval* stage from the DSO and identification of actual flexibility needs, the service provider is *Scheduled and Instructed* to deliver the service. During the service window (step *Deliver and Monitor*), the asset and network are monitored; the DSO has the option to cancel the service delivery at any point if a network issue arises. Finally, the *Verify and Settle* step happens up to 1 month after the service: DER monitoring data must be submitted and compared to a baseline to

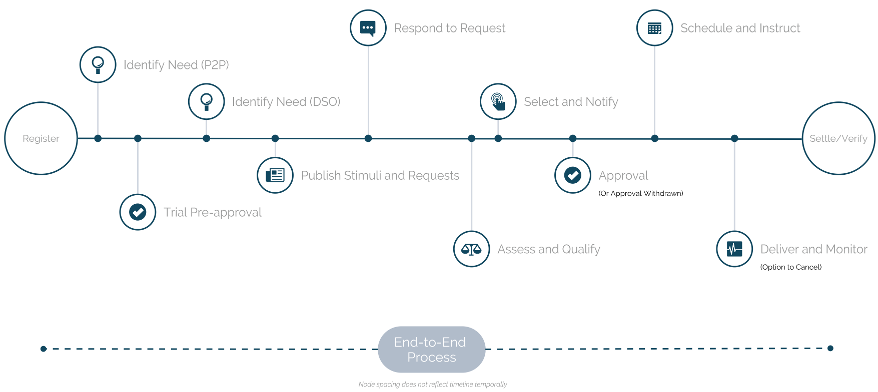


Fig. 3 Main steps in the DSO procured and DSO enabled market End-to-End (E2E) process from asset registration to verification and settlement; the spacing of nodes are for illustration only and do not reflect the relative timescale of events

verify the service was delivered, invoices are raised and the requester of the service pays the service provider.

3.3 Market Readiness

A common theme throughout the first three years of the project has been the higher than expected barriers to enable DERs and DER owners to participate in the market. While some of the challenges have been exasperated by the Covid-19 pandemic which has restricted site visits and forced organisations to operate in a more constrained way, we believe the insights gained will be important in the successful implementation of many future LEMs.

The vast majority of DERs that will participate in the future LEM are yet to be installed and, as such, the opportunity exists to ensure the capability is present at installation stage. However, for a LEM to be successful, it also needs to support existing passive DERs that have little or no experience of flexibility or active participation in an energy system (e.g., a building that can offer DSR); this support can be extended beyond physical energy assets to potential market participants and communities. This has led to the following definition of *Non-traditional DERs* used within the project:

Non-traditional DERs: *Small but numerous assets of any type put forward for market participation by an organisation where energy (including flexibility services) is not already a component of their business activity. It is defined not just by technology but also by the combination of a market actor's core business and previous experience. It should not be considered a clear binary label, rather a scale described by the capability of the asset-actor combination.*

During the first period of the full market trials, two technology types (V2G and fixed lithium-ion battery storage) participated in 69 Sustain–Peak Management (SPM) events scheduled between 15:00 and 19:00, with a total of 540 kWh dispatched. These were operated by two service providers, both of whom had prior experience of the energy sector but only one had prior experience of flexibility markets. Meanwhile, around 30 other organisations were considering future participation or engaged in the early stages of market registration and asset activation process. Some of the barriers highlighted during this time that had greater impact for non-traditional participants are discussed below. Boxed content provides some examples from ongoing work within LEO to support DER participation in and understanding of the market.

DER potential: The first stage towards developing a case for flexibility provision is to establish the amount of capacity available for a single DER or DER portfolio. Without this understanding, service providers cannot gain access to market platforms or MSPs. Doing this accurately can be a complex, time-consuming process requiring expertise on energy generation or use, building control systems and machinery operation (in the case of DSR), historic data, and dynamic models of DER performance. For non-traditional DERs such as commercial/domestic DSR, those with a high degree of variability (e.g., due to weather), or public institutions that may operate over medium to large estates (tens or hundreds of potential DERs), this can be challenging without the knowledge or expertise in-house or the resource to procure external support.

Building Thermal Model

To estimate the potential flexibility provided by shedding the load of the chiller within a local authority's library building over pre-specified time intervals (typically one hour in the afternoon), we trained a thermal dynamics model from dedicated tests conducted during the MVS phase of trials, an example of which is shown in Fig. 4. The thermal dynamics model takes as input the external temperature forecast for the day in which the flexibility delivery is requested, and outputs the estimated zone's temperature trajectory and HVAC system energy expenditure.

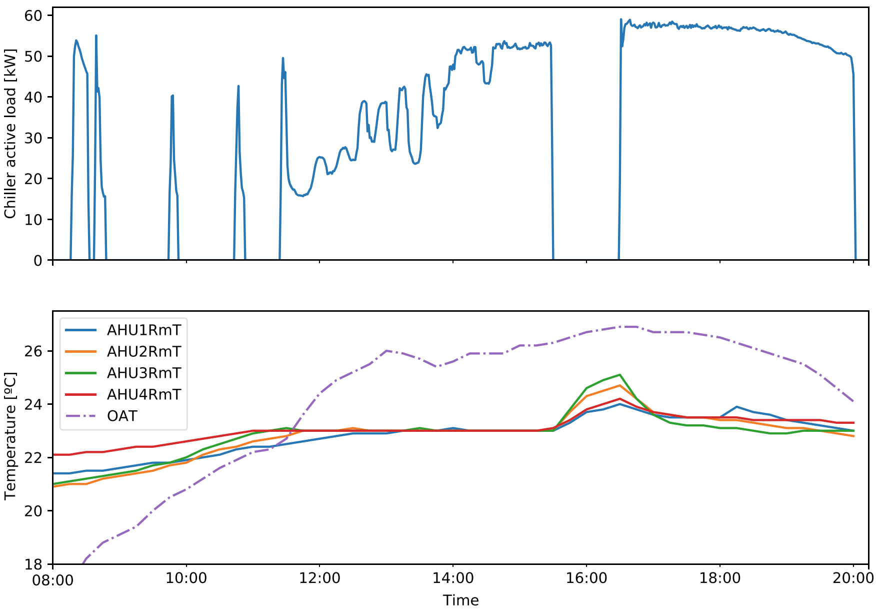


Fig. 4 Flexibility event (chiller load shedding) on Sep 6 2021, 3.30–4.30 p.m. The top plot shows the metered active load of the chiller. The bottom plot shows the (averaged) temperatures relative to the four main library zones; the dashed trace indicates the outside temperature. Notice the slight rebound effect at the end of the service interval, where the HVAC load increases in order to restore the temperatures to within the desired setpoint as soon as possible

Cost of enablement: Once potential flexibility has been identified, there are likely to be costs related to activating a DER, the level of which depends on the DER and operator's starting position, and requirements imposed by the market (e.g., metering and levels of automation). Our LEO experience with DSR in public institutions such as local authorities and universities has highlighted HVAC hardware and building management systems (BMS) software tend to be outdated or poorly implemented.

Costs of enablement are likely in the range of £1000–£10,000 which can be hard to justify with limited understanding of the value that can be extracted from LEMs at this early stage. This is likely to be more prohibitive to non-traditional DERs and operators. The MSPs offered by SSEN are designed to help with this barrier by offering upfront capital which is paid back through guaranteed market utilisation over a set period. Initially, the MSP have not been popular, with potential market participants citing perceived complexity and the value of support being too low versus the high cost to activate a DER as reasons for not using them. Work is ongoing to better tailor these to meet participant needs.

Legal arrangements: Market participants, with and without prior experience of energy and flexibility markets, have found it challenging to sign some of the legal contracts required to participate in the market. In particular, for more traditional market participants and aggregators, minor disagreements over specific clauses are expected to be solved in the long term with standardised LEM contracts developed by recognised industry and regulatory bodies. For non-traditional participants with little to no experience as active participants in the energy sector, in-house legal teams may not have the capability to make informed decisions, requiring external legal advice and therefore a higher cost of participation.

Availability and Delivery: The more traditional DERs had the best availability (declaring themselves unavailable the least) and best record of successful delivery irrespective of the operator's market experience. Uncertainty associated with an asset, perhaps because of weather dependence or responsibility to deliverer another primary service (away from flexibility—e.g., personal transport in the case of V2G) plays an important role here. Competitive bids must be made well in advance (weeks to months) with reduced remuneration or penalties if actual delivery is lower, risking loss of revenue on already marginal value. Accurate forecasting of load to allow for informed market bidding can be costly and complex to implement. It is unlikely that small scale DER and public institutions will have this capability, if not already part of their primary business. To reduce the risk to the DSO, future markets must be designed to accommodate asset uncertainty, ensuring these are not unfairly disadvantaged without the resultant LEM having large overcapacity at high cost or poor service security.

Forecasting

Following a data-driven approach, month ahead forecasts were synthesised for the local authority library DSR case study. Openly available historic temperatures from 2000 to 2019 (Pfenninger and Staffell 2016; Staffell and Pfenninger 2016) were filtered to within a range of ±5 days around the corresponding day of delivery in past years. The interval was chosen to account for possible year-to-year variations, while also achieving a more statistically significant sample set. Figure 5 shows the empirical probability distribution of the historical temperature values measured from 2000 to 2019 at 4 p.m. on three days in June (these corresponded to the days selected for flexibility delivery in the first three commercial market trials within Project LEO).

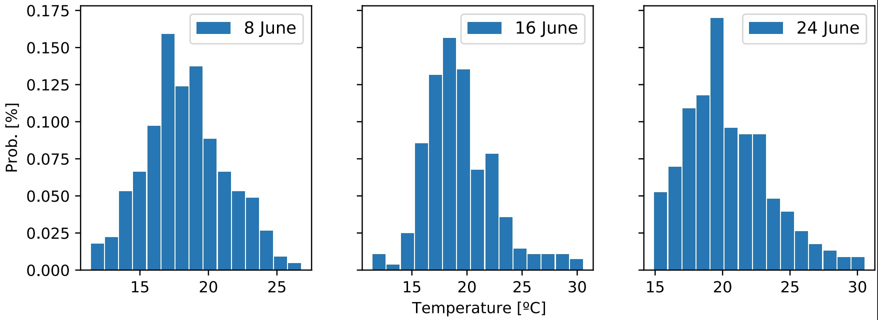


Fig. 5 Empirical probability distribution of temperature in Oxford, for three selected days in June, relative to the 20-year interval 2000–2019

Based on the obtained temperature statistics, a forecast of flexibility delivery (in kW per hour) was derived by using the selected historical temperature data as input to the thermal dynamics model mentioned above. As a result, the empirical probability distribution of the provided flexibility could be synthesised, as shown in Fig. 6. This forecast can then be used to inform the capacity offered in response to any flexibility request, using the cumulative distribution as measure of risk of underdelivery.

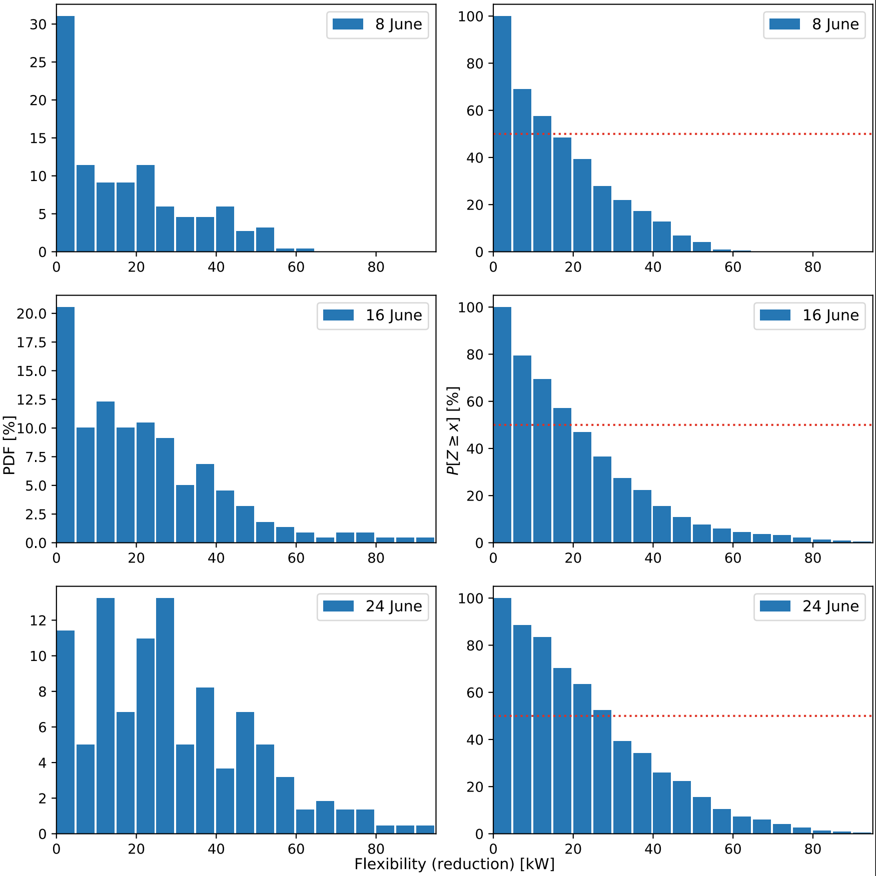


Fig. 6 Probability mass function (left) and cumulative distribution (right) of the flexibility provision during 4–5 p.m. for three selected days in June, estimated by feeding the identified thermal dynamics model with historical temperature data. Note that the cumulative distribution is defined as $\mathbb{P}\{Z \geq x\}$, i.e., the probability that the delivered flexibility exceeds the value on the x-axis (in kW per hour)

Competition and liquidity: The lack of liquidity and competition within the market is a common problem with new markets, particularly at demonstrator stage. In the first trial period, many of the offers to provide flexibility were at or close to the price ceiling. While this could be an indication that the market is not offering enough value to participants, it is more likely just a sign that the trial is non-competitive. This could be reflective of a real market situation but also highlights the importance of understanding how to encourage greater market participation.

Bid Analysis

Figure 7 shows some of the outputs of a Bid Analysis Tool designed for LEO. The tool is intended to help inexperienced market participants better understand bidding strategies and how these affect the potential profitability of service provision. Market and asset parameters such as price ceilings, total availability hours, expected utilisation hours, asset round trip efficiency, levelised cost of storage, cost of energy and cost of personnel can be set before testing how different availability and utilisation bid strategies affect profit.

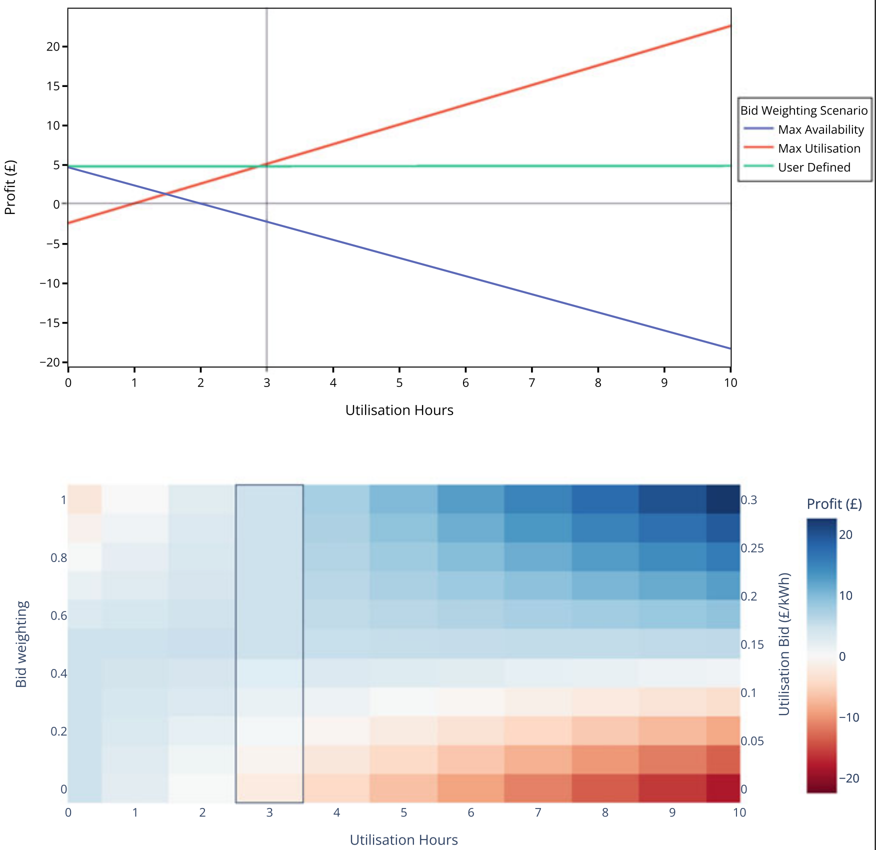


Fig. 7 Outputs from the LEO bid analysis tool: how the actual number of utilisation hours versus an expected utilisation of 3 h out of 10 available hours affects profit potential depending on bid strategy

As can be seen from Fig. 7, there is the possibility (for the set of parameters chosen in this example) of a monetary loss following service delivery, if the instructed utilisation differs significantly from the expected one (3 h in this example—note this value affects other parameters at bidding stage to comply with the total contract price ceiling). This is most prominent if an asset is over utilised having chosen a bidding strategy that is weighted towards availability. Anticipating an assets utilisation could be critical to ensuring the correct bid strategy is made. The green line presents a strategy that is independent of actual utilisation which might offer comfort in having a known profit, but does not guarantee the maximum one.

Baselining: Following the service window, all flexibility deliveries are verified by the DSO using metering data provided by the DER operator. At present, the position of metering, temporal resolution and accuracy of measurement is mostly the choice of the service provider so as not to force a set of regulations that restrict access to the market at such an early stage; half hourly metering from the site's supply point meter (MPAN meter) is the minimum requirement.

The service delivery is determined by comparing the submitted metering data to a baseline. The service provider can choose between two methods for baselining. The first is one recommended by the Energy Networks Association as a future standard across all DSOs, the implementation of which is being tested through TRANSITION and LEO trials known as Historic Baseline with Same Day Adjustment (SDA), a modified X-in-Y method which is commonly used within the industry (Energy Networks Association (ENA) 2022). This is performed by the DSO using historic metering data up to 8 weeks prior to the service window with any previous event days removed. The second option is through a nominated baseline. This method uses a day ahead forecast provided by the service provider and submitted before 17:00 the day before delivery. While more lightweight in terms of data processing on the DSO side, it does require the ability to audit a DER to validate submitted baselines if unusual behaviour is identified.

The favoured baseline method is highly dependent on service provider forecasting and data processing capability, the market service, the DER type, how it is connected to the network and where the location of metering is relative to the DER. There are concerns from service providers as to how participation in other non-DSO services might impact the calculated baseline, while for the DSO, concerns regarding exposure of the market to gaming have been raised. Work is ongoing to explore other possible baseline methodologies which make use of more advanced data analytic tools.

Settlement Rule

In the event a DER under (or over) delivers on the instructed flexibility response, there is potential that network security is put at risk. To incentivise high delivery without being too strict (e.g., by applying penalties) such that inexperienced DERs with relatively high output uncertainty are not discouraged, a settlement rule is applied that reduces the utilisation payment by a greater amount for higher under delivery. This is shown in Fig. 8.

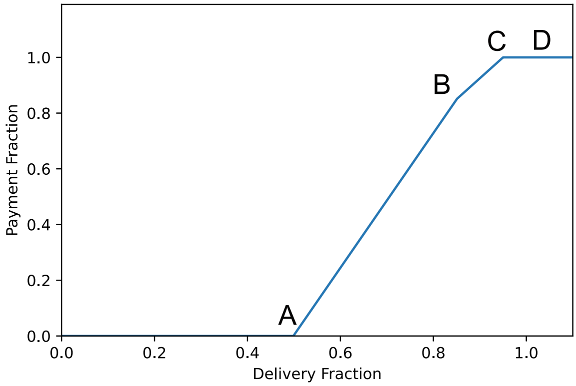


Fig. 8 The settlement rule used within project LEO to determine the fraction of utilisation payment rate as a function of the fraction of service delivered

The settlement rule was justified in a qualitative way with the key regions being: **(right of point D)** Any over delivery is limited to 100% of payment, there are no penalties for over delivery. **(C–D)** Under delivery down to 95% is still paid at 100% of the agreed utilisation rate—this reflects that there is likely some ability for the network to 'run hot'. **(B–C)** Delivery lower than 95% sees the payment rate reduce gradually at 1.5% per 1% under-delivery down to 85% of delivery. **(A–B)** Below 85%, the payment rate reduces more strongly at 2.42% for every 1% of delivery fraction down to 50% of delivery. **(left of point A)** There is zero payment if delivery is lower than 50%. Further quantitative work is ongoing to see how such a settlement rule might influence bid strategy of market participants and the resulting risks that might impose on the DSO, and how a settlement rule could be designed that better reflects the requirements of the DSO.

Personnel resource: Ultimately, non-traditional market participants typically do not consider energy services, particularly flexibility, part of their business or life—energy is usually just seen as a cost incurred as part of delivering their primary function. In our experience with LEO, we have identified a personnel gap that needs to be be bridged to drive market innovation and LEM participation forward.

Organisations often have dedicated staff that deal with the procurement of energy (with little working knowledge of the estate), building managers whose role it is to maintain a building and ensure it is operating to the standard expected of its users (mostly irrespective of energy costs) and facilities management teams who upkeep hardware. It is indeed rare to encounter personnel that have the in-depth knowledge and responsibility across all three areas and with the ability—or desire—to participate in competitive flexibility markets on behalf of the organisation.

3.4 Digital Realities

The data cores of access, management, and validation (wrapped by short-term network resilience and mid-term net-zero objectives) are very different in practice where current energy ecosystems present many obstacles to implementation. The ideals of data best practices do not often translate into real-world operations and planning as systems inherently have internal inertia to overcome. This section will briefly touch on particular examples of the challenges in SLES data frameworks, using localised learnings from flexibility trials and markets to highlight generalised issues that are commonly faced in practice.

Within LEO, one of the chief causes of a primary data constraint, whereby flexibility services and participation were immediately limited, was the insufficient technical capability of assets to interface with the market. Our work uncovered many of the complexities that assets (buildings participating in DSR services in particular) can face in an immature flexibility market. Trials within both publicly and privately owned buildings showed that data infrastructure are the first impingement point for unlocking flexibility services. Buildings were often equipped with outdated and inadequate BMS that were unable to provide the level of automated connectivity needed to engage with the DSO for service provision. Considerable person-hours and stakeholder consultation was needed to be able to get necessary systems in place, and when in place, organisations often lacked the skilled personnel for continued monitoring and participation. Cases of these data roadblocks highlight some of the initial barriers in fostering LEMs and obvious data impediments in access can gravely limit the scale of services.

Although DSR is highlighted here to demonstrate issues with data access, complexities experienced in data management cannot be easily summarised with specific examples. The diverse stakeholders in a large consortium (such as that of LEO) are likely to carry out independent processes for internal data management and analysis: this brings certain challenges to attain unified and streamlined processes of data protocols and standards. To many energy agents, particularly those in emerging flexibility markets, these issues around data standards and management are very common. With so many actors in various aspects of energy procurement, operations, and research, data streams are complex and poorly regulated. The Energy Data Taskforce Report, "*A Strategy for a Modern, Digitalised Energy System*", by the Energy Systems Catapult (Energy Systems Catapult 2021) has highlighted many of these concerns and the report shows that there is a clear divergence in data standards, sometimes within single organisations and projects, where the consequences of poor implementation of proper data practices can have long-term costs if action is not well-timed.

With the increased activity of LEO and associated connected assets and plugin projects, datasets will invariably possess an increasing amount of format diversity. Efforts to address these issues have led to the development of data templates that can be used for both high- and low-resolution (temporal) datasets before they are uploaded to the relevant platforms for further analysis and processing. This step allows for a standardisation of data from market trials, but more support is needed for partners beyond such *ad hoc* solutions. In LEO specifically, certain tools have been considered which allow partners the opportunity to run an automated 'health scan' of their datasets to better facilitate further processing, cleaning, and analysis. For flexibility trials, these tools are complemented by data pipelines where each ingested dataset (multimedia data) is automatically scrapped for metadata to produce data certificates, giving clear provenance of the dataset's creation, sharing party, licencing, data description etc. The latter, though practiced with larger energy data catalogues such as the UKERC Energy Data Catalogue (UK Energy Research Centre (UKERC) 2022), often falls short as a widely adopted best practices in SLES management.

General challenges with baselining were anticipated in Sects. 2.2, 2.7 and 3.3. The research through market trials in LEO has highlighted some specific gaps for validation and data analysis. In essence, the process is simple in its framework but becomes quite complex for effective validation. Measured data brings its own issues of ownership, storage, formatting, and analysis If asset data are poor in resolution, quality, or access, validation becomes very difficult and local markets can be easily manipulated or disrupted. Validating services within LEMs is crucial to their evolution and longevity, but many data issues must be addressed in a SLES to facilitate required processes.

Across all the data cores, open-access tools are needed for wider energy system analysis and management. Web-based, transparent, open-access tools will not only demonstrate best data management practices through real-world projects and implementation but will open the opportunity for end-users to translate learnings at a local level and accelerate transitions through more coordinated efforts where data play a more central role in planning. The need for open-access tools internally will also support project needs, particularly centered around analysis and value extraction, helping local incubators of energy transitions to optimise data streams from SLESs. LEO's core implementation of the MVS Programme and theory of change has incrementally flagged many data qualms from service providers, the DSO, and wider stakeholders. We believe that this *build-measure-learn* approach is crucial to rapid LEM evolution.

4 Conclusion and Outlook

This chapter has presented some of concepts behind LEMs and how through demonstrator projects such as Project LEO, these concepts can be translated into reality. Driven by the decentralisation and digitalisation of energy system, LEMs are seen as a mechanism to manage local active participation in the energy system underpinned by cost-efficient and sustainable network operation that exploits new digital infrastructure and data in innovative way.

Flexibility services are seen as a way to deliver on this cost-efficient operation allowing for constraint alleviation, connection of more variable renewable sources, the deferral or avoidance of costly network upgrades and peer-to-peer energy and capacity trading. To be successful, LEMs will need to engage with the small and many, potentially thousands of DERs per low-voltage substation at the grid edge. In order to do this, a number of technical, regulatory, commercial and social challenges need to be factored into the design. To get social acceptance and guaranteed participation, any LEM must be designed in a way that is perceived as fair and equitable to system users.

Demonstrating these concepts in real-world environments and communities is vital to uncover major barriers that could block the successful implementation of any LEM. Project LEO presented us with a unique opportunity to work in a broad collaboration that involves network operators, local authorities, academia, energy suppliers, aggregators, local DER owners and social enterprises with direct links into local communities. Implementing such a radical system change required an agile approach to be developed where DER enablement and system integration was progressively tested and adapted through MVS trials.

One of the main challenges faced was the difficulty in enabling as market participants non-traditional DERs that had limited or no prior experience as an active player within energy or flexibility markets. More specifically, potential market participants found it challenging to (i) make assessments of DER potential, (ii) justify the cost of activation in immature markets where the value of participation are still unclear, and (iii) overcome legal arrangements and understand the complexity of the market. Market trials in LEO continue to explore these challenges, trying to understand what is necessary and where support or simplification can be achieved to encourage greater participation.

In order to improve the likelihood of successful adoption of LEMs, we make the following recommendations for the basis for further work:

- Open and easily accessible tools are needed to provide quick assessment of a potential market participant's capability of participating in LEMs. This should utilise open, shared datasets and established market outputs for technical and economic assessment, but should also include social and institutional assessments to ensure the full range of capabilities are developed. This should be a multi-stage approach, much like the MVS methodology presented in Sect. 3 of this chapter, that directs organisations or individuals to more detailed (and potentially costly) interventions only if it is sensible to do so.
- The value of ESO- and DSO-procured flexibility within LEMs is yet to be fully understood but likely to be marginal. Automation will be key to reducing operational costs associated with market participation from both the service procurement and delivery sides. Automation requires continued innovation in digital platforms and standards that ensure integration and interoperability. However, there will be

a cost associated with the deployment of this technology: it is important the right balance is made that does not restrict market entry or the ability to compete for small inexperienced participants and maintains enough value in the market to be attractive.

- For non-traditional market actors that have little to no experience in the energy or flexibility markets, the in-house knowledge or personnel capable of making decisions to participate in LEMs are unlikely to be in place. This needs to be accounted for and such a role should be generally encouraged. It is expected that there will be a growth of trusted local organisation capable of offering support in this sense.
- A balance has to be struck between the required complexity in a market that ensures its successful operation and having it simple enough that it can be easily understood and engaged with by the prospective participants. While automated decision-making (e.g., service bidding performed by some AI algorithm) and post-event analysis and verification can help overcome some of these necessary complexities, simplifications should be considered wherever possible.
- Finally, intermediaries and aggregators are likely to play an important role in helping the majority of future participants engage with LEMs. They have the ability through building diversified portfolios to manage the risks associated with highly uncertain assets, helping to activate DERs and manage the legal arrangements between flexibility providers and local network operators. The concept of a social aggregator that takes a not-for-profit approach embedded within a community is likely to have good knowledge of local context and aspirations and therefore be welcomed and trusted by the community.

Acknowledgements The authors would like to thank the Project LEO consortium without whom the learning outputs presented would not have been possible: Scottish and Southern Electricity Networks, Low Carbon Hub, Origami Energy, Piclo, Nuvve, EDF, Oxfordshire County Council, Oxford City Council, Oxford Brookes University and other researchers and staff at the University of Oxford. The authors are also grateful to Dr. Elnaz Azizi for the helpful discussions and proofreading. This work was supported by Innovate UK grant ref. 104781—Project LEO, and EPSRC project EP/S031901/1 EnergyREV—Market Design for Scaling up Local Clean Energy Systems.
The data that support the findings of this study are available from the corresponding author, SW, upon reasonable request.

References

Abbas AO, Chowdhury BH (2021) Using customer-side resources for market-based transmission and distribution level grid services—a review. Int J Electr Power Ener Syst 125. https://doi.org/10.1016/j.ijepes.2020.106480

Ashtine M, Wheeler S, Wallom D, McCulloch M (2021) Smart and agile local energy systems hold the key for broader net-zero energy transitions. In: 2021 IEEE power and energy society innovative smart grid technologies conference, ISGT 2021. https://doi.org/10.1109/ISGT49243.2021.9372166

Aunedi M, Ortega JEC, Green TC (2022) Benefits of flexibility of smart local energy systems in supporting national decarbonisation

Azizi E, Beheshti MTH, Bolouki S (2022) Quantification of disaggregation difficulty with respect to the number of smart meters. IEEE Trans Smart Grid 13(1):516–525. https://doi.org/10.1109/TSG.2021.3113716
Cardoso CA, Torriti J, Lorincz M (2020) Making demand side response happen: a review of barriers in commercial and public organisations. Ener Res Soc Sci 64:101443
Carley S, Konisky DM (2020) The justice and equity implications of the clean energy transition. Nat Ener 5(5:8):569–577. https://doi.org/10.1038/s41560-020-0641-6
Catapult ES (2021) Delivering a digitalised energy system: energy digitalisation taskforce report
Centre for sustainable energy: smart and fair? Phase one report. Exploring social justice in the future energy system
CGI. Scottish and Southern electricity networks: best practice report—market facilitation for DSO. https://ssen-transition.com/wp-content/uploads/2019/05/1TOC_Best-Practice_Market-Facilitation_Electricity-Consolidated.pdf. Accessed 26 May 2022
Charbonnier F, Morstyn T, McCulloch MD (2022) Coordination of resources at the edge of the electricity grid: systematic review and taxonomy. Appl Ener 318:119188. https://doi.org/10.1016/J.APENERGY.2022.119188
Chitchyan R, Bird C (2021) Bristol as a smart local energy system of systems: skills case study. Available at SSRN 3966236
Correa-Florez CA, Michiorri A, Kariniotakis G (2020) Optimal participation of residential aggregators in energy and local flexibility markets. IEEE Trans Smart Grid 11(2):1644–1656. https://doi.org/10.1109/TSG.2019.2941687
Council of European Energy Regulators: guidelines of good practice for flexibility use at distribution level. https://www.ceer.eu/documents/104400/-/-/db9b497c-9d0f-5a38-2320-304472f122ec (2017)
Eid C, Codani P, Perez Y, Reneses J, Hakvoort R (2016) Managing electric flexibility from distributed energy resources: a review of incentives for market design. Renew Sustain Ener Rev 64:237–247. https://doi.org/10.1016/j.rser.2016.06.008
ElectraLink: 40% of total renewable output no longer 'invisible' with launch of new energy data analytics service by ElectraLink (2016). https://www.electralink.co.uk/2016/10/40-total-renewable-output-no-longer-invisible-launch-new-energy-data-analytics-service-electralink/. Accessed 23 May 2022
Energy Networks Association (2018) Open networks future worlds: developing change options to facilitate energy decarbonisation, digitisation and decentralisation. https://www.energynetworks.org/industry-hub/resource-library/open-networks-2018-ws3-14969-ena-futureworlds-aw06-int.pdf. Accessed 30 May 2022
Energy Networks Association (2020a) Open networks project: active power services implementation plan. https://www.energynetworks.org/industry-hub/resource-library/open-networks-2020-ws1a-p3-ffinal-implementation-plan.pdf. Accessed 27 May 2022
Energy Networks Association (2020b) Open networks project: DNO flexibility services revenue stacking. https://www.energynetworks.org/industry-hub/resource-library/open-networks-2020-ws1a-p5-dso-revenue-stacking.pdf. Accessed 30 May 2022
Energy Networks Association (ENA): open networks WS1A P7 baseline methodologies final report version 1.1 (2022)
Energy systems catapult: a strategy for a modern digitalised energy system (2021). https://esc-production-2021.s3.eu-west-2.amazonaws.com/2021/07/Catapult-Energy-Data-Taskforce-Report-A4-v4AW-Digital.pdf. Accessed 25 May 2022
ENTSO-E, CEDEC, E.DSO, Eurelectric, GEODE (2019) TSO-DSO report: an integrated approach to active system management. https://docstore.entsoe.eu/Documents/Publications/Position%20papers%20and%20reports/TSO-DSO_ASM_2019_190416.pdf. Accessed 30 May 2022
Fele F, Margellos K (2021) Probably approximately correct Nash equilibrium learning. IEEE Trans Autom Control 66(9):4238–4245. https://doi.org/10.1109/TAC.2020.3030754

Fele F, Maestre JM, Camacho EF (2017) Coalitional control: cooperative game theory and control. IEEE Control Syst Mag 37(1):53–69. https://doi.org/10.1109/MCS.2016.2621465

Fleurbaey M, Kartha S, Bolwig S, Chee YL, Chen Y, Corbera E, Lecocq F, Lutz W, Muylaert MS, Norgaard RB, Okereke C, Sagar A, Baer P, Brown DA, Francisco J, Hauschild MZ, Jakob M, Schroeder H, Thogersen J, Urama K (2014) Sustainable development and equity. In: Climate change 2014: mitigation of climate change. Contribution of working group iii to the fifth assessment report of the intergovernmental panel on climate change [Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, Von Stechow C, Zwickel T, Minx JC (eds)], pp 283–350

Ghezzi A, Cavallo A (2020) Agile business model innovation in digital entrepreneurship: lean startup approaches. J Bus Res 110:519–537. https://doi.org/10.1016/J.JBUSRES.2018.06.013

Han L, Morstyn T, McCulloch M (2021) Estimation of the shapley value of a peer-to-peer energy sharing game using multi-step coalitional stratified sampling. Int J Control Autom Syst 19:1863–1872. https://doi.org/10.1007/s12555-019-0535-1

Heinrich C, Ziras C, Jensen TV, Bindner HW, Kazempour J (2021) A local flexibility market mechanism with capacity limitation services. Ener Policy 156:112335. https://doi.org/10.1016/j.enpol.2021.112335

Heinrich C, Ziras C, Syrri ALA, Bindner HW (2020) Ecogrid 2.0: a large-scale field trial of a local flexibility market. Appl Ener 261:114399. https://doi.org/10.1016/j.apenergy.2019.114399

Huggins S. Developing an ethical framework for local energy approaches. https://project-leo.co.uk/reports/developing-a-ethical-framework-for-local-energy-approaches/. Accessed 26 May 2022

Jazaeri J, Alpcan T, Gordon RL (2020) A joint electrical and thermodynamic approach to HVAC load control. IEEE Trans Smart Grid 11(1):15–25. https://doi.org/10.1109/TSG.2019.2916064

Klyapovskiy S, You S, Michiorri A, Kariniotakis G, Bindner HW (2019) Incorporating flexibility options into distribution grid reinforcement planning: A techno-economic framework approach. Appl Ener 254:113662. https://doi.org/10.1016/j.apenergy.2019.113662

Kok C, Kazempour J, Pinson P (2019) A DSO-level contract market for conditional demand response. In: 2019 IEEE Milan PowerTech, pp 1–6. https://doi.org/10.1109/PTC.2019.8810943

Laur A, Nieto-Martin J, Bunn DW, Vicente-Pastor A (2020) Optimal procurement of flexibility services within electricity distribution networks. Eur J Oper Res 285(1):34–47. https://doi.org/10.1016/j.ejor.2018.11.031

Le Cadre H, Mezghani I, Papavasiliou A (2019) A game-theoretic analysis of transmission-distribution system operator coordination. Eur J Oper Res 274(1):317–339. https://doi.org/10.1016/j.ejor.2018.09.043

Lezama F, Soares J, Hernandez-Leal P, Kaisers M, Pinto T, Vale Z (2019) Local energy markets: paving the path toward fully transactive energy systems. IEEE Trans Power Syst 34(5):4081–4088. https://doi.org/10.1109/TPWRS.2018.2833959

Lopes F (2021) Chapter 3—from wholesale energy markets to local flexibility markets: structure, models and operation. In: Pinto T, Vale Z, Widergren S (eds) Local electricity markets. Academic Press, pp 37–61. https://doi.org/10.1016/B978-0-12-820074-2.00009-5

Low Carbon Hub and Origami Energy: Low carbon hub portfolio: routes to market (2021). https://project-leo.co.uk/wp-content/uploads/2022/01/D3.7-Routes-to-Market.pdf. Accessed 31 May 2022

Low carbon hub: our impact (2022). https://www.lowcarbonhub.org/about/our-impact/. Accessed 31 May 2022

Low carbon hub: people's power station (2022). https://peoplespowerstation.org/. Accessed 31 May 2022

Maidment C, Vigurs C, Fell M, Shipworth D (2020) Privacy and data sharing in smart local energy systems: insights and recommendations

Morris E, McArthur S (2021) A plug and play artificial intelligent architecture for smart local energy systems integration

Morstyn T, Farrell N, Darby SJ, McCulloch MD (2018) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat Ener 3:94–101. https://doi.org/10.1038/s41560-017-0075-y
National Grid ESO (2022) Electricity charging policy and guidance. https://www.nationalgrideso.com/industry-information/charging/charging-guidance. Accessed 30 May 2022
Ofgem (2016) Industrial and commercial demand-side response in GB: barriers and potential. Analysis of Ofgem's surveys on demand-side response (DSR) provision by large industrial and commercial consumers. https://www.ofgem.gov.uk/system/files/docs/2016/10/industrial_and_commercial_demand-side_response_in_gb_barriers_and_potential.pdf. Accessed 17 Dec 2021
Origami Energy (2021) The low carbon hub: project LEO whitepaper: vision on the inclusion of small flexibility (under 7 kW) from the grid edge. https://project-leo.co.uk/reports/whitepaper-vision-on-the-inclusion-of-small-under-7kw-flexibility-from-the-grid-edge-and-its-role-in-future-energy-system/. Accessed 25 May 2022
Origami energy: commercial MVS report (2022)
Pfenninger S, Staffell I (2016) Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114:1251–1265. https://doi.org/10.1016/J.ENERGY.2016.08.060
Piclo, Element Energy, Oakes, G (2022) Modelling the GB flexibility market. Part 1: The value of flexibility
Prat E, Herre L, Kazempour J, Chatzivasileiadis S (2021) Design of a continuous local flexibility market with network constraints. In: 2021 IEEE Madrid PowerTech, PowerTech 2021—conference proceedings. https://doi.org/10.1109/POWERTECH46648.2021.9494978
Project LEO: Local energy Oxfordshire: about the project (2018). https://project-leo.co.uk/about/. Accessed 31 May 2022
Pumphrey K, Walker SL, Andoni M, Robu V (2020) Green hope or red herring? examining consumer perceptions of peer-to-peer energy trading in the united kingdom. Ener Res Soc Sci 68. https://doi.org/10.1016/j.erss.2020.101603
Ries E (2011) The lean startup: how constant innovation creates radically successful businesses
Rossetto N (2018) Measuring the intangible: an overview of the methodologies for calculating customer baseline load in PJM. Florence School of Regulation policy Briefs 2018/05
Savelli I, Morstyn T (2021) Electricity prices and tariffs to keep everyone happy: A framework for fixed and nodal prices coexistence in distribution grids with optimal tariffs for investment cost recovery. Omega 103:102450. https://doi.org/10.1016/j.omega.2021.102450
Savelli I, Morstyn T (2021) Better together: harnessing social relationships in smart energy communities. Ener Res Soc Sci 78:102125. https://doi.org/10.1016/j.erss.2021.102125
Schittekatte T, Meeus L (2020) Flexibility markets: Q&A with project pioneers. Util Policy 63:101017. https://doi.org/10.1016/j.jup.2020.101017
Scottish and Southern Electricity Networks O (2019) Analysis of DSO flexibility markets. https://ssen-transition.com/wp-content/uploads/2019/08/TRANSITION-Analysis-of-relevant-international-experience-of-DSO-flexibility-markets.pdf. Accessed 30 May 2022
Scottish and Southern Electricity Networks (2022) Southern electric power distribution. https://www.ssen.co.uk/about-ssen/library/charging-statements-and-information/southern-electric-power-distribution/. Accessed 30 May 2022
Scottish and Southern Electricity Networks: market stimulation packages. https://ssen-transition.com/get-involved/market-stimulation-packages/. Accessed 26 May 2022
Scottish and Southern Energy Networks (SSEN) (2022) SSEN transition. https://ssen-transition.com/. Accessed 30 May 2022
Spanó E, Niccolini L, Pascoli SD, Iannacconeluca G (2015) Last-meter smart grid embedded in an internet-of-things platform. IEEE Trans Smart Grid 6(1):468–476. https://doi.org/10.1109/TSG.2014.2342796
Spiliotis K, Ramos Gutierrez AI, Belmans R (2016) Demand flexibility versus physical network expansions in distribution grids. Appl Ener 182:613–624. https://doi.org/10.1016/j.apenergy.2016.08.145

Staffell I, Pfenninger S (2016) Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114:1224–1239. https://doi.org/10.1016/J.ENERGY.2016.08.068

Stanley R, Johnston J, Sioshansi F (2019) Chapter 6—Platforms to support nonwire alternatives and DSO flexibility trading. In: Sioshansi F (ed) Consumer, prosumer, prosumager. Academic Press, pp 111–126. https://doi.org/10.1016/B978-0-12-816835-6.00006-1

Tao Z, Moncada JA, Poncelet K, Delarue E (2020) Energy-only vs. capacity markets: impact of hedging opportunities considering risk-averse investors. In: 2020 17th international conference on the European energy market (EEM), pp 1–6. https://doi.org/10.1109/EEM49802.2020.9221895

Tushar W, Saha TK, Yuen C, Morstyn T, McCulloch MD, Poor HV, Wood KL (2019) A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. Appl Ener 243:10–20. https://doi.org/10.1016/j.apenergy.2019.03.111

UK Energy Research Centre (UKERC): UKERC energy data catalogue (2022). https://ukerc.rl.ac.uk/DC/. Accessed 30 May 2022

UK Research and Innovation (UKRI) (2022) Prospering from the energy revolution challenge. https://www.ukri.org/what-we-offer/our-main-funds/industrial-strategy-challenge-fund/clean-growth/prospering-from-the-energy-revolution-challenge/. Accessed 27 May 2022

Verba N, Baldivieso-Monasterios P, Dong S, Braitor A, Konstantopoulos G, Gaura E, Morris E, Halford A, Stephen C (2022) Cyber-physical components of an autonomous and scalable SLES. arXiv:2201.08720

Vespermann N, Hamacher T, Kazempour J (2021) Risk trading in energy communities. IEEE Trans Smart Grid 12(2):1249–1263. https://doi.org/10.1109/TSG.2020.3030319

Vigurs C, Maidment C, Fell M, Shipworth D (2022) Building and unlocking flexibility with smart local energy systems (SLES)

Wheeler S (2022a) Minimum viable system trials: compilation report. https://project-leo.co.uk/reports/minimum-viable-systems-trials-compilation-report/

Wheeler S (2022b) MVS A1.1 Oxford bus company technical report. https://project-leo.co.uk/reports/mvs-a1-oxford-bus-company-technical-report/

Wheeler S, Ashtine M (2022a) MVS a procedural learnings. https://project-leo.co.uk/reports/mvs-a-procedural-learnings-2/

Wheeler S, Ashtine M (2022b) MVS A2 Sandford hydro technical report. https://project-leo.co.uk/reports/mvs-a2-sandford-hydro-technical/

Wheeler S, Ashtine M, Vijay A (2022) MVS A3.1 technical report: Oxford behind the meter. https://project-leo.co.uk/reports/mvs-a3-sackler-library-obm-technical-report/

Wilkinson MD, Dumontier M, Aalbersberg IJ, Appleton G, Axton M, Baak A, Blomberg N, Boiten J-W, da Silva Santos LB, Bourne PE et al (2016) The fair guiding principles for scientific data management and stewardship. Sci Data 3(1):1–9

Ziras C, Heinrich C, Bindner HW (2021) Why baselines are not suited for local flexibility markets. Renew Sustain Ener Rev 135:110357. https://doi.org/10.1016/j.rser.2020.110357

Local Energy Markets: Design and Structures

Ivan Leuskov, Saber Talari, and Wolfgang Ketter

1 Introduction

1.1 Problem Statement

Energy market has been historically centralized and limited to few clear and separated roles: generation, transmission, distribution, and consumption of the energy. A typical cycle in this vertically aligned market structure can be described as follows: energy is first produced by few of the large generation units, then transmitted and distributed to the end consumers such as private domestic households, businesses, or industrial producers (Khorasany et al. 2018). Until the late 1970s all of those roles, except consumption, were monopolized by the government which managed and controlled them either directly or through government-related agencies. During the last decades of the twentieth century many countries have carried out a liberalization of the energy market through its demonopolization and deregulation (Mousavi et al. 2021).

This liberalization, however, had not changed the traditional, centralized top-down business model of the energy trading. Despite the fact that in many countries the number of energy generators had risen, high market shares were still controlled by a small number of big market players (Dinther et al. 2021). That was still an improvement for the energy consumers, who benefited from more competitive pricing and rate plans (Mousavi et al. 2021). Despite the liberalization, consumers were as before excluded from any market activities except of consuming itself.

The solution for this problem came in the early 2000s as many countries began to legalize and incentivize private energy generation out of renewable energy sources (Dinther et al. 2021). There were some theoretical studies (Ketter et al. 2018) together

I. Leuskov · S. Talari (✉) · W. Ketter
University of Cologne, Cologne, Germany
e-mail: talari@wiso.uni-koeln.de

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_2

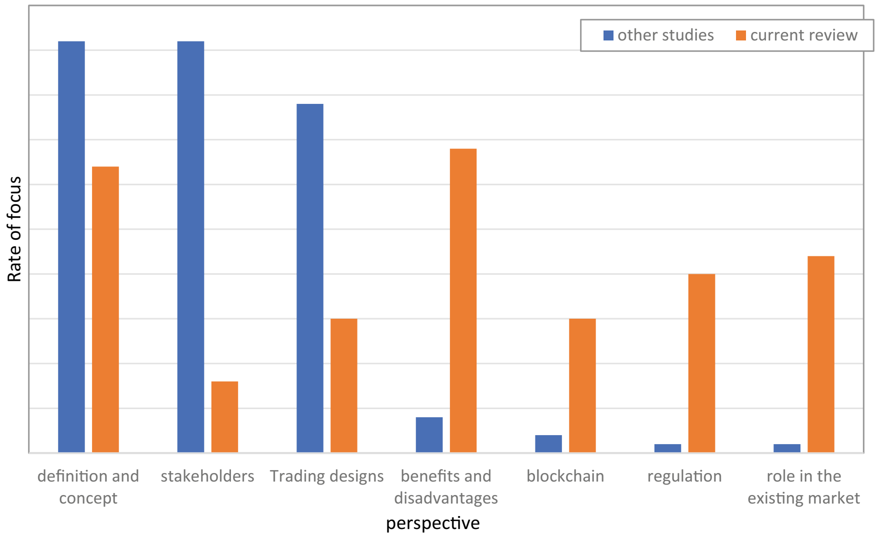


Fig. 1 Different aspects of local energy markets covered in this chapter versus other studies

with developing some open-source platforms (Ketter et al. 2013, 2016) in past year regarding local market design such as retail electricity markets. Those eventually gave many consumers, who were often at the bottom of this chain, a possibility to take part in the other steps of energy trading. Around this time first researchers started to theorize about the possibility of local energy trading in the local energy markets (LEM) where the generator, transmitter, distributor, and consumer of energy could be located in the same local community (Kamrat 2001, 2002; Tomšič and Urbančič 2000).

Over the past three years, not only have the new studies on these topics emerged, but some problems and questions, that were unanswered before, have received their resolution or have been reconsidered. Moreover, new problems and research gaps have appeared that need to be identified and addressed. We study LEM in this chapter from different perspectives as depicted in Fig. 1. It is shown that some of these perspectives such as blockchain, regulation and emerging in existing markets still need more investigation. Noted that rate of focus for. Other studies (blue bar) in Fig. 1 is based on number of papers that explored certain perspective and for current study (orange bar) is based on the number of papers that refered to for that certain perspective.

1.2 Objectives

This chapter covers mainly four important points of LEM as follows:

1. Concept of the LEM

To understand the concept of LEMs in the modern research both older (before September 2018) and newer (after September 2018) publications are considered. Although many scholars have already sufficiently studied the definition and general concept of the local energy market in the past, those topics have been actively researched in the last years as well. Other events like the implementation of the first real LEM community project in 2016 have significantly affected the theoretical foundation that we had before and encouraged new publications on previously studied perspectives. The following topics are to be studied withing the concept of LEMs: modern definition of LEM, its key concepts such as stakeholders, their roles and motivation, market trading designs and energy pricing.

2. Benefits and challenges of LEMs

The benefits and challenges that LEM offers to consumers, prosumers (consumers who also produce their own energy) and other stakeholders are studied. In order to fully cover the benefits of LEMs, it is essential to show how researchers differentiate traditional and local energy markets and which stakeholders can benefit from which market. That opens up a subtopic of disadvantages for some of the market players on both sides that is to be reviewed as well. The first objective here is to understand what attracts people to a LEM and what solutions can it offer to the existing energy problems. The second goal is to find out what can hinder the LEMs' expansion or discourage stakeholders to participate in such markets.

3. The role of LEMs in the existing energy market structure

This point aims to highlight LEMs' fit in the existing energy market structure. The questions that have to be answered here are: What role do LEMs play in the current energy market? What are the reasons they have become more important and widely used in the recent years? And what does the new research have to offer to the problem of regulation and legal framework of such markets?

4. Features of blockchain-based LEMs

This point will address the development and the state of a new dimension of LEM research—blockchain-based LEMs. It is crucial to understand what features and challenges this technology can bring into such market systems and why it has become relevant at all in the LEM field. And since this review is being done in 2022, when the first blockchain-based LEM has been implemented, it is finally possible to answer what features it has, how it has been implemented, and what it contributes to the research of this topic.

This chapter is structured as follows: Sect. 2 presents the concept of LEM including market designs and current stakeholders, the benefits and challenges of LEM are covered in Sect. 3, Sect. 4 investigate the position of LEM in existing electricity market and regulations proposed for such a market to be merged, Sect. 5 investigates the blockchain implementation of LEM, Sect. 6 reviews a few implemented LEM projects, some discussions are made in Sects. 6.1, 6.2, 6.3 and 6.4, and finally it concludes in Sect. 7.

2 Concept of LEM

2.1 Definition

The modern definition of LEM differs from what the researchers in the early 2000s were expecting it to become. For instance, previously the locality of an energy market was often understood much wider. Early LEM studies were dedicated to the "local" energy markets in large regions or even countries like Poland, Slovenia, Denmark, or California (Bushnell and Wolak 2000; Kamrat 2001; Lund and Münster 2006; Tomšič and Urbančič 2000). The biggest differences between a local and a bigger, for example, national energy market, were seen not in stakeholders, market designs or benefits but rather in technical details like voltage and power grid capacity (Kamrat 2001).

Researchers of the recent years consider local energy market in comparison with a traditional and centralized one where all the key factors are mostly the opposite. A traditional top-down energy market is in most countries a centralized, globally scaled (oriented towards multiple large regions or geographical areas) and vertically aligned market, usually, but not always, based on non-volatile, fossil-fuel energy that delivers energy to costumers according to the fixed rates defined in the long-term contracts (Khorasany et al. 2018; Sorknæs et al. 2020).

The LEM is, in turn, commonly defined today as a decentralized, locally scaled (limited by one or a few smaller communities) market that tends to be horizontally scaled and is usually based on volatile, renewable energy. In such markets the energy trading is not a static process that can be predicted and defined by a long-term contract. The reason for that is the fact that energy in LEMs is produced by local, rather small energy prosumers who sell it only when they have an energy surplus (Sorknæs et al. 2020).

While defining a LEM it is also important to distinguish it from other similar concepts around it. The ones that are most often related to it are Microgrid (MG) markets and Peer-to-Peer (P2P) Electricity Trading. An MG is a basic unit of a bigger energy grid and is a minified version of a typical energy grid. It consists of local power supply generators that transport energy loads to the local end points or to bigger grids outside of it (Hu and Bhowmick 2020). An energy market that is built around such microgrids is called Microgrid Electricity Market (MEM). Several MEM can form a LEM. Therefore, MEMs can be operated by a MG operator (MGO) or through a P2P market structure.

A LEM, however, is by its nature often a MEM as well as the energy is produced, traded, and consumed inside smaller local communities that use microgrids for that (Cornélusse et al. 2019). There are, for instance, MG communities that are not considered LEMs as they are part of centralized energy market that controls and supplies them (Xu and Lu 2019; Hoicka and MacArthur 2018). P2P energy trading is, in turn, a way of direct exchange between two trading agents. It can be implemented in any

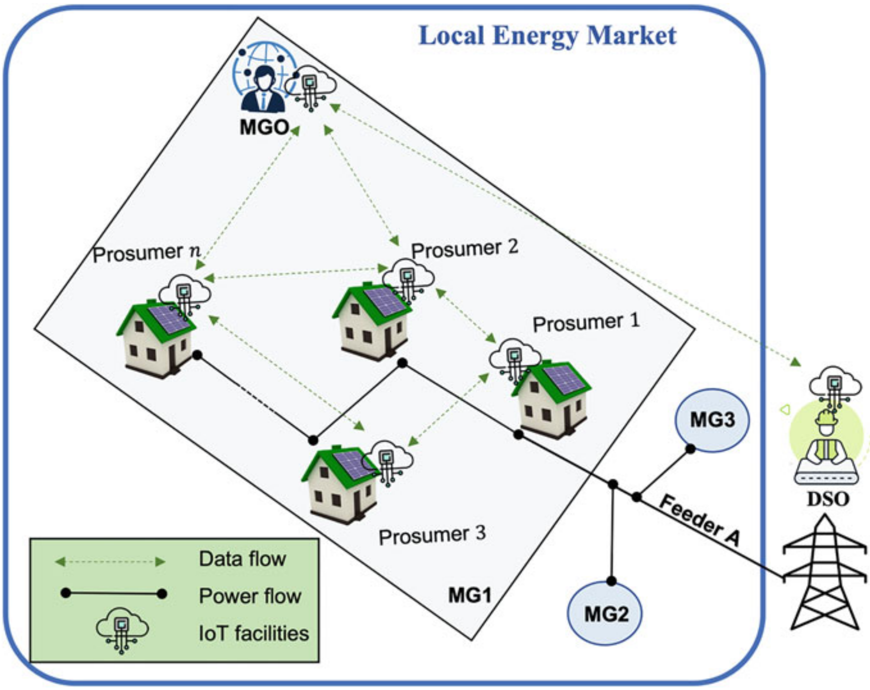


Fig. 2 Possible LEM implementation containing few MEMs

type of a market and be both local and non-local (Zhang et al. 2018). A visual showcase that demonstrates a possible LEM implementation containing a few MEMs is presented in the Fig. 2.

2.2 Market Design

The pricing model in LEM is dynamic and can rarely be fixed in a contract. Instead, it varies depending on the time of the day, supply, and demand (Liu et al. 2017; Ma et al. 2021). This is another perspective that evolved with years. First, it was theorized that local energy trading similarly to traditional markets would take place on the basis of medium and long-term contracts (Kamrat 2001). However, already in the middle of 2000s this opinion shifted towards an idea of price variation that can happen as often as hourly. Such price volatility greatly depends on many factors like surplus of energy in the local area, weather conditions or capacity to store enough electricity in a specific area (Lund and Münster 2006). Current research supports this belief as well, as the volatile renewable energy, limited capacity of local prosumers or demand of consumers create natural low and high price periods in LEMs (Bose et al. 2021; Mengelkamp et al. 2019a).

Even though the locality of energy is true for every LEM, the way the trading is being done, also called market trading design, is often different. One of the possibilities to categorize these designs is to separate them into direct and indirect energy trading of consumers and prosumers. Some of the most important direct trading designs use P2P (Ma et al. 2021; Siano et al. 2019), auction mechanisms (Park et al. 2019; Richter et al. 2019; Zade et al. 2022) or are based on optimization algorithms that use energy supply and consumer data like their bids and other preferences to enhance direct trading (Georgilakis 2020; Wörner et al. 2019). An indirect trading is done via market participation of a 3rd party. This party brings an element of centralization into LEM by buying energy surplus from prosumers and selling it to other consumers, controlling power consumption and generation of LEM microgrids (Honarmand et al. 2021).

A decentralized nature of LEMs fits quite well into the P2P trading design. Establishing the entire energy trading process in a local market requires, however, some technical experience and specific hardware. Due to this fact, direct trading designs with a help of a 3rd party (but without its direct participation in the trading itself) like auction or aggregator models were often a more popular and convenient option for consumers and prosumers (Mengelkamp et al. 2019b). In the latest literature review on LEM in 2018 that fact led the authors to assume that most of the LEM trading in the future would be happening using the auction mechanism. Another solution was offered through the development of the blockchain technology in the 2010s. The blockchain-based LEMs in the last couple of years have offered a way of trading within a LEM without any intermediaries and has greatly helped P2P trading design to become even more popular (Heck et al. 2021).

The dynamic nature of LEM price model is rather a well-studied and agreed upon fact today. Much more complicated subproblem here is the price elasticity. This problem had remained a research gap for many years due to the inefficient data and number of factors that affect the price in a LEM market (Mengelkamp et al. 2019b). Yet the scholars lately were able to create and test a mathematical load-serving entities model in a real LEM environment. This model accounts different factors in a LEM market and connects their changes to the end price (Ostadijafari et al. 2021). Based on the current and forecasted electricity supply and demand together with the historical price data of a particular market, it was able to calculate a price profile for up to one day ahead. Nevertheless, the price model was developed in a market with some action limitations as the consumers were not allowed to change their bids once they were placed. This study helped greatly to understand how typical consumer and prosumer in LEM business relationships work in a rather controlled environment.

A new research gap here is the understanding how this price elasticity model works in a market open to manipulations like extensive bidding in order to lower the energy price. In a virtual trading model, designed specifically for LEMs by Sichuan University, it has been shown that different trading designs can affect the profit or loss at a LEM (Gao et al. 2021). For instance, when a certain market player (simulated by a virtual power plant in the study) with the role of a prosumer uses market data to generate an optimal buy and sell strategy, they can make profit, maximize its market share, and even make the energy prices go much higher for other consumers at the market. That research shows a great theoretical model of manipulations at a LEM market. What is left for the future studies is to test this concept within a real project.

2.3 Stakeholders

Finally, the last perspective of the LEM concept is its stakeholders. The key stakeholders can be presented based on their functionality: generation, distribution, and consumption of energy. The generation stakeholders are prosumers and local energy companies, distribution ones are represented by distribution companies, aggregators and microgrid agents, consumers consist of prosumers and consumers (Fuentes González et al. 2021; Mengelkamp et al. 2019b).

There are, of course, many other stakeholders that are not directly participating in the energy trading cycle. Two most important ones that are often focused by today's literature are intermediaries that allow LEM processes to function without its own auction mechanism and local authorities that regulate all the LEM processes (Fuentes González et al. 2021; Rae et al. 2020). Their influence on the LEMs, however, is not the same. Whereas intermediaries mostly provide hardware, software, or some specific services to such markets without affecting their existence and operations, authorities can do that and, thus, play a significant role here. This role comprises the legal status of LEMs which allows them to exist in the first place, and the support or lack of it towards their general development and acceptance and trust of the local residents (Mourik et al. 2021).

Some aspects of this problem like stakeholders' motivation and their objectives were still not extensively studied and we could not fully understand what made LEMs participants to choose this energy market model over a centralized one. In recent years, however, a few publications investigated this research gap on many real-life LEM projects around the world which allowed to review their results.

Firstly, one of the strongest motivations for participating in a LEM for consumers is the fact that many local areas are experiencing quality, security, and cost problems with their current centralized energy providers. For energy providers it is much easier, faster, profitable and less expensive to create a new point of connection or to provide constant and sufficient energy output to a city, rather than supplying energy to a small rural area where needs more infrastructure (Rae et al. 2020).

Secondly, many remote or hard-to-reach terrains, that are often suited rural, have no or very limited access to the centralized grid and, hence, to its energy. Even though it is possible to connect such isolated areas, for many big market players it is often infeasible and presents certain financial risks and engineering difficulties. Due to these issues, consumers in rural, isolated and hard-to-reach local communities can be interested in stand-alone energy systems or LEMs. LEMs can be especially a good fit, considering the fact that some of those areas have an access to renewable resources like water, solar or wind (Rae et al. 2020).

Thirdly, the climate change problem has greatly prompted the ideas of climate-neutral energy that have become even more important and relevant both in politics and society. This, in turn, has sparked an interest of different stakeholders like consumers and authorities on different levels towards renewable-based LEMs. These increasing concerns and awaited solutions for them have motivated the creation of many LEM pilot projects in the recent years. (Fuentes González et al. 2021; Honarmand et al. 2021; Meeuw et al. 2020; Pires Klein et al. 2020; Rae et al. 2020).

Fourthly, in the recent price rate comparisons between centralized energy providers and LEMs it has been shown that the electricity produced in a LEM can cost up to 10% less for a consumer (Pires Klein et al. 2020). With the help of optimization algorithms that provide the optimal time for buying energy from different renewable sources, the electricity cost reduction can go up to 50% (Yahaya et al. 2020). At this point in time, we do not have enough quantitative data that could prove that the same price reduction would be true in most of the LEMs across different regions. However, if the same trend is going to continue, it is reasonable to assume that this could be a great motivation source for potential LEM participants.

Finally, authorities in many regions are interested in integrating renewable resources into energy trading and distribution. It has been analyzed that LEMs can be of great help here (Honarmand et al. 2021). To fulfill sustainable, green, or even net-zero policies and to achieve decarbonization many authorities on different levels (international, national, regional, and local) have to integrate more renewable energy into the energy market. One of the ways to do it, is to encourage local energy trading and LEMs. Instead of trying to convince bigger energy market players to switch to renewable energy, the authorities could integrate LEMs into the existing system. This integration is a much easier task due to active participation of LEM communities that take care of most of the processes by themselves and are mostly based on the renewable energy (Dudjak et al. 2021; Honarmand et al. 2021; Mourik et al. 2021).

3 Benefits and Challenges of LEMs

One of the important aspects of the LEM concept that had received rather little attention in the research before 2018 is its advantages for stakeholders and actors. Between 2018 and 2021, a significant amount of research on this problem has been conducted and, hence, it seems possible and relevant to give an overview here. To achieve that, this perspective was studied across two dimensions: benefits that a LEM brings and challenges the stakeholders must face to participate in or be part of it. Much like in a previous section, some aspects are shown in the comparison with LEMs' main competitor—traditional top-down energy providers.

3.1 Benefits

The early researchers saw the potential benefits from LEMs mainly in improving flaws of the current centralized electricity system, e.g., inflexibility of the energy grid, its unreliability, interruptions of energy loads, transmission losses, environmental impact, not constantly smooth power output for the end consumers, high costs, and security vulnerabilities (Carley 2009; He et al. 2008; Lund and Münster 2006).

Many of these problems have been addressed and improved in the latest LEM implementations. In the recent research it has become evident that in the real projects and use-cases LEMs were able to improve grid flexibility (Mendes et al. 2019), network stability (Honarmand et al. 2021), energy security and resilience (Proka et al. 2020), and offer lower electricity prices than traditional energy providers (Gärttner et al. 2018). While we only have data from tens of real LEM projects, it would be premature to assume that those benefits are either always true or the same for all the possible LEM communities. However, the recent publications do demonstrate that LEMs often have either lower energy prices (up to 10%) than centralized energy providers or their prices are much more affected by the competitive environment (Gärttner et al. 2018; Mengelkamp et al. 2018; Pires Klein et al. 2020; Stephant et al. 2021; Yahaya et al. 2020). Prosumers benefit from LEMs also by selling their generated energy there which brings them more revenue as on a centralized market (Chen and Su 2018).

Yet one of the most significant benefits of LEM that people can feel in their everyday life is the availability of energy in difficult terrains and remote regions. For many big market players investing in an expensive infrastructure and providing energy for such regions may not always be profitable. LEMs, in turn, develop independently and do not have to be profitable for all market players to appear and continue to exist (Rae et al. 2020). That was demonstrated in a case study in Nepal conducted by Kathmandu University (Shrestha et al. 2019). The researchers have investigated the problem of unstable national grid in Nepal where about 10% urban and 15% rural population were out of reach of centralized electricity and, thus, did not have access to enough energy. The others (mostly, in urban areas) who did have access, often had to face blackouts up to 16 h a day due to the shortage and overuse of the national grid sources. However, thanks to the investments into the distribute energy generation, microgrids and support towards LEMs in the last 5 years, Nepalese government was able to improve this situation. Currently more than 25% of its population is using energy produced in MEMs that often form natural LEMs which are not always connected to the centralized energy grids (Shrestha et al. 2019).

Etukudor et al. (2020) presented a similar case study for sub-Saharan Africa, southern Asia, and India where LEMs provided an opportunity to access low-cost electricity as well. Considering the fact that more than 12% of global population has still no access to any form of electricity (about 22% in the rural areas), the LEMs are introducing significant positive impact (Shrestha et al. 2019). According to the results of the study, a well-designed LEM can provide energy to local rural areas, do it cheaper than existing market providers, offering at the same time extra revenues to local prosumers. This is an especially important point, as it demonstrates that LEMs in different environments can be profitable for both direct actors: consumers and prosumers, motivating the latter to participate in creating such markets as well.

Finally, another global benefit of a LEM is its contribution towards renewable energy and decarbonization. Many countries, regions, cities, and communities in the recent years have set their goals to lower greenhouse gas emissions in order to slow the climate change down (CDP 2017). In case of cities, the energy transition is especially relevant as they are responsible for at least two-thirds of global final energy use and produce more than 70% of CO_2 emissions. In some regions like EU where more than 70% of its population live in urban areas, there is no possibility to achieve climate goals without transforming towards renewable energy (Bisello and Vettorato 2018). There have been proposed several energy roadmaps that intend to reduce greenhouse gas emissions. In the EU the goal is set to lower these emissions by 85–90% by 2050 (Mueller and Dornmair 2050).

In the recent research, LEMs are often expected to contribute to solution to this problem. By integrating them in already existing energy grids or creating new net-zero or low carbon districts, it is possible to lower regional and cities carbon footprint or even create nearly net zero energy cities (Dudjak et al. 2021; Ford et al. 2021; Piderit et al. 2019; Villa-Arrieta and Sumper 2019). Although local energy and LEMs are, indeed, considered as an important factor in achieving such goals as net-zero, some scholars emphasize that they alone are not enough (Piderit et al. 2019), for instance, believes that we also need net-zero architecture and building construction in order to lower carbon footprint in the cities.

Even though LEM is functionally limited to provide only energy, it can also provide electricity for the charging stations for electric vehicles and, hence, contribute to the vital sector of decarbonisation—transportation (Heendeniya et al. 2020).

Table 1 LEM benefits overview

LEM benefits	Stakeholders that benefit the most	Reference
Grid flexibility	Consumers, prosumers	Mendes et al. (2019)
Network stability	Consumers, distribution stakeholders	Honarmand et al. (2021)
Energy security and resilience	Consumers	Proka et al. (2020)
Lower energy prices (compared to current providers)	Consumers	Gärttner et al. (2018), Mengelkamp et al. (2018), Pires Klein et al. (2020), Stephant et al. (2021), Yahaya et al. (2020)
Higher prosumer revenue (compared to current providers)	Prosumers	Chen and Su (2018), Etukudor et al. (2020)
Energy availability in difficult terrains	Consumers, authorities	Etukudor et al. (2020), Shrestha et al. (2019)
Decarbonization	Authorities	Bisello and Vettorato (2018), CDP (2017), Dudjak et al. (2021), Ford et al. (2021), Heendeniya et al. (2020), Piderit et al. (2019), Villa-Arrieta and Sumper (2019)

The final overview is presented in the Table 1. It features the LEM benefits themselves, stakeholders that benefit the most from them and the corresponding publications that are dedicated to such benefits.

3.2 Challenges

There are certainly some challenges that LEM stakeholders have to face. One of them is the fact that typical energy grid design cannot always fit a LEM. The problem is that most of nowadays utility grids were not designed for bidirectional power flow and P2P energy exchange. This means that in some cases to achieve optimal energy output, additional investment into the utility upgrades and reconstructions must be made. That, in turn, increases the costs for entering a LEM market for its participants (D'Alpaos and Andreolli 2020; Ma et al. 2021; Meeuw et al. 2018).

However, (Dudjak et al. 2021) believes that these challenges are not inevitable. They suggest that if a LEM is designed with an appropriate market model and control mechanism, network problems such voltage violations or congestion can be avoided. To this end, it is important for LEMs to be connected to the centralized energy grids for purposes of energy reserves and let the consumers to have a choice of multiple energy providers.

Another challenge is the limited growth of LEMs. In the recent years real LEMs have become more popular both in the research and real-life projects but are still mostly represented through pilot projects and single case studies. In order to play a significant role in the current and future sustainable and renewable energy policies, they need attention and interest from general population as well (D'Alpaos and Andreolli 2020; Pressmair et al. 2021; Zia et al. 2020).

This limited growth of LEMs can partly be explained through the lack of legal framework (Zia et al. 2020). In some countries, there are no specific laws or policies allowing local energy trading in general or LEMs in particular. In other countries only certain aspects of local energy trading are prohibited. For example, in some European states it is not allowed to export self-generated energy through the existing energy grid or to combine energy generation with energy storage facilities on the customer premises (Mendes et al. 2018). Other legal barriers limit the possibility of creating representative LEM projects. According to the European Union legal energy obligations, it is not possible to create or to host a LEM without possibility for its consumers to access at least one more energy provider. That creates the problem of uncertainty of the amount and source of the energy consumed by participants in a specific local energy trading setting (Waal et al. 2020).

Although these regulations are aimed to avoid any blackouts or safety issues in isolated communities, this still slows down many LEM studies that could provide sufficient data for creating real life functioning local energy communities. In the recent years, however, several countries, including the Netherlands and the UK, have introduced "regulatory sandboxes" that allow temporary derogation of some rules in order to run a fully representative and controlled experiment with decentralized and sustainable electricity. This has also attracted some researchers to study such regulation (Waal et al. 2020).

Finally, a significant challenge of the LEM model is the volatility of the energy it produces. Because most LEMs are based on renewable energy, the energy they generate is highly volatile. In LEM study cases that used solar panels as main energy generators the electricity production in the winter months was up to 5 times less than in spring and summer. On top of that, it is important to remember that there is no solar power at night which reduces the time window when energy can be generated. That all led to the problem that energy reserves in winter had no energy left, while in the summer months they were up to 90% full and could not save the excessive energy produced (Priyadarshini et al. 2020; Sjöstrand and Zäther 2017).

Needless to say that the seasonal and even daily volatility is true for other renewable energy sources like wind (Zhang et al. 2020). LEMs based on other renewable sources like thermal or hydro energy are still much less studied and the research does not yet provide good study cases or experiments that would have reliable data to study. One of the reasons for that is the fact that such natural resources like large and powerful water or thermal reserves are usually too big to be used or integrated into one local community and are often already in use by the local government for bigger regions (Hennig and Harlan 2018).

The researchers emphasize that energy volatility entails price volatility for LEM consumers as well, creating time periods with rather high electricity prices (Greenberg et al. 2021; Vespermann et al. 2021). It should be mentioned that the same is true for the integration of the renewable energy into centralized energy markets as well (Koolen et al. 2021). Nonetheless, the uncertainty of LEMs' energy output can partly be solved by investing into local energy storages that can save the energy on generation peaks and use it when the generation slows down (Zhao et al. 2020). In fact, recent LEM market design research shows that those prosumers who invest into an efficient storage system can benefit from decreased energy and cost volatility personally and share these benefits across other LEMs participants by selling their storage rights or providing more stability into energy trading (Vespermann et al. 2021).

The final overview of LEM challenges is presented in the Table 2. It consists of the challenges themselves, stakeholders that are affected the most by them and the corresponding publications that are dedicated to them.

Table 2 LEM challenges overview

LEM challenges	Stakeholders that are affected the most	Reference
Incompatibility with centralized grids	Prosumers, local energy companies, distribution stakeholders	D'Alpaos and Andreolli (2020), Ma et al. (2021), Meeuw et al. (2018)
Limited growth and too few functioning LEMs	Consumers	D'Alpaos and Andreolli (2020), Pressmair et al. (2021), Zia et al. (2020)
Unclear regulation and lack of legal framework	Consumers, prosumers	Mendes et al. (2018), Waal et al. (2020), Zia et al. (2020)
Energy volatility	Consumers	Hennig and Harlan (2018), Priyadarshini et al. (2020), Sjöstrand and Zäther (2017), Zhang et al. (2020)
Price volatility	Consumers	Greenberg et al. (2021), Vespermann et al. (2021a, b), Zhao et al. (2020)

4 The Status of LEMs in the Existing Market Structure

Even though actively functioning LEM communities are yet represented in small quantities, it is still important to study their role in the existing energy market structure. Two dimensions that have been mainly addressed earlier are first the goal of different LEMs in current energy markets and second their legal status.

4.1 Role of LEMs

Much like in a traditional market, different kind of energy can be produced and traded in a LEM. For instance, one of the most common forms of energy traded and consumed in private households would be electricity that is used for multiple purposes like lighting, appliances, and electronics. Other forms, such as heat that is used for space and water heating, must be generated first, and is traded separately. Both of these energy types were expected and considered as essential by early LEM scholars (Block et al. 2008; Kamrat 2001).

Some real-life LEM implementations utilize this design and are able to provide both electricity and heat to their consumers (Brolin and Pihl 2020; Richter et al. 2019). Though in most of the LEM projects, the main transactional object is limited to electricity only (Ableitner et al. 2019; Honarmand et al. 2021; Shrestha et al. 2019). One of the possible explanations for this trend could be that demand and production of electricity is generally much higher than of heat. For instance, annual electricity consumption in Sweden in 2016 was 130.1 TWh, whereas total heating consumption for the same year reached only 51.4 TWh (Brolin and Pihl 2020). Similar ratio can also be found in Germany, Italy, Norway, Portugal, and other European countries (Askeland et al. 2019; Bellocchi et al. 2019; Figueiredo et al. 2019). Another reason is lower demand for buying heat, less stakeholders want to invest in such LEMs, rather focusing on electricity trading (Fuentes González et al. 2021). Eventually, it must be noted that not all the space heating is done directly via heat energy rather through electricity such as heating boilers, heat pumps, or similar heating systems which significantly raise electricity consumption (Monie et al. 2020). For example, at the Norwegian energy market up to 53% of all the heating is made via electric heating (Askeland et al. 2019).

Heat and electricity balance has not been intensively studied and explained yet. The fact that there are just too few LEM projects that have heat prosumers further inhibits the research in this direction. That might change in the future due to a couple of factors. In the recent publications it has been demonstrated that the heat production in LEMs can be financially feasible for trading agents and prosumers following certain market models (Davoudi and Moeini-Aghtaie 2022). Moreover, trading multiple energy forms (like heat and electricity) in the same LEM can contribute to market synergies and efficiency of usage of energy resources (Brolin and Pihl 2020) and help balancing fluctuation of energy production (Siano et al. 2019).

Considering functions that LEMs have in the current centralized energy markets, a few of them can be named:

1. As most of the LEM implementations demonstrate, their market focus is oriented towards private households, leaving such areas like industry, public sector or agriculture out of its sight (Figueiredo et al. 2019). Decarbonization of industry, for example, is a complex problem that does not have any clear solutions just yet. Taking into consideration that it accounts for 40% of global energy demand and about quarter of CO_2 emissions, this problem attracts a lot of scientific attention and is being actively studied. Some researchers suggest that a viable solution to this challenge could be a concept, similar to the LEM one, that is applied to local industrial clusters (IEA 2019; Igogo et al. 2021; Pierri et al. 2021).
2. In volatile renewable energy markets it is vital to have enough reserves that can be activated at critical time periods. This support role can be fulfilled by LEMs that can sell their reserves or overproduced capacities to the centralized markets (Firoozi et al. 2020; Zhang et al. 2021). One of the designs for an interaction between a LEM and centralized energy markets is proposed and implemented through the balancing markets system (Firoozi et al. 2020). It consists of balancing service providers, an energy community management centre, a LEM, a balancing and a centralized energy market. The management centre is focused on tracking energy reserves of LEMs. It transports this information to the balancing service provider that accepts LEM prosumers' energy bids (amount of money that prosumers want to sell a specific amount electricity for) and places them on the balancing market. Finally, the balancing market is the marketplace where the bids and asks (amount of money that consumers want to buy a specific amount

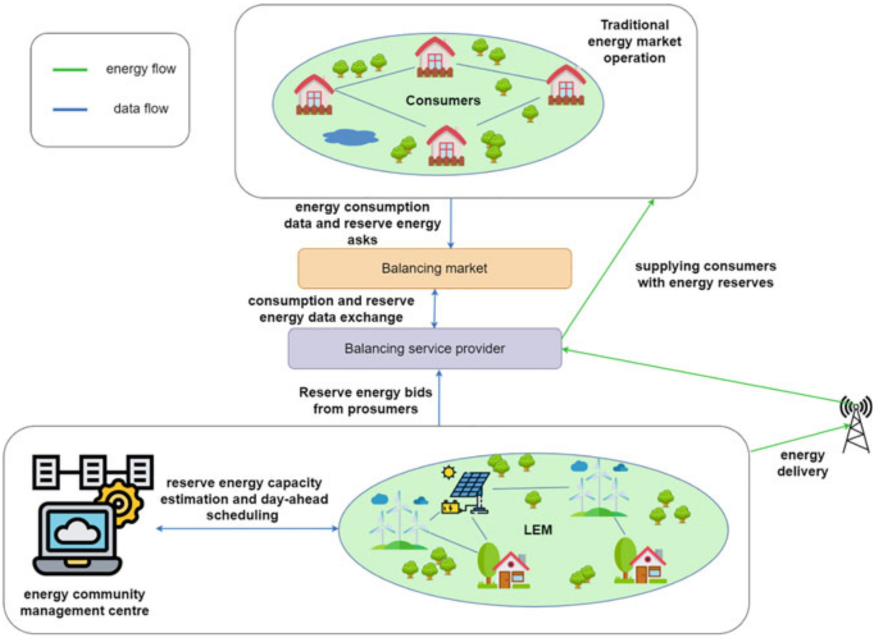


Fig. 3 Interaction between centralized energy market and a LEM for energy reserves trading purposes

electricity for) from the centralized market are compared, and, finally, the energy exchange happens through balancing service provider. This process is visualized in Fig. 3.

3. Scholars tend to think that in the near future LEMs will operate in parallel with existing centralized energy markets without any serious competition to them (Mengelkamp et al. 2019c; Zhou et al. 2020). Although LEMs are intended to compete with such markets, their limitations and slow expansion at the moment do not allow them to conquer a bigger market share (Schmitt et al. 2019; Shrestha et al. 2019). In the recent years, there has not been much progress here. Some researchers, for example (Mureddu et al. 2020), believe that this situation is not going to be improved in the foreseeable future. They are of opinion that besides the slow expansion and typical grid problems, LEMs lack of automated energy trading and management systems. In their research they have proposed a possible solution by automating LEM's processes with the help of the Internet of Things (IoT).

4.2 Regulation

One of the contributing factors for the delayed growth of LEMs is its regulation by the local authorities (Pressmair et al. 2021). Considering that direct and strict government control over the energy market was the standard practice around the world for many years, early LEM researchers expected that new market concepts in this area would attract the same authorities' attention and be regulated as well (Hvelplund 2004; Kamrat 1999, 2001).

The legal foundation for LEMs is based upon independent power producer (IPP) or non-utility generator (NUG) entities. During the 1990s energy market liberalization, many countries (USA, Canada, India, Turkey, France, Italy, etc.) allowed independent energy production by private companies and individuals. This deregulation had helped many private companies to enter the market but did not attract significant amount of single or small IPPs (Kamrat 2001; Woolf and Halpern 2001). The researchers pointed out that energy markets, especially ones based on renewable energy, had many barriers on various levels and overall just too complicated and expensive to enter for smaller prosumers or local communities (Fouquet 2013). Few local markets had to work together with private companies or directly buy energy from them, which did not allow them to create a full cycle LEM (Moner-Girona 2009).

Despite the legality of independent energy production in many countries, the current regulation level of LEMs does not encourage their development or make their existence easier than before. Recent publications point out that nowadays regulatory schemes are primarily based on the conventional power system designs (Lin and Wang 2022; Zhou et al. 2020) and the current regulation drawbacks are listed as follows:

1. It is still often unclear which market designs are allowed on different authority levels (e.g., national, or regional). In some cases, authorities do not keep up with technological advancement and do not respond in a timely manner with new laws for P2P and LEM energy trading (Ahl et al. 2019; Tushar et al. 2018). Some scholars, for example (Tushar et al. 2018), argue that by not adopting new policies for P2P trading and supporting local energy production, the governments around the world do not only ignore such emerging markets but also discourage their development and implementation. By not taking actions for regulating LEMs and P2P, they risk to negatively affect the traditional energy system in general.
2. The pricing and taxing mechanisms are often not adjusted for LEMs or even renewable energy markets. For instance, traditional energy prices include a significant tax and surcharges part which is not present in renewable energy due to its marginal cost (Tushar et al. 2018).
3. The investment threshold to acquire a prosumer utility set to start a LEM is quite high. The same can be true for the rate of return for investments in LEMs. Without any government incentives or a ready market, new prosumers are reluctant to engage into LEMs (Cali and Çakir 2019; Morstyn et al. 2018). This situation has not got any better worldwide in the recent years as no radical changes in the

legislation or regulation of P2P energy trading has been witnessed (Zhou et al. 2020).

Overall, it is sufficient to say that specific LEM regulation policies still remain a research gap as there is just not enough projects data, real legal documents, or sources to study. Nevertheless, there is still one research direction that is being actively studied here—policy suggestion. The overall consensus is that it is absolutely vital to fit LEMs into current energy legal systems in order to let them be widely implemented (Dobravec et al. 2021; Ford et al. 2021; Kona et al. 2019; Lin and Wang 2022; Tushar et al. 2018).

Possible policies that are suggested by the recent research are:

(a) To legally define the role, status, responsibilities, and limitations of P2P energy trading and LEMs;
(b) Agree upon clear and appropriate tax and fee systems for such markets;
(c) Offer incentives in forms of direct and indirect support for new and existing prosumers and consumers in LEMs;
(d) Generate legal protection for vulnerable customers;
(e) Incorporate new blockchain technology scenarios in such markets into these regulations (Diestelmeier 2019; Mello et al. 2020; Zhou et al. 2020).

There is a number of detailed theoretical models developed by the scholars around the world that are ready to be implemented and transformed into a real LEM as soon as it becomes possible or supported by local authorities (An et al. 2020; Demidov et al. 2020; Jordan et al. 2018; Stańczak and Radziszewska 2018).

For example, a successfully implemented LEM pilot project in Namibia by Demidov et al. (2020) shows that a similar P2P energy exchange platform could be developed in many other rural African countries. It utilizes a solar off-grid system and is able to provide a stable and cheap energy output with only 12 solar panels, 3 batteries and the P2P management system developed by the authors. The missing components for the wider usage of such LEMs are the initial investment in the utility grid and the operational costs, which are too high for the local residents. This and similar concepts could be developed and implemented with government incentives or other kind of support.

5 Features of Blockchain-Based LEMs

5.1 Definition and Concept

In the last section of this chapter, blockchain-based LEMs and blockchain implementation in such markets is covered. To this end, following problems are being discussed: (a) the definition of blockchain technology (b) the potential need of LEM for blockchain, (c) the application blockchain in LEM, (d) benefits and challenges of blockchain in LEM and, (e) the legal status of blockchain-based LEMs.

In a top-down centralized energy system, all transactions, supply, demand, and user data are collected, managed, and stored by the energy providers. In LEMs, however, all these data should be managed directly by the market participants: consumers and prosumers. Beside the data, LEMs participants need a way of clearing and paying for the energy transactions in a transparent, reliable, and secure manner (Kirpes et al. 2019). The blockchain concept can be extremely handy in such a situation. The core idea is to have shared and distributed database to be used, updated, and controlled in a decentralized way by all its participants. None of users have an authority role to manipulate the database. Yet it allows decentralized transactions with different data structures to be completed transparently and safely without any 3rd parties' support (Andoni et al. 2019). The implementation of such structure may raise some concerns on costly investment of necessary software and hardware. This may lead to grow the tendency to establish distributed market, however, it implies losing the security, and privacy features which causes additional costs (Andoni et al. 2019; Blom and Farahmand 2018).

The first theoretical use of blockchain technology for P2P energy trading was suggested in 2014 (Mihaylov et al. 2014). The first real application in the energy sector was done by BAS Nederland and a couple other energy providers from the Netherlands in 2017 that started to accept Bitcoin as payment for their energy bills (Andoni et al. 2019). Despite active academic research on adoption of blockchain technology in the energy markets, it has had a long way to a real empirical data study.

Currently, the general energy market research has just recently moved forward from theoretical concepts to the first limited and experimental blockchain projects (Enescu et al. 2020; Esmat et al. 2021; Wörner et al. 2019). The same development can be observed in the LEM context. Until 2020, the research has been limited to market feasibility analysis (Blom 2018; Mengelkamp et al. 2017; Yin et al. 2021), and theoretical models/proof-of-concepts of blockchain implementations (Kirpes et al. 2019; Meeuw et al. 2020; Mengelkamp et al. 2018). However, in 2021 a first completely blockchain-based LEM was developed and implemented in Switzerland

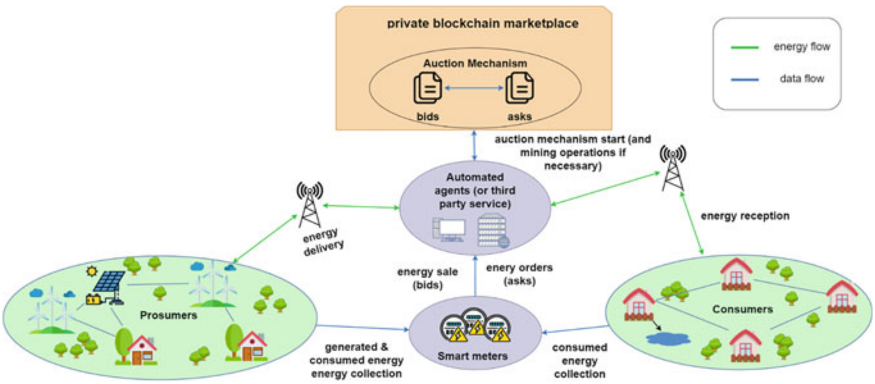


Fig. 4 A typical blockchain-based LEM overview

(Strepparava et al. 2022). As other first pilot projects' and real uses-cases' results are out. Some of the projects are studied in detail in Sect. 6. A typical blockchain-based LEM model is demonstrated in the Fig. 4.

5.2 Advantages

One of the main benefits that the blockchain technology provides is the ability of setting up decentralized markets which is free from any intermediaries or 3rd party agents. In other words, all the technical features of the P2P energy trading process that are needed to create a LEM such as consensus mechanism, placing and fulfilling bid and ask orders, agent identification, and payment method are provided through the blockchain technology. In case of payment transactions two models are possible: (a) mining the cryptocurrency by consumers which of course causes more energy consumption, (b) purchasing with real local currency and then exchanging for the cryptocurrency.

Additional Application Program Interface (API) or software may still be needed to automate other LEM processes. Two examples are: (a) to connect smart meters that register energy consumption and transmit potential demand to the virtual marketplace, (b) establishing smart contracts for an automated order or sale of energy (Hermann 2019; Mengelkamp et al. 2018).

Other advantages of this technology for LEMs are transparency, reliability, and equality of all the market participants. With the help of blockchain, the energy prices can be determined by consumers' demand and prosumers' supply. All the participants of the market are equal in these terms, and nobody has a control over the price regulation. Moreover, if a marketplace has been correctly designed and implemented, all the LEM agents can rely on the system in terms of integrity of energy data, money flow, security of their transactions, and currency they are cleared with. All of these processes are stored in the transaction log which makes it possible to trace and check all the cleared energy trading in the past (Kirpes et al. 2019; Khalid et al. 2020; Meeuw et al. 2020; Mengelkamp et al. 2018).

Some scholar pointed out that using blockchain-based LEMs causes lower transaction costs due to the absence of 3rd party agents (Mengelkamp et al. 2018; Mengelkamp et al. 2018). Others, however, disagree and believe that such transaction cost decrease greatly depends on the consensus mechanism design (i.e., a design that regulates who and how can create new blocks in the database and the complexity of these processes). For instance, LEMs with Proof-of-Work (PoW) consensus mechanism have even higher transaction costs than LEMs that are not based around blockchain. These costs are connected to the amount of energy that has to be spent for mining the required amount of cryptocurrency and organize all of the transactions (Heck et al. 2021; Strepparava et al. 2022).

The recent data from the first fully blockchain-based LEM also suggests that blockchain technology contributes to balancing energy production and consumption. It helps to correctly estimate future supply and demand offering price stability to LEM customers. This balance can be explained by the freedom of choice in such markets as customers can easily switch to other prosumers in case their prices would become too high. That creates a natural competition for prosumers (Strepparava et al. 2022).

Finally, the Strepparava et al. (2022) also demonstrates that with the help of blockchain and IoT it is not only possible to create a decentralized and secure, but also a user-friendly LEM. Indeed, this blockchain-based LEM shows a high degree of automation that is also accessible to a wide range of users. The energy consumption is monitored through smart meters, the data exchange and energy bids are implemented through smart contracts and the security of all the transactions is ensured by the blockchain. Considering potential provision of many technical features of such markets by blockchain platforms, the complexity of creating a blockchain-based LEM has significantly decreased.

5.3 Challenges

The main challenges of blockchain-based LEM market are observed as follows.

Firstly, the regulation of such LEMs is especially problematic. As shown in the previous chapter, the legal status of LEM and P2P energy trading is unclear in many countries and hinders further development. Similarly, the legal issues for blockchain technology are vague and incomplete. When both of them are combined together into a blockchain-based LEM, even more regulatory obstacles arise as both of those technologies have to be legal and clearly regulated in order for such markets to exist (Ahl et al. 2019; Mengelkamp et al. 2018; Strüker et al. 2019; Wu and Tran 2018). In the last two years there have been some improvements to this problem. Some countries have decided to provide their help and resources for such LEMs. For example, Switzerland has supported the two biggest blockchain-based LEM case studies so far (Ableitner et al. 2019; Strepparava et al. 2022). While other blockchain LEM case studies like (Mengelkamp et al. 2018) had to function under complicated legal restrictions or make some limitations to their projects in order to be able to implement. Both Zhao et al. (2020) and Mengelkamp et al. (2017) enjoyed the full support of the Swiss Federal Office of Energy. Such "legal sandboxes" certainly help the research of such LEMs. However, today they still remain rather a rare legal exception than a common trend.

Secondly, energy costs and security in a blockchain-based LEM can vary depending on the consensus mechanism. The two most commonly used ones are PoW and Proof-of-Authority (PoA). PoW requires a lot of computational power to solve a numerical problem to create a new block and perform a certain process (e.g., to mine a single piece of a cryptocurrency), high-performance hardware and consumes a significant amount of energy. In return, it offers a high degree of privacy and decentralization as the blockchain is "democratically" controlled by all the participants equally. On the other hand, PoA is designed in almost the opposite way and can be operated on low-performance hardware without a high energy and computational power consumption. Therefore, since the control over the blockchain is given to few responsible participants (authorities) in this method, blockchain have less decentralization and privacy.

One of the solutions to this problem is to implement new consensus mechanisms that are more balanced. For example, (Strepparava et al. 2022) used Proof-of-Stake mechanism that has found a compromise between security and energy consumption by allowing specific users, who already control significant parts of the blockchain, to decide on the new blocks. It is, so far, the first implementation of such consensus mechanism for blockchain-based LEMs which has also demonstrated its efficiency by establishing fully functioning LEM with rather low hardware requirements and energy resources needed.

6 Existing LEM Projects

A summary of already implemented LEM projects are discussed in this section. This provides a better understanding of theoretical concepts discussed in previous sections in real-world experiments.

6.1 Walenstadt Community Microgrid

One real-world implementation for a local energy market with a blockchain based P2P marketplace is the Walenstadt community microgrid (Meeuw et al. 2020). The Walenstadt community microgrid is a field project, where 37 households participate in a LEM. 25 out of 37 households are prosumers, 8 prosumers can store energy, and 2 apartments have installed Photovoltaics (PV). Every entity who participates in the LEM, by either consuming, producing or storing energy is equipped with a Raspberry Pi SBCs computing device accumulating to a total of 75 devices. These computing devices act as smart metering devices and are running the blockchain application. Not every computing device has the same function. Every participant in the system runs the agent software, which measures their preferences and transforms them into orders. However, only prosumers and other energy production entities also run a validator node of the blockchain, which execute the clearing and settling of the application.

To trade the locally produced energy, participants are provided with a web-app, where they can define their buy/sell prices and see an overview of their consumed and produced energy. Figure 5 shows the phases the market application goes through.

The first phase is the bidding phase. In this phase the connected agents can submit their orders to the orderbook. A transaction includes information like buy/sell price and amount of energy. The blockchain checks the transaction, forwards it to the market application, where it gets validated. If everything is correct the order is added to the stash of orders. The next phase is the clearing phase. Here every 15 min a clearing interval is triggered by the application. In the clearing phase the orderbook

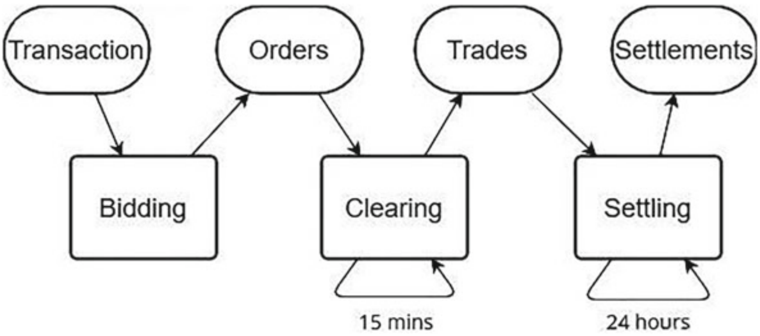


Fig. 5 Flow of information through the market application

is cleared and orders are transformed into trades among the participants. The last phase is the settling phase. Every 24 h the accumulated trades of the past period are aggregated into a list to manage automated payments and billing purposes.

6.1.1 Technical Details

The minimum required transactions per seconds (tps) are >0.1, with 75 devices participating and a 900 s clearing interval. The number of validators plays a significant role in capabilities of transactions per second and latency, while a higher degree of validators increases decentralization, it simultaneously decreases tps and increases latency. Measurements conclude that the 27 validators in the microgrid achieve a transaction throughput 8 times higher than the need and a latency of 12 s.

The application is built in JavaScript and runs on the NodeJs environment, and the limits of the computation device are dependent on the efficiency of the implementation. The blockchain uses the tendermint consensus mechanism, which allows the application to work even if up to one third of the validators are faulty.

6.1.2 Application Tests

The market application was tested in several ways, to find out how bandwidth and degree of decentralization affect throughput rate and latency.

One test investigated the tps limits at low to medium decentralization (1–12 validators) at data rates ranging from 50 to 750 kbit/s. The highest tps of 10.5 was achieved with one validator at a data rate of 150 kbit/s, from there on the higher data rate limits do not affect the tps capabilities substantially in the case of one validator. With higher degrees of decentralization, the tps decreases. Lower degrees of decentralization (1–4 validators) achieve tps of 5–10 at 350 kbit/s, while medium degrees of decentralization do not achieve a stable network under 250 kbit/s.

Another test performed at low to high degrees of decentralization (1–64 validators) with high data rate limits from 1000 kbit/s to no limit. All test configurations offered a stable network. The impact of data rates on low decentralization (1–8 validators) was not substantial. At medium degrees of decentralization, however, data rate had an impact on tps so that a 32-validator system required 2000 kbit/s to process over 1 tps. A 12-validator system also required a tps of 4 at that data rate. At high degrees of decentralization (48–64 Validators) the data rate does not impact the capabilities and the tps stays constant at 0.4.

Eventually, a test was conducted that observed the latency at maximum transactional throughput. As expected, the latency rises with the number of validators. The tests for 1–12 validators produced latencies of 1.2–9.8 s at data rates ranging from 50 to 750 kbit/s, and latency generally decreased with increasing data rate. Medium degrees of decentralization (12–40) achieve latencies ranging from 6.9 to 120.6 s. A 32-validator system has a latency of 20.2 s at 1000 kbit/s, however, the latency stays the same from 1500 kbit/s upwards at 10 s. A 40-validator system is more dependent on data rate, it has a latency of 120.5 s at 1000 kbit/s which lowers to 27.8 s at no limits. High degrees of decentralization (40–64 validators) always have higher latency that 100 s.

6.2 The LAMP Project

The LAMP project is another implementation of a local energy market in Landau, Germany (Gärttner et al. 2018). Similar to Walenstadt microgrid, participants can trade locally in P2P fashion using blockchain technology and are provided with an app to configure their trading activities.

The main objectives of the LAMP project are:

- Deployment of a blockchain based LEM under German Regulation,
- Analysis of German households' behaviour, acceptance, and participation towards LEM,
- Assessment of level of self-sufficiency, comparison between simulated or real local energy prices and actual green electricity prices.

6.2.1 Simulation of the Project

Before practical implementation, several simulations were conducted. The Simulation was structured as follows: 20 residential households based on randomized H0 consumption patterns and five PV 5 kWp systems based on German PV data were simulated. The locally produced energy is only an extension of the existing German electricity tariffs, so supply and stability are always assured.

Under the assumption that participants learn from their past trades, an algorithm was implemented that changes the probability to choose a definite price for their local electricity. The mean overall electricity price is approximately 0.24 €/kWh, which is only 94% of the original electricity tariff. However, the mean for only local electricity is 0.20 €/kWh.

Even if the price for only local electricity cannot be exploited due to temporal differences in production and demand, it means that there are opportunities to resolve this issue by storing energy or the introduction of more local generation.

6.3 The Brooklyn Microgrid

The Brooklyn microgrid is a project that consists of two main components, the virtual community energy market platform and the physical microgrid (Mengelkamp et al. 2018).

The virtual community energy market platform provides the technical infrastructure. It is based on a blockchain using the Tendermint protocol. It implements the TransActive Grid blockchain architecture and TransActive Grid smart meter. The physical microgrid is an addition to the existing distribution grid. It ensures safety in case of power outages and therefore can operate uncoupled from the traditional grid. However, the existing generation capacity is not able to balance energy supply and demand for a longer period (Mengelkamp et al. 2018).

The Microgrid uses the traditional grid run by the independent system operator Con Edison to aggregate the demand and supply. According to the website of the Brooklyn Microgrid (https://www.brooklyn.energy/) the DSO is balancing the loads.

Trading is mostly done automatically by the energy management system, as is only requires the participants information for preferred energy sources and price limits. However, the pricing mechanism still must be tested and changed to increase

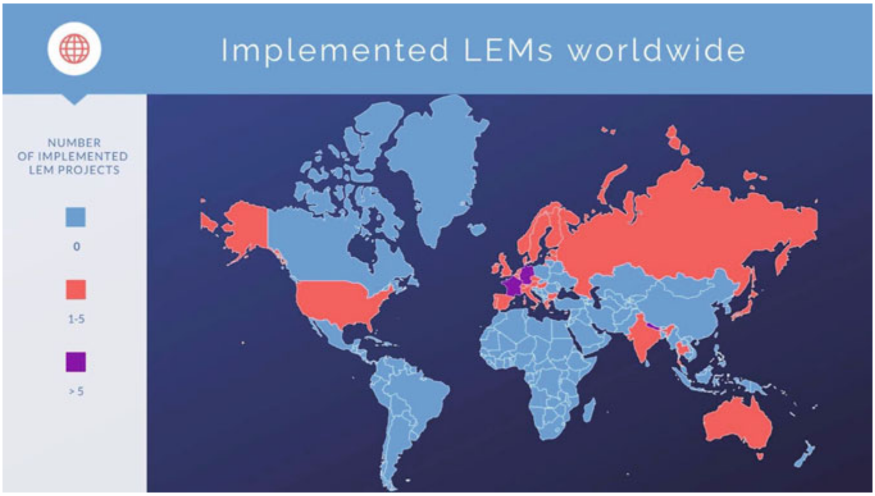


Fig. 6 Current or previously implemented LEM projects worldwide

efficiency, as is only a fixed price is charged. Moreover, the legal environment must adapt, because it is not yet allowed to directly trade P2P energy.

6.4 Other Current and Previous LEM Projects

A map of countries that had or currently have active LEM projects is presented in the Fig. 6.

7 Conclusions

The goal of this chapter was to conduct a systematic and structured review of LEMs. This chapter can be considered as the summary and the interpretation of the LEM research in recent years. There have been identified the four most important perspectives that are studied and discussed in the recent publications: the concept of a LEM, its benefits and challenges, its role in the existing energy market structure, and the blockchain-based LEM. The total of three new research gaps have been identified These gaps are listed as follows:

1. though we have received working mathematical models for the price elasticity, the research still lacks the real-world data from LEMs with high number of participants that could support the results of such models.
2. it is evident that not all the LEM stakeholders have the same amount of influence and decision power in terms of existence, further expansion, and overall development of the LEM concept. One of the most significant ones in these terms is the government and authorities that regulate LEMs. Despite the fact, that as of today very few changes have happened in the energy law concerning such markets, it is still important to follow this problem and study new "legal sandboxes" that might offer new regulatory perspectives.
3. blockchain-based LEMs still remain a research gap due to the low number of real use-cases and pilot projects. New studies here could confirm or deny the results of the first data on benefits, security, and the efficiency of blockchain technology for such markets.

These gaps could be used for the future research works to get improved.

References

Ableitner L, Meeuw A, Schopfer S, Tiefenbeck V, Wortmann F, Wörner A (2019) Quartierstrom—Implementation of a real world prosumer centric local energy market in Walenstadt, Switzerland. abs/1905.07242

Ahl A, Yarime M, Tanaka K, Sagawa D (2019) Review of blockchain-based distributed energy: implications for institutional development. Renew Sustain Energy Rev 107:200–211. https://doi.org/10.1016/j.rser.2019.03.002

An J, Lee M, Yeom S, Hong T (2020) Determining the Peer-to-Peer electricity trading price and strategy for energy prosumers and consumers within a microgrid. Appl Energy 261:114335. https://doi.org/10.1016/j.apenergy.2019.114335

Andoni M et al (2019) Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev 100:143–174. https://doi.org/10.1016/j.rser.2018.10.014

Askeland K, Bozhkova KN, Sorknæs P (2019) Balancing Europe: can district heating affect the flexibility potential of Norwegian hydropower resources? Renew Energy 141:646–656. https://doi.org/10.1016/j.renene.2019.03.137

Bellocchi S, Klöckner K, Manno M, Noussan M, Vellini M (2019) On the role of electric vehicles towards low-carbon energy systems: Italy and Germany in comparison. Appl Energy 255:113848. https://doi.org/10.1016/j.apenergy.2019.113848

Bisello A, Vettorato D (2018) 3.5—Multiple benefits of smart urban energy transition. In: Droege P (2018) Urban energy transition, 2nd edn. Elsevier, pp 467–490. https://doi.org/10.1016/B978-0-08-102074-6.00037-1

Block C, Neumann D, Weinhardt C (2008) A market mechanism for energy allocation in micro-CHP grids. In: Proceedings of the 41st annual Hawaii international conference on system sciences (HICSS 2008), pp 172–172. https://doi.org/10.1109/HICSS.2008.27

Blom F (2018) A feasibility study of blockchain technology as local energy market infrastructure. NTNU

Blom F, Farahmand H (2018) On the scalability of blockchain-supported local energy markets. In: 2018 international conference on smart energy systems and technologies (SEST), pp 1–6. https://doi.org/10.1109/SEST.2018.8495882

Bose S, Kremers E, Mengelkamp E, Eberbach J, Weinhardt C (2021) Reinforcement learning in local energy markets. Energy Inform 4. https://doi.org/10.1186/s42162-021-00141-z

Brolin M, Pihl H (2020) Design of a local energy market with multiple energy carriers. Int J Electr Power Energy Syst 118:105739. https://doi.org/10.1016/j.ijepes.2019.105739

Bushnell J, Wolak FA (2000) Regulation and the leverage of local market power in the California electricity market. SSRN Electron J. https://doi.org/10.2139/ssrn.503464

Cali U, Çakir O (2019) Energy policy instruments for distributed ledger technology empowered peer-to-peer local energy markets. IEEE Access 7:82888–82900. https://doi.org/10.1109/ACCESS.2019.2923906

Carley S (2009) Distributed generation: an empirical analysis of primary motivators. Energy Policy 37(5):1648–1659

CDP (2017) Cities emissions reduction targets, data retrieved from CDP Open Database. https://data.cdp.net/w/j5zb-bfpp/hh8z-a6hj?cur=e2_HtmDjl9r&from=2f6gp18cViN. Accessed 14 Dec 2021

Chen T, Su W (2018) Local energy trading behavior modeling with deep reinforcement learning. IEEE Access 6:62806–62814. https://doi.org/10.1109/ACCESS.2018.2876652

Cornélusse B, Savelli I, Paoletti S, Giannitrapani A, Vicino A (May 2019) A community microgrid architecture with an internal local market. Appl Energy 242:547–560. https://doi.org/10.1016/j.apenergy.2019.03.109

D'Alpaos C, Andreolli F (2020) The economics of Solar Home Systems: state of art and future challenges in local energy markets, Valori E Valutazioni, no 24. https://www.proquest.com/scholarly-journals/economics-solar-home-systems-state-art-future/docview/2529187630/se-2

Davoudi M, Moeini-Aghtaie M (2022) Local energy markets design for integrated distribution energy systems based on the concept of transactive peer-to-peer market. IET Gener Transm Distrib 16(1):41–56. https://doi.org/10.1049/gtd2.12274

Demidov I, Dibaba H, Pinomaa A, Honkapuro S, Nieminen M (2020) System platform enabling peer-to-peer electricity market model for off-grid microgrids in rural Africa. In: 2020 17th international conference on the European energy market (EEM), pp 1–6. https://doi.org/10.1109/EEM49802.2020.9221915

Diestelmeier L (May 2019) Changing power: Shifting the role of electricity consumers with blockchain technology—policy implications for EU electricity law. Energy Policy 128:189–196. https://doi.org/10.1016/j.enpol.2018.12.065

Dobravec V, Matak N, Sakulin C, Krajačić G (2021) Multilevel governance energy planning and policy: a view on local energy initiatives. Energy Sustain Soc 11(1):2. https://doi.org/10.1186/s13705-020-00277-y

Dudjak V et al (2021) Impact of local energy markets integration in power systems layer: a comprehensive review. Appl Energy 301:117434. https://doi.org/10.1016/j.apenergy.2021.117434

Enescu FM et al (2020) Implementing blockchain technology in irrigation systems that integrate photovoltaic energy generation systems. Sustainability 12(4). https://doi.org/10.3390/su12041540

Esmat A, de Vos M, Ghiassi-Farrokhfal Y, Palensky P, Epema D (2021) A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. Appl Energy 282:116123. https://doi.org/10.1016/j.apenergy.2020.116123

Etukudor C, Couraud B, Robu V, Früh W-G, Flynn D, Okereke C (2020) Automated negotiation for peer-to-peer electricity trading in local energy markets. Energies 13(4). https://doi.org/10.3390/en13040920

Figueiredo R, Nunes P, Meireles M, Madaleno M, Brito MC (2019) Replacing coal-fired power plants by photovoltaics in the Portuguese electricity system. J Clean Prod 222:129–142. https://doi.org/10.1016/j.jclepro.2019.02.217

Firoozi H, Khajeh H, Laaksonen H (2020) Optimized operation of local energy community providing frequency restoration reserve. IEEE Access 8:180558–180575. https://doi.org/10.1109/ACCESS.2020.3027710

Ford R, Maidment C, Vigurs C, Fell MJ, Morris M (May 2021) Smart local energy systems (SLES): a framework for exploring transition, context, and impacts. Technol Forecast Soc Change 166:120612. https://doi.org/10.1016/j.techfore.2021.120612

Fouquet D (2013) Policy instruments for renewable energy–From a European perspective. Renew Energy 49:15–18

Fuentes González F, Webb J, Sharmina M, Hannon M, Pappas D, Tingey M (2021) Characterising a local energy business sector in the United Kingdom: participants, revenue sources, and estimates of localism and smartness. Energy 223:120045. https://doi.org/10.1016/j.energy.2021.120045

Gao H, Zhang F, Xiang Y, Ye S, Liu X, Liu J (2021) Bounded rationality based multi-VPP trading in local energy market: a dynamic game approach with different trading targets. CSEE J Power Energy Syst 1–12. https://doi.org/10.17775/CSEEJPES.2021.01600

Gärttner J, Mengelkamp E, Weinhardt C (2018) Decentralizing energy systems through local energy markets: the LAMP-Project

Georgilakis PS (2020) Review of computational intelligence methods for local energy markets at the power distribution level to facilitate the integration of distributed energy resources: state-of-the-art and future research. Energies 13(1):1–37. https://doi.org/10.3390/en13010186

Greenberg D, Byalsky M, Yahalom A (2021) Valuation of wind energy turbines using volatility of wind and price. Electronics 10(9). https://doi.org/10.3390/electronics10091098

He MM et al (2008) An architecture for local energy generation, distribution, and sharing. In: 2008 IEEE energy 2030 conference, pp 1–6. https://doi.org/10.1109/ENERGY.2008.4781028

Heck K, Mengelkamp E, Weinhardt C (2021) Blockchain-based local energy markets: decentralized trading on single-board computers. Energy Syst 12:1–16. https://doi.org/10.1007/s12667-020-00399-4

Heendeniya CB, Sumper A, Eicker U (2020) The multi-energy system co-planning of nearly zero-energy districts—Status-quo and future research potential. Appl Energy 267:114953. https://doi.org/10.1016/j.apenergy.2020.114953

Hennig T, Harlan T (2018) Shades of green energy: geographies of small hydropower in Yunnan, China and the challenges of over-development. Glob Environ Change 49:116–128. https://doi.org/10.1016/j.gloenvcha.2017.10.010

Hermann A et al (2019) Blockchain in decentralized local energy markets. In: Enterprise interoperability VIII, Cham, pp 239–248

Hoicka CE, MacArthur JL (2018) From tip to toes: mapping community energy models in Canada and New Zealand. Energy Policy 121:162–174. https://doi.org/10.1016/j.enpol.2018.06.002

Honarmand ME, Hosseinnezhad V, Hayes B, Siano P (2021) Local energy trading in future distribution systems. Energies 14(11):1–19. https://doi.org/10.3390/en14113110

Hu J, Bhowmick P (2020) A consensus-based robust secondary voltage and frequency control scheme for islanded microgrids. Int J Electr Power Energy Syst 116:105575. https://doi.org/10.1016/j.ijepes.2019.105575

Hvelplund F (2006) Renewable energy and the need for local energy markets. Double special issue 2nd Dubrovnik conference sustainable development of energy, water and environment systems/03 PRES 2004 process integration modelling and optimisation for energy saving and pollution reduction, vol 31, no 13, pp 2293–2302. https://doi.org/10.1016/j.energy.2006.01.016

IEA (2019) Transforming Industry through CCUS. International Energy Agency

Igogo T, Awuah-Offei K, Newman A, Lowder T, Engel-Cox J (2021) Integrating renewable energy into mining operations: opportunities, challenges, and enabling approaches. Appl Energy 300:117375. https://doi.org/10.1016/j.apenergy.2021.117375

Jordan EA, Kusakana K, Bokopane L (2018) Prospective architecture for local energy generation and distribution with peer-to-peer electricity sharing in a South African context. In: 2018 open innovations conference (OI), pp 161–164. https://doi.org/10.1109/OI.2018.8535971

Kamrat W (1999) Methodology of investment effectiveness evaluation in the local energy market, pp 1–12

Kamrat W (2001) Modeling the structure of local energy markets. IEEE Comput Appl Power 14(2):30–35. https://doi.org/10.1109/67.917583

Kamrat W (2002) Investment risk forecasting in a local energy market. Energy Convers Manag 43(4):515–522. https://doi.org/10.1016/S0196-8904(01)00029-2

Ketter W, Collins J, Reddy P (2013) Power TAC: a competitive economic simulation of the smart grid. Ener Econ 39:262–270

Ketter W, Peters M, Collins J, Gupta A (2016) A multiagent competitive gaming platform to address societal challenges. Mis Q 40(2):447–460

Ketter W, Collins J, Saar-Tsechansky M, Marom O (2018) Information systems for a smart electricity grid: emerging challenges and opportunities. ACM Trans Manag Inf Syst TMIS 9(3):1–22

Khalid R, Javaid N, Almogren A, Javed MU, Javaid S, Zuair M (2020) A blockchain-based load balancing in decentralized hybrid P2P energy trading market in smart grid. IEEE Access 8:47047–47062. https://doi.org/10.1109/ACCESS.2020.2979051

Khorasany M, Mishra Y, Ledwich G (2018) Market framework for local energy trading: a review of potential designs and market clearing approaches. IET Gener Transm Distrib 12:5899–5908. https://doi.org/10.1049/iet-gtd.2018.5309

Kirpes B, Mengelkamp E, Schaal G, Weinhardt C (2019) Design of a microgrid local energy market on a blockchain-based information system. It Inf Technol 61. https://doi.org/10.1515/itit-2019-0012

Kona A, Bertoldi P, Kılkış Ş (2019) Covenant of mayors: local energy generation, methodology, policies and good practice examples. Energies 12(6). https://doi.org/10.3390/en12060985

Koolen D, Bunn D, Ketter W (2021) Renewable energy technologies and electricity forward market risks. Energy J 42(4). https://doi.org/10.5547/01956574.42.4.dkoo

Lin Y, Wang J (2022) Realizing the transactive energy future with local energy market: an overview. Curr Sustain Energy Rep. https://doi.org/10.1007/s40518-021-00198-0

Liu N, Yu X, Wang C, Li C, Ma L, Lei J (2017) Energy-sharing model with price-based demand response for microgrids of peer-to-peer prosumers. IEEE Trans Power Syst 32(5):3569–3583. https://doi.org/10.1109/TPWRS.2017.2649558

Lund H, Münster E (2006) Integrated energy systems and local energy markets. Ener Policy 34:1152–1160. https://doi.org/10.1016/j.enpol.2004.10.004

Ma L, Wang L, Liu Z (2021) Multi-level trading community formation and hybrid trading network construction in local energy market. Appl Energy 285:116399. https://doi.org/10.1016/j.apenergy.2020.116399

Meeuw A et al (2020) Implementing a blockchain-based local energy market: Insights on communication and scalability. Comput Commun 160:158–171. https://doi.org/10.1016/j.comcom.2020.04.038

Meeuw A, Schopfer S, Ryder B, Wortmann F (2018) LokalPower: enabling local energy markets with user-driven engagement. In: Extended abstracts of the 2018 CHI conference on human factors in computing systems, New York, NY, USA, pp 1–6. https://doi.org/10.1145/3170427.3188610

Mello J, Villar J, Bessa RJ, Lopes M, Martins J, Pinto M (2020) Power-to-Peer: a blockchain P2P post-delivery bilateral local energy market. In: 2020 17th international conference on the European energy market (EEM), pp 1–5. https://doi.org/10.1109/EEM49802.2020.9221901

Mendes G, Nylund J, Annala S, Honkapuro S, Kilkki O, Segerstam J (2018) Local energy markets: opportunities, benefits, and barriers. AIM. https://doi.org/10.34890/443

Mendes G, Ferreira JR, Albuquerque S, Trocato C, Kilkki O, Repo S (2019) Pushing the transition towards transactive grids through local energy markets. AIM. https://doi.org/10.34890/183

Mengelkamp E, Notheisen B, Beer C, Dauer D, Weinhardt C (2018) A blockchain-based smart grid: towards sustainable local energy markets. Comput Sci Res Dev 33:1–8. https://doi.org/10.1007/s00450-017-0360-9

Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C (2018) Designing microgrid energy markets: a case study: the Brooklyn Microgrid. Appl Energy 210:870–880. https://doi.org/10.1016/j.apenergy.2017.06.054

Mengelkamp E, Schoenland T, Huber J, Weinhardt C (2019a) The value of local electricity—a choice experiment among German residential customers. Energy Policy 130:294–303. https://doi.org/10.1016/j.enpol.2019.04.008

Mengelkamp E, Diesing J, Weinhardt C (2019b) Tracing local energy markets: a literature review. It Inf Technol 61(2–3):101–110. https://doi.org/10.1515/itit-2019-0016

Mengelkamp E, Schlund D, Weinhardt C (2019c) Development and real-world application of a taxonomy for business models in local energy markets. Appl Energy 256:113913. https://doi.org/10.1016/j.apenergy.2019.113913

Mengelkamp E, Gärttner J, Weinhardt C (2017) The role of energy storage in local energy markets. https://doi.org/10.1109/EEM.2017.7981906

Mihaylov M, Jurado S, Avellana N, Van Moffaert K, de Abril IM, Nowé A (2014) NRGcoin: virtual currency for trading of renewable energy in smart grids. In: 11th international conference on the European energy market (EEM14), pp 1–6. https://doi.org/10.1109/EEM.2014.6861213

Moner-Girona M (May 2009) A new tailored scheme for the support of renewable energies in developing countries. Energy Policy 37(5):2037–2041. https://doi.org/10.1016/j.enpol.2008.11.024

Monie SW, Nilsson AM, Åberg M (2020) Comparing electricity balancing capacity, emissions, and cost for three different storage-based local energy systems. IET Renew Power Gener 14(19):3936–3945

Morstyn T, Farrell N, Darby SJ, McCulloch MD (2018) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat Energy 3(2):94–101. https://doi.org/10.1038/s41560-017-0075-y

Mourik RM, Sonetti G, Robison RAV (2021) The same old story – or not? How storytelling can support inclusive local energy policy. Energy Res Soc Sci 73:101940. https://doi.org/10.1016/j.erss.2021.101940

Mousavi F, Nazari-Heris M, Mohammadi-ivatloo B, Asadi S (2021) Energy market fundamentals and overview 1–21. https://doi.org/10.1016/B978-0-12-820095-7.00005-4

Mueller IM, Dornmair R (2017) The European energy system 2050—A review of current pathways for renewable and conventional technologies in Europe. In: International ETG congress 2017, pp 1–6

Mureddu M, Galici M, Ghiani E, Pilo F (2020) A decentralized market solver for local energy communities. In: 2020 55th international universities power engineering conference (UPEC), pp 1–6. https://doi.org/10.1109/UPEC49904.2020.9209855

Ostadijafari M, Jha RR, Dubey A (2021) Demand-side participation via economic bidding of responsive loads and local energy resources. IEEE Open Access J Power Energy 8:11–22. https://doi.org/10.1109/OAJPE.2020.3035536

Park L, Jeong S, Kim J, Cho S (2019) Joint geometric unsupervised learning and truthful auction for local energy market. IEEE Trans Ind Electron 66(2):1499–1508. https://doi.org/10.1109/TIE.2018.2849979

Piderit MB, Vivanco F, van Moeseke G, Attia S (2019) Net zero buildings—a framework for an integrated policy in Chile. Sustainability 11(5). https://doi.org/10.3390/su11051494

Pierri E, Hellkamp D, Thiede S, Herrmann C (2021) Enhancing energy flexibility through the integration of variable renewable energy in the process industry. In: 28th CIRP conference life cycle engineering, Jaipur, India, vol 98, pp 7–12, 10–12 Mar 2021. https://doi.org/10.1016/j.procir.2020.12.001

Pires Klein L, Krivoglazova A, Matos L, Landeck J, de Azevedo M (2020) A novel peer-to-peer energy sharing business model for the Portuguese energy market. Energies 13(1). https://doi.org/10.3390/en13010125

Pressmair G, Kapassa E, Casado-Mansilla D, Borges CE, Themistocleous M (2021) Overcoming barriers for the adoption of local energy and flexibility markets: a user-centric and hybrid model. J Clean Prod 317:128323. https://doi.org/10.1016/j.jclepro.2021.128323

Priyadarshini L, Dash PK, Dhar S (May 2020) A new exponentially expanded robust random vector functional link network based MPPT model for local energy management of PV-battery energy storage integrated microgrid. Eng Appl Artif Intell 91:103633. https://doi.org/10.1016/j.engappai.2020.103633

Proka A, Hisschemöller M, Loorbach D (2020) When top-down meets bottom-up: Is there a collaborative business model for local energy storage? Energy Res Soc Sci 69:101606. https://doi.org/10.1016/j.erss.2020.101606

Rae C, Kerr S, Maroto-Valer MM (2020) Upscaling smart local energy systems: a review of technical barriers. Renew Sustain Energy Rev 131:110020. https://doi.org/10.1016/j.rser.2020.110020

Richter B, Mengelkamp E, Weinhardt C (2019) Vote for your energy: a market mechanism for local energy markets based on the consumers' preferences, p 6. https://doi.org/10.1109/EEM.2019.8916544

Schmitt C, Cramer W, Vasconcelos M, Thie N (2019) Impact of spot market interfaces on local energy market trading. In: 2019 16th international conference on the European energy market (EEM), pp 1–6. https://doi.org/10.1109/EEM.2019.8916248

Shrestha A et al (2019) Peer-to-Peer energy trading in micro/mini-grids for local energy communities: a review and case study of Nepal. IEEE Access 7:131911–131928. https://doi.org/10.1109/ACCESS.2019.2940751

Siano P, De Marco G, Rolán A, Loia V (2019) A survey and evaluation of the potentials of distributed ledger technology for peer-to-peer transactive energy exchanges in local energy markets. IEEE Syst J 13(3):3454–3466. https://doi.org/10.1109/JSYST.2019.2903172

Sjöstrand P, Zäther R (2017) Design and modeling of a local energy market. https://odr.chalmers.se/handle/20.500.12380/254821. Accessed 14 Dec 2021

Sorknæs P et al (2020) Smart energy markets—future electricity, gas and heating markets. Renew Sustain Ener Rev 119:109655. https://doi.org/10.1016/j.rser.2019.109655

Stańczak J, Radziszewska W (2018) Modeling of dynamic market of energy with local energy clusters. Control Cybern 47(2)

Stephant M, Abbes D, Hassam-Ouari K, Labrunie A, Robyns B (2021) Distributed optimization of energy profiles to improve photovoltaic self-consumption on a local energy community. Simul Model Pract Theory 108:102242. https://doi.org/10.1016/j.simpat.2020.102242

Strepparava D, Nespoli L, Kapassa E, Touloupou M, Katelaris L, Medici V (2022) Deployment and analysis of a blockchain-based local energy market. Energy Rep 8:99–113. https://doi.org/10.1016/j.egyr.2021.11.283

Strüker J, Albrecht S, Reichert S (2019) Blockchain in the energy sector. In: Treiblmaier H, Beck R (eds) Business transformation through blockchain: volume II, Springer International Publishing, Cham, pp 23–51. https://doi.org/10.1007/978-3-319-99058-3_2

Tomšič MG, Urbančič A (2000) Energy market opening and the national energy programme in Slovenia. Institut 'Jožef Stefan' 145–160. https://doi.org/10.1016/j.enpol.2004.10.004

Tushar W, Yuen C, Mohsenian-Rad H, Saha T, Poor HV, Wood KL (2018) Transforming energy networks via peer-to-peer energy trading: the potential of game-theoretic approaches. IEEE Sig Process Mag 35(4):90–111. https://doi.org/10.1109/MSP.2018.2818327

van Dinther C et al (2021) Engineering energy markets: the past, the present, and the future 113–134. https://doi.org/10.1007/978-3-030-66661-3_7

Vespermann N, Hamacher T, Kazempour J (2021) Access economy for storage in energy communities. IEEE Trans Power Syst 36(3):2234–2250. https://doi.org/10.1109/TPWRS.2020.3033999

Vespermann N, Hamacher T, Kazempour J (2021) Risk trading in energy communities. IEEE Trans Smart Grid 12(2):1249–1263. https://doi.org/10.1109/TSG.2020.3030319

Villa-Arrieta M, Sumper A (2019) Economic evaluation of nearly zero energy cities. Appl Energy 237:404–416. https://doi.org/10.1016/j.apenergy.2018.12.082

van der Waal EC, Das AM, van der Schoor T (2020) Participatory experimentation with energy law: digging in a "Regulatory Sandbox" for local energy initiatives in the Netherlands. Energies 13(2). https://doi.org/10.3390/en13020458

Woolf F, Halpern J (2001) Integrating independent power producers into emerging wholesale power markets, no. 2703. World Bank Publications

Wörner A, Meeuw A, Ableitner L, Wortmann F, Schopfer S, Tiefenbeck V (2019) Trading solar energy within the neighborhood: field implementation of a blockchain-based electricity market. Energy Inform 2(1):11. https://doi.org/10.1186/s42162-019-0092-0

Wu J, Tran NK (2018) Application of blockchain technology in sustainable energy systems: an overview. Sustainability 10(9). https://doi.org/10.3390/su10093067

Xu C, Lu W (May 2019) Development of smart microgrid powered by renewable energy in China: current status and challenges. Technol Anal Strateg Manag 31(5):563–578. https://doi.org/10.1080/09537325.2018.1524864

Yahaya AS et al (2020) Blockchain based sustainable local energy trading considering home energy management and demurrage mechanism. Sustainability 12(8). https://doi.org/10.3390/su12083385

Yin F et al (2021) A secured social-economic framework based on PEM-blockchain for optimal scheduling of reconfigurable interconnected microgrids. IEEE Access 9:40797–40810. https://doi.org/10.1109/ACCESS.2021.3065400

Zade M, Lumpp SD, Tzscheutschler P, Wagner U (2022) Satisfying user preferences in community-based local energy markets—auction-based clearing approaches. Appl Energy 306:118004. https://doi.org/10.1016/j.apenergy.2021.118004

Zhang C, Wu J, Zhou Y, Cheng M, Long C (2018) Peer-to-Peer energy trading in a microgrid. Appl Energy 220:1–12. https://doi.org/10.1016/j.apenergy.2018.03.010

Zhang Y, Gu C, Li F, Cheng S, Zhou B (2020) Energy procurement in local energy markets using portfolio theory for customers. In: 2020 IEEE power & energy society general meeting (PESGM), pp 1–5. https://doi.org/10.1109/PESGM41954.2020.9281621

Zhang Z, Li F, Park S-W, Son S-Y (2021) Local energy and planned ramping product joint market based on a distributed optimization method. CSEE J Power Energy Syst 7(6):1357–1368. https://doi.org/10.17775/CSEEJPES.2020.03220

Zhao D, Wang H, Huang J, Lin X (2020a) Storage or no storage: duopoly competition between renewable energy suppliers in a local energy market. IEEE J Sel Areas Commun 38(1):31–47. https://doi.org/10.1109/JSAC.2019.2951970

Zhou Y, Wu J, Long C, Ming W (2020b) State-of-the-art analysis and perspectives for peer-to-peer energy trading. Engineering 6(7):739–753. https://doi.org/10.1016/j.eng.2020.06.002

Zia MF, Benbouzid M, Elbouchikhi E, Muyeen SM, Techato K, Guerrero JM (2020) Microgrid transactive energy: review, architectures, distributed ledger technologies, and market analysis. IEEE Access 8:19410–19432. https://doi.org/10.1109/ACCESS.2020.2968402

Active Players in Local Energy Markets

Flora Charbonnier, Thomas Morstyn, and Malcolm McCulloch

1 Introduction

1.1 Motivation: The Emergence of Local Energy Markets

Power systems are undergoing a fundamental transition due to the rise of distributed ownership of energy resources at the edge of the electricity grid. Local energy markets are therefore emerging as coordination facilitators that can both help integrate higher shares of renewable energy and provide community benefits. This chapter presents the key active players in local markets, each with its own set of constraints and objectives. It then lays out a taxonomy of possible coordination mechanisms to help each participant reach their objectives as well as create value for energy systems and society.

The increased distribution of energy resources comes as a result of the switch away from traditional carbon-intensive energy generation technologies. Historically, the carbon-intensive electricity generation was centralised and dispatchable—any power imbalance in the electricity grid could be resolved by varying generation to match demand, simply by burning more coal, oil and gas when needed. However, to keep anthropogenic warming within 1.5 °C of pre-industrial levels, both electrification of primary energy provision and decarbonisation of power generation are necessary. Renewable energy could thus supply 70–85% of electricity globally by 2050 in 1.5 °C-compatible pathways[1] (Masson-Delmotte 2018). Beyond climate benefits, distributed solar and wind resources have a lower barrier to ownership due to the widespread distribution of resources, their modular nature and lower capital investment requirements. This means that the generation technology ownership is

F. Charbonnier (✉) · M. McCulloch
Department of Engineering Science, University of Oxford, Oxford, England
e-mail: flora.charbonnier@pmb.ox.ac.uk

T. Morstyn
School of Engineering, University of Edinburgh, Edinburgh, Scotland

[1] Interquartile range with no or limited overshoot (high confidence).

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_3

increasingly available for small, distributed owners in addition to traditional players. Moreover, intermittent and non-dispatchable generation needs to be matched by adequate distributed flexibility to maintain the electricity grid power balance, frequency stability and network constraints. This creates a need for demand-side response, which small distributed players can also provide.

Although a wealth of energy generation, storage and flexibility technologies exist and are being developed through all layers of the electricity grid, a key outstanding challenge is the coordination of these distributed energy resources at an unprecedented scale (Charbonnier et al. 2022). Local energy markets can provide such decentralised coordination and were defined in (Energy Systems Catapult 2019) as:

> initiatives to establish a marketplace to coordinate the generation, supply, storage, transport, and consumption of energy from decentralised energy resources (e.g. renewable energy generators, storage and demand-side response providers) within a confined geographical area.

Thanks to the use of information and communication technologies (ICT), local markets provide a framework for community-led development and asset coordination (Dudjak et al. 2021). Such markets can be instrumental in the local deployment of renewable energy as well as numerous associated benefits at the energy system, network management, and community levels (Council of European Energy Regulators 2019). At the energy system level, smart distributed flexibility coordination can be a substitute for additional investments in centrally managed types of flexibility such as peak generation capacity, electricity network capacity (for national or international imports) or large-scale storage, as generally 20% of the power generation capacity is underused but required to meet the peak demand 5% of the time (Haider et al. 2016). Smart distributed asset coordination can thus help limit the need for new generation, transmission and distribution grid investments and can promote energy security and independence. At the network management level, active players can participate in local markets to provide numerous services to each other and to the network operators, such as decentralised demand-side response and operational services like frequency management, spinning reserves provision, voltage regulation, system balancing and network congestion management (Abbas and Chowdhury 2021; Eid et al. 2016). At the community level, local markets can foster numerous community co-benefits for environment protection, reduced storage costs, alignment of demand with decarbonised energy provision in time and space, incentives for the contribution of numerous players in investment, reduced consumer bills, and social cohesion (Abrishambaf et al. 2019; European Commission 2016; Pumphrey et al. 2020; Siano 2014; Vázquez-Canteli and Nagy 2019).

1.2 Scope: The Make-Up of Local Energy Markets

Different types of distributed energy resources can be exploited in local markets, involving various existing and emerging players, and trading different products.

The types of energy resources considered in this chapter include storage units—either traditional standalone stationary batteries or intermittently available electric vehicle (EV) batteries—and other components of flexibility that may be conceptualised as virtual storage by shifting electricity consumption in time without impacting service provision. Such flexibility may be provided by the thermal inertia of buildings for thermal loads and other smartly controlled household loads like fridges, dishwashers and washing machines, and industrial loads (Kandasamy et al. 2017; Römer et al. 2012).

Local markets can involve not only professional energy traders—who can readily access national markets—but also non-professional residential, community and small commercial energy resource owners who may engage in energy trading as a secondary activity or as a joint community investment. Particularly, residential consumers could play an essential role in enabling variable and distributed electricity generation (The European Parliament 2019). The Committee on Climate Change estimates that as much as 53% of household demand could be flexible in the future (Vivid Economics 2019). As residential loads make up for example 35% of the UK total electricity demand and 55% of the current total energy consumption if including heat and transport as well (both of which are undergoing electrification), they represent a significant share of potential demand-side response (Department for Business Energy and Industrial Strategy 2020). Moreover, demand-side response potential is broadly proportional to the peak electricity demand (O. Léautier 2019), of which UK households already represent about 50% (Darby 2020). The electrification of primary energy supply for residential demand, such as for heat and transport, could cause a significant further increase in peak electricity demand if these loads are uncoordinated, with adverse consequences for low-voltage distribution networks (McKenna and Thomson 2016; Muratori 2018). As residential customers disproportionately consume electricity during the peak hours, the marginal value of flexibility is increased compared to commercial or industrial users who consume more electricity at non-critical hours (O. Léautier 2019). While coordinating these units thanks to local markets represents a significant opportunity, new market arrangements are needed to integrate these incoming small- and medium-scale resource owners. Particular technical constraints include computation and communication requirements due to the disaggregation of the potential into a large number of small units, as well as the required interplay with occupant needs and preferences, limited tracking and control of distributed units, and the need to shield vulnerable users from the variability associated with wholesale operation.

Finally, local energy markets can trade different types of energy products. Beyond local energy management aiming at cutting local bills only, active participants can trade energy, flexibility, and import/export capacity, among others. In energy trading, energy-generating players can sell their energy generation against some payment. The relevant quantity is the amount of energy. In flexibility trading, the quantity of interest is power, i.e., the change in energy consumption that can be provided instantaneously to contribute to grid balancing and constraint management. Flexibility can be provided by changing behaviour or using storage, i.e., mechanisms that decouple behaviour from energy consumption. This flexibility can be relevant at different time scales, from seasonal storage, harvesting solar energy in the summer to be used in winter months (just like humans have done with wheat for millennia), load profile reshaping throughout a day to align consumption with low-cost and carbon-free renewable energy availability, to second-by-second management of frequency and network constraints. Energy and flexibility markets need not be completely separate, as an energy market with time-varying prices can incentivise flexibility in consumption and storage. Finally, players connected under the same sub-station may trade their import and export capacity so that another generator or consumer may increase its capacity for an agreed period without affecting the network. This can improve contractual efficiency when players have contractual agreements stating how much power they can import from/export to the grid, which may be underutilised at certain periods (Origami Energy 2021).

The remainder of this chapter is organised as follows. First, in Sect. 2 the objectives and constraints associated with each of the active players, as well as the relationships between them, are presented. Then, in Sect. 3, possible coordination mechanisms allowing players to reach personal and shared objectives are categorised in an exhaustive taxonomy. Next, in Sect. 4, we illustrate the value of coordination between players in a numerical case study. Finally, we conclude and propose avenues for future research in Sect. 5.

2 Active Players in Local Energy Markets

Local energy markets are composed of people interacting with energy assets and each other. These technical and human components are linked through a network of social relationships, physical electricity networks, financial agreements, data exchange, and smart coordination mechanisms. Together, these parts form a complex system with technical, economic and social interactions. We identify seven key active players illustrated in Fig. 1 and presented in the remainder of this section: energy suppliers, network operators, regulator and government, active participants, passive participants, coordinators, and community.

The connections that will link these players are not yet fully shaped as local energy markets are gradually emerging. Depending on future market design, these players may sit in different organisations with different groupings and relationships. Different coordination structures that may lead to various local market nomenclatures are categorised in Sect. 3.

2.1 Energy Suppliers

- **Definition**: Energy suppliers act as intermediary agents, buying energy on the wholesale energy markets on one side and selling it to energy consumers on the other.

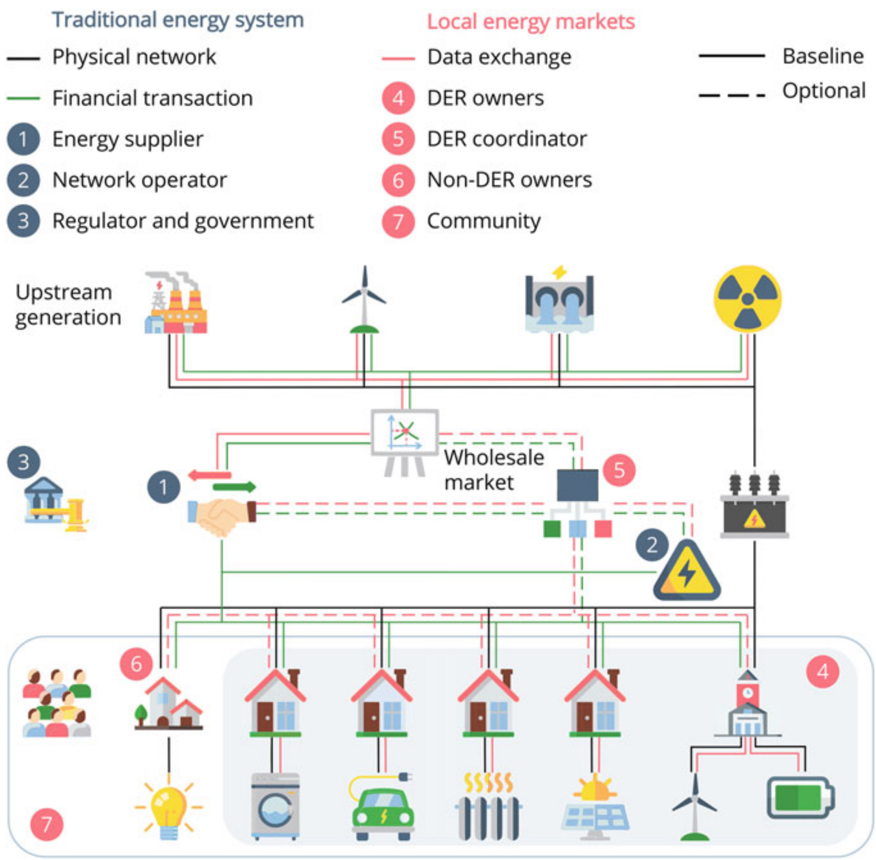


Fig. 1 Active players in local energy markets. Black lines show physical energy networks, such as electrical lines and gas pipes. Green lines denote financial transactions between players. Red lines represent data exchange using information and communications technology infrastructure. Dashed lines are potential future connections depending on future local energy market design

While they are exposed to market prices, energy suppliers traditionally provide fixed or predictable tariffs to their consumers. A percentage of the bills settled by consumers is forwarded to the network operators to contribute towards electricity network operation. The role of the energy supplier is thus to shelter non-professional users from the wholesale market's risks and uncertainties and provide them with a reliable supply of energy and prices.

- **Objective**: When participating in local markets, a key objective for energy suppliers is to handle uncertainty in energy patterns, both on the supply and the demand side, to reduce insurance costs. Indeed, suppliers need to incur costs to hedge—at least partially—against uncertainty either in renewable generation, gas availability (e.g., 2021–2022) gas supply crisis (Gilbert et al. 2021), or in consumer consumption, when continuously balancing supply and consumer demand.

- **Participation in local energy markets**: As existing professional players in energy markets, energy suppliers have the skills, capacity, expertise, relationships with customers, access to infrastructure such as smart metering and appetite for innovation required for effective participation in local markets.
  Critical for the energy suppliers' participation in local markets will be adequate business models, which can both be replicable at scale beyond individual community pilot projects, and fit to local needs. The contracts between suppliers and consumers will determine the risk exposure of suppliers and thus the hedging costs that they incur. For example, suppliers carry the full risk of adverse market movements in the case of fixed tariffs. In variable tariffs, some risk ownership is transferred towards consumers—this can be a win-win contractual arrangement provided consumers can respond to prices, as this also decreases the hedging costs that are eventually pushed onto inflexible consumers.
  Reducing the risks borne by energy suppliers, both thanks to the overall reduction of variability in power imbalances through smart coordination of players and the transfer of some risk ownership to customers through time-varying tariffs, can lower the bar to entry for incoming, smaller energy suppliers. As evidenced by Great Britain's 2021 energy supply crisis, smaller suppliers have so far been vulnerable to market movements. Only larger, established suppliers have developed hedging strategies thanks to their access to liquidity, credit and sophisticated trading teams (Mayr et al. 2022). By lowering this barrier, the interaction of energy suppliers with local markets can allow smaller energy supply players to enter the industry, with further potential disruption of the sector ahead.

2.2 Network Operators

- **Definition**: We make the distinction between the transmission system operator (TSO) and distribution system operator (DSO).
  A TSO is an entity entrusted with operating, ensuring the maintenance of and developing the system that transports energy in the form of natural gas or electrical power on a national or regional level, using fixed infrastructure. It also manages its interconnections with other systems and ensures the long-term ability of the system to meet reasonable demands for the transmission of electricity. In addition, it may seek demand-side response services to help maintain overall power balancing.
  Increases in distributed generation will require Distribution Network Operators (DNOs) to transition and adopt Distribution System Operator (DSO) functions, such as active network management, using new technology and real-time data to make interventions on the network. The role is thus extended from merely owning and operating a regional network to transport electricity from generators to customers, to also provide a two-way interface between active market participants and networks and more proactively manage local power flows and act as the balancing entity for load and generation. The DSO is therefore increasingly integrating grid

and market operation roles (Apostolopoulou et al. 2016), and will be a significant stakeholder in local energy markets.

- **Objective**: The objectives of network operators when interacting with local markets are to help manage network constraints, minimise network losses, and help maintain power balance for stable frequency values. This can reduce both operational and infrastructure costs.
- **Participation in local energy markets**: Network operators are large-scale, institutionalised, professional entities that already invest heavily in smart control to help them reach their goals. They therefore have the expertise, capacity, and motivation to be integrated into local markets. The regulated incentive regimes set by the regulator are a crucial driver for the participation of the network operator in liberalised markets. These give network operators a reason to aim for particular levels of reliability (e.g., managing the technical challenges of uncertainty in energy patterns (Samadi et al. 2013) and decarbonisation (e.g., by facilitating renewable connections).
  They may contribute to local markets in three different ways. Firstly, they may interact with day-ahead or real-time energy markets to incentivise adequate load management in line with their network management goals. Secondly, they may broadcast punctual demands for ancillary services, which may complement the primary, continuous, local market trading system. Finally, the system operator can participate in joint energy infrastructure investments to help reach both network and community engagement objectives, leading to cross-sectoral partnerships between distribution network operators, energy retailers and community organisations (Creamer et al. 2018). Community cooperation can become a crucial part of long-term network infrastructure planning as community assets grow. As the impact of social motivations and cooperation on energy markets grows, understanding these dynamics can help network operators to predict consumer energy behaviours more accurately and thus improve distribution network operation and planning to accommodate energy market flows (Savelli and Morstyn 2021).

2.3 Regulators

- **Definition**: In local markets, regulators define policies and perform oversight activities. Regulators may include national governmental structures, local authorities, and independent regulatory agencies, i.e., government authorities which are not directly elected by the people nor directly managed by elected officials and who are responsible for autonomously licensing and regulating activities independently from both private and political interests (Arblaster 2018).
- **Objective**: The duties of regulators are both towards achieving overarching national and international policies and towards the local communities.
  Overarching societal policy objectives include decarbonisation, environmental protection, and energy security.

Community objectives include reducing energy poverty, limiting the tragedy of the commons to align personal interests with common ones and ensuring proper investment and management of shared resources, ensuring fairness, limiting pollution and maximising community co-benefits. Regulators seek to ensure sustainable and fair benefits for all players, including passive players. They must ensure fair competition for energy communities, removing undue barriers and distortions in existing markets (Council of European Energy Regulators 2019).

In order to protect consumers in markets where there is a lack of self-regulating effective competition—particularly for utility industries like the electricity and energy industries which are infrastructure-heavy and create natural monopolies where the structure of costs and demand makes competition unlikely and costly. Regulators seek to promote more choice for customers, transparent markets, fair and affordable prices and a limitation of abusive market behaviours.

- **Participation in local energy markets**: Regulators have welcomed energy communities as mechanisms that can help them reach their decarbonisation targets and involve citizens more strongly in energy matters (Council of European Energy Regulators 2019). Depending on the strength and stability of national and local governments and institutions, they can have a significant role in designing legislation and incentives for local markets, lowering investment risks, investing directly in local energy projects, and fostering cross-sectoral cooperation between players.

  Firstly, regulators can draw on a comprehensive toolkit to design both legislation and market incentives to foster beneficial local markets. For example, they may promote stable legal frameworks detailing rights and obligations for all players, levy carbon taxes to align personal and societal interests, legislate on health and environment protection, set standards for markets transparency and fairness, financially support vulnerable players and ensure economic efficiency, both in terms of operational market pricing and infrastructure development (Council of European Energy Regulators 2019). However, regulatory progress is currently very heterogeneous, with gaps between technology and regulations hampering development in some countries (Inês et al. 2020).

  Secondly, regulators and a pivotal role to play in lowering investment risks. Despite the consistent decline in the capital cost of energy resources technology, investors still often perceive risks as high, limiting the availability of affordable risk-adjusted capital for developing local market projects. Such risks that increase the price of capital include technical operational uncertainty (due to intermittent renewable generation and interaction with variable markets and consumers), political, regulatory, currency and liquidity risks, and grid interconnection and transmission-line delay risks. Regulators can act on many of these factors to promote a scale-up of investments, thanks to stable investment environments, transparent contractual arrangements, clear infrastructure planning, and risk mitigation instruments and structures. Moreover, they can provide technical assistance to local communities with limited project management experience and skills to limit project development risks (Wuester et al. 2016).

  Thirdly, public finance institutions can provide public capital directly through grant funding and debt-based instruments like on-lending and co-lending structures to break down financing barriers (Wuester et al. 2016). Governments' investments in projects may also come with technical and institutional knowledge, drawing on decades of skills-building, such as building retrofitting projects, to help project development and share knowledge. Local authorities, for example, can provide loans at low rates and provide stability as long-standing institutions with good knowledge of community groups and communities, able to provide help with financing and regulatory guidance, such as around planning constraints.

Finally, local governments may help foster strong cross-sectoral partnerships—helping standardise partnerships between public and private financial institutions; aggregate smaller projects together; foster project knowledge sharing between local financial institutions and local networks; and share risk-mitigation between policymakers, public financial institutions and private investments.

2.4 Active Participants

- **Definition**: In local markets, active participants can be both energy professionals and non-professionals, with players coming from the residential, commercial and institutional sectors. Active participants trade products or services at the local level thanks to their ownership of energy resources such as distributed generation (e.g., PV, wind, combined heat and power, fuel cells), energy storage (e.g., flywheels and batteries—either standalone or intermittently available EV vehicles—for short-scale flexibility, hydrogen or ammonia storage for longer timescales), and demand response (e.g., using the flexibility in thermal loads provided by buildings' and fridges' thermal inertia, and other flexible household, commercial and industrial loads such as dishwashers, washing machines, and industrial processes). These active participants are often designated as *prosumers*, "pro-active consumers with distributed energy resources, actively managing their consumption, production and storage of energy" (Morstyn et al. 2018a).
- **Objective**: The primary objective of active participants in local energy markets is to reduce their individual costs while maintaining their comfort or utility. Costs to minimise include energy bill payments and asset degradation (e.g., managing the life of batteries); revenues to maximise include local generation sales and payments for flexibility services provided.

  A secondary objective in taking part in local markets is not only to minimise the expectancy of their energy costs but also to minimise their risk exposure through the coordination of resources to manage operational uncertainty. There are two main motivations for reducing risks. Firstly, small, non-professional players have a low risk appetite, with strong preferences for reliability over profit maximisation (Frederiks et al. 2015). Generators would like reliable income flows by being matched to flexible resources at the right times and places. Consumers would like to shape their energy profiles to minimise their exposure to high prices while diversifying service provision revenues to smooth out the variability in their bills. Local markets participants can further hedge such price volatility risks through risk trading (Vespermann et al. 2021). Secondly, lowering development and operational risks is necessary to secure funding for energy projects. It is currently challenging to obtain funding from commercial banks without securing long-term contracts or guarantees by large-scale conglomerates. However, as the energy resources are increasingly small and distributed, distributed energy resource owners do not always have access to such costly insurance. As part of an energy community, project developers can receive technical, financial and social support in identifying investment options, developing the infrastructure and tools required to participate in local markets, and reducing the risks to lower financing costs.

Finally, beyond personal utility optimisation goal, distributed resource owners may also seek to contribute toward societal and community objectives, fulfil altruism goals and fit within the social and normative norms of their community (Nolan et al. 2008).

- **Participation in local energy markets**: As detailed in Sect. 1, the participation of prosumers in local energy markets could unlock significant value. The integration of industrial and large commercial actors into energy markets is already well underway, with dedicated teams of professionals managing asset flexibility under well-defined contractual arrangements. However, there are significant remaining barriers to the participation of smaller, non-professional actors in the project initiation, financing, development and operation stages.

  Firstly, engaging with small-scale resource owners so that they have the knowledge and motivation necessary to participate in local markets will require strong outreach and engagement. The provision of demand-side response so far principally focuses on larger industrial and commercial consumers (Charles River Associates 2017), while the majority of customers are still only given the option to trade with utility companies (Chen and Su 2019). Despite the potential benefits to customers, there historically has been a relatively low level of engagement in the energy market, with strong inertia in customers' response to competitive offerings and most customers sticking with their current energy assets, tariffs and energy supplier despite having the option of better managing their energy usage. The process of searching and switching is seen as arduous, with potential gains perceived as not worth the time and effort. There is low awareness, understanding and trust in unknown energy tariffs, services, and companies. This inertia is a significant barrier to engagement with novel players (Moon et al. 2015), which could be overcome through engagement with community, outreach by energy suppliers, and information provision by the government.

  Secondly, financing energy resources and communication and control infrastructure to provide higher value in local market participation is challenging. Low-scale residential and commercial buildings particularly may not have access to funding options for initial investments in resources such as wall insulation (for higher thermal inertia and flexibility), heat pumps, electric vehicles, smart appliances, and smart meters and controllers. The lack of such resources reduces opportunities for gains from local market participation. Many users will require support from the government, public and private banks, network operators, and community financing. Widening access to financing options can help ensure that the value offered by participation in local markets is not only accessible to those who need it least. Thirdly, the project development stage includes developing infrastructure, installing ICT resources, and connecting millions of potential active participants to the digital market layers. There have been varying levels of success in building stock management programmes across countries in the past decades (Nicol et al. 2015)—this home building and retro-fitting process needs to be extended in scope and sped up for the timely development of widespread distributed energy resources that can provide value to local energy markets.

Finally, the operation of small-scale, non-professional distributed resources owners participating in local markets poses its own set of challenges. Privacy and acceptance concerns mean that sharing personal data for cooperation should be limited and carefully managed. Moreover, the limited value offered by each small-scale active participant may not justify investments in costly control and two-way communication devices, which may further restrict the granularity of information available for real-time coordination of assets. Distributed energy resources operation mechanisms should be transparent and fully automated, as local distributed energy resources owners in the residential and small-scale commercial sectors do not have the time, skills and resources to manage them—they favour minimal involvement over active control of their energy management (Pumphrey et al. 2020).

Moreover, the interaction between markets and people is crucial, particularly when dealing with assets in participants' homes. Beyond cost, comfort is the primary consideration for potential demand-side response participants (Darby 2019). Energy consumption is not a social practice in itself but is rather derived from practices such as cooking, showering or driving (Pumphrey et al. 2020). Interference must be limited, as changes in consumption patterns and temperature set-points and required efforts to acquire information all cause dissatisfaction (Vázquez-Canteli and Nagy 2019), and affecting occupants' comfort makes them less likely to engage with demand response schemes (Darby 2020).

In summary, the active participation of distributed resource owners in energy markets offers significant opportunities. Novel control mechanisms tailored to the set of opportunities and constraints presented by community participants can provide smart coordination and participation mechanisms to achieve some level of coordination within a smart energy community. However, technical and business model innovation, along with strong community engagement, will be required.

2.5 Passive Participants

- **Definition**: Not all energy users will have the ability or willingness to participate in local energy markets, and some may keep operating in a non-connected, non-flexible fashion. The local energy markets cannot be decoupled from the other electricity network members. While these participants are considered passive actors in the system, they are key stakeholders of these markets, as members of the communities in which these will occur and as consumers in a changing network and energy industry.

- **Objective**: Passive participants should at least not be negatively affected by local markets and at best receive co-benefits from these markets. A critical risk is that local markets may increase costs of the distribution network operator and that the passive participants disproportionately bear these costs as flexible resource owners shift away from traditional energy supply billing systems that usually settle network management costs.
  On the other hand, passive participants may reduce these costs if local markets improve network management. Such co-benefits for passive participants are highly desirable, as they are likely to be poorer, more vulnerable users with lower awareness of market opportunities and lower access to capital for investment in flexible resources. They are also more likely to rent their home and not have the opportunity to initiate retrofitting projects, especially if housing owners do not pay operational costs and are incentivised to invest in housing options with low capital costs and high energy costs. Energy poverty is a major societal problem exacerbated by current pressures on the gas market; local markets should therefore be designed to help manage this issue.
  Other potential co-benefits from local markets for passive participants include reduced air pollution, revenues for the local community, and social cohesion.
- **Participation in local energy markets**: The protection of non-market participants has been identified as a critical regulatory objective. A key aim is for example to design pricing signals that help use the value of flexibility to serve the system as a whole and not just to the participating players by passing on costs onto the rest of the community (Council of European Energy Regulators 2019). Further regulations enforcing duties for energy market designers and participants to generate neutral or positive externalities for non-participants may be developed in the future.

2.6 Coordinator

- **Definition**: Here, coordinators refer to intermediaries between active participants, the upstream energy markets, the energy supplier and the network operator that seek to redistribute data and financial flows to promote cooperation within the local markets.
  In future local markets, a standalone actor such as a distinct aggregator entity may take on this role, or it may be the responsibility of one or multiple other players, such as in peer-to-peer trading where the data, control and financial settlement management role is distributed between players. Whether or not a separate actor takes it on, this coordination role is always present in local markets.
  The coordinator can take on various levels of computation and decision-making, ranging from direct control, where aggregators make all decisions on behalf of the players, to simply acting as a market platform to facilitate data exchange so that

players can have agency in their coordination decisions (see Sect. 3). The level of involvement of the aggregator will depend on participant preferences and availability of ICT hardware and software infrastructure, including data-heavy computations, low-cost local sensors, high-speed communications, and digital platforms.

- **Objective**: The coordinator aims to maximise the diversity of owner types to maximise value. The trades facilitated through the coordinator include energy trading (with intra-community bids and collectives bids on the wholesale market upstream) and demand-side response services such as congestion management and balancing services offered by resource owners to distribution and transmission network operators and energy suppliers. For example, through its Power Responsive Initiative, the GB system operator has ambitions to procure by 2020 30–50% of its Balancing Services through demand-side response, from 6% in 2016 (Ofgem 2016).

  Players managed by the coordinator may represent a variety of heterogeneous loads to maximise opportunities for valuable matching of energy use decisions, such as residential, commercial and residential users, as well as various types of energy storage and generation technologies.
- **Participation in local energy markets**: The coordinator role is still emerging. Regulations and policies are vital in enabling aggregators' business models, though the technology is ahead of regulation and policy in many places, with a lack of clarity for coordination frameworks. The aggregator and energy supplier roles may be combined and offered as a package, with a single communication point for consumers. However, the private incentives of the supplier and the community and network coordination goals may be misaligned. Alternatively, the coordination role may be combined with that of the distribution system operator in charge of maintaining the balance between supply and demand (Apostolopoulou et al. 2016); though there are concerns around combining regulated and unregulated roles. In another scenario, the aggregator may be an independent service provider; although this may add complexity to the system, maintaining the independence of the coordinator minimises the chances of bias. Finally, large-scale energy resource owners can take on the aggregator role for their own portfolio, though this is usually not for domestic players. The levels of aggregation may be nested within a single portfolio, and a combination of portfolios that trade and deliver services together in higher layers of the energy markets.

  To engage with a bigger, diverse pool of participants, the coordinator has to go beyond the large scale industrial and commercial companies that have traditionally participated in demand-side response. Medium-term movements in the energy sectors toward expanding smart metering and smarter energy markets can improve the range of consumers that are aware of and willing to take advantage of demand-side response opportunities. However, engaging with small- and medium-scale potential participants remains costly due to the comparatively low size of potential flexibility tendered. The coordinator will have a key role in bridging that gap, assisting consumers in the transition, and offering value through scale, portfolio effects and simplification (Ofgem 2016).

  Smart cooperation within energy neighbourhoods opens up new opportunities for pursuing shared community goals in ways that would otherwise not be possible under individual schemes, thanks to the larger project scales considered, the lower perceived risks for individual players teaming together, and the benefits of shared information and coordination. While the definition of the coordinator role is still being shaped, this actor will offer significant opportunities for co-creation of value for future local markets (Savelli and Morstyn 2021).

2.7 Community

- **Definition**: Active and passive participants, local institutions and other people interacting with the local area form a community. This community is greater than just the sum of its loads and assets. It also contains social relationships that can influence individual behaviours and personal choices, foster cooperation, and build solidarity (Savelli and Morstyn 2021). Thus, European regulators have acknowledged that "energy communities" refer to both "Citizens" and "Renewable Energy Communities" (Council of European Energy Regulators 2019).
- **Objective**: Communities engaging with local markets aim at delivering value fairly to their individual members.
  Moreover, shared co-benefits to the community include air quality improvement, aiding vulnerable members of the community, combatting energy poverty, and promoting energy justice through both fair cost allocation and participative community consultation (Savelli and Morstyn 2021).
  Beyond benefits for local community members, community energy encompasses projects at a collective level, which seek to extend opportunities beyond that of individuals acting in isolation (Council of European Energy Regulators 2019), fostering pro-social, philanthropic behaviours through both regulations and social influence. Communities may also come together to pursue larger national policy goals, such as net-zero emission targets. Indeed, international and national climate policies need to be implemented at all lower levels of governance so that the sum of local projects may fit within the nationally determined carbon budgets.
- **Participation in local energy markets**: Communities can be critical enablers for local markets, thanks to social connections and community financing.
  While community has inherent value, it also acts as a facilitator for local markets. People do not live in isolation but rather influence each other's preferences and behaviours (Elder 1994). Harnessing the social relationships connecting people of a community can help attract and retain local energy participants and help enhance the functioning of smart local energy systems by facilitating cooperation towards shared objectives. Creating a virtuous cycle, the scope of new opportunities for cooperation will increase as participation increases (Savelli and Morstyn 2021). Indeed, normative social influence and information on community co-benefits can be more potent motivators for changing energy management practices than individual monetary gains (Dietz 2015; Nolan et al. 2008). Community-led awareness building and normative influence towards participation can have sizeable impacts on energy systems design, local objectives achievement, and national policy ambi-

tions (Niella et al. 2016). These networks can range from informal social networks to established official community organisations (political, non-profits, social enterprises, local community renewable energy companies). Such community organisations can provide support thanks to their knowledge, trust and relationships. Community financing can be a lever for deploying low-carbon technologies at the distribution level through local institutions and crowd-funding. Communities may also extend their cooperation beyond their own members, forming partnerships with distribution network operators, and the commercial, regulation and charity sectors. A range of barriers can obstruct the development and financing of renewable energy projects due to the front-loaded cost structure of most renewable energy projects (Wuester et al. 2016). Community financing could offer cheaper capital and increase public acceptance of local energy projects.

3 Mechanisms for the Coordination of Active Players in Local Energy Markets

As presented in Sect. 2, each participant comes with their own constraints, objectives—which may at times be conflicting—and information. What mechanisms can be used to coordinate participants in an energy market? There are seven main coordination categories, each of which can be implemented in different ways depending on the market design and context.

We categorise coordination strategies based on *agency*, *information* and *game type* in a systematic taxonomy presented in (Charbonnier et al. 2022), as illustrated in Fig. 2 and further developed in the subsections below. Coordination strategies are categorised using three questions: Can participants perform local decisions independently? Are players competing or cooperating? How is information shared?

3.1 Agency: Can Participants Perform Local Decisions Independently?

The question of agency is of particular importance in local markets as there are challenges associated with the control of resources with different owners, goals and characteristics (Darby 2020), which encourages local market structures to consider independent decision opportunities in their design.

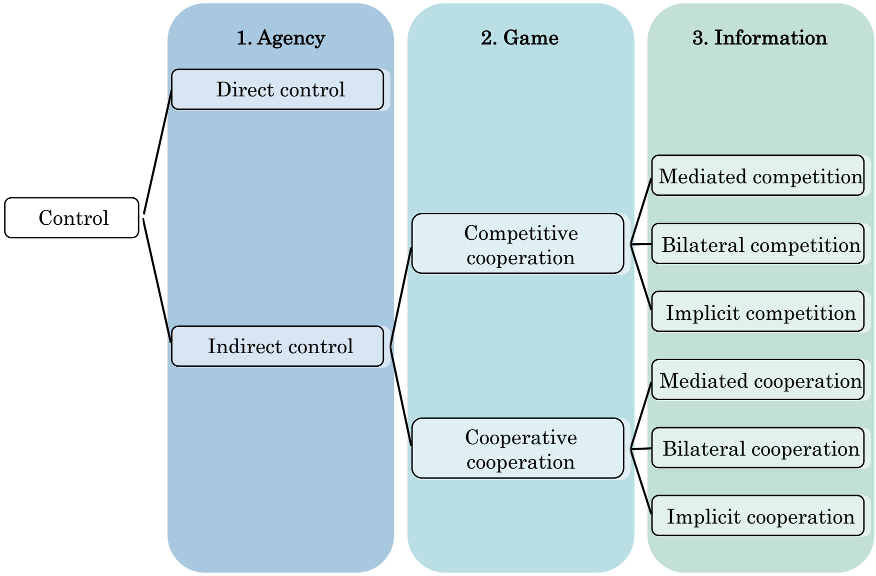


Fig. 2 Three layers of the systematic taxonomy of categories of coordination: (1) Agency: Are coordinated units operated independently? (2) Game type: Do players compete or cooperate? (3) Information: How is individual information shared? Adapted from (Charbonnier et al. 2022)

The selection of *direct* or *indirect control* in Fig. 2 is informed by how smart and flexible the units[2] are, whether their individual interests are aligned, and the legal and physical context in which the local market takes place (Meng et al. 2016).

3.1.1 Direct Control

In a *direct control* strategy, units communicate personal data to a central controller, which then decides on their control actions. The central controller can decide to maximise a system objective rather than the individual objectives of the distributed units.

Direct control is well suited to small-scale microgrids (Morstyn et al. 2018c), or generally in situations where an aggregator directly owns a set of distributed energy resources. Design and operation optimisation can then even be considered concurrently as a coupled problem (Cao et al. 2019). However, it may not be best suited to local markets due to privacy and security concerns from private, residential participants to be coordinated. Players may indeed not feel inclined to share personal data and yield the control of appliances in their own homes. Furthermore, direct control

[2] Note that the level at which a controlled unit is defined may be a household, a building, a neighbourhood, etc. Each coordination level can be nested; i.e., an aggregator may perform direct control of units downstream and trade in the wholesale market in a mediated competition upstream.

is computationally challenging– or indeed intractable—at a large scale (Guerrero 2018), requires costly ICT equipment, and presents a single communication and computation point-of-failure around the central controller (Abrishambaf et al. 2019; Mai et al. 2021; Meng et al. 2016).

Examples of implementations of direct control are provided in Box 1.

1. Implementations of direct control in the literature:
There are different technical approaches to direct control, such as:

- Optimisation: A central optimisation may be conducted to decide all distributed units' energy use decisions. For example, receding horizon global optimisation frameworks deal with uncertainty by determining the optimal decision variables for the current time step by performing a system optimisations over a given horizon using predictions for future system variables and costs updated at each time step (Fortenbacher et al. 2017; Heussen et al. 2010; Ji et al. 2019; Morstyn et al. 2018c). This approach may be combined with other methods for mitigating uncertainty, such as stochastic optimisation, in which different random sets of variables are generated and used (Ji et al. 2019), or worst-case scenario optimisation, in which the least favourable scenario is considered (Fortenbacher et al. 2017) among others.
- Rule-based control: Direct control may also be rule-based, with "if–then" rules designed ahead of implementation. For example, to respond to signals to augment or reduce fridges' thermal storage (Stadler et al. 2007), for an aggregator to turn units on and off based on their power consumption (Hao et al. 2015), to time EV charging based on electricity prices, charge requirements and generation availability (Fazal et al. 2012), and for utilities to respond to pre-determined trigger grid conditions (Siano 2014). The rules applied by the scheduler can be either manually defined or determined using statistical methods such as reinforcement learning (RL) (O'Neill et al. 2010).

3.1.2 Indirect Control

As an alternative to direct control, local market players can retain agency and make independent decisions at the local level. The types of indirect control are then determined based on the game type and information structure of the local market. Computations, communication and decision-making are typically performed at the local level by an *agent*, "a computer system that is capable of independent action on behalf of its user or owner" (Wooldridge 2002).

3.2 Game Type: Do Units Compete or Cooperate?

Secondly, coordination strategies can be classified based on the class of game in which players participate.

3.2.1 Cooperation

Players may *cooperate* towards shared objectives to create additional social value compared to the sum of personal value when decisions are made selfishly (Han et al. 2019). While cooperation between players can create substantial societal benefits, competitive market frameworks offer insufficient incentives for competitive individuals to create these positive societal and system externalities (Römer et al. 2012). Both market and regulatory mechanisms can help incentivise cooperation between players to unlock these benefits. A shared goal may chiefly be the equitable attainment of individual objectives or may extend to further systems objectives. For example, agents can cooperatively manage network constraints to limit voltage variations, current harmonics, network congestion and stability issues (Mai et al. 2021). If not incorporating these shared infrastructure constraints in local market design, negative impacts during operation may lead to increased asset investment requirements (Guerrero et al. 2020).

3.2.2 Competition

Alternatively, market players may *compete* with each other, to each pursue the maximisation of their utility[3] only, such as to maximise individual profits and/or serve personal comfort and preferences. Users with heterogeneous preferences can therefore freely pursue their objectives, and price signals act as the coordination messaging for all devices and systems to inform local decisions towards commonly beneficial coordination of the distributed resources (Abrishambaf et al. 2019). Despite the selfishness of individual players' decision-making, local market design can build in incentive mechanisms to align self-interested decisions with ancillary objectives such as network management or aggregator profits (O. Léautier 2019). The particularity of electricity compared to other types of liberalised markets is that they heavily managed and regulated systems with shared responsibilities between players due to

[3] Utility was defined by Jeremy Bentham as "that property in any object, whereby it tends to produce benefit, advantage, pleasure, good, or happiness (all this in the present case comes to the same thing) or (what comes again to the same thing) to prevent the happening of mischief, pain, evil, or unhappiness to the party whose interest is considered" (Bentham 1879). A utility function, in turn, is an economist's convenient representation of an individual's preferences that permits mathematical analysis (Hashimzade et al. 2017).

the need to manage the constraint of the shared infrastructure, protect consumers and manage risks for public institutions. Therefore, the market signals can be computed by a system operator who can solve a dispatch optimisation problem centrally. Thus, in marginal pricing frameworks, trading outcomes can be modelled analogously to an optimisation with ideal market signals matching dual variables (Wilson 2002), although no optimisation actually occurs. Therefore, in the case of centrally computed market signals, competitive coordination can for example minimise long-term climate change impacts using marginal costs pricing signals to align personal and societal interests (Parry 2007). On the other hand, in the absence of the inclusion of externalities in prices (greenhouse gas emissions, network constraints and losses), markets may not maximise whole-system welfare.

3.3 Information: How is Individual Information Shared?

Finally, coordination strategies are categorised based on the information sharing structure.

As energy resources are increasingly decentralised, data is ownership and communication structures are transforming (Charbonnier et al. 2022). In local markets, active participants offer not only their generation and flexibility capacity but also the value of their data ownership and computation and communication capabilities. However, as noted in Sect. 3.1.1), such exchange of data may pose trust, privacy and ethical challenges. Therefore, guaranteeing the proper use of personal data, which may include clues to private lives and behaviour (Rottondi and Verticale 2017), will be crucial in maintaining trust. Moreover, communication and control infrastructure may incur costs that sometimes outweigh the benefits offered by an individual home. Therefore, trade-offs between the value of information and the costs of privacy (Yao 2017) and infrastructure should be carefully weighed.

These trade-offs are reflected by the different information architectures possible under indirect control, as further described in the following subsections.

3.3.1 Mediated Coordination

In mediated coordination, there is two-way communication between the market participants and a central coordinator. The coordinator collects information such as load and generation curve predictions, bids, or constraints, and, in return, broadcasts signals intended to incentivise globally optimal action based on the insights gained from this centralisation of data information. Such broadcasts may for example take the form of matches for trade agreements between peers, price signals, and partial central optimisation results to input in local computation by agents, depending on the market design.

In this approach, well established mathematical theories such as auction theory and optimisation theory guarantee reliable desired outcomes thanks to the real-time monitoring of the distributed resources by the coordinator, and the ability to directly send control signals to agents. It however relies on the safe and reliable two-way communication of information, itself conditioned on the availability of both adequate technical infrastructure and participant engagement—indeed, players are required to overcome security and privacy concerns and have the will, trust, interest and ability to adequately receive, process and respond to the coordinator's signals (Darby 2019). Both financial and technical assistance will be required to install the required infrastructure and respond appropriately to signals (Siano 2014). Incorrect or unreliable information, whether due to forecasting or technical inaccuracies or due to strategic behaviour (Morstyn and Mcculloch 2020), can cause sub-optimal or infeasible market outcomes.

As shown in the third layer of the taxonomy (Fig. 2), mediated coordination can be implemented in either a *competitive* and *cooperative* setting (Charbonnier et al. 2022).

In *mediated competition*, market players compete, which we define here as being selfish, or seeking to maximise their individual utility function solely. This can be achieved using *unidirectional price signals* or *organized markets*. In the first case, the coordinator seeks to influence market agents to match optimal global outcomes based on players' information, such as their cost functions, constraints, demand and generation forecasts. Such centrally determined pricing signals can internalise the externality effect of customers, where actions by players create a negative externality effect for other customers' prices (Haider et al. 2016). Alternatively, mediated competition can use "organised markets" (Siano 2014) like wholesale markets, in which a central coordinator receives bids and settles trade matchings centrally. Bidding-based negotiation fosters price discovery, revealing the marginal value of players' energy use given fragmented unknown personal characteristics, preferences and opportunity costs, without explicitly collecting this information like in explicit centralised optimisation (Arlt et al. 2021). Examples of technical approaches to mediated competition are provided in Box 2.

2 Implementations of mediated competition in the literature:

Examples of approaches to mediated competition are the following:

- Unidirectional price signals: pricing signals can be computed using Distribution Locational Marginal Pricing (DLMP), where import-export price spreads limit the likelihood of network constraint violations under uncertainty (Morstyn et al. 2020). The coordinator assesses and allocates distribution network losses in transactions (Di Silvestre et al. 2018). In other implementations, RL can be used to determine both the dynamic price signal (Kim et al. 2016; Lu and Hong 2019) and the response of agents to these signals (Babar et al. 2018; Kim et al. 2016).

- Iterative methods: There can be iterations between the distributed agents and the coordinator until convergence occurs. In non-cooperative Stackelberg games, both market-makers and consumers seek to maximise their own objective functions by iteratively updating their prices and demand bids (Maharjan et al. 2013). Market agents can gradually learn to mimic a Nash equilibrium throughout iterations, where electricity prices are re-computed as functions of the aggregate demand (Zhu 2014).
- Organised markets: examples include unilateral auction mechanisms (Zhang et al. 2020), continuous double auction mechanisms (Arlt et al. 2021; Guerrero 2018; Guerrero et al. 2020), demand reduction bids (Siano 2014), and nested negotiations between DSO and aggregators and between aggregators and agents (Morstyn et al. 2019b). The auction mechanisms can also include an allocation of congestion costs (Zhao et al. 2017). The market agents may use RL algorithms to refine individual bidding strategies (Dauer et al. 2013; Kim and Lee 2020; Sun et al. 2015; Vayá et al. 2014; Ye et al. 2020), and the coordinator to determine the market clearing (Chen and Su 2019; Claessens et al. 2013).

In *mediated cooperation*, the coordinator computes signals based on information collected from the distributed agents, but agents then respond in a cooperative way rather than in a purely selfish way (Fig. 2). The most straightforward shared objective may be that of the minimisation of the sum of individual costs. Reaching this optimal state may involve actions that go against immediate individual interests. The coordinator may act as a "social planner", a benevolent mediator which sets adequate strategies either to maximise a social welfare function—which may go beyond the elementary goal of individual costs minimisation—or at least to reach Pareto efficient allocations (Black et al. 2012).

Note that mediated cooperation still maintains some level of agency and privacy at the local level, unlike direct control, where the coordinator has full access to personal data and total control of the distributed resources. Here, the role of the coordinator is to collect partial information from units and redistribute the right signals to guide cooperation, while further computations and decision-making compatible with shared objectives are performed at the local level.

Examples of technical implementations are provided in Box 3.

3 Implementations of mediated cooperation in the literature:
There are numerous examples of frameworks for mediated cooperation in the literature, including:

- Iterative methods: A category of mediated cooperation relies on iterations between central and distributed computations. In some strategies, the coordinator collects information on power systems and appliances' flexibility characteristics to update instructions sent to the agents regularly. Their response in turn influences the network and appliance flexibility potential (Hurtado et al. 2018; Tindemans et al. 2015). In (Tindemans et al. 2015), appliances are expected to follow the rules set by the coordinator, while in (Hurtado et al. 2018), a local control system aims to provide energy flexibility services using a multi-agent Q-learning mechanism including a model of the other agents. Alternatively, the coordinator can directly share network information with agents, who then assess themselves the impact on the network of their privately organised trades and update their decisions accordingly. Agents then communicate their updated set of trades to the coordinator, which can iteratively broadcast updated network information until convergence (Wu and Varaiya 1999). Instead of negotiating trades directly, agents can also run optimisations locally that include augmented terms to help align individual decision-making with global constraints and objectives. Sharing the results with the coordinator, centrally computed signals can be iteratively updated to inform, in turn, the local optimisations (Andrianesis and Caramanis 2019; Morstyn and McCulloch 2019).
- Coalitions: A mediated assists players cooperation within coalitions with common goals. Members form a coherent block for trading in markets, as handled by a community manager (Moret and Pinson 2019; Sousa et al. 2019). Game theory mechanisms can inform coalition formation based on individual players' characteristics, and coalition operation is determined centrally based on shared optimisation results (Han et al. 2019; Tushar et al. 2020).
- Statistical approaches: Using RL, agents can learn to cooperate with a central entity towards shared goals. The individual reward functions can include the utility of other agents as well as local technology and network constraints, and sharing learnings within cooperative swarms can help speed up learning thanks to updated knowledge (Zhang et al. 2017). The coordinator can inform the learning and the decision-making by redistributing information about their neighbours to each agent, helping to make informed decisions while pursuing common goals such as using consumption flexibility to help integrate renewable energy and limiting peak loads (Dusparic 2013; Dusparic et al. 2015).

3.3.2 Bilateral Coordination

In *bilateral coordination*, agents no longer share data centrally but rather bilaterally with one another (Fig. 2).

While this still requires adequate communication infrastructure, the robustness to communication link failure is improved as the system is not vulnerable to a single point of failure. The cost of ICT infrastructure for gradual expansion of complex systems with larger numbers of distributed resources is reduced compared to central control architectures (Mai et al. 2021). However, the computational resources requirements may increase with the number of agents as the number of communication iterations until algorithm convergence increases, and limited minimal network latency is required for feasibility (Guerrero et al. 2020).

Security concerns over shared personal data may be somewhat alleviated as all data is no longer centralised in a single location. Multiple proposals have been put forward to implement the distributed transactions safely. Distributed ledger technologies (DLTs) such as the blockchain have been particularly popular in recent local market trials. A secure, decentralised digital ledger documents financial transactions (Li et al. 2018), in multiple points without a single point of failure (Bandeiras et al. 2020). They however pose significant outstanding legal, environmental and implementation risks (Charbonnier et al. 2022).

As shown in Fig. 2, bilateral cooperation can be implemented in a *competitive* or a *cooperative* manner.

Competing market agents can directly negotiate transactions through peer-to-peer trading to maximise their individual utility. This provides them with complete autonomy over their choices, and the opportunity to select trades according to personal preferences may be attractive to market participants. However, each actor only acts with a limited understanding of their competitors' decisions and utility functions (Herbert 1982; Yang et al. 2011). With limited information available to agents acting with bounded rationality, a computationally burdensome exhaustive optimisation or the global decision space is inaccessible. In real-life settings, the professional and non-professional players often use rules of thumbs or heuristics, with significant optimality gaps (Blasch et al. 2019) and dampened response to market signals (Farhi and Werning 2019). Due to these inefficiencies and the fact that market players do not account for shared constraints and objectives such as managing grid constraints, there may be significant impacts on the physical networks that host these local markets. Therefore, the market design will be critical in assessing and mitigating the potential negative impacts arising from consumer behaviour (Sousa et al. 2019; Yang et al. 2011). Examples of proposed implementations of bilateral competition are provided in Box 4.

4 Implementations of bilateral competition in the literature:
Examples of works on bilateral competition include the development of the theory of bilateral contract networks—multi-sided matching markets with both

downstream and upstream bilateral contracts—in Guerrero et al. (2020), analysis of their stability potential in Fleiner et al. (2015). Building on this theory, fully distributed, iterative P2P negotiation mechanisms are proposed in Morstyn et al. (2019a, 2020). Blockchain-based bidding mechanisms (Ableitner et al. 2019; Hayes et al. 2020; Tushar et al. 2019) have also been proposed to manage the implementation of bilateral competition frameworks.

In *bilateral cooperation*, market participants negotiate energy exchange arrangements bilaterally similarly to in bilateral competition, but seeking to cooperatively reach theoretically proven whole system market solutions. At each iteration, local responses not only account for personal utility but also shared objectives and constraints. Computational scalability may be limited as the complexity increases with the number of agents due to the number of bilateral iterations required until the group has converged to a solution (Morstyn et al. 2020).

Bilateral cooperation arrangements, which rely on individual cooperation while preserving individual agency, may be vulnerable to unilateral strategic behaviour. Single participants deviating from shared objectives may add biases to the iterative response signals and prevent convergence to optimal cooperative outcomes (Morstyn and Mcculloch 2020). Cooperative game theory-based profit-sharing allocations can mitigate this risk by incentivising cooperation in robust ways, though computing such solutions is exponentially complex, limiting scalability (Han et al. 2019). In addition, ring-fencing the distribution networks can provide further safeguarding, along with a clear allocation of distribution costs in incentive regulation (Jamasb and Pollitt 2007).

A few proposed implementations of bilateral cooperation are listed in Box 5.

5 Implementations of bilateral cooperation in the literature:
Examples of bilateral cooperation strategies can be found in the literature that use iterative negotiation to reach shared objectives (Guerrero et al. 2020; Morstyn et al. 2020). Shared objective functions may also be maximised using Types of distributed optimisation such as dual decomposition and the alternating direction method of multipliers (ADMM) (Sousa et al. 2019). Global and local constraints can thus be decoupled using Lagrangian multipliers (Khorasany et al. 2020). Scalability is still an ongoing concern for these approaches—for example, the convergence time of ADMM may be sensitive to problem-specific numerical properties and thus be impractical (Moret and Pinson 2019). Other proposals were put forward where agents cooperate through bilateral transfer learning with distributed W-learning (Taylor 2014).

3.3.3 Implicit Coordination

In *implicit coordination*, players do not share personal information, with at most one-way communication of market signals to agents. Agents can monitor their local environment and use past system information to inform their decentralised decision-making.

While centralised and bilateral information and financial transactions between players help coordinate decision-making, in practice, electron flows through electricity networks only depend on injection and extraction points at the level of individual control actions.

Although a sub-optimality gap will exist as individual decision-making is not informed by real-time personal data from other agents, implicit coordination offers a low-complexity, low-cost option where the costs of two-way ICT infrastructure outweigh the potential benefits of precise distributed energy resource information monitoring (Siano 2014), particularly for small-scale applications. It may also solve problems of privacy and acceptability concerns by market participants, as well as maximal robustness against individual failures (Guerrero et al. 2020; Mai et al. 2021). Furthermore, as interoperability of different heterogeneous software and hardware components was listed as a key obstacle in real-world implementation challenges, the simplicity of this information structure reduces implementation risks (Darby 2020; Siano 2014).

Implicit coordination can be further divided into *implicit competition* and *implicit cooperation* coordination categories.

Today, most energy consumers currently make decisions corresponding to an *implicit competition*: they do not share personal data and solely seek to minimise their own bills while maintaining comfort. However, decentralised decision-making with no assessment of the impacts on the global system of the sum of individual selfish decisions may cause sub-optimality, particularly at scale. Varying prices signals, designed to help align consumption with the available generation, may moreover have the unintended impact of creating new peaks if sent uniformly to all consumers, as some of the natural diversity of grid loads may be lost, with overloads on upstream transformers and capacity issues (Crozier et al. 2018; Guerrero et al. 2020). This uncoordinated response to price signals is particularly unpredictable in implicit coordination where the detailed distributed energy resources states and behaviours are unknown (Kok and Widergren 2016). Therefore, implicit competition market design should help align selfish market signal responses to limit adverse global impacts.

Examples of both market-maker and consumer sides are presented in Box 6.

6 Implementations of implicit competition in the literature:
Examples of competitive mechanisms to guide implicit coordination include critical-peak pricing, time-of-use pricing (TOU) and real-time pricing (Siano 2014).

As self-interested units are only concerned with the local scale, implicit competition strategies leave the realm of agent coordination to focus on single local energy management systems for load scheduling. Both optimisation (Lee and Lee 2011) and rule-based control can be used (Yang et al. 2015). Rules for load scheduling can be learned using RL algorithms (Cao 2019; Wang and Zhang 2018), learning appliance scheduling strategies that seek to maximise the statistical expectancy of rewards by interacting with both the environment and the user (Wen et al. 2015), to conserve energy while ensuring user comfort (Dalamagkidis et al. 2007). Particle swarm optimisation and genetic algorithms have also been investigated to best utilise thermal energy storage (Schellenberg et al. 2020).

To combine the advantages of low-cost ICT infrastructure and privacy protection while avoiding the pitfalls associated with implicit competition, *implicit cooperation* allows market participants to keep personal information private while cooperatively pursuing system-wide goals. Possible implementations are listed in Box 7. This space of possible coordination strategies is in its infancy under-researched, as very few strategies have so far explored its potential beyond frequency control.

7 Implementations of implicit cooperation in the literature:
Examples of existing implicit cooperation strategies have primarily focused on hard-wired voltage and frequency control based on local information (Mai et al. 2021; Morstyn et al. 2018b; Tayab et al. 2017; Tindemans et al. 2015). In Rozada et al. (2020) agents learn statistically optimal control policies to restore frequency using locally available information. This is a promising approach for distributed coordination, although more complex systems with electric vehicles and smart heating loads have not been investigated. In addition, the convergence may become an issue at scale—at most eight agents have so far been considered.

Strategies that have so far sought to extend this approach beyond frequency control to include energy scheduling include Marinescu et al. (2017), where W-learning is used to include both objectives of sufficient EV charging and avoiding generation peaks in demand. This study found that when agents are not informed of the effect of other agents' decisions, the combined individual decisions incur negative consequences on the environment. Subsequently, in Charbonnier et al. (2022) a strategy is proposed that increases the scalability of implicit cooperation of agents using local information only, using RL algorithms that learn from offline optimisations ahead of implementation to statistically assess the impact of individual actions on shared objectives.

4 The Value of Cooperation: Numerical Case Study

Let us now consider a numerical case study illustrating the value of the coordination of distributed energy resources that can be fostered in local energy markets. We further illustrate the value of cooperation between players and how this cooperation can be rewarded to incentivise coalition formation.

We start by describing the system used for the case study. We then compare the value obtained by competing players, i.e., players that consider an optimisation without accounting for others players, and cooperating players who follow the results of a global optimisation to inform their local control actions. Finally, we show that the global value obtained in the case study can be redistributed amongst players such that all participants are incentivised to cooperate.

4.1 System Description

Let us consider the system in Fig. 3.

4.1.1 Variables

We consider a set of time steps $t \in \mathcal{T}$ and a set of agents $i \in \mathcal{A}$. Participants 1–4 own an EV, flexible household loads, electric space heating and PV generation, respectively. The input data listed in Table 1 for the one-day case study was generated

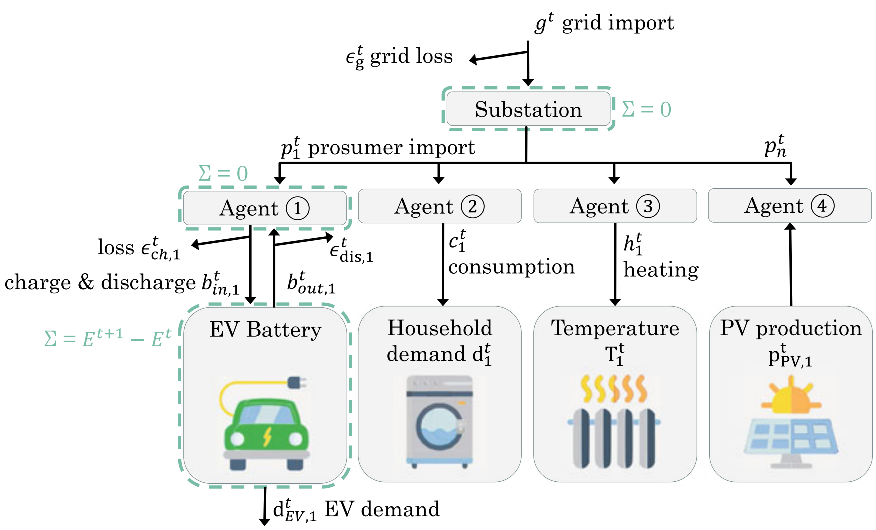


Fig. 3 Case study local system model. Green dotted lines denote energy balances. Each agent owns a different energy resource

Table 1 Case study inputs for time steps $t \in \mathcal{T}$ and agents $i \in \mathcal{A}$

μ_i^t	EV at-home availability (1 if available, 0 otherwise)
$\mathrm{d}_{\mathrm{EV},i}^t$	EV demand for required trips
d_i^t	Household electric demand
$\mathrm{p}_{\mathrm{PV},i}^t$	PV production
$\mathrm{T}_{\mathrm{e}}^t$	External temperature
ϕ^t	Solar heat flow rate

Table 2 Case study decision variables for time steps $t \in \mathcal{T}$ and agents $i \in \mathcal{A}$

$b_{\mathrm{in},i}^t$	Energy flows into EV battery
$b_{\mathrm{out},i}^t$	Energy flows out of EV battery
h_i^t	Electric heating consumption
c_i^t	Agent consumption

Table 3 Local and global impacts of decision variables for time steps $t \in \mathcal{T}$ and agents $i \in \mathcal{A}$

E_i^t	Battery energy levels
$\epsilon_{\mathrm{ch},i}^t$	Charging losses
$\epsilon_{\mathrm{dis},i}^t$	Discharging losses
p_i^t	Agent import
$T_{\mathrm{m},i}^t$	Building mass temperature
$T_{\mathrm{air},i}^t$	Indoor air temperature
g^t	Total grid import

using the Home Energy Data Generation (HEDGE) methodology in https://github.com/floracharbo/HEDGE, as set out in (Charbonnier et al. 2022). Decision variables are *italicised* and listed in Table 2. These have both local and system impacts (Fig. 3 and Table 3). Local impacts include battery energy levels, losses, agent imports, building mass temperature and indoor air temperature. System impacts arise through the costs of total grid import and distribution network trading. Distribution network losses and reactive power flows are not included. Case study parameters are tabulated in Table 4. Energy units are used unless specified otherwise.

4.1.2 Objective Functions

We consider two objective functions: the individual objective function, which represents individual costs for a given player, and the global objective function which represents the total systems costs arising from individual control actions, including grid losses, distribution network congestion, and greenhouse gas externalities.

- **Individual objective function**: Individual players i seek to minimise their individual cost of energy $c_{i,\mathrm{e}}^t$ and their battery degradation costs $c_{i,\mathrm{b}}^t$ for all time steps $t \in \mathcal{T}$.

Table 4 Case study parameters

E_0	Initial battery energy level
$\underline{E}$	Minimum battery energy level
$\overline{E}$	Maximum battery energy level
η_{ch}	Charge efficiency
η_{dis}	Discharge efficiency
$\overline{b_{in}}$	Maximum charge per time step
f_{i,k,t_C,t_D}	Flexibility Boolean indicating if time t_C lies within the acceptable range to meet demand $d_{i,k}^{t_D}$ of type k by agent i at time t_D
κ	2×5 matrix of temperature coefficients
$\underline{T}_i^t$	Lower temperature bound agent i at time t
$\overline{T}_i^t$	Upper temperature bound agent i at time t

$$\min C_{i,\text{indiv}} = \sum_{\forall t \in \mathcal{T}} c_{i,\text{e}}^t + c_{i,\text{b}}^t \tag{1}$$

Energy can be bought at a time-varying price C_{import}^t and sold at a lower, fixed feed-in tariff C_{export}.

$$c_{i,\text{e}}^t = \begin{cases} C_{\text{import}}^t p_i^t & \text{if } p_i^t > 0 \\ C_{\text{export}} p_i^t & \text{otherwise} \end{cases} \tag{2}$$

Storage battery depreciation costs c_{b}^t are modelled as proportional to throughput using the depreciation coefficient C_{b}, assuming a uniform energy throughput degradation rate (Dufo-López 2014).

$$c_{i,\text{b}}^t = C_{\text{b}}\left(b_{\text{in},i}^t + b_{\text{out},i}^t\right) \tag{3}$$

- **Global objective function**: Beyond only individual costs, agents may seek to minimise the sum of grid (c_{g}^t), distribution (c_{d}^t) and storage (c_{s}^t) costs. The objective function is thus:

$$\min C_{\text{tot}} = \sum_{\forall t \in \mathcal{T}} c_{\text{g}}^t + c_{\text{d}}^t + c_{\text{b}}^t \tag{4}$$

The grid costs are calculated at the coalition level rather than the individual level:

$$c_{\text{g}}^t = \begin{cases} C_{\text{g}}^t \left(g^t + \epsilon_g\right) & \text{if } g^t > 0 \\ C_{\text{export}} g^t & \text{otherwise} \end{cases} \tag{5}$$

Here losses in the main grid upstream of local imports are also accounted for, approximated as

$$\epsilon_g = \frac{R}{V^2}\left(g^t\right)^2 \tag{6}$$

Moreover, the grid cost coefficient $\mathrm{C}_{\mathrm{g}}^{t}$ is the sum of both the grid electricity price and the product of the carbon intensity of the generation mix at time t and the Social Cost of Carbon which reflects the long-term societal cost of emitting greenhouse gases (Parry 2007).

$$\mathrm{C}_{\mathrm{g}}^{t} = \mathrm{C}_{\mathrm{import}}^{t} + \mathrm{I}_{\mathrm{carbon}}^{t}\mathrm{SoC} \tag{7}$$

The impacts of local market outcomes on upstream energy prices are neglected. Grid losses are approximated using the nominal root mean square grid voltage V and the average resistance between the main grid and the distribution network R (Morstyn and McCulloch 2019), based on the assumption of small network voltage drops and relatively low reactive power flows (Coffrin et al. 2012). The second-order dependency disincentivises large power imports and exports to minimise the likelihood of system instabilities due to transmission and distribution networks' interactions.

$$c_{\mathrm{d}}^{t} = \mathrm{C}_{\mathrm{d}} \sum_{i \in \mathcal{A}} \max\left(-p_i^t, 0\right) \tag{8}$$

Distribution costs c_{d}^{t} are proportional to the distribution charge C_{d} on exports. The resulting price spread between individual imports and exports decreases risks of network constraints violation by incentivising the use of local flexibility first (Morstyn et al. 2020). Distribution network losses due to power flows between agents are neglected so there is no second-order dependency.

4.1.3 Constraints

The system convex constraints are the following (Charbonnier et al. 2022), for time steps $t \in \mathcal{T}$ and agents $i \in \mathcal{A}$ are:

- Agent and substation energy balance (see Fig. 3)

$$p_i^t = c_i^t + h_i^t + \frac{b_{\mathrm{in},i}^t}{\eta_{\mathrm{ch}}} - \eta_{\mathrm{dis}} b_{\mathrm{out},i}^t - \mathrm{p}_{\mathrm{PV},i}^t \tag{9}$$

$$\sum_{i \in \mathcal{A}} p_i^t = g^t \tag{10}$$

- Battery energy balance

$$E_i^{t+1} = E_i^t + b_{\mathrm{in},i}^t - b_{\mathrm{out},i}^t - \mathrm{d}_{\mathrm{EV},i}^t \tag{11}$$

- Battery charge and discharge constraints

$$\mathrm{E}_0 = E_i^{t_0} = E_i^{t_{\mathrm{end}}} + b_{\mathrm{in},i}^{t_{\mathrm{end}}} - b_{\mathrm{out},i}^{t_{\mathrm{end}}} - \mathrm{d}_{\mathrm{EV},i}^{t_{\mathrm{end}}} \tag{12}$$

$$\mu_i^t \underline{\mathrm{E}}_i \leq E_i^t \leq \overline{\mathrm{E}}_i \tag{13}$$

$$b_{\mathrm{in},i}^t \leq \mu_i^t \overline{\mathrm{b}_{\mathrm{in}}} \tag{14}$$

$$b_{\mathrm{out},i}^t \leq \mu_i^t \overline{\mathrm{E}}_i \tag{15}$$

- Consumption flexibility—the demand $\mathrm{d}_{i,k}^{t_\mathrm{D}}$ of type k (fixed or flexible) at time t_D by agent i must be met by the sum of partial consumptions $\hat{c}_{i,k,t_\mathrm{C},t_\mathrm{D}}$ at times $\{t_\mathrm{C}...t_\mathrm{C} + \mathrm{n}_{\mathrm{flex}}\}$ within the time frame $\mathrm{n}_{\mathrm{flex}}$ specified by the flexibility of each type of demand in matrix $\mathrm{f}_{i,k,t_\mathrm{C},t_\mathrm{D}}$

$$\sum_{t_\mathrm{C} \in \mathcal{T}} \hat{c}_{i,k,t_\mathrm{C},t_\mathrm{D}} \mathrm{f}_{i,k,t_\mathrm{C},t_\mathrm{D}} = \mathrm{d}_{i,k}^{t_\mathrm{D}} \tag{16}$$

- Consumption—the total consumption at time t_C is the sum of all partial consumptions $\hat{c}_{i,k,t_\mathrm{C},t_\mathrm{D}}$ meeting parts of demands from current and previous time steps t_D:

$$\sum_{t_\mathrm{D} \in \mathcal{N}} \hat{c}_{i,k,t_\mathrm{C},t_\mathrm{D}} = c_{i,k}^{t_\mathrm{C}} \tag{17}$$

- Heating—a Crank-Nicholson scheme (ISO 2007) is employed to model heating; the workings to obtain this equation are included in Charbonnier et al. (2022):

$$\begin{bmatrix} T_{\mathrm{m},i}^{t+1} \\ T_{\mathrm{air},i}^{t+1} \end{bmatrix} = \kappa \left[1, T_{\mathrm{m},i}^t, \mathrm{T}_\mathrm{e}^t, \phi^t, h_i^t\right]^\mathsf{T} \tag{18}$$

$$\underline{\mathrm{T}}_i^t \leq T_{\mathrm{air},i}^t \leq \overline{\mathrm{T}}_i^t \tag{19}$$

- Non-negativity constraints

$$c_i^t, h_i^t, E_i^t, b_{\mathrm{in},i}^t, b_{\mathrm{out},i}^t, \hat{c}_{i,l,t_\mathrm{C},t_\mathrm{D}} \geq 0 \tag{20}$$

Note that this case study takes the assumption that an optimisation can be performed over the whole day given perfect knowledge of all current and future variables—in real-world applications, this is not possible as there is uncertainty in future variables such as PV generation, household loads, EV loads and availability, and weather. This case study is intended to illustrate the difference between an inflexible baseline, a competitive scenario, and a cooperative scenario only. Moreover, this simulation relies on market mechanisms to reward cooperation, such as network constraint management, payments for minimising grid losses, and carbon pricing in the local market. In most jurisdictions, regulatory and market mechanisms are not in place, which means there are no incentives for local cooperation beyond individual cost minimisation.

4.2 The Value of Cooperation

We now take an example day to illustrate the sub-optimality gap resulting from different control actions by agents. Each agent can select actions in one of the following scenarios:

- Baseline: Players are passive, i.e., have no flexibility. No optimisation is performed, EVs are charged as soon as they are plugged in, heating is maintained at the median comfort temperature as early as possible, and no flexible loads are delayed.
- Selfish optimisations (competitive): individual players optimise their local control actions to minimise their private costs only, comprising of local energy bills for the energy delivered and the battery depreciation costs (see Sect. 4.1.2, $C_{i,\mathrm{indiv}}$). Competitive players ignore the costs of grid losses, distribution network congestion, and greenhouse gas emissions.
- Global optimisation (cooperative): a global optimisation is performed over the coalition formed. Global costs are minimised (see Sect. 4.1.2, C_{tot}).

We populate this model with data generated from the Customer-Led Network Revolution (CLNR) trials for PV generation and household consumption data (Wardle 2014a, b), the British National Travel Survey (NTS) for travelling energy consumption and patterns (Department for Transport 2019), and the Octopus agile tariff for January 2020 for energy prices (Octopus Energy 2019) (see Charbonnier et al. 2022 for more details on case study data). For one example day, total costs are shown in Fig. 4, and inputs and control actions are illustrated in Fig. 5. Results clearly show three key conclusions:

- Significant value can be unlocked through the coordination of residential energy resources relative to the inflexible baseline
- Further total value is obtained through cooperation rather than selfish optimisations
- The value created can be redistributed to participants, with both personal and excess global value created.

This case study illustrates how energy market stakeholders, including households, networks, and society, can gain from cooperative value creation given appropriate coordination and remuneration design.

5 Conclusion

Emerging local energy market business models acting as coordinators for distributed energy resources create opportunities both for renewable energy integration and systems and community co-benefits. Such benefits include reduced customer bills, network management, reduced air pollution, and social cohesion.

We have first presented seven key active players in local energy markets: energy suppliers, network operators, regulator and government, active participants, pas-

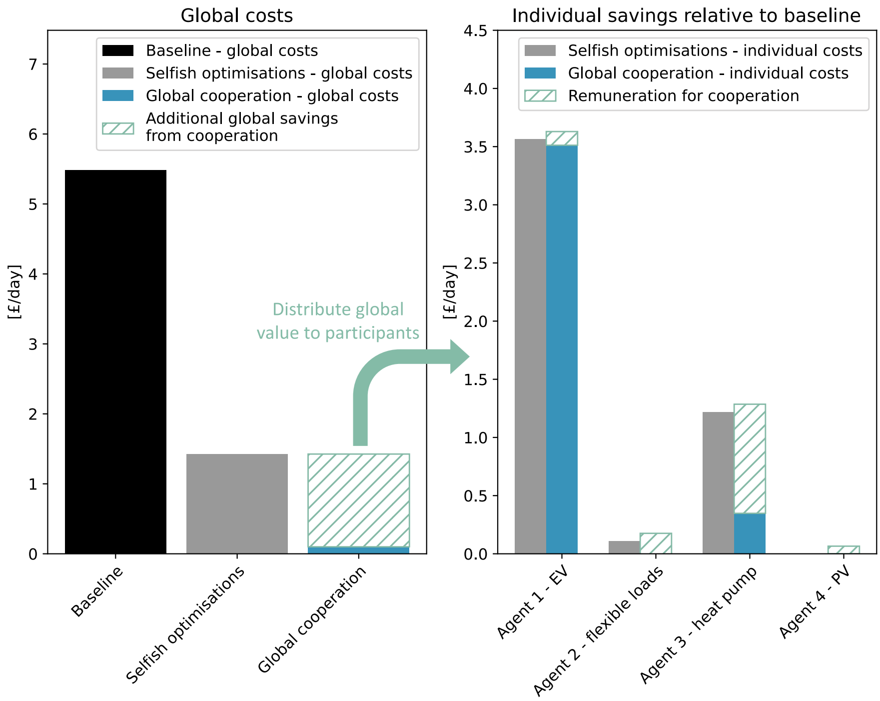


Fig. 4 The left-hand side bar plot shows the global costs (C_{tot}, including individual, network and greenhouse gas emissions costs) incurred if all participant are non-flexible (baseline, no optimisation performed), are competitive (selfish optimisations min $C_{i,\text{indiv}}$), and are cooperative (global optimisations min C_{tot}). This shows that while global costs are reduced compared to the baseline in both the selfish and the global optimisations, further global savings can be obtained in the cooperative case. The right-hand side depicts the savings in individual costs $C_{i,\text{indiv}}$ for each participant in the competitive and cooperative cases. While individual participants save money in both the competitive and cooperative scenarios relative to the inflexible baseline scenario, they may incur losses in potential individual saving opportunities when cooperating rather than selfishly minimising their own costs only. However, the additional global value in hatched green is larger than the sum of individual opportunity losses and can be redistributed amongst the participants such that all are gaining from participating. Here, the individual losses are first compensated, and the excess value is then split equally amongst participants as an example for the simulated day

sive participants, coordinators, and community. Together, they form a web of interdependencies and relationships through physical, social, financial and digital connections. While they each pursue their own goals and sit at varying degrees of readiness for local energy market participation with specific sets of constraints, we have presented different structures in which they can be coordinated based on their level of agency, communication structure, and level of cooperation. A numerical case study has demonstrated how cooperation can create further value relative to individual utility optimisation and how this value can be redistributed to benefit all.

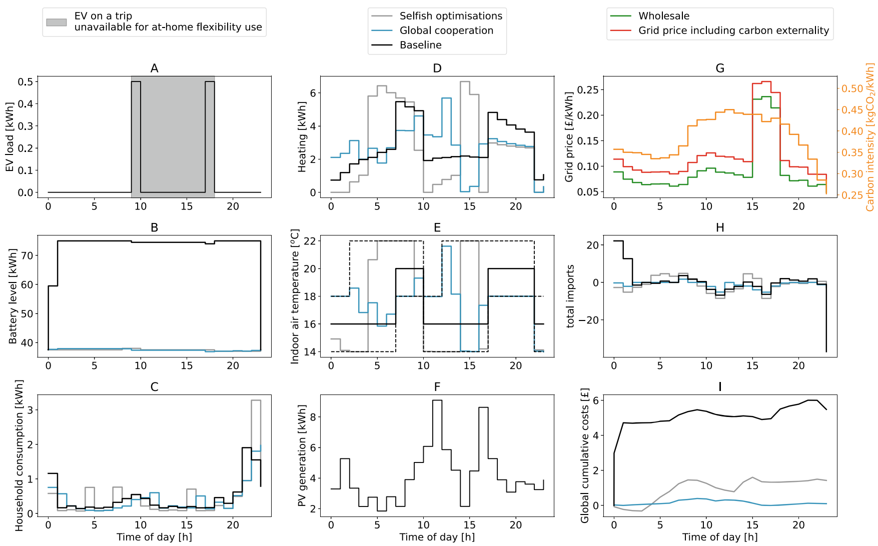


Fig. 5 Case study input data and control actions by agent under baseline, cooperative and competitive scenarios. Subplot A shows the EV at-home availability and consumption of agent 1. The car cannot be charged while on a trip, and enough charge has to be available beforehand for the travelling loads. Subplot B shows the battery level profiles. Subplot C shows the total household load consumption over time for agent 2. As the total household electric demand is fixed, displacing consumption does not increase total consumption. Subplot D shows the heating energy profile for agent 3, resulting in the temperatures in subplot E. The baseline profile maintains the median desired temperature, whereas the flexible policies can go above or below that median, within the desired temperature bounds. Variation in heating loads within the acceptable temperature bounds may increase overall consumption, though at a lower overall cost. Subplot F shows the PV generation of agent 4. Subplot G shows the wholesale prices and the grid carbon intensity for the example day and the resulting grid cost coefficient C_g given a social cost of carbon of 70 £/tCO_2. Subplot H shows the total imports (positive), and exports (negative) for the group of four agents based on the strategy adopted. Subplot I shows cumulative rewards over time for each of the strategies. An interplay is thus illustrated by the two policies between the costs of battery depreciation and distribution network congestion on the one hand and the opportunity for energy arbitrage to save on grid energy and emissions costs on the other

The field of local energy markets is still emerging, and active research is ongoing in several areas. First, the role of the distributed energy resource coordinator is still being shaped, with numerous potential frameworks and business models possible (Behrangrad 2015; Eid et al. 2016). Secondly, protection measures for non-market players are a crucial area of concern given rising energy poverty and that those most impacted by potential bill increases are least likely to benefit from access to local energy markets (Savelli and Morstyn 2021). Finally, the way in which future local energy markets will allocate network tariffs to manage impacts on the shared physical grid infrastructure is still emerging (Dudjak et al. 2021).

Acknowledgements This work was supported by the Saven European Scholarship and by the UK Research and Innovation and the Engineering and Physical Sciences Research Council (award references EP/S000887/1, EP/S031901/1, and EP/T028564/1).

References

Abbas AO, Chowdhury BH (2021) Using customer-side resources for market-based transmission and distribution level grid services—a review. Int J Electr Power Ener Syst 125(May 2020):106480. https://doi.org/10.1016/j.ijepes.2020.106480

Ableitner L (2019) Quartierstrom. Implementation of a real world prosumer centric local energy market in Walenstadt, Switzerland. arXiv:1905.07242

Abrishambaf O, Lezama F, Faria P, Vale Z (2019) Towards transactive energy systems: an analysis on current trends. Ener Strateg Rev 26:100418. https://doi.org/10.1016/j.esr.2019.100418

Andrianesis P, Caramanis MC (2019) Optimal grid—distributed energy resource coordination: distribution locational marginal costs and hierarchical decomposition. In: 2019 57th annual Allerton conference on communication, control, and computing, Allerton, pp 318–325. https://doi.org/10.1109/ALLERTON.2019.8919689

Apostolopoulou D, Bahramirad S, Khodaei A (2016) The interface of power: moving toward distribution system operators. IEEE Power Ener Mag 46–51

Arblaster M (2018) Economic regulation of air traffic management: principles and approaches. In: Arblaster M (ed) Air traffic management. Elsevier, pp 143–172. https://doi.org/10.1016/B978-0-12-811118-5.00007-2. https://www.sciencedirect.com/science/article/pii/B9780128111185000072

Arlt M-L, Chassin DP, Kiesling LL (2021) Opening up transactive systems: Introducing tess and specification in a field deployment. Energies 14(13). https://doi.org/10.3390/en14133970. https://www.mdpi.com/1996-1073/14/13/3970

Babar M, Nguyen PH, Cuk V, Kamphuis IG, Bongaerts M, Hanzelka Z (2018) The evaluation of agile demand response: an applied methodology. IEEE Trans Smart Grid 9(6):6118–6127. https://doi.org/10.1109/TSG.2017.2703643

Bandeiras F, Pinheiro E, Gomes M, Coelho P, Fernandes J (2020) Review of the cooperation and operation of microgrid clusters. Renew Sustain Ener Rev 133(August):110311. https://doi.org/10.1016/j.rser.2020.110311

Behrangrad M (2015) A review of demand side management business models in the electricity market. Renew Sustain Ener Rev 47:270–283. https://doi.org/10.1016/j.rser.2015.03.033

Bentham J (1879) An introduction to the principles of morals and legislation. Clarendon Press, Oxford

Black J, Hashimzade N, Myles G (2012) A dictionary of economics. Oxford University Press. https://doi.org/10.1093/acref/9780199696321.001.0001

Blasch J, Filippini M, Kumar N (2019) Boundedly rational consumers, energy and investment literacy, and the display of information on household appliances. Resour Ener Econ 56:39–58

Cao J (2019) Deep reinforcement learning based energy storage arbitrage with accurate lithium-ion battery degradation model. IEEE Trans Smart Grid 14(8):1–9

Cao J, Crozier C, McCulloch M, Fan Z (2019) Optimal design and operation of a low carbon community based multi-energy systems considering EV integration. IEEE Trans Sustain Ener 10(3):1217–1226. https://doi.org/10.1109/TSTE.2018.2864123

Charbonnier F, Morstyn T, McCulloch MD (2022) Scalable multi-agent reinforcement learning for distributed control of residential energy flexibility. Appl Ener 314:118825

Charbonnier F, Morstyn T, McCulloch M (2022) Coordination of resources at the edge of the electricity grid: systematic review and taxonomy. Appl Ener

Charles River Associates, An assessment of the economic value of demand-side participation in the Balancing Mechanism and an evaluation of options to improve access (2017)
Chen T, Su W (2019) Indirect customer-to-customer energy trading with reinforcement learning. IEEE Trans Smart Grid 10(4):4338–4348. https://doi.org/10.1109/TSG.2018.2857449
Claessens BJ, Vandael S, Ruelens F, De Craemer K, Beusen B (2013) Peak shaving of a heterogeneous cluster of residential flexibility carriers using reinforcement learning. In: 2013 4th IEEE/PES innovative smart grid technologies Europe. ISGT Europe 2013, pp 1–5. https://doi.org/10.1109/ISGTEurope.2013.6695254
Coffrin C, Van Hentenryck P, Bent R (2012) Approximating line losses and apparent power in AC power flow linearizations. In: IEEE power and energy society general meeting, pp 1–8. https://doi.org/10.1109/PESGM.2012.6345342
Council of European Energy Regulators, Regulatory aspects of self- consumption and energy communities CEER report, Tech. Rep. (2019). https://www.ceer.eu/documents/104400/-/-/8ee38e61-a802-bd6f-db27-4fb61aa6eb6a
Creamer E, Eadson W, Pinker A, Tingey M, Markantoni M, Foden M, Speight TB, Barnacle ML (2018) Community energy?: Entanglements of community, state, and private sector. Geogr Compass 12(7):1–16. https://doi.org/10.1111/gec3.12378
Crozier C, Apostolopoulou D, McCulloch M (2018) Mitigating the impact of personal vehicle electrification: a power generation perspective. Ener Policy 118(2013):474–481. https://doi.org/10.1016/j.enpol.2018.03.056
Dalamagkidis K, Kolokotsa D, Kalaitzakis K, Stavrakakis GS (2007) Reinforcement learning for energy conservation and comfort in buildings. Building Environ 42(7):2686–2698. https://doi.org/10.1016/j.buildenv.2006.07.010
Darby SJ (2019) Smart and sustainable, fast and slow. In: Eceee summer study proceedings 2019-June, pp 939–948
Darby SJ (2020) Demand response and smart technology in theory and practice: customer experiences and system actors. Ener Policy 143(April):111573. https://doi.org/10.1016/j.enpol.2020.111573
Dauer D, Flath CM, Ströhle P, Weinhardt C (2013) Market-based EV charging coordination. In: Proceedings—2013 IEEE/WIC/ACM international conference on intelligent agent technology, IAT 2013 2, pp 102–107. https://doi.org/10.1109/WI-IAT.2013.97
Department for Business Energy and Industrial Strategy, Energy consumption in the UK (2020)
Department for Transport, National Travel Survey 2002-2017 (2019). http://doi.org/10.5255/UKDA-SN-5340-10
Di Silvestre ML, Gallo P, Ippolito MG, Sanseverino ER, Zizzo G (2018) A technical approach to the energy blockchain in microgrids. IEEE Trans Ind Inform 14(11):4792–4803. https://doi.org/10.1109/TII.2018.2806357
Dietz T (2015) Altruism, self-interest, and energy consumption. PNAS 112(6):1654–1655. https://doi.org/10.1073/pnas.1423686112
Dudjak V, Neves D, Alskaif T, Khadem S, Pena-bello A, Saggese P, Bowler B, Andoni M, Bertolini M, Zhou Y, Lormeteau B, Mustafa MA, Wang Y, Francis C, Zobiri F, Parra D, Papaemmanouil A (2021) Impact of local energy markets integration in power systems layer: a comprehensive review. Appl Ener 301(March):117434. https://doi.org/10.1016/j.apenergy.2021.117434
Dufo-López R, Lujano-Rojas JM, Bernal-Agustín JL (2014) Comparison of different lead-acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. Appl Ener 115:242–253
Dusparic I (2013) Multi-agent residential demand response based on load forecasting. In: 2013 1st IEEE conference on technologies for sustainability, SusTech 2013, pp 90–96. https://doi.org/10.1109/SusTech.2013.6617303
Dusparic I, Maximizing renewable energy use with decentralized residential demand response. In: 2015 IEEE 1st international smart cities conference, ISC2 2015. https://doi.org/10.1109/ISC2.2015.7366212

Eid C, Codani P, Perez Y, Reneses J, Hakvoort R (2016) Managing electric flexibility from Distributed Energy Resources: A review of incentives for market design. Renew Sustain Ener Rev 64:237–247. https://doi.org/10.1016/j.rser.2016.06.008
Elder GH (1994) Time, human agency, and social change: perspectives on the life course. Soc Psychol Q 57(1):4–15. http://www.jstor.org/stable/2786971
Energy Systems Catapult (2019) The policy and regulatory context for new Local Energy Markets. Technical Report, August, Energy Systems Catapult
European Commission (2016) An EU strategy on heating and cooling, Technical report. https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_ACT_part1_v14.pdf
Farhi E, Werning I (2019) Monetary policy, bounded rationality, and incomplete markets. Am Econ Rev 109(11):3887–3928
Fazal R, Solanki J, Solanki SK (2012) Demand response using multi-agent system. In: 2012 North American power symposium, NAPS 2012. https://doi.org/10.1109/NAPS.2012.6336401
Fleiner T, Janko Z, Tamura A, Teytelboym A (2015) Trading networks with bilateral contracts. In: EAI endorsed transactions on serious games, pp 1–39. https://doi.org/10.4108/eai.8-8-2015.2260329
Fortenbacher P, Mathieu JL, Andersson G (2017) Modeling and optimal operation of distributed battery storage in low voltage grids. IEEE Trans Power Syst 32(6):4340–4350. arXiv:1603.06468. https://doi.org/10.1109/TPWRS.2017.2682339
Frederiks ER, Stenner K, Hobman EV (2015) Household energy use: applying behavioural economics to understand consumer decision-making and behaviour. Renew Sustain Ener Rev 41:1385–1394
Gilbert A, Bazilian MD, Gross S (2021) The emerging global natural gas market and the energy crisis of 2021–2022, Technical Report, Dec 2021, Brookings
Guerrero J, Chapman AC, Verbic G (2018) Decentralized P2P energy trading under network constraints in a low-voltage network. IEEE Trans Smart Grid 1–10. arXiv:1809.06976. https://doi.org/10.1109/TSG.2018.2878445
Guerrero J, Gebbran D, Mhanna S, Chapman AC, Verbič G (2020) Towards a transactive energy system for integration of distributed energy resources: home energy management, distributed optimal power flow, and peer-to-peer energy trading. Renew Sustain Energ Revi 132
Haider HT, See OH, Elmenreich W (2016) A review of residential demand response of smart grid. Renew Sustain Ener Rev 59:166–178. https://doi.org/10.1016/j.rser.2016.01.016
Han L, Morstyn T, McCulloch M (2019) Incentivizing prosumer coalitions with energy management using cooperative game theory. IEEE Trans Power Syst 34(1):303–313. https://doi.org/10.1109/TPWRS.2018.2858540
Hao H, Sanandaji BM, Poolla K, Vincent T (2015) Aggregate flexibility of thermostatically controlled loads. IEEE Trans Power Syst 30(1):189–198. https://doi.org/10.1109/TPWRS.2014.2328865
Hashimzade N, Myles G, Black J (2017) Utility function
Hayes BP, Thakur S, Breslin JG (2020) Co-simulation of electricity distribution networks and peer to peer energy trading platforms. Int J Electr Power Ener Syst 115(May 2019):105419. https://doi.org/10.1016/j.ijepes.2019.105419
Herbert S (1982) Models of bounded rationality. MIT Press, Mass, London, Cambridge
Heussen K, Koch S, Ulbig A, Andersson G (2010) Energy storage in power system operation: the power nodes modeling framework. In: IEEE PES innovative smart grid technologies conference Europe, ISGT Europe, pp 1–8. https://doi.org/10.1109/ISGTEUROPE.2010.5638865
Hurtado LA, Mocanu E, Nguyen PH, Gibescu M, Kamphuis RI (2018) Enabling cooperative behavior for building demand response based on extended joint action learning. IEEE Trans Ind Inform 14(1):127–136. https://doi.org/10.1109/TII.2017.2753408
Inês C, Guilherme PL, Esther M-G, Swantje G, Stephen H, Lars H (2020) Regulatory challenges and opportunities for collective renewable energy prosumers in the EU. Ener Policy 138:111212. https://doi.org/10.1016/j.enpol.2019.111212. www.sciencedirect.com/science/article/pii/S0301421519307943

ISO (2007) Calculation of energy use for space heating and cooling ISO/FDIS 13790:2007(E)
Jamasb T, Pollitt M (2007) Incentive regulation of electricity distribution networks: lessons of experience from Britain. Ener Policy 35(12):6163–6187. https://doi.org/10.1016/j.enpol.2007.06.022
Ji C, You P, Pivo EJ, Shen Y, Gayme DF, Mallada E (2019) Optimal coordination of distribution system resources under uncertainty for joint energy and ancillary service market participation
Kandasamy NK, Tseng K, Soong B (2017) A virtual storage capacity using demand response management to overcome intermittency of solar pv generation. IET Renew Power Gener 11(09 2017). https://doi.org/10.1049/iet-rpg.2017.0036
Khorasany M, Mishra Y, Ledwich G (2020) A decentralized bilateral energy trading system for peer-to-peer electricity markets. IEEE Trans Ind Electron 67(6):4646–4657. https://doi.org/10.1109/TIE.2019.2931229
Kim JG, Lee B (2020) Automatic P2P energy trading model based on reinforcement learning using long short-term delayed reward. Energies 13(20). https://doi.org/10.3390/en13205359
Kim B, Zhang Y, Van Der Schaar M, Lee J (2016) Dynamic pricing and energy consumption scheduling with reinforcement learning. IEEE Trans Smart Grid 7(5):2187–2198
Kok K, Widergren S (2016) A society of devices: integrating intelligent distributed resources with transactive energy. IEEE Power Ener Mag 14(3):34–45. https://doi.org/10.1109/MPE.2016.2524962
Léautier T-O (2019) Imperfect markets and imperfect regulation: an introduction to the microeconomics and political economy of power markets. MIT Press
Lee JW, Lee DH (2011) Residential electricity load scheduling for multi-class appliances with Time-of-Use pricing. In: 2011 IEEE GLOBECOM workshops. GC Wkshps, pp 1194–1198. https://doi.org/10.1109/GLOCOMW.2011.6162370
Li Z, Kang J, Yu R, Ye D, Deng Q, Zhang Y (2018) Consortium blockchain for secure energy trading in industrial internet of things. IEEE Trans Ind Inform 14(8):3690–3700, cited by 388. https://doi.org/10.1109/TII.2017.2786307. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85039778045&doi=10.1109%2fTII.2017.2786307&partnerID=40&md5=72ec5d315d1ddcf4cae831e0632d11cb
Lu R, Hong SH (2019) Incentive-based demand response for smart grid with reinforcement learning and deep neural network. Appl Ener 236(December 2018):937–949. https://doi.org/10.1016/j.apenergy.2018.12.061
Maharjan S, Zhu Q, Zhang Y, Gjessing S, Basar T (2013) Dependable demand response management in the smart grid: a stackelberg game approach. IEEE Trans Smart Grid 4(1):120–132. https://doi.org/10.1109/TSG.2012.2223766
Mai TT, Nguyen PH, Tran QT, Cagnano A, De Carne G, Amirat Y, Le AT, De Tuglie E (2021) An overview of grid-edge control with the digital transformation. Electr Eng 103(4):1989–2007
Marinescu A, Dusparic I, Clarke S (2017) Prediction-based multi-agent reinforcement learning in inherently non-stationary environments. ACM Trans Auton Adapt Syst 12(2). https://doi.org/10.1145/3070861
Masson-Delmotte V (2018) Global warming of 1.5C. An IPCC special report on the impacts of global warming of 1.5C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change
Mayr E, Zhang Z, Iftikhar B (2022) Gone bust? The crisis in Britain's energy supply market, Technical report, FTI
McKenna E, Thomson M (2016) High-resolution stochastic integrated thermal-electrical domestic demand model. Appl Ener 165:445–461
Meng L, Sanseverino ER, Luna A, Dragicevic T, Vasquez JC, Guerrero JM (2016) Microgrid supervisory controllers and energy management systems: a literature review. Renew Sustain Ener Rev 60:1263–1273
Moon N, Rodgers D, Mchugh S (2015) Energy market investigation—a report for the competition and markets authority by GfK NOP, Technical Report

Moret F, Pinson P (2019) Energy collectives: a community and fairness based approach to future electricity markets. IEEE Trans Power Syst 34(5):3994–4004. https://doi.org/10.1109/TPWRS.2018.2808961

Morstyn T, Farrell N, Darby SJ, McCulloch MD (2018a) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat Ener 3(2):94–101. https://doi.org/10.1038/s41560-017-0075-y

Morstyn T, Hredzak B, Agelidis V (2018b) Control strategies for microgrids with distributed energy storage systems: an overview. IEEE Trans Smart Grid 9(4):3652–3666. https://doi.org/10.1109/TSG.2016.2637958

Morstyn T, Hredzak B, Aguilera R, Agelidis V (2018c) Model predictive control for distributed microgrid battery energy storage systems. IEEE Trans Control Syst Technol 26(3):1107–1114. arXiv:1702.04699. https://doi.org/10.1109/TCST.2017.2699159

Morstyn T, McCulloch M (2019) Multiclass energy management for peer-to-peer energy trading driven by prosumer preferences. IEEE Trans Power Syst 34(5):4005–4014. https://doi.org/10.1109/TPWRS.2018.2834472

Morstyn T, Mcculloch M (2020) Peer-to-Peer energy trading. In: Analytics for the sharing economy: mathematics engineering and business perspectives (March). https://doi.org/10.1007/978-3-030-35032-1

Morstyn T, Teytelboym A, Hepburn C, McCulloch M (2020) Integrating P2P energy trading with probabilistic distribution locational marginal pricing. IEEE Trans Smart Grid 11(4):3095–3106. https://doi.org/10.1109/TSG.2019.2963238

Morstyn T, Teytelboym A, McCulloch M (2019a) Bilateral contract networks for peer-to-peer energy trading. IEEE Trans Smart Grid 10(2):2026–2035. https://doi.org/10.1109/TSG.2017.2786668

Morstyn T, Teytelboym A, McCulloch M (2019b) Designing decentralized markets for distribution system flexibility. IEEE Trans Power Syst 34(3):1–12. https://doi.org/10.1109/TPWRS.2018.2886244

Muratori M (2018) Impact of uncoordinated plug-in electric vehicle charging on residential power demand. Nat Ener 3(3):193–201. https://doi.org/10.1038/s41560-017-0074-z

Nicol S, Roys M, Ormandy D, Ezratty V (2015) The cost of poor housing in the European Union, Technical report, BRE. https://www.bre.co.uk/filelibrary/Briefingpapers/92993_BRE_Poor-Housing_in_-Europe.pdf

Niella T, Stier-Moses N, Sigman M (2016) Nudging cooperation in a crowd experiment. PLOS ONE 11(1):1–20

Nolan JM, Schultz PW, Cialdini RB, Goldstein NJ, Griskevicius V (2008) Normative social influence is underdetected. Person Soc Psychol Bull 34(7):913–923. https://doi.org/10.1177/0146167208316691

Octopus Energy (2019) Octopus energy API

Ofgem PC (2016) Aggregators–barriers and external impacts. Technical Report, May, OFGEM

O'Neill D, Levorato M, Goldsmith A, Mitra U (2010) Residential demand response using reinforcement learning. In: 2010 First IEEE international conference on smart grid communications, pp 409–414. https://doi.org/10.1109/smartgrid.2010.5622078

Origami Energy, Value chain for flexibility providers, Technical report, Local Energy Oxfordshire (LEO) (2021). https://project-leo.co.uk/wp-content/uploads/2021/06/LEO-D2.8-Value-Chain-for-Flexibility-Providers-v2.1-LEO-cover.pdf

Parry M (2007) Climate change 2007: impacts, adaptation and vulnerability. Published for the Intergovernmental Panel on Climate Change [by] Cambridge University Press, Cambridge

Pumphrey K, Walker S, Andoni M, Robu V (2020) Green hope or red herring? Examining consumer perceptions of peer-to-peer energy trading in the United Kingdom. Ener Res Soc Sci 68(Sept 2019):101603. https://doi.org/10.1016/j.erss.2020.101603

Römer B, Reichhart P, Kranz J, Picot A (2012) The role of smart metering and decentralized electricity storage for smart grids: the importance of positive externalities. Ener policy 50:486–495

Rottondi C, Verticale G (2017) A privacy-friendly gaming framework in smart electricity and water grids 5:14221–14233

Rozada S, Apostolopoulou D, Alonso E (2020) Load frequency control: a deep multi-agent reinforcement learning approach. In: IEEE power and energy society general meeting 2020-Aug, pp 0–4. https://doi.org/10.1109/PESGM41954.2020.9281614

Samadi P, Mohsenian-Rad H, Wong VWS, Schober R (2013) Tackling the load uncertainty challenges for energy consumption scheduling in smart grid. IEEE Trans Smart Grid 4(2):1007–1016. https://doi.org/10.1109/TSG.2012.2234769

Savelli I, Morstyn T (2021) Better together: harnessing social relationships in smart energy communities. Ener Res Soc Sci 78:102125

Schellenberg C, Lohan J, Dimache L (2020) Comparison of metaheuristic optimisation methods for grid-edge technology that leverages heat pumps and thermal energy storage. Renew Sustain Ener Rev 131(June):109966

Siano P (2014) Demand response and smart grids-A survey. Renew Sustain Ener Rev 30:461–478. https://doi.org/10.1016/j.rser.2013.10.022

Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E (2019) Peer-to-peer and community-based markets: a comprehensive review. Renew Sustaina Ener Rev 104:367–378. arXiv:1810.09859. https://doi.org/10.1016/j.rser.2019.01.036

Stadler M, Krause W, Sonnenschein M, Vogel U (2007) The adaptive fridge—comparing different control schemes for enhancing load shifting of electricity demand. Environ Protect 199–206

Sun Y, Somani A, Carroll T (2015) Learning based bidding strategy for HVAC systems in double auction retail energy markets. In: Proceedings of the American control conference 2015-July, pp 2912–2917. https://doi.org/10.1109/ACC.2015.7171177

Tayab UB, Roslan MAB, Hwai LJ, Kashif M (2017) A review of droop control techniques for microgrid. Renew Sustain Ener Rev 76(March):717–727. https://doi.org/10.1016/j.rser.2017.03.028

Taylor A (2014) Accelerating learning in multi-objective systems through transfer learning. In: Proceedings of the international joint conference on neural networks, pp 2298–2305. https://doi.org/10.1109/IJCNN.2014.6889438

The European Parliament, The Council of the European, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (2019)

Tindemans S, Trovato V, Strbac G (2015) Decentralized control of thermostatic loads for flexible demand response. IEEE Trans Control Syst Technol 23(5):1685–1700. https://doi.org/10.1109/TCST.2014.2381163

Tushar W (2019) A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. Appl Ener 243(November 2018):10–20. https://doi.org/10.1016/j.apenergy.2019.03.111

Tushar W, Saha T, Yuen C, Morstyn T, Nahid-Al-Masood, Poor H, Bean R (2020) Grid influenced peer-to-peer energy trading. IEEE Trans Smart Grid 11(2):1407–1418. arXiv:1908.09449. https://doi.org/10.1109/TSG.2019.2937981

Vayá MG, Roselló LB, Andersson G (2014) Optimal bidding of plug-in electric vehicles in a market-based control setup. In: Proceedings—2014 power systems computation conference, PSCC 2014. https://doi.org/10.1109/PSCC.2014.7038108

Vázquez-Canteli J, Nagy Z (2019) Reinforcement learning for demand response: a review of algorithms and modeling techniques. Appl Ener 235(Oct 2018):1072–1089. https://doi.org/10.1016/j.apenergy.2018.11.002

Vespermann N, Hamacher T, Kazempour J, Member S (2021) Risk trading in energy communities 12(2):1249–1263

Vivid Economics, Imperial College London, Accelerated electrification and the GB electricity system, report prepared for Committee on Climate Change, pp 1–79 (2019). https://www.theccc.org.uk/wp-content/uploads/2019/05/CCC-Accelerated-Electrification-Vivid-Economics-Imperial-1.pdf

Wang H, Zhang B (2018) Energy storage arbitrage in real-time markets via reinforcement learning. In: IEEE power and energy society general meeting, vol 2018, pp 1–11. arXiv:1711.03127. https://doi.org/10.1109/PESGM.2018.8586321

Wardle R (2014a) Dataset (TC1a): basic profiling of domestic smart meter customers

Wardle R (2014b), Dataset (TC5): Enhanced profiling of domestic customers with solar photovoltaics (PV)

Wen Z, O'Neill D, Maei H (2015) Optimal demand response using device-based reinforcement learning. IEEE Trans Smart Grid 6(5):2312–2324. https://doi.org/10.1109/TSG.2015.2396993

Wilson R (2002) Architecture of power markets. Econometrica 70(4):1299–1340. https://doi.org/10.1111/1468-0262.00334

Wooldridge M (2002) Intelligent agents: the key concepts. Springer, Berlin, Heidelberg

Wuester H, Lee JJ, Lumijarvi A (2016) Unlocking renewable energy investment: the role of risk mitigation and structured finance. Technical report IRENA

Wu F, Varaiya P (1999) Coordinated multilateral trades for electric power networks: theory and implementation. Int J Electr Power Ener Syst 21:75–102. https://doi.org/10.1049/cp:19951190

Yang H, Zhang M, Lai M (2011) Complex dynamics of cournot game with bounded rationality in an oligopolistic electricity market. Optim Eng 12(4):559–582

Yang L, Nagy Z, Goffin P, Schlueter A (2015) Reinforcement learning for optimal control of low exergy buildings. Appl Ener 156:577–586. https://doi.org/10.1016/j.apenergy.2015.07.050

Yao J (2017) Cybersecurity of demand side management in the smart electricity grid: Privacy protection, battery capacity sharing and power grid under attack, PhD thesis, copyright—Database copyright ProQuest LLC; ProQuest does not claim copyright in the individual underlying works. https://www.proquest.com/dissertations-theses/cybersecurity-demand-side-management-smart/docview/1957432786/se-2?accountid=13042. Accessed 20 May 2021

Ye Y, Qiu D, Sun M, Papadaskalopoulos D, Strbac G (2020) Deep reinforcement learning for strategic bidding in electricity markets. IEEE Trans Smart Grid 11(2):1343–1355. https://doi.org/10.1109/TSG.2019.2936142

Zhang X, Bao T, Yu T, Yang B, Han C (2017) Deep transfer Q-learning with virtual leader-follower for supply-demand Stackelberg game of smart grid. Energy 133:348–365. https://doi.org/10.1016/j.energy.2017.05.114

Zhang Z, Li R, Li F (2020) A novel peer-to-peer local electricity market for joint trading of energy and uncertainty. IEEE Trans Smart Grid 11(2):1205–1215. https://doi.org/10.1109/TSG.2019.2933574

Zhao J, Lu J, Lo KL (2017) A transmission congestion cost allocation method in bilateral trading electricity market. Ener Power Eng 09(04):240–249. https://doi.org/10.4236/epe.2017.94b029

Zhu M (2014) Distributed demand response algorithms against semi-honest adversaries. In: IEEE power and energy society general meeting, Oct 2014, pp 0–4. https://doi.org/10.1109/PESGM.2014.6939191

Energy Community Preferences of Solar Prosumers and Electricity Consumers in the Digital Energy Ecosystem

Sanna Tuomela, Tuomo Hänninen, Enni Ruokamo, Netta Iivari, Maria Kopsakangas-Savolainen, and Rauli Svento

1 Introduction

In the strategies for energy transition and smart grids, energy consumers will become energy citizens who actively manage their energy demand and supply together with other digital energy ecosystem actors (Goulden et al. 2014), and participate in energy markets selling and buying micro-generated energy and demand flexibility (Schick and Gad 2015). The European Commission estimates that by 2050, almost half of EU households may be producing renewable energy (European Union 2019; Kampman et al. 2016). The energy community is widely considered one of the most important emerging organizational and business models in the energy transition. Estimates suggest that by 2030, energy communities could own some 17% of installed wind

S. Tuomela (✉)
Innolab, University of Vaasa, Oulu, Finland
e-mail: sanna.tuomela@uwasa.fi

Interact Research Unit, University of Oulu, Oulu, Finland

T. Hänninen
Centre for Wireless Communications, University of Oulu, Oulu, Finland

E. Ruokamo
Finnish Environment Institute and Department of Economics, Accounting and Finance, Oulu Business School, University of Oulu, Oulu, Finland

N. Iivari
Interact Research Unit, University of Oulu, Oulu, Finland

M. Kopsakangas-Savolainen
Finnish Environment Institute, Helsinki, Finland

R. Svento
Oulu Business School, University of Oulu, Oulu, Finland

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_4

capacity and 21% of solar in Europe (Caramizaru and Uihlein 2020). The dual transition of digitalization and energy fosters the emergence of new kinds of actor and role in the digital energy ecosystem. The evolving digital infrastructure and the role of energy citizens (CE Delft 2016; Matschoss et al. 2019) advance innovations that are emerging in the energy ecosystem, and open up opportunities to local and virtual communities to share, pool and trade energy and energy-related knowledge (Hyysalo 2021). A more decentralized energy system, where consumers play an active role, may be more democratic and participative, offering citizens opportunities to make their own decisions on what type of energy they want to use, and make energy an ecological resource subject to collective decision-making (Lennon et al. 2019). The new EU rules actively promote this with provisions on self-consumption of energy, and local and renewable energy communities (European Union 2019). Energy prosumers and consumers are key actors in the digital energy ecosystem, potentially through energy communities. A virtual digital energy ecosystem provides more means for energy system management, and widens the potential of traditionally local, financial and ideology based energy communities (Meelen et al. 2019; van der Schoor and Scholtens 2015). A virtual energy community may, for example, provide flexibility services for a distribution system operator (DSO) or a large renewable energy (RE) power plant (Huuki et al. 2020). On the other hand, the diversity and complexity of the growing number of distributed RE resources, and the changing roles of energy ecosystem actors, pose challenges to managing the energy system.

In the ongoing energy transition, citizens, who have long been relatively passive consumers of energy, are increasingly producing energy, and thus becoming prosumers. The term “prosumer” refers to the simultaneous behavior of producing and consuming (Toffler 1980). In the energy community context, prosumers produce energy, for example using solar panels, that is primarily for their own use, but may also trade, share and pool energy through digital applications such as energy communities (Brown et al. 2020; Gržanić et al. 2022; Kotilainen et al. 2016). The growing number of energy prosumers and interest in clean and local energy are advancing opportunities for energy co-operatives, P2P energy markets, and virtual power plants, meaning that consumers increasingly produce and share or trade energy, and energy production is dispersed and merged into energy consumers’ everyday activities (Olkkonen et al. 2017). Also, energy consumers without their own source of energy production have more opportunities to participate in energy markets through digital technologies and services, such as energy communities. Energy consumers may have a major role to play in contributing and creating new solutions and knowledge in digital energy ecosystems (Hyysalo 2021). Recent developments in the digital energy ecosystem have led to a growth in the number of energy communities, in many different forms and with varying degrees of success (Espe et al. 2018). The active participation of prosumers and energy consumers has become a critical issue in the future development of energy communities (Espe et al. 2018; Kotilainen et al. 2016; Vernay and Sebi 2020). However, end-user preferences have to date been largely ignored by other digital energy ecosystem actors. Here, those preferences are reflected against the framework of the digital energy ecosystem, providing a useful conceptual structure to understand solar prosumers and energy consumers as end-users of the energy community in a complex socio-technical energy system.

A digital ecosystem is defined as a distributed socio-technical system formed through the integration of technologies and networks, system users, and social and knowledge sharing, with functions such as adaptability, self-organization, and sustainability (Bakhtadze et al. 2019; Nachira et al. 2007). The digital energy ecosystem is based on smart grid technologies, decentralized RE production, and a network of actors, business models, and processes (Kotilainen et al. 2016; Tsujimoto et al. 2018). New and incumbent actors interact in the ecosystem network. They include, for example, distribution system operators (DSOs), prosumers, energy consumers, aggregators, local communities, and energy technology manufactures (e.g., home energy management systems and solar panels). It is recognized that users and user communities affect the creation of a sustainable ecosystem, and the other actors in the ecosystem (Hienerth et al. 2014; Khavul and Bruton 2013), and determine the success of new actors in the digital energy ecosystem, such as digital service providers, telecom operators, and data management companies (Kotilainen et al. 2016). Manifold social, economic, political, psychological, and other factors affect the implementation of interactions in the digital energy ecosystem network (Dong et al. 2007), and this study focuses on those factors from the end-users' perspective.

Energy communities have received much attention in recent years as a means to empower energy consumers and engage them with the energy transition (Brummer 2018; Caramizaru and Uihlein 2020). An energy community is "a configuration of technologies, services and infrastructures, regulations, and actors (e.g., producers, suppliers, policy-makers and users) that fulfills a societal function" (Schot 2016), such as balancing energy demand and supply. According to the European Union Clean Energy Package "[c]itizens can join in energy communities pooling their energy, and benefit from incentives for renewable energy production" (European Union 2019). An energy community may take many forms, from virtual and distributed to local renewables, with varying degrees of collective capacity (Bauwens et al. 2016; Soeiro and Ferreira Dias 2020a, b). It may, for example, be a local grassroots initiative for producing and sharing energy within a local community or housing company, or an entirely virtual, distributed group of actors pooling and/or sharing their energy for energy markets (Hyysalo 2021).

Energy transition requires increased awareness of the end-user's role in the energy system (Lennon et al. 2019). Hence, research on energy transition has in recent years expanded from technology and economic research to social science and the humanities, with the focus on energy users and their changing role (Ingeborgrud et al. 2020). In this chapter, we present end-users' preferences on how to improve the energy community end-user experience (UX). Here, UX is widely understood to include also the users' emotions, beliefs, preferences, and perceptions that are present prior to the use of or participation in the energy community (e.g., Chen and Duh 2009; Tuomela et al. 2021). In energy strategy planning, and for the design of efficient and useful energy services, applications and initiatives, it is essential to understand end-user preferences, concerns and motivations. Furthermore, solar prosumers, and electricity consumers without energy micro-production, have different roles in the energy community, thus their preferences may differ and result in different requirements for the energy community. Here, the terms users, consumers and members of the energy community are used interchangeably, ultimately describing individuals as prosumers, energy consumers, users of digital energy community services and solutions, and as participants in the energy community. Despite the interest in energy communities, very little is known about end-users' preferences, and how solar prosumers' preferences differ from those of electricity consumers (Morstyn et al. 2018). Policy makers, energy technology designers, and energy market stakeholders need to better understand end-users' preferences regarding the energy community, in order to create solutions and services that meet users' expectations and needs, and design effective strategies to promote energy communities. In this chapter, we analyze and discuss the solar prosumers and energy consumers' interest and preferences regarding the energy community. Methodologically, we propose the adoption an ecosystem framework. We argue that adopting a digital energy ecosystem perspective is especially suited to the analysis of energy communities, given that they must coordinate and integrate their actions with other ecosystem actors, if they are to accelerate transformation of the energy sector (Bauwens et al. 2016; Vernay and Sebi 2020).

This chapter answers the following research questions: (R1) What preferences do electricity users have concerning energy communities? and, (R2) How do the preferences of solar prosumers and electricity consumers differ regarding energy communities? We utilize survey data collected from Finnish energy prosumers and electricity consumers. Here, the term electricity consumer describes people not engaged in their own energy micro-production, thus excluding solar prosumers who both produce and consume.

The chapter is structured as follows. The first section provides a brief overview of the literature on energy community users' preferences and experiences. In the research design section, we present the applied method and research setting. The third section analyses the survey results. Finally, the discussion reflects our findings with other studies in the field, and presents suggestions for further research.

2 Related Research

Energy community, to which manifold characteristics and functions are attributed, is a relatively new entity in the energy sector. Energy (sustainable/low-carbon/clean-energy) communities vary in structure, size and composition, responsible stakeholder(s), purpose, and features. Members of the energy community can be households, prosumers (i.e., individuals who consume and produce energy), businesses, and institutions. Depending on their characteristics, energy communities have diverse consequences and impacts on people, places, and energy the sector (Soeiro and

Ferreira Dias 2020a). The common factor is the goal to decarbonize the energy system and increase the use of renewable energy (Summeren et al. 2020).

Multiple conceptualizations have been presented on energy community activities. In the EU, the Renewable Energy Directive (European Union 2018) defines 'energy community' as a legal entity that "is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises; has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders" (Roberts et al. 2019). Two types of energy community are further defined: 'Renewable energy community' and 'Citizen energy community' (Roberts et al. 2019). Citizen energy communities (CEC) "may engage [people or organizations] in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders" (Roberts et al. 2019). Renewable energy community (REC) is a special instance of CEC, referring to an entity where members are located in the proximity of renewable energy projects controlled or owned by the community (Hunkin and Krell 2018). REC may produce, consume, store and sell renewable energy, to share within the community and access all suitable markets (Roberts et al. 2019). Small and geographically local community energy initiatives produce or invest in the production of renewable energy primarily to cover their own energy needs (Dóci et al. 2015), with an emphasis on the social and shared identity aspect of the energy community, and provide the local community a form of co-operation and collaboration to reduce their energy carbon footprint (Heiskanen et al. 2010). Other conceptualizations of energy community activities include 'Prosumer community group', referring to a community of prosumers generating and sharing energy (Espe et al. 2018; Rathnayaka et al. 2014), and 'local energy initiative' (LEI) (Ghorbani et al. 2020).

Energy communities require and inspire new business models and technology applications in energy markets (Reis et al. 2021). The energy community may be a (local) RE production and sharing network, or a two- or multi-sided platform that matches two or more user groups (Abdelkafi et al. 2019; Eisenmann et al. 2006; Hagiu 2013). The platform may offer user groups diverse pricing and value proposals, but it is important to have a sufficiently high volume of users to attract those from other groups (Hagiu 2013; Huuki and Svento 2021; Kallio et al. 2020). One of the first energy community applications was peer-to peer (P2P) energy selling and buying in a blockchain-enabled microgrid (Brooklyn Microgrid 2021; Mengelkamp et al. 2018), but more applications, such as local RE communities and Virtual Power Plants (VPP), are being implemented as the concept of an energy community evolves (Mourik et al. 2019; Summeren et al. 2020). P2P energy trade transactions are made via distributed ledger, such as blockchain, instead of bilateral agreements between utilities and consumers/prosumers (Ioannis et al. 2017; Nidhin Mahesh et al. 2019;

Wu et al. 2022). In the meantime, Internet of Things (IoT) enables detailed accounts of energy flows (Ferreira and Martins 2018) and energy ecosystems (Yin et al. 2021).

An energy community may comprise a local microgrid, connected to or isolated from the main grid (Fahad Zia et al. 2018; Hirsch et al. 2018). Microgrids can provide flexibility and other services to the grid, improving stability and resilience (Fahad Zia et al. 2018; Harrison 2021). Most microgrids have to date been installed for industrial or remote use, and only 13% for community use (in 2015) (Emerging Microgrid Business Models 2016; Vanadzina et al. 2019). Regulations and laws for electricity markets vary by country, and may either deter or enable the evolution of energy community business models. In Europe, for example Austria, Spain, France, Germany, and Belgium have introduced legal frameworks that allow collective self-consumption (CSC), whereas in many other European countries sharing and pooling energy through CSC is heavily regulated and restricted (Frieden et al. 2019).

There are several driving forces for energy communities. For example, a need for demand-side flexibility and management (Lund et al. 2015; Paterakis et al. 2017); consumers' willingness to produce and use energy from renewable sources (Heiskanen and Matschoss 2017; Mundaca and Samahita 2020); the development of P2P markets for distributed energy facilitated by digitalization (IEA 2017; Morstyn et al. 2018; Zhang et al. 2018); new possibilities for end-users to participate in energy markets (Kotilainen et al. 2016; Teotia and Bhakar 2016); new and improved technologies for decentralized energy production, management and sharing (IEA 2020; Zhou 2016); and, the availability of detailed information on energy production, use and markets, due to smart meters, smart grids and IoT (Baidya et al. 2021; Kotilainen et al. 2016). Furthermore, energy communities may be a means to lower the barriers to active agency in energy markets, engaging and empowering people as energy citizens (European Commission 2015; Heiskanen et al. 2010; Ingeborgrud et al. 2020; Young and Middlemiss 2012).

Previous studies have identified that energy communities provide energy citizens with the capacity to work together, to transform their energy infrastructure at the local level (Raven et al. 2008), and foster individual and household energy behavior change (Heiskanen et al. 2010). Energy community participation may also reduce feelings of helplessness and disempowerment in changing energy consumption conventions (Tukker et al. 2008), give people confidence in enacting change, and spread knowledge that others are participating. Hence, together with other community members, energy communities are collectively making a significant difference (Heiskanen et al. 2010; Soeiro and Ferreira Dias 2020a). In their case study in the Netherlands, Van der Schoor and Scholtens (2015) identified the development of a shared vision, the level of activities, and the type of organization as important factors of the strength of the local energy initiatives. Also, according to a study on emerging energy community business models in Finland, participating in energy communities can be a way to build your identity, to represent yourself as environmentally conscious and supporting local and micro-generated renewable energy (Kallio et al. 2020). Studies on energy users' preferences regarding energy communities, and motivations or barriers to participate in one, are more scant.

Soeiro and Ferreira Dias (2020a) found in a survey of community energy participants in Europe that the environmental impacts are much more important to them than the financial. According to Doci and Vasileiadou (2014), motivations to invest in renewables at community level are both economic and environmental (normative), but also hedonic, such as the presence of other people, having fun, and integrating in a strong community. This social dimension seems to be an important condition for the realization of local energy projects (Ioannis et al. 2017), though social conflicts are identified as a potential barrier (Soeiro and Ferreira Dias 2020a). The survey by Kalkbrenner and Roosen (2016), on motives and willingness to participate in community energy amongst German energy users, revealed that the attitude towards community energy is positive, yet the willingness to volunteer is greater than the willingness to invest money. People emphasize the importance of social rather than just environmentally motivated aspects (Kalkbrenner and Roosen 2016). Also, a survey among 599 citizens in the Netherlands indicated that environmental concerns, renewables acceptance, energy independence, community trust, community resistance, education, energy-related education, and awareness of local energy initiatives were the most important factors in determining the citizens' willingness to participate in community energy systems (Koirala et al. 2018). In a literature review on community energy initiatives in Germany, the UK and USA, Brummer (2018) identified several societal benefits conferred by community energy (e.g., economic benefits, knowledge and acceptance, and climate protection and sustainability), as well as regulatory barriers in these countries impeding the formation and resilience of community energy initiatives. However, Brummer did not study motives and preferences concerning the energy community from the participants' perspective. Participation in energy co-operatives may increase acceptance of local renewable projects (Brummer 2018; Soeiro and Ferreira Dias 2020a). Yet, conflicts of interest within co-operatives, and conflicts pertaining to values underlying a cooperative's strategy, are more pronounced than in more formal and hierarchical organizations (Yildiz et al. 2015). Both the ownership of a renewable energy system, and living in a rural rather than urban community, increase the likelihood of participation in community energy (Kalkbrenner and Roosen 2016).

Besides citizens, also business and public stakeholder objectives in joining an energy community are heterogenous and possibly conflicting (Heuninckx et al. 2022). In a participatory study on a Flemish energy community, financial incentives were potential members' main motives for participation, but the decision to join is often influenced also by a variable combination of social, economic, technical, and environmental motivations. For example, local governments mainly want an energy community to yield social and environmental advantages, whereas the local DSO seeks value added to its main grid, and expects the energy community can help avoid major grid investments (Heuninckx et al. 2022).

A case study on RE prosumer communities found that energy resources were usually owned by energy cooperatives, municipalities and communities, most of which interacted with the grid by supplying excess energy from the community to the power grid (Adu-Kankam and Camarinha-Matos 2019). Also, collaboration was an integral component of their mode of operations. Furthermore, co-ownership of renewable energy production affects people's willingness to demand flexibility (Roth et al. 2018), and probably increases awareness on demand flexibility. However, energy communities are mushrooming, often without a coherent operational model(s), and consequently the user experience and user roles vary greatly (e.g., Gorroño-Albizu et al. 2019). For example, the Farm Power energy community was not considered especially easy-to-use for the consumer, and there have been challenges in attracting customers (Kallio et al. 2020). Also, more services, such as demand-side management, were expected to be part of the community's services in the future, as now only small producers are selling electricity to buyers (Kallio et al. 2020). Pumphrey et al. (2020) interviewed domestic consumers, business consumers, domestic prosumers and business prosumers for their preferences on the peer-to-peer energy trading in the UK. The interviews identified ease of payment as a key theme for electricity trading, but the authors noted there may be tensions with sustainability and greater awareness of energy-related environmental impacts. Consumers identified a lack of engagement with the process of receiving energy, and cost, but prosumers identified positive associations with power, and personal and business image.

3 Methods and Materials

Our survey is a part of the value-based research on energy communities, aiming to identify stakeholder values and implement them in the digital energy ecosystem. Two key energy community stakeholders were identified and involved in the survey: solar prosumers and electricity consumers, as potential initiators of and participants in the energy community. A large national DSO provided a list of 1361 contacts for the survey. However, the DSO did not influence the survey contents or analysis of the results in any way, nor did the company finance the research. The survey was targeted to 1361 households resident in a detached or semi-detached house, and 33% of these households were solar panel owners. The survey questionnaire was tested on three test users before sending to the surveyees. The survey was conducted in January–February 2020. The invitation to answer the online survey was sent via email, the response rate was 45% (n = 617), and 41% of the respondents were solar panel owners.

The survey gathered versatile information on energy communities, including general interest to participate in an energy community, motives for and barriers to participation, preferred spatial scale, size and operator, and desired services and features that the energy community might offer. We utilized the previous literature on energy communities in planning the survey questions (Brummer 2018; Doci and Vasileiadou 2014; Soeiro and Ferreira Dias 2020a). We assumed in the survey that the concept "energy community" would be new to many respondents, and therefore defined it at the beginning of the question set concerning energy community as follows: "In the energy community, members share the benefits of electricity generation and procurement with each other. The energy community consists of households and possibly small local energy producers and municipal actors. Typically, surplus electricity generated by home photovoltaic (PV) systems can be distributed and procured through the energy community. The community will increase the choice of members to participate in the electricity market and will influence the way electricity is used and the environmental impact of energy consumption. The energy community allows participation in joint procurement (for example, solar power plants or electricity storage facilities).” We are aware of the ambiguous nature of the term, and while we wanted the survey respondents to get an idea of the possibilities of the energy community, we looked to avoid overly guiding their views and perceptions.

4 Energy Community Preferences by Solar Prosumers and Electricity Consumers

Energy consumers and prosumers were asked about their interest in participating in an energy community, the motives for and barriers to being an energy community member, their preferences on size, locality, and the nature of the responsible organization, and preferred features of the energy community. The energy community preferences of the solar prosumers and electricity consumers were analyzed side by side.

4.1 Interest and Motives to Participate in the Energy Community

The overall response to the question on interest in participating in an energy community was rather positive, as can be seen in Fig. 1. Most respondents were either interested or slightly interested in participating in an energy community. Hesitancy may have been due to the novelty and lack of examples of energy communities. Those who expressed themselves very interested in participating in an energy community amounted to 13% of all respondents, but 16% were not at all interested. Solar prosumers were slightly more interested in participating compared with electricity consumers.

Figure 2 shows that two-thirds of the respondents were interested in participating in an energy community first and foremost for economic gain, followed by environmental friendliness. One-third sought independence from the big energy companies, whereas just over half reported they would like to use micro-generated electricity, and a quarter to participate out of curiosity and experimentation. Energy security and social community aspects in production and consumption were considered relatively important but not necessary factors, which also applied to information on energy consumption, and participation in electricity markets together with others. Prosumers were more eager to try out new ways to produce and share energy, and

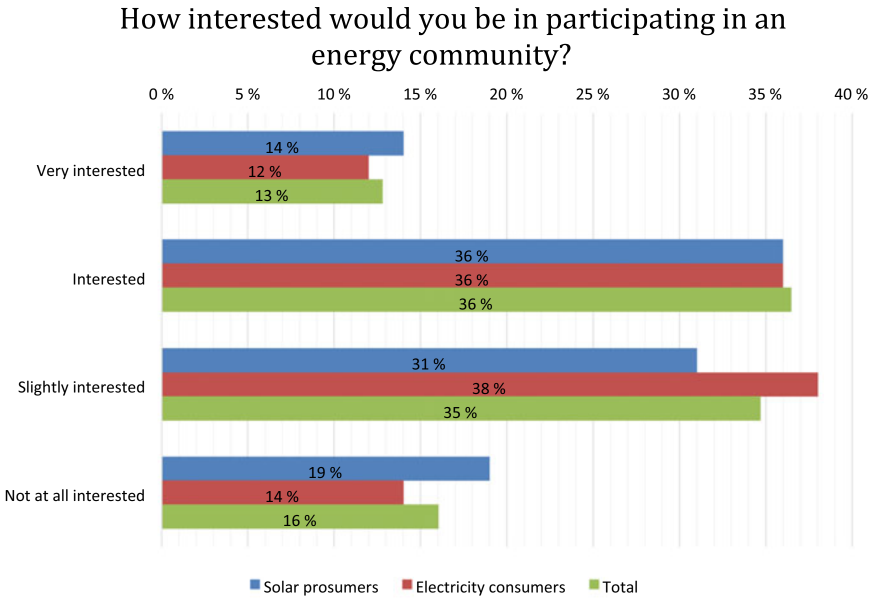


Fig. 1 Interest in participating in an energy community

with other prosumers and consumers to participate in and influence energy markets. Energy users without their own production sought economic gains more often than did solar prosumers. Taken as a whole, intrinsic motivations that relate to the enjoyment of participation and energy management are less important than the extrinsic, such as cost savings and personal benefits.

Presumed technical challenges, doubts over whether electricity would cost less in an energy community, and reluctance to go to any trouble regarding electricity consumption were considered hindrances to participation in an energy community by around a third respondents in each case (see Fig. 3). Also, one in six respondents did not believe participation would benefit them or distrusted energy companies. One in eight had no interest whatsoever in energy communities. Yet, few doubted the environmental benefits of the energy community or the significance of solar power as a mode of production. Also, relatively few respondents expressed a reluctance to buy electricity directly from other households, were indifferent to how electricity is produced, or not interested in energy and electricity.

The "Other, what?" question concerning factors that reduce interest in the energy community was answered by 65 respondents. Most cited doubts concerning economic issues such as price (9), initial investments (4), and an insufficiently positive cost–benefit ratio as barriers to participate in an energy community. Problematic community dynamics (3) and a lack of knowledge concerning energy communities (5) decreased interest for some respondents, as well as the high age of the respondent (2) and legal and regulatory barriers (2).

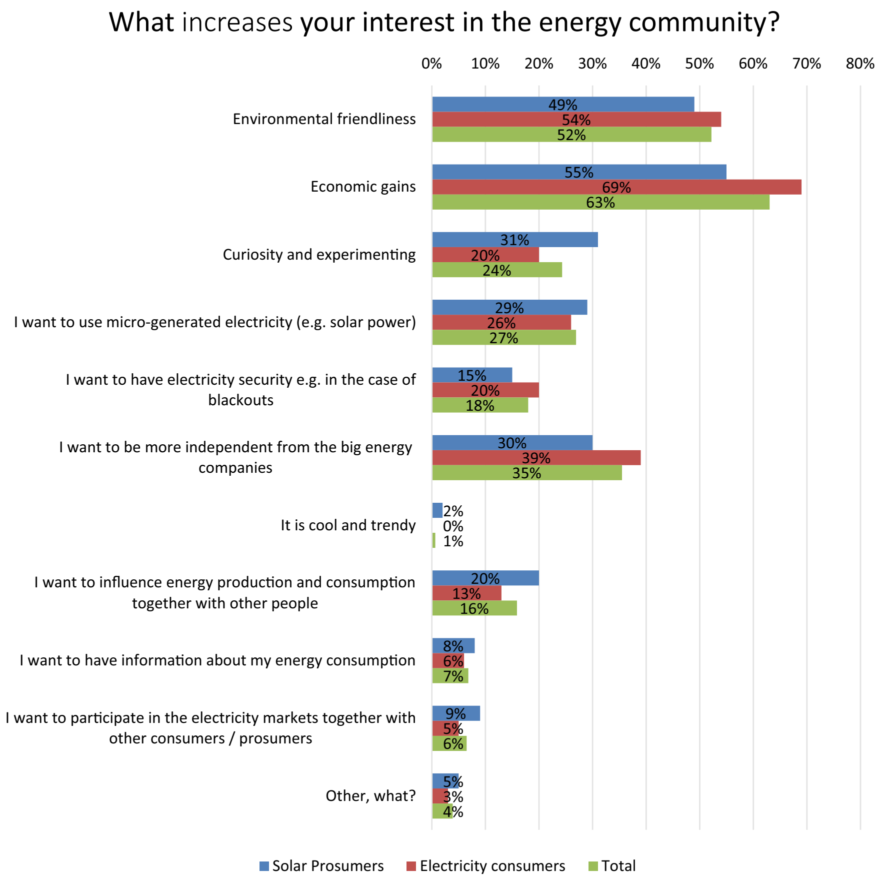


Fig. 2 Factors that increase interest in an energy community (up to 3 options per respondent)

4.2 Preferred Type of Energy Community

Respondents' preferences concerning the location and formation of an energy community were divided (see Fig. 4). Almost half thought it should be formed locally, for example, in their own town or in the neighborhood. More than a third felt that the energy community members' location was not significant. Only one in ten thought it should be national, and very few preferred that an energy community would comprise family or friends. Figure 5 indicates it was challenging for the respondents to estimate a good number of participating households, with 39% answering "I don't know". A fifth thought the energy community should have more than 50 households, whereas one in six preferred a smaller energy community of 10–20 households. Both a very small energy community of less than 10 and one with 21–50 households were preferred by one in nine respondents. When it came to the matter of what form of organization the energy community should take, Fig. 6 indicates that over half of

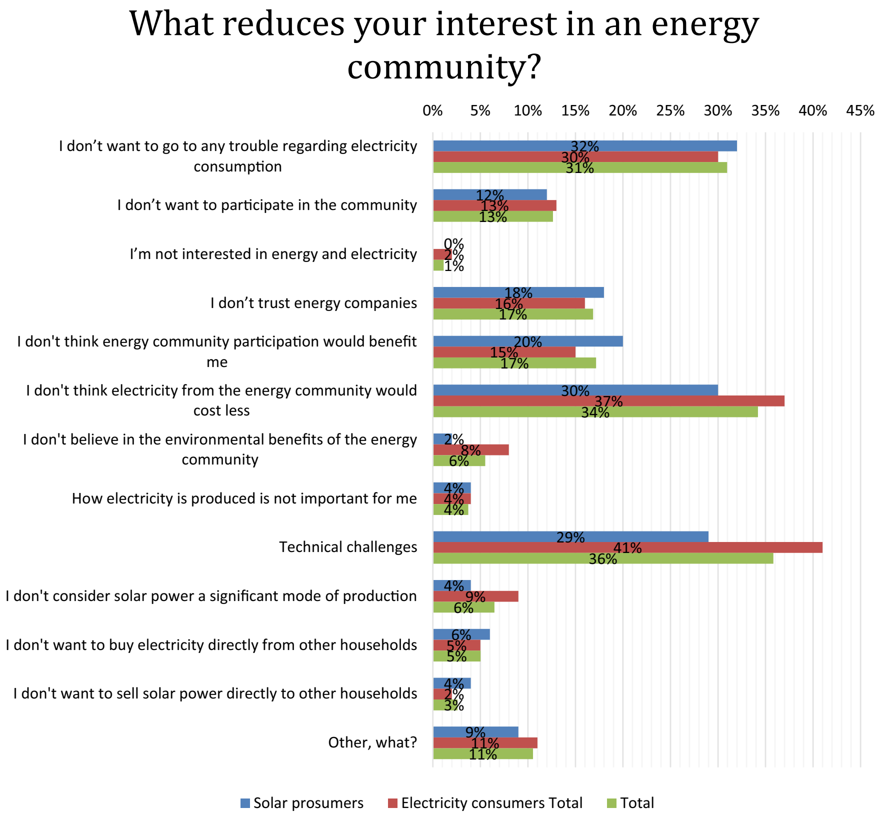


Fig. 3 Factors that reduce interest in participating in an energy community (up to 3 options per respondent)

the respondents considered the energy company should be a non-profit, and slightly less than half preferred a co-operative comprised of the community members. A fifth felt the energy community should be managed by the public sector, for example, a municipality or city. Slightly less preferred an energy community owned by an energy company or an SME. Hardly anyone wanted to participate in an energy community owned by a large private company.

4.3 *Features of the Energy Community*

Highlighting the importance of P2P energy trading, the majority of those who responded felt that an energy community should provide its participants with the potential to buy and sell energy (see Fig. 7). Also, around half of the respondents were interested in the potential to acquire common energy storage systems and common

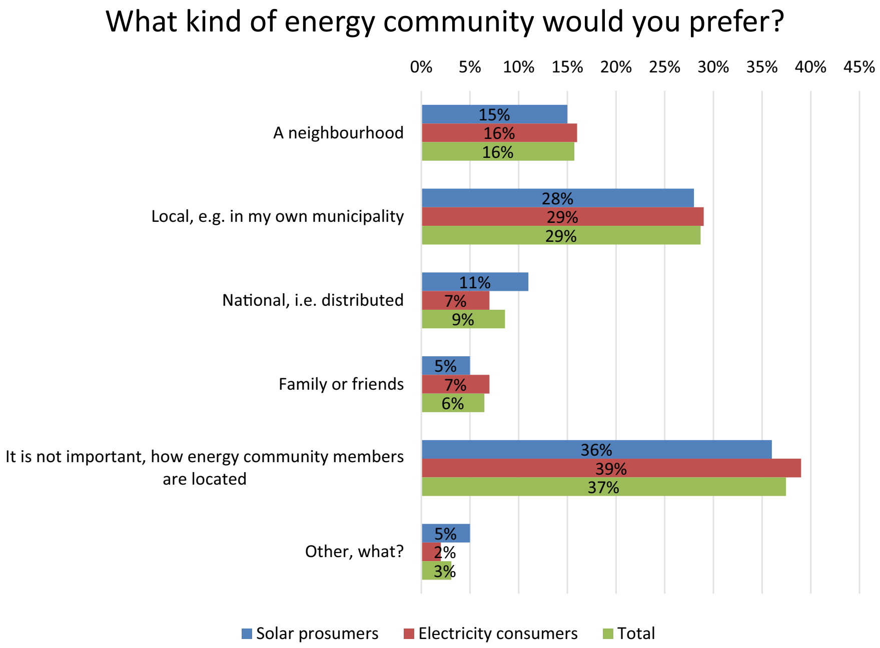


Fig. 4 Preferences on the type of energy community

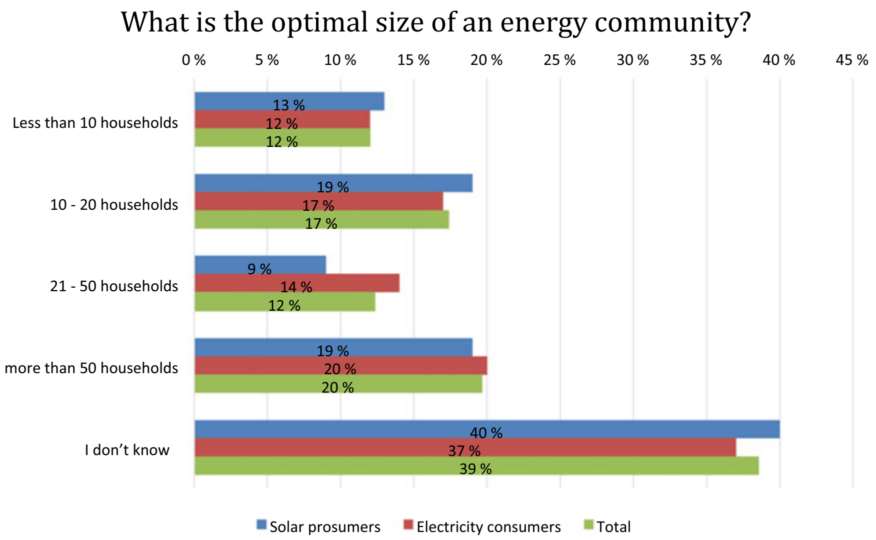


Fig. 5 The optimal size for an energy community

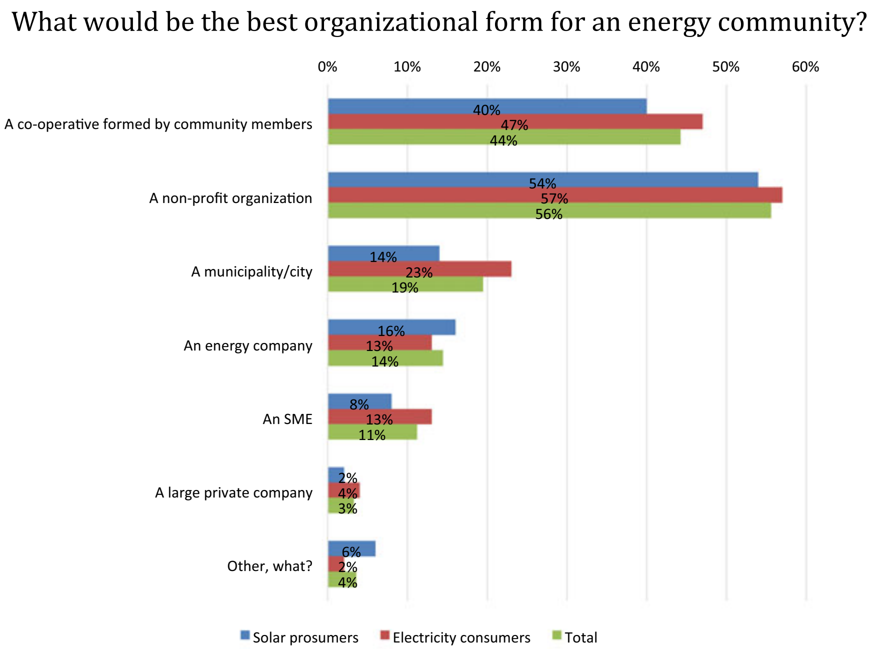


Fig. 6 Preferences concerning the responsible organization for the energy community

PV systems through the energy community. An energy account showing the benefits gained in the energy community was important to a third of respondents.

A small minority suggested the energy community should offer a service to monitor household energy use (19%), tips for energy saving (16%), and the potential to compare your own electricity consumption with that of other community members (12%). It was somewhat surprising that only 15% indicated they would like to have a demand flexibility service in the energy community. This might be due to a lack of awareness of demand response and the needs and capitalizing possibilities of demand flexibility.

4.4 Solar Prosumers Versus Electricity Consumers

Solar prosumers and electricity consumers would presumably differ in terms of experience and awareness on energy micro-production and energy communities. Therefore, we expected the motives and preferences of the two groups to be more diverse. Contrary to expectations, solar prosumers and electricity consumers were relatively unanimous in their views on most questions. In both groups, most were to some extent interested in participating in an energy community. Only one fifth of solar prosumers and one in seven electricity consumers were not at all interested. Surprisingly, more

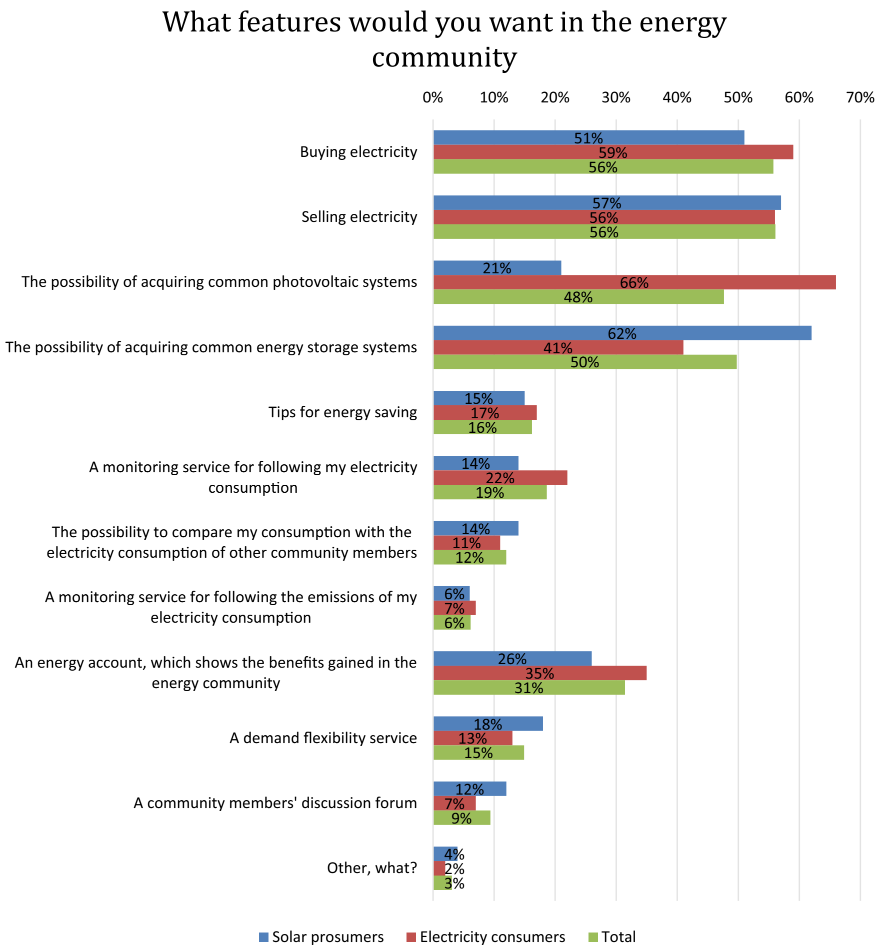


Fig. 7 Desired features of an energy community

solar prosumers were not at all interested in participating in the energy community than were electricity consumers. The four most common motives for participation were economic gains (55% solar prosumers, 69% electricity consumers), environmental friendliness (49 and 54%), independence from the big energy companies (30 and 39%) and curiosity an experimenting (31 and 20%).

The most significant difference between the solar prosumers and electricity consumers was in their responses to the question on the features they would like to have in the energy community. Two-thirds (66%) of the electricity consumers wanted to be able to acquire common PV systems, versus only 21% of the solar prosumers. On the other hand, a larger share (62%) of the solar prosumers was interested in the possibility to acquire common storage systems through the energy community, whereas only 41% of electricity consumers considered it important. Also, more electricity consumers expected economic gains from the energy community (69%) than did solar prosumers (55%), yet they were more doubtful on the potential for cheaper electricity in the energy community (37%) than were the solar prosumers (30%). A larger share (41%) of electricity consumers than solar prosumers (29%) believed technical challenges would reduce their interest in the energy community.

Respondents contributed 98 comments and ideas in the survey's open comments field. Most (23; 10 solar prosumers, 13 electricity consumers) reflected concerns about too high electricity transmission and distribution costs. Some electricity consumers (12) and even a few solar panel owners (3) considered solar panels too expensive and inefficient in the North, thus decreasing the opportunity for a successful energy community based on sharing solar energy. Solar panel owners raised the need for storage (5) and net billing (5) as factors fostering energy communities. Besides the transmission and distribution costs as well as the profitability of solar panels, there were other kinds of doubt over energy communities, such as how to construct a good business model (4), potential disagreements between community members (1), and the extra effort that involvement in an energy community would require of the energy user (3). Nevertheless, 16 respondents made positive comments about the interesting topic and research, and two said they had learnt about new and exciting opportunities through the questionnaire.

5 Discussion

This research looked to increase our knowledge on the preferences of two key stakeholder groups in the energy community: solar prosumers, and electricity consumers without their own energy micro-generation. To explore the views of potential users, we conducted a survey receiving 607 responses. The study provides a basis to understand end-users and participants in the energy community, and an agenda for future research.

The survey results elucidate what kind of energy community the users would prefer, and the minor differences between the solar prosumers and electricity consumers. Energy community may still be a distant and unclear concept to many respondents, yet half were either interested or very interested in participating in an energy community. Only one in six were not at all interested. It would appear that extrinsic factors, that is, seeking external rewards, such as cost savings and personal benefits, are more important for interest and participation in an energy community than intrinsic motivations that relate to the enjoyment of participation and energy management. The factors which reduce interest in an energy community may reflect also the users' understanding of the fact that initiating and operating the energy community is rarely technically and economically feasible without creating exceptions in regulations and support schemes (Brummer 2018). The findings are in line with previous research where a lack of information, investment costs, long payback time, and a lack of proper business models were found to slow the adoption of clean energy technologies (Peñaloza et al. 2022). Although our results differ slightly from the previous findings stating that high environmental awareness increases the likelihood of adoption of clean energy technologies (Peñaloza et al. 2022; Perlaviciute et al. 2018; Van der Werff and Steg 2016), it can nevertheless be argued that environment friendliness is an important factor for participation in the energy community. The results also indicate the need for information campaigns on energy communities, as well as further clarification of the concept and business models for different types of energy community.

As expected, the survey results show there are strong barriers to interest and participation in an energy community, and doubts regarding the community's feasibility and financial rationality. Two in five electricity consumers doubt electricity would cost less in the energy community. Technical challenges are also seen as a barrier to either building or participating in an energy community. Solar prosumers have fewer reservations concerning the energy community's technical challenges or economic benefits, but are reluctant to expend time or effort on energy consumption. Also, a fifth of the respondents did not think participation in the energy community would benefit them. Besides the members' (un)willingness to participate (Doci and Vasileiadou 2014; van der Schoor and Scholtens 2015), other studies have brought up other digital energy ecosystem barriers, such as strong dependency on national policy and legal frameworks (Herbes et al. 2017), and on public support (Herbes et al. 2017; Seyfang et al. 2014).

In terms of the organizational form of the energy community, users lack trust in energy companies and other businesses, preferring a co-operative or other non-profit structure. Solar prosumers are slightly more in favor of energy companies, while a quarter of consumers consider a municipality or city the preferred energy community organizer. As for size and locality, four in ten respondents said it is not important where energy community members are located. On the other hand, one-third said it should be local, for example, in their own municipality. The optimal size for an energy community depends greatly on its objectives and functionalities, and 40% of the respondents could not estimate an optimum. In order to capitalize flexibility in the energy markets, the flexible load volume should be big, that is, aggregated from a large number of households (Powells and Fell 2019). On the other hand, a local RE community may comprise a small number of households. In the digital energy ecosystem, both scaling up and scaling down are evidenced. For example, many utilities are expanding into global markets, but at the same time local energy production and use is becoming more common. Energy community is an umbrella concept that covers both trends: a virtual power plant energy community may pool demand flexibility loads and locally produced energy, and sell it to international energy markets, whereas local RE initiatives may provide opportunities for people to produce renewable energy together with others, and share it locally. However, the concept 'energy community' is currently too ambiguous and would require more precise definition to be understandable to users. The preferences of solar prosumers and consumers concerning the energy community are largely in accordance, and no significant differences were found between them, aside from desired features. Two-thirds of solar prosumers are interested in having common energy storage systems through the energy community, compared to 41% of consumers. On the other hand, two-thirds of consumers would like the opportunity to acquire solar panels together with others in the energy community. Unsurprisingly, buying and selling energy interests more than half of both user groups, in relation to which users would like to have an account that shows transactions and illustrates the benefits gained in the energy community. A demand flexibility service, monitoring and comparing energy consumption, and tips for energy saving are less important features, and a discussion forum with other users, or monitoring the emissions from your own energy consumption, interest less than one in ten users.

Further interdisciplinary research is needed to bridge the gap between EU clean energy and energy citizen ambitions and the reality of energy community development, as well as the potential for the development and wider dissemination of new forms of such communities (Blasch et al. 2021) and a holistic understanding of the digital energy ecosystem dynamics and new business models resulting from the energy transition (Nolden et al. 2020).

Energy communities present promising potentiality for increased RE production and use, energy resilience, and citizen activation on sustainability efforts. Despite this potential and wide interest, energy communities still today play a marginal role in the digital energy ecosystem, and seem vulnerable to shutting down (Seyfang et al. 2014; Vernay and Sebi 2020). Energy communities demonstrate the common understanding that solving energy issues requires integrated solutions at all ecosystem levels: societal, technological, business, and institutional (Klein and Coffey 2016; Vernay and Sebi 2020). To realize the full potential of energy communities in the digital energy ecosystem, and to accelerate energy transition by the energy community's key actors, we need a wider understanding on the preferences, objectives and barriers involved. Our study provides considerable insight into solar prosumers' and energy consumers' preferences, highlighting strong interest in participating in the energy community, and shared end-user objectives. However, users are aware of the numerous barriers and hindrances to building and/or participating in energy communities. These results have implications also for other digital energy ecosystem actors, as they face questions concerning their purpose, offerings and transition to digital technology. Ultimately, the prosumers and consumers will make the decisions that determine the role of the energy community in the digital energy ecosystem, and thereby shape energy transition.

The most important limitation of the survey results lies in the fact that the concept 'energy community' is highly ambiguous and rapidly changing. Thus, the preferences and perceptions of the energy community may be based on very different assumptions and understanding of the concept in question. In addition, since the respondents are identified in the survey as 'households' instead of individuals with demographic attributes, we are unable to break down the responses by age, gender, occupation, or other factors. There might be different preferences within a household, and we encourage the reader to bear this in mind.

We have continued the research with solar prosumers and electricity consumers, with a special focus on the values of potential energy community users. The interview research results will be published in 2022. In addition, we aim to combine the survey data used in this study with another survey's data focusing on the determinants of residential solar PV adoption. The latter data also include the respondents of this study, and enable more detailed quantitative analyses on the effects of sociodemographic and home characteristics on household preferences for energy communities.

Further research should be conducted on awareness and motives to participate in and initiate energy communities. The survey responses presented here came from the person who carries the main responsibility for decisions concerning energy use and investments in the household. Usually, that person is the male adult in the family. Interest and activity in energy-related issues is highly gendered and more characteristic of affluent, middle-aged men. Further studies are needed on the different roles and agencies in energy communities and in the energy transition, and to find ways to increase awareness regarding energy systems and markets in all social groups.

Acknowledgements This work was supported by the Academy of Finland via research funding on the "Digitally mediated decarbon communities in energy transition (DigiDecarbon)" project (grant 348210), the Academy of Finland Strategic Research Council project BCDC Energy (grant 292854), and Fortum and Neste Foundation (grant numbers 20190098 and 20200099).

References

Abdelkafi N, Raasch C, Roth AE (2019) Multi-sided platforms. Electr Mark 29:553–559. https://doi.org/10.1007/s12525-019-00385-4

Adu-Kankam K, Camarinha-Matos L (2019) Emerging community ecosystems: analysis of organizational and governance structures of selected representative cases. In: Technological innovation for industry and service systems, DoCEIS 2019, vol 553, pp 24–40. Springer, Cham

Baidya S, Potdar V, Ray P, Nandi C (2021) Reviewing the opportunities, challenges, and future directions for the digitalization of energy. Energy Res Soc Sci 81:102243

Bakhtadze N, Pavlov B, Pyatetsky V, Suleykin A (2019) Digital energy ecosystems. IFAC PapersOnLine 52(13):30–35

Bauwens T, Gotchev B, Holstenkamp L (2016) What drives the development of community energy in Europe? The case of wind power cooperatives. Energy Res Soc Sci 13:136–147

Blasch J, Hansen P, Kamin T, Golob U, Andor M, Sommer S, Mlinarič M et al (2021). New clean energy communities in polycentric settings: four avenues for future research. Energy Res Soc Sci 82:102276

Brooklyn Microgrid (2021) Retrieved from https://www.brooklyn.energy/

Brown D, Hall S, Davis ME (2020) What is prosumerism for? Exploring the normative dimensions of decentralised energy transitions. Energy Res Soc Sci 66:101475

Brummer V (2018) Community energy—benefits and barriers: a comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. Renew Sustain Energy Rev 94:187–196. https://doi.org/10.1016/j.rser.2018.06.013

Caramizaru A, Uihlein A (2020) Energy communities: an overview of energy and social innovation. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/180576,JRC1194

CE Delft (2016) The potential of energy citizens in the European Union. CE Delft. Retrieved from https://friendsoftheearth.eu/wp-content/uploads/2016/09/ce-delft-the-potential-of-energycitizens-eu.pdf

Chen V, Duh H (2009) Investigating user experience of online communities: the influence of community type. In: 2009 International conference on computational science and engineering. IEEE

Doci G, Vasileiadou E (2014) “Let’s do it ourselves”: individual motivations for investing in renewables at renewables at community level. Technische Universiteit Eindhoven, Eindhoven

Dóci G, Vasileiadou E, Petersen AC (2015) Exploring the transition potential of renewable energy. Futures 66:85–95

Dong H, Hussain F, Chang E (2007) An Integrative view of the concept of digital ecosystem. In: Proceedings of the third international conference on networking and services, pp 42–44. IEEE Computer Society, Washington, DC, USA

Eisenmann T, Parker G, Van Alstyne MW (2006) Strategies for two-sided markets. Harvard Bus Rev 84(10)

Emerging Microgrid Business Models (2016) Boulder

Espe E, Potdar V, Chang E (2018) Prosumer communities and relationships in smart grids: a literature review, evolution and future directions. Energies 11(2528). https://doi.org/10.3390/en11102528

European Commission (2015) Towards an integrated strategic energy technology (SET) plan: accelerating the European energy system transformation. EC, Bryssels

European Union (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Retrieved from http://data.europa.eu/eli/dir/2018/2001/oj

European Union (2019) Clean energy for all Europeans. Publications office of the European Union, Luxembourg

Fahad Zia M, Elbouchikhi E, Benbouzid M (2018) Microgrids energy management systems: a critical review on methods, solutions, and prospects. Appl Energy 222:1033–1055. https://doi.org/10.1016/j.apenergy.2018.04.103

Ferreira JC, Martins A (2018) Building a community of users for open market energy. Energies 11(2330). https://doi.org/10.3390/en11092330

Frieden D, Tuerk A, Roberts J, d’Herbemont S, Gubina A (2019) Collective self-consumption and energy communities: overview of emerging regulatory approaches in Europe. Compile Research Consortium

Ghorbani A, Nascimento L, Filatova T (2020) Growing community energy initiatives from the bottom up: simulating the role of behavioural attitudes and leadership in the Netherlands. Energy Res Soc Sci 70:101782. https://doi.org/10.1016/j.erss.2020.101782

Gorroño-Albizu L, Sperling K, Djørup S (2019) The past, present and uncertain future of community energy in Denmark: critically reviewing and conceptualising citizen ownership. Energy Res Soc Sci 57:101231. https://doi.org/10.1016/j.erss.2019.101231

Goulden M, Bedwell B, Rennick-Egglestone S, Rodden T, Spence A (2014) Smart grids, smart users? The role of the user in demand side management. Energy Res Soc Sci 2:21–29

Gržanić M, Capuder T, Zhang N, Huang W (2022) Prosumers as active market participants: a systematic review of evolution of opportunities, models and challenges. Renew Sustain Energy Rev 154:111859

Hagiu A (2013) Strategic decisions for multisided platforms. MIT Sloan Manage Rev

Harrison J (2021) How local energy systems provide resilience. Delta Energy & Environment Ltd.

Heiskanen E, Matschoss K (2017) Understanding the uneven diffusion of building-scale renewable energy systems: a review of household, local and country level factors in diverse European countries. Renew Sustain Energy Rev 75:580–591. https://doi.org/10.1016/j.rser.2016.11.027

Heiskanen E, Johnson M, Robinson S, Vadovics E, Saastamoinen M (2010) Low-carbon communities as a context for individual behavioural change. Energy Policy 38(12):7586–7595. https://doi.org/10.1016/j.enpol.2009.07.002

Herbes C, Brummer V, Rognli J, Blazejewski S, Gericke N (2017) Responding to policy change: new business models for renewable energy cooperatives—barriers perceived by cooperatives’ members. Energy Policy 109:82–95

Heuninckx S, te Boveldt G, Macharis C, Coosemans T (2022) Stakeholder objectives for joining an energy community: Flemish case studies. Energy Policy 162:112808. https://doi.org/10.1016/j.enpol.2022.112808

Hienerth C, Lettl C, Keinz P (2014) Synergies among producer firms, lead users, and user communities: the case of the LEGO producer-user ecosystem. J Prod Innov Manage 31(4):848–866

Hirsch A, Parag Y, Guerrero J (2018) Microgrids: a review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev 90:402–411

Hunkin S, Krell K (2018) Renewable energy communities: a policy brief from the policy learning platform on low-carbon economy. European Union. Interreg Europe. Retrieved Aug 20, 2020, from https://www.interregeurope.eu/fileadmin/user_upload/plp_uploads/policy_briefs/2018-08-30_Policy_brief_Renewable_Energy_Communities_PB_TO4_final.pdf

Huuki H, Svento R (2021) Unobserved preferences and dynamic platform pricing under positive network externality. NETNOMICS Econ Res Electr Netw. https://doi.org/10.1007/s11066-020-09140-w

Huuki H, Karhinen S, Böök H, Lindfors AV, Kopsakangas-Savolainen M, Svento R (2020) Utilizing the flexibility of distributed thermal storage in solar power forecast error cost minimization. J Energy Storage 28:101202

Hyysalo S (2021) Broadening the inquiry: new Internet-based energy communities. In: Hyysalo S (eds) Citizen activities in energy transition, pp 62–95. Routledge, London. https://doi.org/10.4324/9781003133919

IEA (2017) Digitalization & energy. International Energy Agency, Paris

IEA (2020) Energy technology perspectives 2020. International Energy Agency, Paris. Retrieved from https://www.iea.org/reports/energy-technology-perspectives-2020

Ingeborgrud L, Heidenreich S, Ryghaug M, Moe Skjølsvold T, Foulds C, Robison R, Mourik R et al (2020) Expanding the scope and implications of energy research: a guide to key themes and concepts from the social sciences and humanities. Energy Res Soc Sci 63. https://doi.org/10.1016/j.erss.2019.101398

Ioannis K, Raimondo G, Dimitrios G, Rosanna DG, Georgios K, Gary S, Igor NF et al (2017) Blockchain in energy communities: a proof of concept. European Commission

Kalkbrenner BJ, Roosen J (2016) Citizens' willingness to participate in local renewable energy projects: the role of community and trust in Germany. Energy Res Soc Sci 13:60–70. https://doi.org/10.1016/j.erss.2015.12.006

Kallio L, Heiskanen E, Apajalahti E-L, Marschoss K (2020) Farm power: how a new business model impacts the energy transition in Finland. Energy Res Soc Sci 65

Kampman B, Blommerde J, Afman M (2016) The potential of energy citizens in the European Union. CE Delft, Delft

Khavul S, Bruton G (2013) Harnessing innovation for change: sustainability and poverty in developing countries. J Manage Stud 50(2):285–306

Klein SJ, Coffey S (2016) Building a sustainable energy future, one community at a time. Renew Sustain Energy Rev 867–880

Koirala PB, Araghi Y, Kroesen M, Ghorbani A, Hakvoort RA, Herder PM (2018) Trust, awareness, and independence: insights from a socio-psychological factor analysis of citizen knowledge and participation in community energy systems. Energy Res Soc Sci 38:33–40

Kotilainen K, Sommarberg M, Järventausta P, Aalto P (2016) Prosumer centric digital energy ecosystem framework. In: MEDES proceedings of the 8th international conference on management of digital ecosystems, pp 47–51. ACM, Biarriz. https://doi.org/10.1145/3012071.3012080

Lennon B, Dunphy N, Gaffney C, Revez A, Mullally G, O'Connor P (2019) Citizen or consumer? Reconsidering energy citizenship. J Environ Plan Policy Manage 1–14. https://doi.org/10.1080/1523908X.2019.1680277

Lund PD, Lindgren J, Mikkola J, Salpakari J (2015) Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 45:785–807. https://doi.org/10.1016/j.rser.2015.01.057

Matschoss K, Repo P, Timonen P (2019). Embedding European citizen visions in sustainability transition: comparative analysis across 30 European countries. Futures 112. https://doi.org/10.1016/j.futures.2019.102437

Meelen T, Truffer B, Schwanen T (2019) Virtual user communities contributing to upscaling innovations in transitions: the case of electric vehicles. Environ Innov Soc Trans 31:96–119

Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C (2018) Designing microgrid energy markets: a case study: The Brooklyn Microgrid. Appl Energy 210:870–880. https://doi.org/10.1016/j.apenergy.2017.06.054

Morstyn T, Farrell N, Darby SJ, McCulloch MD (2018) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat Energy 3:94–101

Mourik R, Breukers S, Summeren L, Wieczorek A (2019) Community-based virtual power plants: against all odds? Proceedings 20(1):25. https://doi.org/10.3390/proceedings2019020025

Mundaca L, Samahita M (2020) What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden. Energy Res Soc Sci 60:101319. https://doi.org/10.1016/j.erss.2019.101319

Nachira F, Dini P, Nicolai AA (2007) Network of digital business ecosystems for Europe: roots, processes and perspectives. In: Digital business ecosystems. European Commission, Bruxelles

Nidhin Mahesh A, Sai Shibu NB, Balamurugan S (2019) Conceptualizing blockchain based energy market for self sustainable community. In: Proceedings of the 2nd workshop on blockchain-enabled networked sensor (BlockSys'19), pp 1–7. ACM, New York, NY, USA. https://doi.org/10.1145/3362744.3363345

Nolden C, Barnes J, Nicholls J (2020) Community energy business model evolution: a review of solar photovoltaic developments in England. Renew Sustain Energy Rev 122:109722

Olkkonen L, Korjonen-Kuusipuro K, Grönberg I (2017) Redefining a stakeholder relation: Finnish energy "prosumers" as co-producers. Environ Innov Soc Trans 24:57–66

Paterakis NG, Erdinç O, Catalão JP (2017) An overview of demand response: key-elements and international experience. Renew Sustain Energy Rev 69:871–891. https://doi.org/10.1016/j.rser.2016.11.167

Peñaloza D, Mata É, Fransson N, Fridén H, Samperio Á, Quijano A, Cuneo A (2022). Social and market acceptance of photovoltaic panels and heat pumps in Europe: a literature review and survey. Renew Sustain Energy Rev 111867

Perlaviciute G, Steg L, Contzen N, Roeser S, Huijts N (2018) Emotional responses to energy projects: insights for responsible decision making in a sustainable energy transition. Sustainability 2526

Powells G, Fell MJ (2019) Flexibility capital and flexibility justice in smart energy systems. Energy Res Soc Sci 54:56–59

Pumphrey K, Walker SL, Andoni M, Robu V (2020) Green hope or red herring? Examining consumer perceptions of peer-to-peer energy trading in the United Kingdom. Energy Res Soc Sci 68:101603. https://doi.org/10.1016/j.erss.2020.101603

Rathnayaka A, Potdar V, Dillon T, Hussain O, Chang E (2014) A methodology to find influential prosumers in prosumer community groups. IEEE Trans Ind Inform 10:706–713

Reis I, Goncalves I, Lopes M, Henggeler Antunes C (2021) Ari istuu tuossa vieressä ja tuumasi että näinkin voi tehdä. Renew Sustain Energy Rev 144:111013

Roberts J, Frieden D, d'Herbemont S (2019) Energy community definitions. compile consortium. Retrieved from https://www.compile-project.eu/wp-content/uploads/Explanatory-note-on-energycommunity-definitions.pdf

Roth L, Lowitzsch J, Yildiz Ö, Hashani A (2018) Does (Co-)ownership in renewables matter for an electricity consumer's demand flexibility? Empirical evidence from Germany. Energy Res Soc Sci 46:169–182. https://doi.org/10.1016/j.erss.2018.07.009

Schick L, Gad C (2015) Flexible and inflexible energy engagements—A study of the Danish smart grid strategy. Energy Res Soc Sci 9:51–59. https://doi.org/10.1016/j.erss.2015.08.013

Schot JK (2016) The roles of users in shaping transitions to new energy systems. Nat Energy 1(5):1–7

Seyfang G, Hielscher S, Hargreaves T, Martiskainen M, Smith A (2014) A grassroots sustainable energy niche? Reflections on community energy in the UK. Environ Innov Soc Trans 13:21–44

Soeiro S, Ferreira Dias M (2020a) Renewable energy community and the European energy market: main motivations. Heliyon 6(7):e04511

Soeiro S, Ferreira Dias M (2020b) Community renewable energy: benefits and drivers. Energy Rep 6(8):134–140. https://doi.org/10.1016/j.egyr.2020.11.087

Summeren LF, Wieczorek AJ, Bombaerts GJ, Verbong GP (2020) Community energy meets smart grids: reviewing goals, structure, and roles in virtual power plants in Ireland, Belgium and the Netherlands. Energy Res Soc Sci 63. https://doi.org/10.1016/j.erss.2019.101415

Teotia F, Bhakar R (2016) Local energy markets: concept, design and operation. In: 2016 national power systems conference (NPSC), pp 1–6. IEEE, Bhubaneswar. https://doi.org/10.1109/NPSC.2016.7858975

Toffler A (1980) The third wave. William Collins Sons, London

Tsujimoto M, Kajikawa Y, Tomita J, Matsumoto Y (2018) A review of the ecosystem concept—Towards coherent ecosystem design. Technol Forecast Soc Chang 136:49–58

Tukker A, Emmert S, Charter M, Vezzoli C, Sto E, Munch Andersen M, Lahlou S et al (2008) Fostering change to sustainable consumption and production: an evidence-based review. J Clean Prod 16:1218–1225

Tuomela S, Iivari N, Svento R (2021) Drivers and barriers to the adoption of smart home energy management systems—users' perspective. In: ACIS 2021 proceedings. ACIS

Vanadzina GM (2019) Business models for community microgrids. In: 16th international conference on the European energy market (EEM), pp 1–7. IEEE, Ljubljana, Slovenia

van der Schoor T, Scholtens B (2015) Power to the people: local community initiatives and the transition to sustainable energy. Renew Sustain Energy Rev 43:666–675. https://doi.org/10.1016/j.rser.2014.10.089

Vernay A-L, Sebi C (2020) Energy communities and their ecosystems: a comparison of France and the Netherlands. Technol Forecast Soc Chang 158:120123. https://doi.org/10.1016/j.techfore.2020.120123

Van der Werff E, Steg L (2016) The psychology of participation and interest in smart energy systems: comparing the value-belief-norm theory and the value-identity-personal norm model. Energy Res Soc Sci 22:107–114

Wu Y, Wu Y, Cimen H, Vasquez JC, Guerrero JM (2022) Towards collective energy community: potential roles of microgrid and blockchain to go beyond P2P energy trading. Appl Energy 119003

Yildiz Ö, Rommel J, Debor S, Holstenkamp L, Mey F, Müller JR, Rognli J et al (2015) Renewable energy cooperatives as gatekeepers or facilitators? Recent developments in Germany and a multidisciplinary research agenda. Energy Res Soc Sci 6:59–73. https://doi.org/10.1016/j.erss.2014.12.001

Yin S, Wang S, Yang M, Guo X, Zhang N (2021) Exploration of the construction path of an energy ecosystem adapted to the power Internet of things. In: IOP conference series. Earth and environmental science, Bristol, p 631

Young W, Middlemiss L (2012) A rethink of how policy and social science approach changing individuals' actions on greenhouse gas emissions. Energy Policy 41:742–747. https://doi.org/10.1016/j.enpol.2011.11.040

Zhang C, Wu J, Zhou Y, Cheng M, Long C (2018) Peer-to-Peer energy trading in a Microgrid. Appl Energy 220:1–12. https://doi.org/10.1016/j.apenergy.2018.03.010

Zhou BL (2016) Smart home energy management systems: concept, configurations, and scheduling strategies. Renew Sustain Energy Rev 61:30–40. https://doi.org/10.1016/j.rser.2016.03.047

An Overview of Implementation of P2P Energy Trading Methods on the Electric Power Systems

Sahar Seyyedeh-Barhagh, Mehdi Abapour, Behnam Mohammadi-ivatloo, and Miadreza Shafie-khah

1 Introduction

In recent years, the development of distributed energy resources (DERs) such as photovoltaic (PV) systems and also electric vehicles (EVs) in the energy network has made significant progress (Barhagh et al. 2020). From the point of view of the grid, DERs can lead to improved network performance by providing flexibility, including resolving issues occurred by voltage fluctuations as well as optimal management of the energy network. On the other hand, consumers can reduce their costs by having energy production at the demand-side and increase profit by trading their surplus energy on a peer-to-peer (P2P) basis (Soto et al. 2021). Optimum utilization of demand-side generation requires some procedures through detailed optimization programs in order to achieve maximum efficiency of the distributed energy resources. Several solutions have been proposed for this purpose. Meanwhile, one of the efficient solutions to manage the performance of DERs is the application of local energy trading framework under the P2P concept. Hence, the employment of P2P energy trading have several benefits including reducing greenhouse gas emissions, reducing

S. Seyyedeh-Barhagh (✉) · M. Abapour · B. Mohammadi-ivatloo
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: sbarhagh@tabrizu.ac.ir

M. Abapour
e-mail: abapour@tabrizu.ac.ir

B. Mohammadi-ivatloo
e-mail: bmohammadi@tabrizu.ac.ir

S. Seyyedeh-Barhagh · M. Shafie-khah
School of Technology and Innovations, University of Vaasa, Vaasa, Finland
e-mail: miadreza.shafiekhah@uwasa.fi

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_5

energy costs, providing flexibility in the demand-side and ancillary services in the grid (Hu et al. 2021).

According to the structure of the power network and characteristics of the consumers, P2P energy transaction can be employed in several approaches. However, the main goal of P2P energy trading in almost all of these approaches is maximizing energy efficiency to manage energy consumption and reduce costs in energy supply. It should be noted that DERs have their own operation limits. Thus, these limitations may lead to the creation of a number of opportunities for the development of local energy transactions (Riaz and Mancarella 2022). For instance, EVs are available in specific hours to participate in the energy transactions according to the characteristics of their owners. On the other hand, the energy production through the PV panels is also possible at certain hours of the day. In such a system, the development of P2P energy trading platform can prevent the energy losses produced by DERs and also lead to a reduction of dependence on the upstream network to meet the demand of consumers (Seyyedeh Barhagh et al. 2020).

The P2P energy transactions not only the owners of DERs can play the role of an energy supplier, but also the distribution network operator can use this capacity to participate in the electric markets with the aim of maximizing its economic profit. This can emphasize the necessity of developing P2P energy trading procedure considering the development of policies to support DERs and encourage them to actively participate in the electricity markets (Luo et al. 2022; Yu et al. 2022).

In this chapter, the development of energy trading under the P2P concept has been presented. To this end, several recent models that utilized P2P energy trading in their works are presented to demonstrate the effectiveness of method in the optimal management of energy consumption. Moreover, a section is dedicated to discuss the models that employed P2P energy trading in management of the operation of EV in the electrical network. Then, the existing and ongoing P2P designed projects worldwide is shown to evaluate the percentage of the implementation of this method in the real world.

Therefore, the rest of this book chapter is organized as follows: Sect. 2 introduces the definition of the P2P energy trading framework in the power system. Then, several existing and ongoing P2P energy trading projects are mentioned in Sect. 3. Finally, the conclusion is drawn in the last section by summarizing the most important findings of this chapter.

2 The Definition of P2P Energy Trading

One of the challenges that can be seen in Liu et al. (2019) is that the electricity market platform is not yet ready to manage the uncertainty of DERs. Therefore, in order to manage the risk of uncertainty of distributed energy resources, it seems essential to design a new structure for the electricity market which one of these new structures can be the P2P energy trading framework. P2P energy trading is a type of interactive energy exchanges that takes into account the views of prosumers while

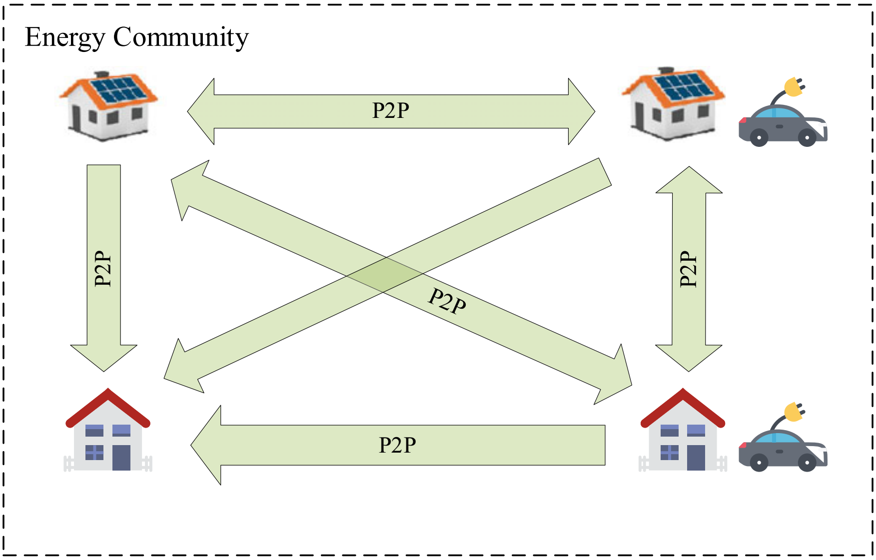


Fig. 1 The structure of a P2P energy trading in an energy community

ensuring the safe and efficient operation of the system. In P2P energy, producers can actively participate in the energy market, negotiate prices with other peers in the connected community, and then trade their energy and flexibility services in watts or negawatts (Tushar et al. 2020). The P2P energy transaction can be described through an illustrative schematic as depicted in Fig. 1. According to the figure, in the recent energy community, a significant part of the amount of power is supplied by DERs and EVs connected to the grid. Hence, the possibility of P2P energy trading method provides consumers the possibility to be converted to prosumers and can trade energy among the units in a P2P manner according to their current energy level to play in a role of a seller or purchaser (Liu et al. 2019). As a result, in such a power transaction approach, both the traders are in a win–win situation. because the buyer can supply the power at a better price than the network price and reduce its costs, and the purchaser can offer its excess power and increases the profit (Khorasany et al. 2020).

According to the energy transaction and information transformation processes among the participants, P2P energy transaction can be classified into three categories: coordinated market, decentralized market, and community market (Tushar et al. 2021).

1. Coordinated market

The trading processes and information sharing are centralized, the market will be coordinated. Thus, all prosumers and DERs could communicate with the centralized

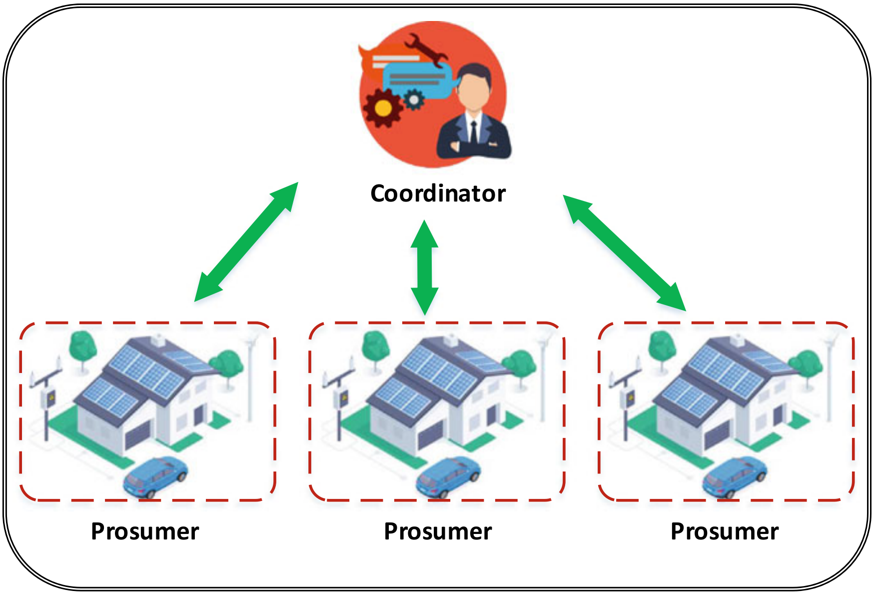


Fig. 2 The simple model illustrating P2P transactions in a coordinated market

coordinator, i.e., Fig. 2. It then controls the amount of buying or selling energy between participants through a P2P energy trading platform. Finally, the total profit of the connected community is distributed by the coordinator among the participants according to the predetermined market rules (Zhang et al. 2020). In this market, participants do not need to have direct communication or negotiation with other peers. While each participant in the energy exchange is not in direct communication with others and does not have an agreement on the price and the volume of the energy in the coordinated market, they have the ability to decide these parameters before sharing this information with the centralized coordinator. The volume of energy parameters is effective. Moreover, the biggest advantage of the coordinated market for P2P energy transactions is maximizing the social welfare of the connected community (Zhou et al. 2020). But it should also be mentioned that with the increase in the penetration of DERs and the computational difficulties regarding the information of P2P energy trading procedure, this market can become complicated (Papadaskalopoulos and Strbac 2013). Another constraint of the coordinated market is the lack of privacy of the participants. Due to the direct control of flexible loads and DERs, the possibility of considering the privacy of participants is low. In Englberger et al. (2021), the decision process of energy management of the consumers is incorporated into the subsequent decision to trade in the P2P market. Moreover, a coordinated P2P energy trading algorithm is provided, allowing customers to use an energy management system to control their energy resources and optimally meet their energy demand, and then offer the surplus amount of their energy in the P2P coordinated market.

2. Decentralized market

Another type of market used for P2P energy trading is decentralized market (Ullah and Do 2022). As shown in Fig. 3, the participants in this market could communicate with each other directly in the connected community and agree on the amount of buying or selling energy without any need for a centralized coordinator (Tushar et al. 2019). Therefore, the process of transactions and information transfer is handled in a distributed manner. The main advantage of the decentralized market is having a direct and complete control by the participants themselves. For instance, they have the option to participate in the energy transaction at any given time interval or not, and their privacy is duly protected. Hence, distributed markets have more advantages for the participants than coordinated markets because of their participant-based features. However, due to the lack of centralized control (Morstyn et al. 2019), the efficiency of decentralized markets is relatively low and we cannot expect to have the maximum social welfare of the entire connected society. In Mehdinejad et al. (2022), the authors have presented a new method called PDSGA for market clearance based on P2P energy trading platform, which is completely distributed. In this method, the participants, including prosumers, consumers, and even retailers, have the right to choose the peer they want to exchange power. In addition, they have the right to trade it within the desired amount and price. In this paper, the main aim is the maximization of social welfare and enhance the profit of the retailers.

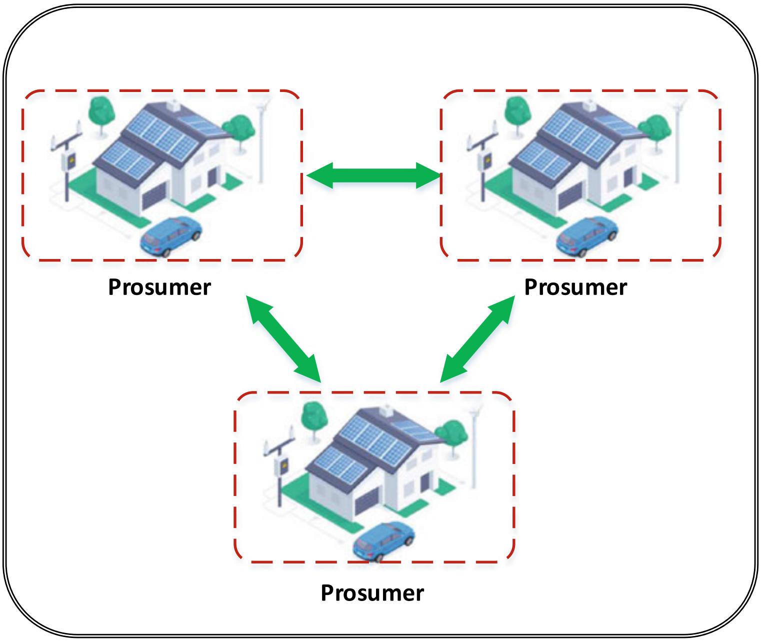


Fig. 3 The simple model illustrating P2P transactions in a decentralized market

The main limitations and challenges of the decentralized market can be mentioned as follow. As the total amount of available energy for trading in the connected community is not completely clear for the third entities including grid operators, retailers, and transmission system operators, the management of distributed P2P market for service providers becomes complex and difficult due to the challenge of maintaining grid limitations and improving it and increasing operational efficiency. To manage such a P2P market, network operators are required to take strict decisions such as reducing network demand in order to maintain network reliability (Guerrero et al. 2018).

3. Community Market

In a community market, the process of buying and selling energy is decentralized, while the communication between participants is centralized (Soto et al. 2021). In this type of P2P market, an operator acts as a coordinator of energy exchange between

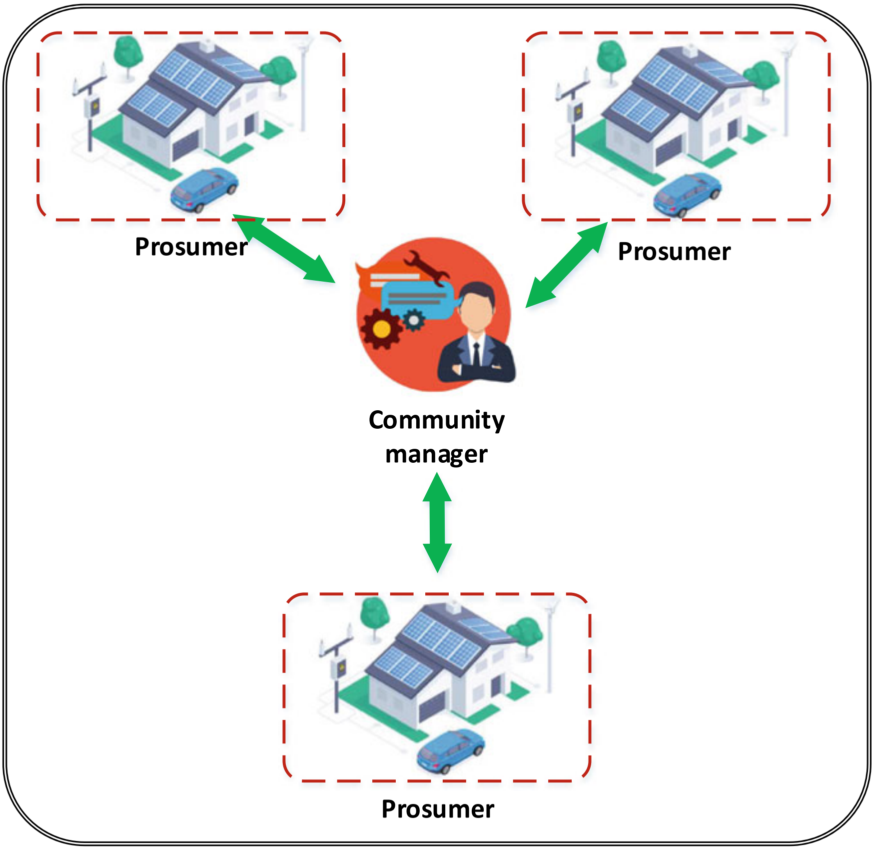


Fig. 4 The simple model illustrating P2P transactions in a community market

prosumers and consumers. But unlike the coordinated market, the community operator cannot directly control the buying and selling process of energy. Instead, this operator influences indirectly through appropriate pricing signals between buyers and sellers to participate in the energy transactions (Tushar et al. 2016), as depicted in Fig. 4. Therefore, in a community market, participants are just required to share limited information with the operator while, at the same time, they can maintain a higher level of privacy (Sousa et al. 2019). In addition, through indirect control, the independency of participants to decide on the amount of energy exchange is also preserved. One of the main focuses of the community market is designing appropriate pricing schemes that can facilitate P2P energy transactions as well as provide energy services to different entities in the grid. In Lin et al. (2021), a market structure for P2P energy trading between virtual power plants is presented. In this work, DERs can participate in the electricity market despite having some limiting characteristics, including having a small scale and non-distributability constraints. Furthermore, a two-level stochastic-based model for day-ahead electricity bidding strategies is proposed, where a Cournot Nash pricing scheme is implemented to make a balance in the production and consumption sides.

In order to better demonstrate the effectiveness of application of the P2P energy trading structure, several recent models that have been developed and designed are mentioned below. In (Mehdinejad et al. 2022), the authors proposed a decentralized model titled "primal–dual sub-gradient algorithm" in order to clear the employed market without involvement of third-parties or disrespecting the privacy of participants. The main improvement of their market comparing the similar works is allowance for participation of local community components such as prosumers, retailers, and consumers through bilateral agreements in energy transactions with each other while the freedom of the players in choosing the peers are enhanced. Therefore, the social welfare and retailers' benefit had been increased. On the other side, several works has been presented about implementation of game theory-based models to study the energy trading challenges in the P2P energy transaction structures. In Luo et al. (2022), Xi Luo et al. proposed a game theory model based on decentralized trading mechanism to evaluate the impact of ownership of DERs on the profit of the players in the P2P energy trading framework. For the risk-averse energy trading of small-scale DRRs and consumers a P2P-based virtual power plant (VPP) has been proposed in Lin et al. (2021). In order to test and validate single-unit and multi-unit P2P auctions in real environment a framework has been proposed in Teixeira et al. (2021) in which there is no need for central operator.

In Chang et al. (2022), Xinyue Chang et al. proposed a vertex scenario-based robust P2P energy trading framework to decrease the system's entire cost, eliminates the voltage deviations, mitigates the line congestion, prioritize the consumption from DERs, and having a fair cooperation of all participants in the P2P energy trading market. It is noteworthy that the uncertainties of the active distribution network considered has been considered too. With the aim of coordinating P2P energy trading among the smart homes with a demand-side management system a closely-optimal scheme, a method titled Energy Cost Optimization via Trade model has been implemented in Alam et al. (2019). Through employment of this strategy, the total cost of all houses has been decreased and any potentially unfair cost distribution has been handled by utilization of Pareto optimality.

It should be noted that for P2P energy trading, it is required to have a secure physical platform where information can be exchanged on that structure. Hence, a P2P energy trade is modeled in the centralized market mode in Zheng et al. (2022). Moreover, the authors proposed a P2P energy trading framework for the local DERs and residential participants embedded with electrical energy storage, in which the objective of each participant is maximizing its personal revenues and minimizing its related costs. Moreover, the authors in Tushar et al. (2016), it is mentioned that normally in the P2P energy exchange, the real value of energy is determined in different conditions, which indicates that supply and demand are not equal.

The effects of the P2P energy trading on the energy losses in grid-connected energy comminutes has been evaluated in Azim et al. (2020). In this paper, it has been concluded that there are various factors involved in investigating the impact of peer-to-peer exchange. Moreover, a type of decentralized market called Continuous double auction is designed in Ullah and Do (2022) for a society containing a solar system, where a P2P energy trading is applied in a fair manner to maximize the profit and social welfare of that society. Besides that, a fully decentralized framework has been employed in Lyu et al. (2021) for energy sharing among smart homes with the aim of maximization of the social welfare through P2P energy transactions.

Furthermore, with the aim of analyzing the effects of vehicle numbers and optimal management approaches, a multi-objective P2P trading model of the zero-emission neighborhood with both hydrogen vehicles and EVs are presented in Liu et al. (2021). The authors proved that the superior supply performances is achieved by the system with hydrogen vehicles, while the system with EVs provides better results on not only on the integration to the local network, but also on the economic and environmental purposes. N. Wang et. al. proposed a P2P multi-energy market mechanism that exploits both electricity–heat coupling and coalitional trading between peers to maximize their benefits (Wang et al. 2022). In order to consider the network constraints in the energy and reserve P2P market, an integrated prosumer–DSO approach has been applied in an iterative sequential approach in Botelho et al. (2022). A modeling of the uncertainty of climate change until 2050 has been presented in Alam et al. (2019) with the transient system, stochastic uncertainty sampling, and artificial intelligent-based methods. The authors tried to address a management scheme for zero-emission communities contains P2P trading and advanced EV storage. The potential of P2P energy trading under different available technologies and market paradigms has been evaluated by analyzing the economic benefits for residential consumers and prosumers, given different solar generation contexts and load flexibility (Neves et al. 2020). In another work, an equilibrium state of supply–demand flow in a P2P market model for residential shared energy storage units has been achieved by game theory, and a framework for pricing and load dispatching has been proposed (Zhang et al. 2022). With the aim of a significant energy coalition of prosumers, a P2P energy trading procedure based on cooperative game theory has been proposed in Li et al. (2020). In addition, a computationally efficient pricing algorithm has been developed to suitably incentivize prosumers for their sustainable participation in the grand coalition.

As the P2P infrastructure seems to be a suitable option and alternative for utilization of EV management with the aim of having a decarbonized society, it is worthwhile to mention a model that employed P2P energy trading mechanism in this topic. Hence, a net-metering has been compared with P2P models using the grid and electric vehicles for the electricity exchange in Sousa et al. (2019). It is concluded that P2P and EVs perform better than net-metering when analyzing technical and economic aspects.

3 Projects on Application of P2P Energy Management in the Realistic Mode

There are a number of projects that they implemented the P2P energy trading frameworks. This section is going to explain about these projects in detail. The experiences of the sample projects carried out regarding the implementation of the P2P energy trading platform show that by applying this type of energy exchange method, the energy communities experienced a reduction in their energy supply costs. There is a paper that is fully dedicated to the existed P2P energy trading projects that is presented in 2017 (Zhang et al. 2017). Meanwhile, some of recent projects are being explained in this section. As the implementation of P2P energy trading projects worldwide has attracted a vast amount of investments. Therefore, several pilot projects have been applied in various conditions in order to verify the effectiveness of the application of this platform in the realistic situation. Thus, some of the projects that were carried out on different continents are presented as follows. For instance, Liton is a P2P energy trading platform launched in 2018 (Lition 2022). This project, implemented in Germany, connects renewable energy producers to consumers on a peer-to-peer basis. According to the information published in this regard, the Liton project led to a 20% cost savings in the energy bills of consumers. In addition, DERs also saw a 30% increase in the economic profit of their units.

As mentioned earlier, P2P energy technology is capable of providing many benefits to the entire power system. One of these implemented projects is called Piclo (2022). Piclo is a P2P power trading company that has signed an agreement with all six existing distribution system operators in the UK. The main goal of this project is to provide flexibility in the entire UK electricity market. The Piclo platform allows distribution system operators to identify flexibility options in the network so that they can meet the needs of the distribution system at any specific location in the network. Part of the project is funded by the British government. This is a project for the distribution system, which transforms distribution system operators from passive to active roles in network management. This platform allows operators to resolve a number of existing limitations without increasing network costs.

In the United States, the Brooklyn Microgrid is an energy community whose members can exchange energy on a P2P basis through blockchain-based smart contracts (Brooklyn Microgrid 2022). The regulatory framework does not allow the expansion of this type of power exchange beyond the microgrid.

In Malaysia, a P2P power exchange pilot project was launched in June 2020 (SEDA 2022). Prosumers are able to sell excess energy produced from PVs to other consumers or even utility through this platform. Exchanges are controlled by the blockchain framework developed by the Australian company, i.e., Power Ledger. The results of this project prove that there has been significant motivation on the part of the PV panels industry towards the implementation of this P2P energy trading technology. This employed project demonstrated that the significant motivation for prosumers and consumers to participate in such projects is the opportunity to exchange energy and achieve economic profit.

In addition, nowadays, a large number of P2P energy trading projects are implemented in isolated mini-grids. As it is less challenging to implement this technology in such isolated mini-grids. In the context of a renewable mini-grid, a P2P transaction can make it easier to access energy and improve the reliability of local power generation resources. In such mini-grids, end-users are usually supplied through PV panels, which are often unable to store their excess energy. By implementing P2P energy trading platform and connecting several consumers with solar panels (Prosumers) to each other and even consumers without distributed generation, access to electrical energy for end-users is improved. A project with these features called Solshare has been implemented in Bangladesh (Lition 2022).

4 Conclusion

This chapter focused on explanation and demonstration of one of the most recent energy management technologies which enables the prosumers to participate in the market actively to increasing their economic benefits, i.e., P2P energy trading technology. Meanwhile, application of this next-generation energy management technology has some benefits to the electrical grid such as reducing the gird losses, decreasing the pressure on the conventional power plants on the peak periods, and increasing the efficiency of electrical energy storges. Moreover, it is explained thoroughly that P2P energy transaction can be classified into three categories such as coordinated market, decentralized market, and community market.

Finally, a number of emerging challenges can be found after studying the recent works and projects in the P2P energy trading framework such as integration of distributed energy resources with the power grid, ensuring the security of participants' information during power exchange, the degree of flexibility of the network in relation to peer-to-peer energy exchange, the stability of the network and avoiding the over-congestion of electric power network, information management due to the high volume of exchanged information, the need for the necessary equipment to perform P2P energy transactions, choosing the proper type of electricity market to perform energy exchange on a peer-to-peer platform.

References

Alam MR, St-Hilaire M, Kunz T (2019) Peer-to-peer energy trading among smart homes. Appl Energy. https://doi.org/10.1016/j.apenergy.2019.01.091

Azim MI, Tushar W, Saha TK (2020) Investigating the impact of P2P trading on power losses in grid-connected networks with prosumers. Appl Energy. https://doi.org/10.1016/j.apenergy.2020.114687

Barhagh SS, Shotorbani AM, Mohammadi-Ivatloo B, Zare K, Farzamnia A (2020) Robust operation of microgrid energy system under uncertainties and demand response program. Indones J Electr Eng Comput Sci 17:1005–10013. https://doi.org/10.11591/IJEECS.V17.I2.PP1005-1013

Brooklyn microgrid | Community powered energy n.d. https://www.brooklyn.energy/. Accessed 15 Aug 2022

Botelho DF, de Oliveira LW, Dias BH, Soares TA, Moraes CA (2022) Integrated prosumers–DSO approach applied in peer-to-peer energy and reserve tradings considering network constraints. Appl Energy 317:119125. https://doi.org/10.1016/J.APENERGY.2022.119125

Chang X, Xu Y, Sun H (2022) Vertex scenario-based robust peer-to-peer transactive energy trading in distribution networks. Int J Electr Power Energy Syst. https://doi.org/10.1016/j.ijepes.2021.107903

Englberger S, Chapman AC, Tushar W, Almomani T, Snow S, Witzmann R et al (2021) Evaluating the interdependency between peer-to-peer networks and energy storages: a techno-economic proof for prosumers. Adv Appl Energy. https://doi.org/10.1016/j.adapen.2021.100059

Guerrero J, Chapman AC, Verbič G (2018) Decentralized P2P energy trading under network constraints in a low-voltage network. IEEE Trans Smart Grid. https://doi.org/10.1109/TSG.2018.2878445

Hu Q, Zhu Z, Bu S, Wing Chan K, Li F (2021) A multi-market nanogrid P2P energy and ancillary service trading paradigm: mechanisms and implementations. Appl Energy. https://doi.org/10.1016/j.apenergy.2021.116938

Khorasany M, Mishra Y, Ledwich G (2020) Hybrid trading scheme for peer-to-peer energy trading in transactive energy markets. IET Gener Transm Distrib. https://doi.org/10.1049/iet-gtd.2019.1233

Li J, Ye Y, Strbac G (2020) Stabilizing peer-to-peer energy trading in prosumer coalition through computational efficient pricing. Electr Power Syst Res. https://doi.org/10.1016/j.epsr.2020.106764

Lin WT, Chen G, Li C (2021) Risk-averse energy trading among peer-to-peer based virtual power plants: a stochastic game approach. Int J Electr Power Energy Syst. https://doi.org/10.1016/j.ijepes.2021.107145

Lition—The blockchain standard for business n.d. https://www.lition.io/. Accessed 15 Aug 2022

Liu Y, Wu L, Li J (2019) Peer-to-peer (P2P) electricity trading in distribution systems of the future. Electr J. https://doi.org/10.1016/j.tej.2019.03.002

Liu J, Yang H, Zhou Y (2021) Peer-to-peer trading optimizations on net-zero energy communities with energy storage of hydrogen and battery vehicles. Appl Energy. https://doi.org/10.1016/j.apenergy.2021.117578

Luo X, Shi W, Jiang Y, Liu Y, Xia J (2022) Distributed peer-to-peer energy trading based on game theory in a community microgrid considering ownership complexity of distributed energy resources. J Clean Prod 351:131573. https://doi.org/10.1016/J.JCLEPRO.2022.131573

Lyu C, Jia Y, Xu Z (2021) Fully decentralized peer-to-peer energy sharing framework for smart buildings with local battery system and aggregated electric vehicles. Appl Energy. https://doi.org/10.1016/j.apenergy.2021.117243

Mehdinejad M, Shayanfar H, Mohammadi-Ivatloo B (2022) Peer-to-peer decentralized energy trading framework for retailers and prosumers. Appl Energy. https://doi.org/10.1016/j.apenergy.2021.118310

Morstyn T, Teytelboym A, McCulloch MD (2019) Bilateral contract networks for peer-to-peer energy trading. IEEE Trans Smart Grid. https://doi.org/10.1109/TSG.2017.2786668

Neves D, Scott I, Silva CA (2020) Peer-to-peer energy trading potential: an assessment for the residential sector under different technology and tariff availabilities. Energy. https://doi.org/10.1016/j.energy.2020.118023

Papadaskalopoulos D, Strbac G (2013) Decentralized participation of flexible demand in electricity markets—Part I: Market mechanism. IEEE Trans Power Syst. https://doi.org/10.1109/TPWRS.2013.2245686

Piclo—The UK's leading independent marketplace for flexible energy systems. n.d. https://www.piclo.energy/. Accessed 15 Aug 2022

Riaz S, Mancarella P (2022) Modelling and characterisation of flexibility from distributed energy resources. IEEE Trans Power Syst. https://doi.org/10.1109/TPWRS.2021.3096971

Seyyedeh Barhagh S, Abapour M, Mohammadi-Ivatloo B (2020) Optimal scheduling of electric vehicles and photovoltaic systems in residential complexes under real-time pricing mechanism. J Clean Prod 246:119041. https://doi.org/10.1016/j.jclepro.2019.119041

Solar power: SEDA introduces P2P trading programme to encourage use of renewable energy—SEDA Malaysia n.d. https://www.seda.gov.my/2019/10/solar-power-seda-introduces-p2p-trading-programme-to-encourage-use-of-renewable-energy/. Accessed 15 Aug 2022

Soto EA, Bosman LB, Wollega E, Leon-Salas WD (2021) Peer-to-peer energy trading: a review of the literature. Appl Energy. https://doi.org/10.1016/j.apenergy.2020.116268

Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E (2019) Peer-to-peer and community-based markets: a comprehensive review. Renew Sustain Energy Rev. https://doi.org/10.1016/j.rser.2019.01.036

Teixeira D, Gomes L, Vale Z (2021) Single-unit and multi-unit auction framework for peer-to-peer transactions. Int J Electr Power Energy Syst. https://doi.org/10.1016/j.ijepes.2021.107235

Tushar W, Chai B, Yuen C, Huang S, Smith DB, Poor HV et al (2016) Energy storage sharing in smart grid: a modified auction-based approach. IEEE Trans Smart Grid. https://doi.org/10.1109/TSG.2015.2512267

Tushar W, Saha TK, Yuen C, Morstyn T, McCulloch MD, Poor HV et al (2019) A motivational game-theoretic approach for peer-to-peer energy trading in the smart grid. Appl Energy. https://doi.org/10.1016/j.apenergy.2019.03.111

Tushar W, Saha TK, Yuen C, Smith D, Ashworth P, Poor HV et al (2020) Challenges and prospects for negawatt trading in light of recent technological developments. Nat Energy. https://doi.org/10.1038/s41560-020-0671-0

Tushar W, Yuen C, Saha TK, Morstyn T, Chapman AC, Alam MJE et al (2021) Peer-to-peer energy systems for connected communities: a review of recent advances and emerging challenges. Appl Energy. https://doi.org/10.1016/j.apenergy.2020.116131

Ullah MH, Park JD (2022) A two-tier distributed market clearing scheme for peer-to-peer energy sharing in smart grid. IEEE Trans Ind Inform. https://doi.org/10.1109/TII.2021.3058511

Wang N, Liu Z, Heijnen P, Warnier M (2022) A peer-to-peer market mechanism incorporating multi-energy coupling and cooperative behaviors. Appl Energy. https://doi.org/10.1016/j.apenergy.2022.118572

Yu VF, Le THA, Gupta JND (2022) Sustainable microgrid design with multiple demand areas and peer-to-peer energy trading involving seasonal factors and uncertainties. Renew Sustain Energy Rev 161:112342. https://doi.org/10.1016/J.RSER.2022.112342

Zhang C, Wu J, Long C, Cheng M (2017) Review of existing peer-to-peer energy trading projects. Energy Proc. https://doi.org/10.1016/j.egypro.2017.03.737

Zhang K, Troitzsch S, Hanif S, Hamacher T (2020) Coordinated market design for peer-to-peer energy trade and ancillary services in distribution grids. IEEE Trans Smart Grid. https://doi.org/10.1109/TSG.2020.2966216

Zhang WY, Zheng B, Wei W, Chen L, Mei S (2022) Peer-to-peer transactive mechanism for residential shared energy storage. Energy. https://doi.org/10.1016/j.energy.2022.123204

Zheng B, Wei W, Chen Y, Wu Q, Mei S (2022) A peer-to-peer energy trading market embedded with residential shared energy storage units. Appl Energy. https://doi.org/10.1016/j.apenergy.2021.118400

Zhou Y, Wu J, Long C, Ming W (2020) State-of-the-Art analysis and perspectives for peer-to-peer energy trading. Engineering. https://doi.org/10.1016/j.eng.2020.06.002

Promoting Just Transition or Enhancing Inequalities? Reflection on Different Energy Community Business Models in Terms of Energy Justice

Ella Tolonen, Shah Rukh Shakeel, and Jouni K. Juntunen

1 Introduction

The energy sector has traditionally relied upon large-scale centralized facilities, owned and operated by big investors, municipalities, or state-owned businesses. The local energy community concept emerged to challenge the dominant operating logic of the industry.[1] These new types of collective energy-related initiatives are increasingly starting to own and operate energy systems for self-consumption, as well as to supply energy to the grid. Energy communities have a crucial role in fostering the energy transition from the bottom up, as they can increase the share of renewable energy production, foster energy efficiency, and decrease transmission losses. This role is increasingly highlighted in the European Union, with the Clean energy for

[1] Despite the recent uptake of community energy, it must be noted that collaborative efforts to produce, distribute and consume energy locally are not a new phenomenon. For example, rural cooperatives for electricity production were explored in the German Reich and the United States in the first half of the twentieth century, and community-owned renewable energy projects, namely wind farms, started to emerge in Denmark and the Netherlands in the 1980s (Feenstra and Hanke 2021).

E. Tolonen
Innovation and Entrepreneurship InnoLab, University of Vaasa, Wolffintie 34, Vaasa, Finland
e-mail: ella.tolonen@uwasa.fi

S. R. Shakeel (✉)
School of Marketing and Communication, and Innovation and Entrepreneurship InnoLab, University of Vaasa, Wolffintie 34, Vaasa, Finland
e-mail: shah.rukh.shakeel@uwasa.fi

J. K. Juntunen
School of Technology and Innovations, and Innovation and Entrepreneurship InnoLab, University of Vaasa, Wolffintie 34, Vaasa, Finland
e-mail: jouni.juntunen@uwasa.fi

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_6

all Europeans package and revised Renewable Energy Directive, which introduced energy communities into European legislation and acknowledged their instrumental role in the energy transition (European Commission 2022).

The promise of citizen-organized collective action has garnered attention among citizens, researchers, policymakers, and businesses. Countries across the globe are looking to adopt measures to facilitate development and increase the share of energy generated from these communities (Brummer 2018). There are currently around 7700 energy community projects in Europe alone, which involve more than two million citizens (European Commission 2021b). Energy community projects are highly heterogeneous and can take many different forms. Differences emerge, for instance, in the choice of energy technology, location, demography, actors involved, and project motivations and goals. There is also a notable distinction between community-led and externally-led energy community projects, which relates closely to power and the distribution of benefits.

As citizens and communities voluntarily take greater responsibility for energy generation, the social and economic implications of energy communities are becoming more visible. Energy communities are often assumed to be without criticism and associated with positive impacts, such as increased community cohesion and wellbeing (Lacey-Barnacle 2020). However, the extent to which they can contribute to strengthening energy justice is becoming an important consideration (Hoffman et al. 2021). The inability to incorporate ethical and societal implications into the new energy paradigm may reinforce old injustices,[2] disproportionally affect vulnerable and energy-poor households (Hanke et al. 2021), and fuel new societal inequalities (Jenkins et al. 2017). Thus, it is vital to adopt from the outset an inclusive and fair approach to energy community projects, to ensure and foster a just energy transition. Energy justice is fundamental also to increasing the acceptability of new renewable energy technologies (Sovacool et al. 2017), and delivering the energy transition in the first place.

It is time for researchers to fully acknowledge that energy communities do not automatically equate to local prosperity and contribute to just energy transition. Projects categorized as energy communities differ substantially in their operational models, and their impacts on local communities and the energy system overall. Energy communities inherently interface with the established energy regime and its infrastructures, actors, and business logic. Recent research has underscored how companies and their business models are vital forces behind sustainability transitions, and can either support or restrain the diffusion of more sustainable ways of organizing production and consumption (Bidmon and Knab 2018; Sarasini and Linder 2018). This chapter discusses how key principles of the energy justice literature are exhibited in different energy community business models, looking to spark more research attention on just energy communities.

[2] Approximately one billion people lack access to electricity, while over one-third of the global population suffers access deficit for clean fuels and technologies (IEA et al. 2020). The issue is not limited to the developing countries alone, as an EU-wide survey showed that 37.5 million people, or 8% of the EU population, are not able to keep their home adequately warm (Bouzarovski et al. 2020).

2 Towards Just Energy Transition from the Bottom Up: The Core Concepts

In this section, we introduce the central concepts of the research: energy communities, energy justice, and energy community business models. The purpose is to elaborate on previous research, provide an overview of prominent frameworks, and discuss the nexus and discrepancies of the three concepts.

2.1 Energy Communities

The increased interest in forming energy communities has sparked research on what the concept of energy community entails, how these initiatives are enacted under different socio-economic, societal, cultural, technological, and regulatory conditions, and on the outcomes and factors influencing the development and operationalization of energy communities. The review of the burgeoning literature reveals that the concept of energy communities has remained multifaceted, with varied conceptualizations, applications and definitions (Bauwens et al. 2022; Gui and MacGill 2018). Predominantly in the literature today, an energy project is regarded as an energy community project when any form or level of joint voluntary citizen participation is attached. It does not necessarily matter whether the community initiates the project, members have decision-making power, revenues are returned to the community, or energy is produced locally (Forman 2017).

Energy community initiatives may vary in terms of their activities, operational modes and overall outcomes. The seminal work by Walker and Devine-Wright (2008) introduced 'process' and 'outcome' viewpoints as the key dimensions of conceptualizing energy community projects.[3] The process dimension concerns who is involved in setting up the projects, while the outcome viewpoint emphasizes the spatial and social distribution of the project outcomes. Research on energy communities can also be divided into outcome- and process-focused approaches.

Outcome-focused studies and definitions underscore energy generation at the local level and self-consumption of the local energy production (Hoz et al. 2020). Community initiatives can help achieve energy autonomy by strengthening energy security and minimizing environmental footprints (Gjorgievski et al. 2021). Process-focused studies see energy communities as organizations where different actors and stakeholders involved in the process share common interests and problems, and are subject to the formal and informal rules that govern the system (Fouladvand et al. 2020). This approach also emphasizes the social benefits of energy communities, and how the communities can act as change agents (Mahzouni 2019). The social benefits highlighted in the process-focused studies may include educational aspects (Boon and Dieperink 2014), upscaling of sustainability practices (Smith et al. 2016),

[3] There is also a third viewpoint in Walker and Devine-Wright's work, which emphasizes that energy community projects should lead to something productive and valuable.

improvement of social coherence (van der Schoor and Scholtens 2015), raising the level of awareness of renewables (Rogers et al. 2008), enhancing acceptance (Busch et al. 2021), and fostering technological diffusion (Nolden 2013). At the societal level, energy communities can impact job creation, economic development, and strengthen local institutions (Busch et al. 2021). As seen above, energy communities can produce different benefits and have various socio-economic impacts.

According to Hicks and Ison, Walker and Devine-Wright's conceptualization of energy communities lacks the specificity to conclude what process or outcome is legitimate for community energy projects (Hicks and Ison 2018). To bridge this gap, they proposed a set of conceptual tools, including five spectrums of community energy,[4] which can support the understanding of community renewable energy through the motivations and choices embedded in the policies and practices of the projects. These spectrums capture the enormous latitude in several aspects of community energy projects, from the range of actors involved to the level of engagement within the project.

The review of the energy community project reveals that initial projects were predominantly local; however, it is currently recognized that communities can take highly dispersed forms. For example, new digital energy communities act as an intermediary, and can provide financial resources (Bonzanini et al. 2016; Lam and Law 2016; Nigam et al. 2018; Vasileiadou et al. 2015), and help in knowledge production and sharing (Hyysalo 2021; Hyysalo et al. 2018).

As this short overview demonstrates, energy communities are multifaceted in various aspects and characteristics. However, there seems to be a consensus that energy communities are groups united by particular interests in renewable energy generation or energy consumption, formed as voluntary initiatives of individuals and stakeholders, in locale-based or dispersed forms, and governed by participatory decision-making (community engagement), to yield various benefits to the community members and society as a whole.

2.2 *Just Transition and Energy Justice*

Just transition is a societal goal that co-exists with the low-carbon transition paradigm. McCauley and Heffron (2018) define just transition as "a fair and equitable process of moving towards a post-carbon society" that must seek fairness and equity concerning major global justice concerns, including, for example, ethnicity, income, and gender.

[4] The five spectrums are: range of actors (ranging from only local individuals to only non-local organizations, business, and government), distribution of voting rights and balance of decision-making power (ranging from one vote per actor to one actor has all votes), distribution of financial benefits (ranging from full community benefit to full non-local investors), decisions around the scale of technology (ranging from scaled in relation to local energy demand and agreement, to scaled to maximize economic efficiencies), and level of engagement (ranging from early timing and a wide set of methods to late timing and a limited set of methods) (Hicks and Ison 2018).

The just transition concept is employed in three different strands of literature, all with their own forms of justice: climate, environmental, and energy justice.

This chapter looks at energy justice, namely a fair distribution of costs and benefits in the global energy system (Sovacool et al. 2013). Jenkins et al. (2016) assert that the notion of energy justice involves, (a) evaluating where injustices emerge, (b) identifying the segments of the society being treated unjustly, and (c) what processes exist for remediation to reveal and mitigate such injustices. Energy justice research strives to apply the principles of justice to energy policy, energy production systems, energy consumption, energy activism, energy security, and climate change (Jenkins et al. 2016). Scholars of energy justice have traditionally approached just transition through the production or consumption lenses, for example, availability of renewable energy sources or implications of energy-saving techniques for wellbeing and community cohesion. Contestations and disputes over energy resources is one of the core themes in the field. In addition to distributional and procedural justice, the energy justice literature has focused on recognition justice concerns, examining who is affected or ignored (Jenkins et al. 2016). The most comprehensive conceptualization of the different issues within the energy justice paradigm was initially executed by Sovacool and Dworkin (2015), who presented a conceptual framework comprising eight energy justice principles. The framework was revisited the following year by Sovacool et al. (2016), and in 2017 extended with two new principles, resistance and intersectionality (Sovacool et al. 2017) (Table 1).

Energy communities are often automatically associated with positive impacts on energy justice, and positive socio-economic benefits for the citizenry (Forman 2017). This is due to the prevailing expectations of energy communities in a local context, and, according to Bommel and Höffken, three main expectations sustain this assumption (2021). According to the first expectation, energy communities inherently have, for example, transparent decision-making processes and fair distribution of profits because procedural and distributive justice are essential to the success of community energy projects. The second expectation entails community energy projects fostering social acceptance of renewable energy, if the distribution of risks, costs and benefits are deemed fair within a community. The third is that the justice benefits mainly relate to the empowerment of community members through, for example, job creation, increasing community resilience, and democratization of the energy supply.

Some scholars have explicitly examined how justice manifests in energy communities. For example, Park looked into how to foster equal opportunities between communities concerning energy communities (2012), Mundaca et al. (2018) researched the role of energy justice in the success of community energy projects, and Lacey-Barnacle explored how the proximity of (community) energy infrastructures influences citizens' sentiment of energy justice (2020). However, the research has to date mainly focused on energy justice issues at the local community level, not considering the broader societal context in which they emerge. Thus, the research arguably does not '(yet) fully employ the inherent scope of the concept' (van Bommel and Höffken 2021). Energy community projects do not exist in a vacuum but are

Table 1 Overview of energy justice principles. Adapted from Sovacool and Dworkin (2015), and Sovacool et al. (2016, 2017)

Energy justice principles	Description
1. Availability	The economy, market or system should guarantee people access to sufficient and reliable energy resources. This includes topics related to physical energy resources and energy infrastructure, provision of energy supply, as well as technologies for energy conservation, transportation, storage, distribution, and investments.
2. Affordability	Access to energy services should be affordable and not constitute a financial burden on consumers, notably the disadvantaged. This includes topics such as price stability and fair prices.
3. Due process	Stakeholders, namely communities, should have the ability to participate in energy policymaking processes and projects that affect them. This includes topics such as fairness and consent for decision-making, adequate impact assessment processes, remedies and compensation mechanisms, and access to arbitration and grievance mechanisms.
4. Transparency and accountability	People should have access to transparent and accountable information on energy and the environment. This includes topics such as democratic and transparent decision-making processes, accounting, public information on revenues and policies, and measures to avoid corruption.
5. Sustainability	Energy sources should be utilized sustainably and not be depleted too quickly. This includes topics such as avoiding undue environmental damage, and sustainable use of energy resources.
6. Intragenerational equity	All people should have equal opportunities to access energy services. This includes topics such as the distribution of energy services in society between different groups.
7. Intergenerational equity	Good quality of life and access to energy services should be guaranteed for future generations, too. This includes topics such as the distribution of energy services between present and future generations, and mitigation and adaptation to climate change.
8. Responsibility	All actors should take responsibility for protecting the environment and reducing the negative impacts of energy production. This includes topics such as governments' responsibility to minimize environmental degradation, especially industrialized countries' responsibility for historical carbon emissions, and responsibility for future generations.
9. Resistance	People should actively stand up to injustices and oppose projects that are unjust, oppressive, and violate the energy justice principles.
10. Intersectionality	How the different aspects of energy justice are connected with other elements of social justice, such as race, class, gender, or power.

intertwined with other (community) energy projects, public and private institutions, energy companies, non-member citizens, and other communities near or far, all of which may be subject or connected to energy justice issues due to energy communities.

Therefore, van Bommel and Höffken have recently argued that research must consider the issues of justice *within, between* and *beyond* energy communities. This framework widens the scope of energy justice research in energy communities to the energy system level. It also illustrates that it is by no means self-evident that energy communities will entail or foster energy justice. The authors also suggest, for example, that research should apply a cosmopolitan justice approach to better cover justice issues related to global supply chains.

2.3 New Business Models to Scale Up Energy Communities

Energy communities are embedded in wide socio-technical structures, and interact with energy generation and transmission companies at the energy system level. These companies rely on various models to create, deliver and capture value with and for the communities (European Commission 2021a; Mlinarič et al. 2019). In the energy transition discourse, emerging business models that utilize citizen-driven shared generation and consumption hold promise for the advancement of the energy transition, and share of clean energy in general.

The business model perspective has been considered increasingly essential to understanding how different organizations create and capture value. According to business model thinking, an organization's long-term success depends upon its ability to create and disseminate value offerings appreciated by the market (Teece 2010). Organizations strive to utilize resources optimally, and aim to benefit from the interaction of internal and external actors to reach the desired outcomes.

Energy community business models tend to transcend conventional profit-making logic, for example, by emphasizing environmental and social outcomes. In these business models, citizens are not just the recipients of the business offerings (Mihailova et al. 2022) but active contributors to the value creation process (Heuninckx et al. 2022). Therefore, companies involved in the energy community sphere often face the challenge of balancing the different business logic and background assumptions underlying the formation of energy communities. Conventional business projects are often founded on a neoliberal ideology. They aim to maximize economic gain, whereas community-led energy is built upon communitarian beliefs that view strong communities as an end in itself, and ideal to instigate and undertake renewable energy projects (Goedkoop and Devine-Wright 2016). In such cases, business models function as systems that bring together stakeholders in ways that facilitate joint value creation (Fischhendler et al. 2021).

The research on energy community business models is still in its early stages. A number of studies have explored different business models incorporated in various energy community settings (Botelho et al. 2021; European Commission 2021a; Hamwi and Lizarralde 2017; Mlinarič et al. 2019). These business models vary in orientation, scope, value creation, and dissemination logic. The following section expands on the most widely used business models in the energy community setting, based on a study by Reis et al. (2021).

Energy cooperatives are initiatives where private citizens jointly own energy generation systems. It is the most common energy community business model in the EU, with over 1900 renewable energy cooperatives serving more than one million people (*RESc*oop.eu 2022). These businesses may operate either for-profit to compete with other market players or non-profit to supply energy locally and reinvest potential profits in the community. Cooperatives can also engage in the management and operation of regional low-voltage distribution networks, which allows them, for example, to influence billing, put in place dynamic pricing models, and impose use-of-system tariffs (for non-members). Cooperatives may operate locally or across a wider geographical area.

Ecopower is the prime example of an energy cooperative in Belgium. Operating for three decades, now with more than 40,000 customers corresponding to 1.5% of the Flemish household market, it has generated 900 million kWh of green power and received 100 million euros in investments.

The Community prosumerism model describes a group of local citizens who join together to acquire energy assets under special financing conditions, thus gaining dimensions to participate in the flexibility markets, collective energy efficiency initiatives, or local energy markets. By joining communities, prosumers increase their negotiating power with external parties on trading conditions. In initiatives that include energy generation or storage, this can be organized collectively through (small-scale) centralized energy installations or individually through, for example, private solar roofs. Long-term power purchasing agreements are often jointly established between community members and energy companies, who purchase surplus generation and supply prosumers with the remaining power they may need. However, all the transactions may also remain within the community boundaries in local energy markets. Revenues from selling surplus energy locally or to the grid can be distributed to the prosumers directly or reinvested in the community.

The Salvin community in Denmark is based on community prosumerism. The energy systems were installed, and energy efficiency measures were implemented to enhance the efficient use of energy. The project aims to scale up the power to 1.5 MWp involving more than 250 households as co-owners of the facilities.

Local energy markets are closely related to community prosumerism, with the difference that all transactions happen are conducted within community boundaries through peer-to-peer trading. Despite its name, the members of local energy markets may also be physically distant and operate virtually. Trading in local energy markets takes place on a dedicated platform where the trading conditions are negotiated directly between the market participants or through intermediaries who act as trading facilitators. Revenues may be distributed between all the market participants, not only the prosumers. The benefit of local energy markets based on proximity is that they often do not need to pay fees for their unused upstream distribution and transmission networks.

Farmivirta is an energy company initiated virtual local energy market in Finland. It enables small-scale energy producers to sell energy directly to customers at a price the producers themselves can determine. In 2017, 10 million kWh of energy was sold through Farmivirta.

Community collective generation initiatives are based on collective energy generation or storage systems installed on or near the consumption sites, often multitenancy buildings. The communities must decide how the generated energy and potential profits from the sales are distributed. Local regulation also plays a vital role in energy distribution, for example, by determining whether surplus energy can be fed to the grid.

Solar Roof is the example of community collective generation in Bulgaria. Consumers initiated the process to develop a community project with an overall capacity of 28 kWp. The project generates roughly 35MWh, meeting 5–7% of the energy consumption need of the building.

Third-party sponsored communities are initiatives strongly supported or driven by external parties, such as utilities or energy technology companies. These external parties often maintain ownership of the assets, make investment decisions, and take governance responsibilities, but local community representatives are in some way involved in the decision-making processes. Community members make long-term power purchasing agreements with the sponsor. When communities are sponsored by a utility company that owns several energy projects, it is typical to employ a pool-and-sleeve method. This supplies energy from a larger geographical area to the community members. When the sponsors are non-profit organizations or social entrepreneurs, energy is often produced more locally, community members more engaged with project development, and the revenues invested back into the community.

Rented solar panels are a third-party sponsored type of initiative launched by Helen energy in Finland. Consumers can choose the panels at one of the designated sites. The power produced by the panels is credited to consumers' overall electricity bill.

The community flexible aggregation model does not include energy generation but is based on communities providing fixed amounts of flexibility to the grid by changing their consumption patterns. Traditionally, the business model has been directed to commercial customers, and only recently applied in the community context. Community flexible aggregation may take the form of a dispatchable program, where the external operator can control members' appliances during peak periods to control the load, or a non-dispatchable program, where the members' consumption is altered through dynamic pricing signals.

Smart Otaniemi is an example of an aggregator business pilot in Finland. The solution offers EV charging aggregation, a Building automation interface, and Direct interface for big loads.

Community ESCO (community-based energy service company) is a model in which external companies partner with communities to provide energy services, for example, energy audits and energy efficiency improvements, or to engage in renewable energy supply (often combined heat and power). The business model enables citizens to acquire energy-as-a-service—they can become prosumers while the ESCO is in charge of the finance, installation, maintenance, and upstream supply. The ESCO's remuneration is solely dependent on energy savings on the customers' side. Although the community ESCO holds the decision-making power, local community members are deeply involved in the processes.

Chase Community Solar in the UK is an example of a Community ESCO. Solar panels and technical setup are installed in a locality to maximize benefits from local PV generation, energy storage, and smart solutions.

E-mobility cooperatives focus on changing transportation behavior and consumption patterns by offering car-sharing or car-pooling services. In addition to low-carbon transport, e-mobility cooperatives can offer grid flexibility through grid-connected energy storage solutions (smart charging schemes). The business model is often combined with community collective generation or community prosumerism.

Sam Mobilitat serves as an example of e-mobile cooperatives launched in Spain. It aims to offer its customers rental services for car-sharing and mobility. The vehicles used are owned by different groups such as individuals, enterprises, and public institutions.

In addition to the archetypes adapted from Reis et al. (2021), we underscore the support that intermediary organizations and digital platforms can provide to those business models. The two main forms of intermediation relate to knowledge-sharing and finance, which are central resources for successful community energy investments and operations. Intermediary organizations, such as consultancy companies, non-governmental organizations, and public institutions can provide energy communities with, for example, practical knowledge and legal expertise to realize projects and facilitate networking between community groups, as well as other resources. Crowdfunding platforms operate as a vehicle to realize community energy investments. By facilitating distributed digital communities, they pool financial resources and form citizen groups around potential renewable energy projects. Knowledge-based digital services provide peer assistance throughout renewable energy projects' lifecycle, from pre-installation initial information search to everyday operations and maintenance. This type of support may be central to all the aforementioned energy community business models. The eight community energy business model archetypes by Reis et al. illustrate the multiple ways and logics with which energy communities may operate, and how varyingly the concept of community manifests in different energy community business models. The business model typically defines the role of the community in a larger energy system, and how benefits and costs are divided between the business ecosystem actors.

3 Analysis of Energy Community Business Models in Terms of Energy Justice

Energy communities can be regarded as a bottom-up approach to the enactment of energy justice, where citizens actively strive to realize aspects of such justice on their own terms (Forman 2017). However, given that there are multiple energy community business models, how they impact energy justice principles also varies. In this section, we observe and analyze the different energy community business models from the perspective of the energy justice principles. The central question is whether and how a business model improves or hinders each energy justice principle. In the analysis,

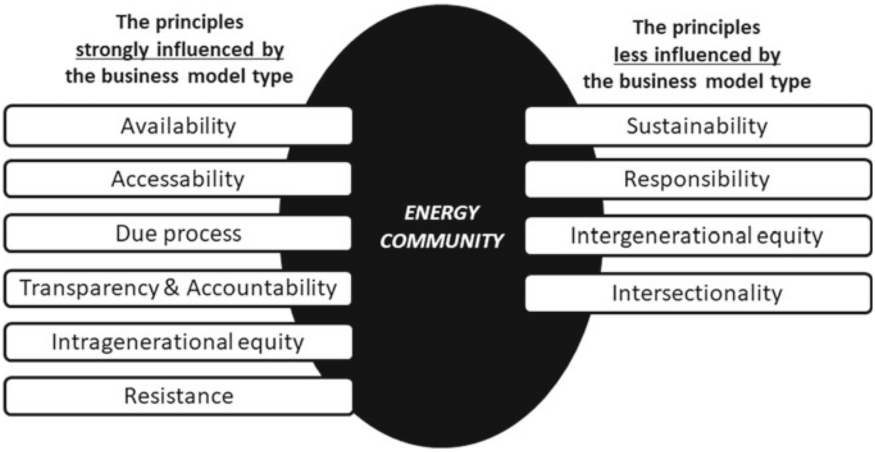


Fig. 1 Conceptual framework of energy justice in the context of energy community business models. The business model type strongly influences the following six energy justice principles: availability, affordability, due process, transparency and accountability, intragenerational equity, resistance. The remaining four principles are less influenced by the business model type

we attempt to consider energy justice issues at the energy system level in the broader societal context (cf. Bommel and Höffken 2022). As there are several potential issues within each energy justice principle, we have not conducted an exhaustive analysis of all perspectives but focused on a few key perspectives.

The section is in two parts. Part one discusses the energy justice principles that, according to our reflective analysis, are strongly influenced by the business model type. Part two discusses the energy justice principles that are less influenced by the type of business model the energy communities have adopted. The analysis is more generic, at the level of energy communities overall. Our division of the ten energy justice principles into two different domains generated a new conceptual framework, for energy justice principles in the context of energy community business models. The framework is presented in Fig. 1.

3.1 Principles Strongly Influenced by the Business Model Type

Availability is about individuals' ability to secure uninterrupted access to energy. The vast majority of energy community business models rely on local energy generation with the involvement of local actors and stakeholders. For instance, in the case of prosumerism, collective generation and local energy markets, the underlying motivation often relates to improving access to clean energy, fighting energy poverty, lowering energy prices, or minimizing generation-related emissions. These business models increase the share of sustainable energy production and provide additional energy sources that the traditional energy sector would not realize.

Striving for increased energy self-sufficiency at the household or community level has sparked an interest in energy communities. Russia's attack on Ukraine and the resulting spike in energy prices has significantly increased interest in resilient and self-sufficient systems. Citizens who engage with *prosumerism, collective generation, local energy markets,* or even *third-party sponsored communities* can improve the security of their energy supply, but often only up to a certain point. Particularly intermittent sources, such as wind and solar, face challenges in improving supply security, while bioenergy-based solutions have the benefit of securing long-term supply. For example, with the current technology, a solar panel installation in a detached home may be only partially able to provide electricity. Thus, in these business models, connection to the transmission network and the ability to purchase energy outside the community are essential to secure constant availability.

By becoming prosumers, citizens can directly contribute to the availability of renewable energy for their own use, and collective generation can provide renewable energy for housing associations and their members. Likewise, when energy generation exceeds members' needs, excess energy can be transmitted to the grid, increasing the share of renewable energy in the overall generation mix. Local energy markets are especially good at enabling more people access to renewable energy, for example, citizens who cannot themselves become prosumers. Third-party sponsored service business models can be good for securing access to low-income communities because they require minimal investment from the community members, as discussed further in the next section.

Through the joint ownership of energy production assets, *energy cooperatives* also contribute directly to energy availability. However, cooperatives are not necessarily tied to a specific location, and the energy produced is supplied directly to the grid. Thus, renewable energy cooperatives do not increase the absolute amount of energy available, but specifically the share of renewable energy by keeping non-renewable energy generation, such as coal-fired power plants, better at bay. Energy cooperatives are the most common form of energy communities in Europe, and also have the most considerable cumulative effect of all the business models.

Prosumerism, collective generation, local energy markets, and third-party sponsored communities currently contribute primarily to improved energy availability in the local context, impacting both the quantity and quality of energy. In contrast, cooperatives have a more substantial impact on the quality of energy produced at the regional and national level.

The rest of the energy community business models—*ESCOs, flexible aggregation, and e-mobility*—indirectly contribute to energy availability by modifying consumption patterns and flattening spikes in energy demand. Thus, these business models help to assure sufficient energy availability throughout the day, and decrease the need to use non-renewable energy sources to meet peak demand, much like energy cooperatives.

It must be noted that energy communities can be crucial to enabling small and underprivileged segments of society access to uninterrupted energy supplies

(Bouzarovski et al. 2020). Regarding energy availability, especially in local energy markets, one central issue is thus the “responsibilization” of citizens—shifting responsibilities from the state to individuals (Argüelles et al. 2017). It could be argued that an individual’s energy access should not be solely dependent on energy community projects that require substantial financial and immaterial resources of citizens. The market’s inability to provide equal access to energy should perhaps be resolved at the institutional level, not by community groups. Although local energy markets can be crucial to guaranteeing access to energy resources in remote locations, should public institutions take responsibility for realizing these projects? The ‘responsibilization’ issue also applies in the context of renewable energy. In the EU, energy communities are officially recognized as one of the measures to deliver the energy transition. The Clean energy for all Europeans report presents estimates that by 2030, energy communities could own 17% of installed wind capacity and 21% of solar, and by 2050 half of EU households could be energy producers (European Commission 2019). But in emphasizing the energy communities this way, is the Union shifting part of governments’ responsibilities to ordinary citizens?

Affordability. The promise of more affordable energy is a typical motivation for citizens to get involved in energy communities. However, to join in, citizens are required by most energy community business models to commit financial investment. The affordability of different business models has temporal, economic, and risk-related trade-offs.

In *community prosumerism*, joint purchasing enables members to pay a lower price for energy generation technology. However, they still need to make substantial financial investments upfront, as renewable energy technologies have long payback periods. Energy technology companies may also offer communities alternative payment arrangements, or citizens can seek low interest loans from the financial sector, which decreases the required upfront capital. Prosumer communities that provide members with alternative financing options for lower upfront capital inputs are more accessible and affordable. However, what citizens are allowed to do with the energy they produce also matters. Legislation that enables prosumers to sell excess energy to the grid with no or minimal transaction fees is fundamental to small-scale solar energy production’s profitability. Studies have also found that net metering can provide around a third more financial savings for a prosumer than gross metering (Auvinen et al. 2020), which is in the hands of the network company and not the community members. The affordability of community prosumerism is, thus, dependent on national legislation, location, and the metering practices in place.

Consequently, participating in *local energy markets* as a prosumer has the same financial considerations as in the community prosumer business model, but joining as a sole energy user is different. Local market energy prices can vary tremendously and exceed the average. Therefore, purchasing energy outside the community’s borders through a grid connection is crucial to ensure affordability.

For energy *cooperatives*, gaining membership often requires citizens to buy shares in the cooperative. Members benefit through more stable energy prices or profit from energy sales, improving long-term energy affordability. In community *collective generation*, projects can be financed directly by the community members or through a housing association. Cooperatives and community generation may be more accessible as they allow small investments, whereas prosumerism requires individual households to make a more significant investment in a complete standalone system. The financial viability of all the business models for energy generation activities at the local level, including collective generation, is highly dependent on regulations that allow members to distribute electricity without fees and taxes (Auvinen et al. 2020).

Third-party sponsored service business models reduce the need for upfront capital investments but require a long-term power purchase agreement between businesses and communities (Reis et al. 2021). Affordability in the long term is highly case specific, and members are not in receipt of any additional profit, since they neither own nor operate the energy generation system. Long-term power purchase agreements carry the risk of communities overpaying for their energy, but supply stability can also positively influence affordability.

A *Community ESCO* influences affordability by decreasing its members' energy demand through energy efficiency measures or enabling them to become prosumers with an energy-as-a-service contract, where the technology is owned and operated by the company. The efficiency measures may require additional upfront costs from the citizens. In ESCO business models, citizens typically benefit from an immediate cost reduction in their monthly energy bills. The investment in energy efficiency and energy savings benefits both the ESCO and involved community members. In other words, this model is highly affordable for members, both in terms of required investments and energy use.

With *flexible generation*, communities can get cheaper energy prices if they provide additional flexibility to the grid according to the contract terms. However, in the model based on price signals, if households cannot adjust their energy use accordingly, they may face higher energy prices for using energy at the 'wrong' time. *E-mobility* business models such as car sharing can substantially decrease the energy needed to fulfil your transportation needs, thus impacting affordability.

In energy community projects, a wide-scale diffusion of the concept eventually replaces other traditional ways of generating, distributing and using energy. In the energy market, a new balance also influences other actors in the system. Positive affordability of community energy may decay energy affordability elsewhere in the system. For example, when decentralized community geothermal heating is scaled up, the profitability of district heating solutions decreases, and the affordability of energy to those not involved with energy communities may be negatively impacted.

In the long run, what may influence affordability is how much risk the individual or the community takes or needs to take in order to realize an energy project or become a member thereof. Energy community projects may be realized in collaboration with the private sector through a shared ownership model to distribute risks (Goedkoop and Devine-Wright 2016). This ownership model may boost citizens' confidence in community projects. However, this aspect partially conflicts with the general aspiration that the community should decide on energy projects that concern them—the degree of financial risk taken by an actor often correlates with their decision-making power (Goedkoop and Devine-Wright 2016). Thus, private actors often drown out the community voices in shared ownership projects.

Due process. Energy community initiatives should pay closer attention to observing due process throughout the project lifecycle, as an inclusive and participatory approach can enable the sustainable operationalization of community initiatives. All relevant actors and stakeholders should have the possibility to participate in the decision-making process. Similarly, careful attention should be paid to the impact assessment process, remedies and compensation mechanisms, and access to arbitration and grievance mechanisms.

Business models based on location and led by community groups—*prosumerism, collective generation, by-community local energy markets,* and *by-community cooperatives (including e-mobility)*—have perhaps a better point of departure to establish such due process practices. Due process may be more inherent to the whole community initiative logic, as initiating and realizing energy projects will likely automatically involve many actors, most notably the community members themselves. However, this is not self-evident, as community-led projects can also be governed by a small, exclusive group of people. In most cases, community groups should also seek external expertise to execute projects professionally, and when collaborating with companies ensure the realization of good and fair contract terms. It can be crucial to engage professional services, for example, financial management, project planning, or generating legal contracts, to ensure the fairness of the whole process and avoid unexpected expenses.

Company managed projects are prone to neglect the voices of the community members. A study on shared ownership energy projects in the UK found that the community actors felt they were only engaged in the process at a late stage (Goedkoop and Devine-Wright 2016). This notion highlights the importance of establishing a good governance mechanism, and project design, that encourage the participation of all parties, especially for projects led by external parties—*externally-led local energy markets and cooperatives (including e-mobility), third-party sponsored communities, flexible aggregation, and community ESCOs.* However, it must be noted that the organization of company driven energy community projects is inherently professional. The due process protocols might therefore be more robust in certain project activities, such as participatory workshops. Involving the communities in the decision-making process helps ensure the righteousness of remedies and compensation mechanisms. Still, these projects could also seek external advice from specific non-profit organizations or intermediaries.

Transparency and accountability propose that initiatives should be democratic, transparent, and inclusive for the energy community members. How different actors and stakeholders can access important information, such as revenues, costs, and policies, can be seen as a measurement of good governance that can minimize corruption and ensure fair processes (Sovacool and Dworkin 2015). The principle is very closely related to due process.

In *prosumerism, collective generation, community-led local energy markets, and community-led cooperatives (including e-mobility),* the decision-making power lies in the hands of the local members, and information is often shared openly. Due to the low hierarchy, communication channels are personal and direct, making it relatively easy for members to communicate and access information. However, it is possible that the lack of professionalization in these initiatives, as referred to in the ‘due process’ discussion, can also hinder the accumulation of and access to information; for example, if the information is not systematically gathered and stored anywhere, or the decision-making processes are not clear and well-documented.

In business models run by external parties, the community members may not have direct access to information. *Externally-led local markets and cooperatives (including e-mobility), third-party sponsored communities*, *flexible aggregation,* and community *ESC*O*s* should ensure information is openly available and actively shared with the members. Here, we see the advantages that may accrue from project professionalization, as the companies can, for example, be accustomed to utilizing information channels.

Intragenerational equity is discussed in three contexts: which communities can set up energy community projects, who can participate in energy communities, and how benefits and potential adverse effects are distributed among the members and non-members.

Communities are different, and their capabilities vary, which directly influences their opportunities to engage with energy communities. Energy-vulnerable groups are often excluded from shaping the energy transition (Bouzarovski et al. 2020). For example, energy cooperatives tend to develop in areas that perform better on social cohesion (Lode et al. 2022). This is likely because energy community projects rely heavily on community members’ time, expertise, and access to finance (Park 2012).[5] From this perspective, business models that include external organizations supporting the community to realize a project, offering both expertise and finance, may be more inclusive and advance the equal distribution of opportunities. This factor is inherent to *third-party sponsored, externally-led cooperatives (including e-mobility), flexible aggregation,* and *ESCOs.* In the rest of the business models, the involvement of external parties is not pre-determined. Intermediaries can play a crucial role as support organizations, especially for community-led energy projects. However, to ensure equal opportunities, acquiring their services should be financed by public institutions and not the energy community projects themselves. Fostering networking between communities and other partners to share skills and resources, provide workshops, and share information on external resources, can encourage broader community participation (Park 2012), and be performed by intermediaries.

The ability to participate in an energy community at the individual level is often a question of money and time. As money is already discussed under the affordability

---

[5] A community must, for example, have the capacities to apply for funding and meet its requirements, which may include previous expertise in such projects. Where there are community energy grant schemes to ease financing, they may not cover all the project costs or only reimburse the members once projects have been executed (Park 2012).

principle, we focus now solely on time. Several studies have concluded that access to energy communities often depends on who has spare time to 'donate' or specific expertise (Feenstra and Hanke 2021). Therefore, business models that require active participation are likely to be the most exclusive. Research has found that men are still participating more than women in local energy initiatives, and are over-represented as prosumers (Standal et al. 2018, 2019).[6] *Prosumerism* is among the business model types that require the most work and dedication from their members. Although energy technology purchases are made jointly, there are several issues to resolve and decisions to be taken by members at the household level. And to maximize the profitability of their investment, prosumers need to actively track the performance of the energy technology and monitor their energy use. The *flexible aggregation* business model also requires excess time, as it is wholly based on the members' ability and willingness to change their energy consumption patterns. From the time perspective, *third-party sponsored communities, energy cooperatives (including e-mobility), ESCOs (especially the energy-as-a-service model),* and *community collective generation* require perhaps the least active participation on the part of the ordinary members who do not have a specific organizational function in the project.[7]

Energy community business models can have several benefits but also adverse side effects, both within and outside the community. The distribution of these impacts is a critical determinant of the fairness of the business model. When community groups and non-profit supporting organizations are not the sole parties realizing energy community business models, there is always the matter of whether the financial benefits are distributed evenly to the community.[8] The question of fairness also relates to whether local citizens affected by certain energy installations are able to get preferential treatment and more favorable terms for share purchases (Goedkoop and Devine-Wright 2016). There are often some negative externalities stemming from the realization of large-scale energy projects to the local environment, such as noise, visual pollution, or decrease in property values. Thus, non-members who live nearby should be compensated for having to bear these adverse effects, for example, in the case of wind energy installations (Westlund and Wilhelmsson 2021). Energy *cooperatives* or *third-party sponsored communities* that operate virtual power plants, where community members do not necessarily live nearby the energy production facility, are especially prone to neglecting local non-member citizens.[9] The other energy

[6] Social inequalities significantly hamper women's capabilities to participate in energy community projects. Feenstra and Hanke elaborated that although energy communities are theoretically open to all members without discrimination, women's ability to participate is limited by other household duties and the resulting lack of time (2021).

[7] In addition, citizens participating in local energy markets as sole energy buyers have limited participation requirements.

[8] In at least Denmark, Belgium, and one German state, legislation exists that obliges commercial wind energy developers to share a certain percentage of the value of their project with the local community (Goedkoop and Devine-Wright 2016). This practically enforces commercial projects as community energy projects with a shared ownership structure.

[9] An example of such a case is the development of two community solar PV farms in the deprived area of Lawrence Weston (Bristol) in the UK. The local community initially opposed the projects as

community business models do not appear to be constrained by such substantial issues related to the distribution of benefits to citizens at the locale, and any negative externalities in play. These business models are based on location; therefore, the beneficiaries are also those impacted by the energy installations.[10]

We should not neglect substantial negative social and environmental impacts downstream of the most renewable energy technologies' supply chains. Community-led energy projects in particular have minimal capacity to influence serious justice concerns, such as child labor, human rights violations, and environmental degradation in, for instance, the Republic of Congo's cobalt industry or China's photovoltaic industry. In step with any other modern, responsible business, energy community projects should seek to minimize their adverse impacts along the supply chain, for example, by purchasing energy technology with trusted sustainability certificates.

Resistance refers to an individual's ability to stand up to injustices and question unjust and oppressive practices that violate the energy justice principles. Overall, by offering a new way for citizens to participate in the energy system, it could be argued that all energy communities foster energy activism. Again, however, we see differences emerging between the business models that have been realized by communities and by companies.

Energy community business models realized by communities can improve avenues for resistance amongst the member citizens, including prosumerism, community collective generation, and by-community local energy markets and cooperatives. These business models strengthen community resistance by democratizing the energy system, and giving local communities more power in energy-related decision-making. In this regard, the community-led business models can be seen as a form of resistance to energy monopolies. For instance, in the case of prosumerism, the process tends to increase the knowledge, understanding and abilities of members to use and set up independent energy systems (Juntunen 2014). This capacity-building improves citizens ability to resist by inculcating confidence and encouraging members to engage in endeavors that can lead to self-sufficiency and autonomy.

We have summarized the discussed energy justice impacts of the energy community business model in Tables 2 and 3.

3.2 Principles Less Influenced by the Business Model Type

Sustainability is a common motivation for the establishment of energy communities. According to our thinking, the sustainability principle is not influenced by the choice of business model per se, but that of technology and related configurations. Energy

---

they were not benefitting from the developments. According to Lacey-Barnacle, for energy justice to be realized in the spatial context, where energy infrastructures are deployed in deprived areas such as Lawrence Weston, the locale must be allowed to benefit from those infrastructures and be included in the process (Lacey-Barnacle 2020).

[10] This is of course highly dependent on the 'due process' and 'transparency and accountability' principles—whether the locale has been included and heard in the decision-making process.

Table 2 Summary of how the different energy community business models influence the energy justice principles of availability, affordability, and intragenerational equity. (+ = positive impact, − = negative impacts, ± = neutral impact/consideration)

	Availability	Affordability	Intragenerational equity
Community prosumerism	+ Energy security at the household level + Access to renewable energy for households' own use + The share of renewable energy in the grid (if supplied)	− Substantial upfront investment with long payback periods + Members get energy generation technology at lower prices ± Profitability dependent on legislation	− Equal opportunities between communities: Knowledge and financial support are not self-evident and might come with additional costs − Equal opportunities between individuals: Requires substantial time and expertise to set up
Community collective generation	+ Energy security at the community level + Access to renewable energy for housing associations or individual use	+ Relatively small investment compared to prosumerism + More stable energy prices + Profit from energy sales	− Equal opportunities between communities: Knowledge and financial support are not self-evident and might come with additional costs + Equal opportunities between individuals: Does not require active participation
Local energy markets	+ Energy security at the community level + Access to renewable energy for your own and other community members' use + Energy access for vulnerable communities − Security of energy supply in a completely closed local market	± For energy producers, the same considerations as for prosumerism apply − For energy users, connection to the grid is important to secure the ability to purchase energy outside	For community-led local energy markets: *The same considerations apply to energy consumers as for community collective generation, and the same considerations apply to prosuming parties as for community prosumerism* For externally-led local energy markets: + Equal opportunities between communities: External organizations provide the marketplace and expertise

(continued)

Table 2 (continued)

	Availability	Affordability	Intragenerational equity
Energy cooperatives	+ The share of renewable energy in the grid + Access to renewable energy at the community level	± Relatively small investment compared to prosumerism + More stable energy prices + Profit from energy sales	− Distribution of impacts: Neglect of local (non-member) citizens; division of financial profits For community-led cooperatives: *The same additional considerations apply as for community collective generation* For externally-led cooperatives: *The same additional considerations apply as for third-party sponsored communities*
Third-party sponsored communities	+ Energy security at the community level + Access to renewable energy at the community level	+ Reduced need for upfront investments − No additional profits for the citizens − Risk of overpaying for energy with long-term power purchasing agreements	+ Equal opportunities between communities: External organizations provide expertise and financial support for communities to realize projects + Equal opportunities between individuals: Does not require active participation − Distribution of impacts: Neglect of local (non-member) citizens
Community flexible aggregation	+ Availability of energy from the grid throughout the day + The share of renewable energy in the grid	+ Reduced energy bills − Risk of higher energy bills (in the price-signal model)	+ Equal opportunities between communities: External organizations provide expertise and financial support for communities to realize projects − Equal opportunities between individuals: Requires substantial time and ability to change consumption patterns

(continued)

Table 2 (continued)

	Availability	Affordability	Intragenerational equity
Community ESCO	+ Availability of energy in the grid + Share of renewable energy in the grid or for members' use (in the energy-as-a-service model)	+ Reduced energy bills + No or minimal investments needed + Cheaper renewable energy (in the energy-as-a-service model) − No additional profits for the citizens	+ Equal opportunities between communities: External organizations provide expertise and financial support for communities to realize projects + Equal opportunities between individuals: Does not require active participation (in the energy-as-a-service model)
E-mobility cooperatives	+ Availability of energy in the grid + Share of renewable energy in the grid	+ Reduced energy bills	− Distribution of impacts: Neglect of local (non-member) citizens For community-led e-mobility cooperatives: *The same additional considerations apply as for community collective generation* For externally-led e-mobility cooperatives: *The same additional considerations apply as for third-party sponsored communities*

communities increase the share of decentralized energy generation from local energy sources. Although those sources can also refer to non-renewables, such as peat or coal, energy communities are primarily associated with renewables, such as wind, solar or biomass. The use of renewable energy sources decreases carbon emissions related to energy production, which is essential to prevent global warming running at a rate linked to a rise in temperature beyond the 2 °C level. The increased utilization of renewables reduces dependence on depletable conventional hydrocarbons, and the environmental depletion associated with drilling and fracking. In addition to these direct effects, energy communities stimulate long-lasting changes in energy consumption patterns and behaviors. The projects increase environmental awareness and knowledge of decentralized renewable energy generation among community members and external parties alike (Rogers et al. 2008). Moreover, they can

Table 3 Summary of how the different energy community business models influence the energy justice principles of due process, transparency and accountability, and resistance. (+ = positive impact, − = negative impacts, ± = neutral impact/consideration)

<table>
<tr><th></th><th>Due process</th><th>Transparency & Accountability</th><th>Resistance</th></tr>
<tr><td>Community prosumerism</td><td rowspan="2">+ Involvement of a diverse set of actors, notably community members
± Requires professional execution of projects (e.g., planning and contracts)</td><td rowspan="2">+ Low hierarchy enables open and direct communication and information flow
± Requires professional execution of projects (e.g., documentation)</td><td rowspan="2">+ Foster energy activism
+ Give citizens more power in energy-related decision-making</td></tr>
<tr><td>Community collective generation</td></tr>
<tr><td>Local energy markets</td><td colspan="3">For community-led local energy markets: The same considerations apply as for community collective generation
For externally-led local energy markets: The same considerations apply as for third-party sponsored communities</td></tr>
<tr><td>Energy cooperatives</td><td colspan="3">For community-led energy cooperatives: The same considerations apply as for community collective generation
For externally-led energy cooperatives: The same considerations apply as for third-party sponsored communities</td></tr>
<tr><td>Third-party sponsored communities</td><td rowspan="3">− Prone to neglect community voices
± Potential for robust processes and protocols (e.g., participatory workshops)</td><td rowspan="3">− Information may not be accessible and actively shared
± Potential for robust processes and protocols (e.g., information channels)</td><td rowspan="3">+ Foster energy activism</td></tr>
<tr><td>Community flexible aggregation</td></tr>
<tr><td>Community ESCO</td></tr>
<tr><td>E-mobility cooperatives</td><td colspan="3">For community-led e-mobility cooperatives: The same considerations apply as for community collective generation
For externally-led e-mobility cooperatives: The same considerations apply as for third-party sponsored communities</td></tr>
</table>

contribute to capacity building and skills development, stimulating innovations in the cleantech sector to improve efficiencies and eliminate bottlenecks, in order to foster the energy transition.

Intergenerational equity refers to addressing the energy needs of the present generation without compromising the ability of future generations to meet their needs. Energy communities strengthen intergenerational equity by promoting sustainability, as discussed earlier, and thus the principle is not affected by the choice of business model. The use of renewable energy sources inherently supports intergenerational equity, as the renewable energy reserves are infinite,[11] and the environmental externalities related to production and consumption are less devastating than with fossil

[11] It must however be noted that renewable energy generation requires a lot of materials, many of which are rare earth elements for which there is a limited supply.

fuels. Also, reducing dependence on traditional fuels prolongs the fossil reserves, making it possible for future generations to utilize these finite resources, if necessary.

Responsibility deals with protecting the environment and mitigating the negative impacts of energy generation and consumption. Different actors and stakeholders can undertake measures to minimize negative externalities, and positively influence the environment and citizenry. Energy communities can achieve this by considering sustainability principles throughout the project lifecycle, including choices related to materials and fuel sources, and establishing partnerships and collaborations that promote and enable preservation. Thus, we do not see the business model type having a significant influence on the responsibility principle.

Intersectionality should be inherent to all nine energy justice principles presented earlier. As energy communities operate locally, they should be aware of how their energy activities influence different social issues and people, especially underprivileged and marginalized groups. Gender, race, sexuality, religion, disability, or language identities, for example, can alone or in combination disproportionately impact individuals and their abilities to engage in energy activities (Sovacool et al. 2017). For example, due to the prevailing social structures, it is typical for men to initiate energy projects in households but for women to do the practical work (Standal et al. 2019). These disproportionate impacts are often neglected in energy-related businesses, and, thus, intersectional business design approaches should also be applied in energy community projects.

4 Discussion

Conventional energy systems have long remained under the influence of large entities in charge of energy generation and transmission. At the same time, ordinary citizens have remained disenfranchised, and their participation limited only to consumption. The development of decentralized energy systems and energy communities offers the potential to make energy issues more indigenous, participatory, inclusive, transparent, accessible, and affordable. Energy communities are often seen as a potential means to transform energy systems by facilitating the use of sustainable energy sources, addressing energy poverty, improving energy access, strengthening energy security, and providing consumers with the opportunity to take an active role in energy generation and transmission.

The possibility of forming and operating your own energy systems through collective initiatives strengthens people and their role in the energy system. However, widespread positive change cannot be achieved until these initiatives are enacted with the logic that they create value for all stakeholders involved or impacted in the process. It is often assumed that the development of energy communities can meet these challenges and the issues that have plagued conventional energy systems.

However, in reality, the process and outcomes of energy communities vary significantly. We need to understand the inherent fundamentals of different energy community business models, and how they impact the development of a more just way of producing and consuming energy.

The purpose of this chapter, and our conceptual assessment of how the energy justice principles are exhibited in the different energy community business models presented, is to spark more focused research on just energy community business models. It is imperative for just energy transition that energy community business models are seriously assessed and considered in terms of the justice principles. Our assessment leans on the previous research, with the additional analysis of energy community business models and their impact on energy justice.

The energy community business models can advance the principles of energy justice. However, the real potential and the actual contribution of the business models on the ground cannot be attained unless the process is enacted in a just manner. Energy communities in themselves do not inherently lead to just or democratic outcomes. Bringing different actors and stakeholders together, setting up the infrastructure, and forming energy communities is only one part of the mix. There need to be operational routines, governing principles, and business models put in place that are inclusive, democratic, and participatory to further accelerate the development and acceptability of energy communities.

At the early stages of the analysis, we realized that the choice of a business model did not directly influence all the energy justice principles. Therefore, we distinguished between two energy principle groups—those strongly influenced by the business model type, and those that the business model type had less influence on. The business model types lead to different energy justice outcomes in terms of availability, affordability, due process, transparency and accountability, intragenerational equity, and resistance.

The energy community business models can be categorized according to the extent to which they are open and participatory, and how strongly they are connected to the community members and ensure their involvement. We can differentiate here between **community-led** and **externally-led** business models. The community-led models operate on community logic, including community prosumerism and collective generation. Externally-led business models operate either on commercial or non-profit logic. These models include community ESCO, third-party sponsored communities, and community flexible aggregation. Local energy markets and cooperatives can fall into either category, being either community or externally-led.

The community-led business models are better aligned to meet the energy justice principles of due process and transparency and accountability. Additionally, they can positively contribute to improving the availability of renewable energy and energy security locally. The citizens' direct involvement and close affiliation to these business models ensures that members can actively participate in the community's affairs, and play a role in the decision-making processes. However, to ensure the long-term success and functioning of the communities, they must often avail themselves of professional organizations' services for assistance in financial and managerial matters, if needed. This support can help communities ensure financial and technical resources are well managed, and that the energy community project can fulfil its desired outcomes. Perhaps surprisingly, the community-led business models did not measure up well in terms of affordability and intragenerational equity. The models required substantial commitment from the members, financially and time-wise, and thus remained rather exclusive. It is important to pay closer attention to these two principles in the business model design, to improve the social equity of the community-led business models. The digital platforms, dispersed knowledge-based communities, and intermediary organizations are all essential to supporting community-led business models to positively impact energy justice. Especially platforms that facilitate knowledge-sharing can be crucial to fostering inclusion and equal opportunities between communities. Thus, these support organizations and platforms play a fundamental role in promoting just energy communities.

It is somewhat easier for the externally-led business models to ensure positive impacts on the principles of affordability and intragenerational equity. These projects often have hierarchical structures and professionalized practices. Since an external group is in charge of enacting projects and taking financial risks, these business models decrease the responsibility and risk of ordinary citizens over the energy supply. The models also positively contribute, most notably to improving the availability of renewable energy in the energy markets. However, caution must be maintained on the principles of due process, and transparency and accountability. The externally-led business models can be less democratic, disregarding the voices of small and marginalized groups, and making participation less inclusive for its members and stakeholders. Therefore, it becomes imperative that the external parties ensure information availability and accessibility, foster participatory and inclusive decision-making processes, and align the operations with community initiatives' core values and principles. They should also pay closer attention to compensation and remedies.

Additionally, it is essential to highlight that energy communities positively contribute to the principles of sustainability, intergenerational equity, and responsibility. The impact is irrespective of business model type. Intersectionality, on the other hand, is regarded more as a design approach that is not inherent to energy communities but should be incorporated into all the business models, as well as the analysis of other energy principles (e.g., intersectional thinking in energy poverty).

Our work has some energy policy implications. During the last two decades, energy policies around the world have shifted from quantity- and cost-driven policies toward climate change mitigation-related policies. These have predominantly focused on technology and economic dimensions to support the energy transition. Interventions that focus on changing power relations, social injustices, or matters of due process are less visible. Climate change requires prompt actions, and energy policy should support those actions. At the same time, we need policies that enable sustainable energy transitions and can mobilize citizen groups to take collective action. In doing so, we need to be sensitive to possible trade-offs between the speed of transition (Newell et al. 2022), performance-related targets such as cost or scale of diffusion, and the social justice-related targets. Market liberalization, where trading principles are enabled for communities (e.g., taxation, fees), is a particularly relevant area for regulation in the energy community realm.

On the other hand, it is necessary to remain vigilant on how businesses around energy communities emerge. The rules and regulations are just about emerging, and issues such as maintaining the freedom to join or leave communities (contractual regulation), and facilitating the inclusivity of different socio-economic groups must be incorporated into the policy agendas. Overall, policies need to address how to dismantle current unbeneficial technology and business-related lock-ins, prevent new lock-ins from emerging, and at the same time foster the energy justice principles.

There are some limitations that should be considered while formulating interpretations and generalizations. First, it is essential to note that energy justice is a complex and multifaceted phenomenon influenced by various social, economic, ecological, and political factors, as well as the regional and national landscape, which transcend a single energy community initiative or business model type. Thus, it is challenging to comprehensively map the actualization and implications of energy community business models for energy justice. Second, this chapter is based on a literature review of extant energy community initiatives that have been implemented in different contexts. The analysis is based on evidence that may not have explicitly considered the (systemic) issues of energy justice. We therefore suggest that future research collects more empirical data, incorporating energy justice lenses to strengthen scholarship on this topic. Third, the study has included eight energy community business model archetypes, which are somewhat loose, high-level categories. In practice, there are many different types of model that communities have adopted, mixing various aspects of different business models, adopting hybrid approaches, or localizing these to better suit the communities' needs. This also makes it challenging to produce overarching generalizations on the findings. More empirical research to compare and contrast different business model applications under different contexts is needed to gain novel insights.

Acknowledgements This work was supported by the Academy of Finland via the "Digitally mediated decarbon communities in energy transitions (DigiDecarbon)" project research funding (grant 348210).

References

Argüelles L, Anguelovski I, Dinnie E (2017) Power and privilege in alternative civic practices: examining imaginaries of change and embedded rationalities in community economies. Geoforum 86:30–41. https://doi.org/10.1016/j.geoforum.2017.08.013

Auvinen K, Honkapuro S, Juntunen J, Ruggiero S (2020) Aurinkosähköä taloyhtiöiden asukkaille, p 88. Aalto University

Bauwens T, Schraven D, Drewing E, Radtke J, Holstenkamp L, Gotchev B, Yildiz Ö (2022) Conceptualizing community in energy systems: a systematic review of 183 definitions. Renew Sustain Energy Rev 156:111999. https://doi.org/10.1016/j.rser.2021.111999

Bidmon CM, Knab SF (2018) The three roles of business models in societal transitions: new linkages between business model and transition research. J Clean Prod 178:903–916. https://doi.org/10.1016/j.jclepro.2017.12.198
Bonzanini D, Giudici G, Patrucco A (2016) The crowdfunding of renewable energy projects. In: Ramiah V, Gregoriou GN (eds) Handbook of environmental and sustainable finance, pp 429–444. Elsevier. https://doi.org/10.1016/B978-0-12-803615-0.00021-2
Boon FP, Dieperink C (2014) Local civil society based renewable energy organisations in the Netherlands: exploring the factors that stimulate their emergence and development. Energy Policy 69:297–307. https://doi.org/10.1016/j.enpol.2014.01.046
Botelho DF, Dias BH, de Oliveira LW, Soares TA, Rezende I, Sousa T (2021) Innovative business models as drivers for prosumers integration—enablers and barriers. Renew Sustain Energy Rev 144:111057. https://doi.org/10.1016/j.rser.2021.111057
Bouzarovski S, Cornelis M, Thomson H, Varo A, Guyet R (2020) Towards an inclusive energy transition in the European Union confronting energy poverty amidst a global crisis. European Commission. https://doi.org/10.2833/103649
Brummer V (2018) Community energy—benefits and barriers: a comparative literature review of Community Energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. Renew Sustain Energy Rev 94:187–196. https://doi.org/10.1016/j.rser.2018.06.013
Busch H, Ruggiero S, Isakovic A, Hansen T (2021) Policy challenges to community energy in the EU: a systematic review of the scientific literature. Renew Sustain Energy Rev 151:111535. https://doi.org/10.1016/j.rser.2021.111535
European Commission (2019) Clean energy for all Europeans
European Commission (2021a) Economies of energy communities: review of electricity tariffs and business models
European Commission (2021b) State of the Energy Union 2021b—contributing to the European green deal and the union's recovery
European Commission (2022) Energy communities—citizen-driven energy actions that contribute to the clean energy transition, advancing energy efficiency within local communities. Energy. Retrieved June 15, 2022, from https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en
Feenstra M, Hanke F (2021) Creating an enabling policy framework for inclusive energy communities: a gender perspective. In: Coenen FHJM, Hoppe T (eds) Renewable energy communities and the low carbon energy transition in Europe, pp 205–226. Springer International Publishing. https://doi.org/10.1007/978-3-030-84440-0_9
Fischhendler I, Herman L, Barr A, Rosen G (2021) The impact of community split on the acceptance of wind turbines. Sol Energy 220:51–62. https://doi.org/10.1016/j.solener.2021.01.055
Forman A (2017) Energy justice at the end of the wire: enacting community energy and equity in Wales. Energy Policy 107:649–657. https://doi.org/10.1016/j.enpol.2017.05.006
Fouladvand J, Mouter N, Ghorbani A, Herder P (2020) Formation and continuation of thermal energy community systems: an explorative agent-based model for the Netherlands. Energies 13(11):2829. https://doi.org/10.3390/en13112829
Gjorgievski VZ (2021) Social arrangements, technical designs and impacts of energy communities: a review. Renew Energy 19
Goedkoop F, Devine-Wright P (2016) Partnership or placation? The role of trust and justice in the shared ownership of renewable energy projects. Energy Res Soc Sci 17:135–146. https://doi.org/10.1016/j.erss.2016.04.021
Gui EM, MacGill I (2018) Typology of future clean energy communities: an exploratory structure, opportunities, and challenges. Energy Res Soc Sci 35:94–107. https://doi.org/10.1016/j.erss.2017.10.019
Hamwi M, Lizarralde I (2017) A review of business models towards service-oriented electricity systems. Proc CIRP 64:109–114. https://doi.org/10.1016/j.procir.2017.03.032

Hanke F, Guyet R, Feenstra M (2021) Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. Energy Res Soc Sci 80:102244. https://doi.org/10.1016/j.erss.2021.102244

Heuninckx S, te Boveldt G, Macharis C, Coosemans T (2022) Stakeholder objectives for joining an energy community: Flemish case studies. Energy Policy 162:112808. https://doi.org/10.1016/j.enpol.2022.112808

Hicks J, Ison N (2018) An exploration of the boundaries of 'community' in community renewable energy projects: navigating between motivations and context. Energy Policy 113:523–534. https://doi.org/10.1016/j.enpol.2017.10.031

Hoffman J, Davies M, Bauwens T, Späth P, Hajer MA, Arifi B, Bazaz A, Swilling M (2021) Working to align energy transitions and social equity: an integrative framework linking institutional work, imaginaries and energy justice. Energy Res Soc Sci 82:102317. https://doi.org/10.1016/j.erss.2021.102317

de la Hoz J, Alonso À, Coronas S, Martín H, Matas J (2020) Impact of different regulatory structures on the management of energy communities. Energies 13(11):2892. https://doi.org/10.3390/en13112892

Hyysalo S (2021) Citizen activities in energy transition: user innovation, new communities, and the shaping of a sustainable future, 1st edn. Routledge. https://doi.org/10.4324/9781003133919

Hyysalo S, Juntunen JK, Martiskainen M (2018) Energy Internet forums as acceleration phase transition intermediaries. Res Policy 47(5):872–885. https://doi.org/10.1016/j.respol.2018.02.012

International Energy Agency (IEA), International Renewable Energy Agency (IRENA), UN Department of Economic and Social Affairs (UN DESA), World Bank, World Health Organization (WHO) (2020) Tracking sdg 7: the energy progress report. https://www.worldbank.org/en/news/press-release/2021/06/07/report-universal-access-to-sustainable-energy-will-remain-elusive-without-addressing-inequalities

Jenkins K, McCauley D, Heffron R, Stephan H, Rehner R (2016) Energy justice: a conceptual review. Energy Res Soc Sci 11:174–182. https://doi.org/10.1016/j.erss.2015.10.004

Jenkins K, McCauley D, Forman A (2017) Energy justice: a policy approach. Energy Policy 105:631–634. https://doi.org/10.1016/j.enpol.2017.01.052

Juntunen JK (2014) Prosuming energy–user innovation and new energy communities in renewable micro-generation, PhD thesis, Aalto University School of Business. https://aaltodoc.aalto.fi/handle/123456789/14143

Lacey-Barnacle M (2020) Proximities of energy justice: contesting community energy and austerity in England. Energy Res Soc Sci 69:101713. https://doi.org/10.1016/j.erss.2020.101713

Lam PTI, Law AOK (2016) Crowdfunding for renewable and sustainable energy projects: an exploratory case study approach. Renew Sustain Energy Rev 60:11–20. https://doi.org/10.1016/j.rser.2016.01.046

Lode ML, Coosemans T, Ramirez Camargo L (2022) Is social cohesion decisive for energy cooperatives existence? A quantitative analysis. Environ Innov Soc Trans 43:173–199. https://doi.org/10.1016/j.eist.2022.04.002

Mahzouni A (2019) The role of institutional entrepreneurship in emerging energy communities: the town of St. Peter in Germany. Renew Sustain Energy Rev 107:297–308. https://doi.org/10.1016/j.rser.2019.03.011

McCauley D, Heffron R (2018) Just transition: integrating climate, energy and environmental justice. Energy Policy 119:1–7. https://doi.org/10.1016/j.enpol.2018.04.014

Mihailova D, Schubert I, Burger P, Fritz MMC (2022) Exploring modes of sustainable value co-creation in renewable energy communities. J Clean Prod 330:129917. https://doi.org/10.1016/j.jclepro.2021.129917

Mlinarič M et al (2019) Typology of new clean energy communities (Deliverable D2.2 developed as part of the NEWCOMERS project, funded under EU H2020 grant agreement 837752). https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d439b9aa&appId=PPGMS

Mundaca L, Busch H, Schwer S (2018) 'Successful' low-carbon energy transitions at the community level? An energy justice perspective. Appl Energy 218:292–303. https://doi.org/10.1016/j.apenergy.2018.02.146

Newell PJ, Geels FW, Sovacool BK (2022) Navigating tensions between rapid and just low-carbon transitions. Environ Res Lett 17(4):041006. https://doi.org/10.1088/1748-9326/ac622a

Nigam N, Mbarek S, Benetti C (2018) Crowdfunding to finance eco-innovation: case studies from leading renewable energy platforms. J Innov Econ 26(2):195. https://doi.org/10.3917/jie.pr1.0033

Nolden C (2013) Governing community energy—feed-in tariffs and the development of community wind energy schemes in the United Kingdom and Germany. Energy Policy 63:543–552. https://doi.org/10.1016/j.enpol.2013.08.050

Park JJ (2012) Fostering community energy and equal opportunities between communities. Local Environ 17(4):387–408. https://doi.org/10.1080/13549839.2012.678321

Reis FG, Gonçalves I, Lopes M AR, Henggeler Antunes C (2021) Business models for energy communities: a review of key issues and trends. Renew Sustain Energy Rev 144:111013. https://doi.org/10.1016/j.rser.2021.111013

REScoop.eu (2022) About our federation. Retrieved May 13, 2022, from https://www.rescoop.eu/the-rescoop-model

Rogers JC, Simmons EA, Convery I, Weatherall A (2008) Public perceptions of opportunities for community-based renewable energy projects. Energy Policy 36(11):4217–4226

Sarasini S, Linder M (2018) Integrating a business model perspective into transition theory: the example of new mobility services. Environ Innov Soc Trans 27:16–31. https://doi.org/10.1016/j.eist.2017.09.004

Smith A, Hargreaves T, Hielscher S, Martiskainen M, Seyfang G (2016) Making the most of community energies: three perspectives on grassroots innovation. Environ Plan A Econ Space 48(2):407–432. https://doi.org/10.1177/0308518X15597908

Sovacool BK, Dworkin MH (2015) Energy justice: conceptual insights and practical applications. Appl Energy 142:435–444. https://doi.org/10.1016/j.apenergy.2015.01.002

Sovacool BK, Heffron RJ, McCauley D, Goldthau A (2016) Energy decisions reframed as justice and ethical concerns. Nat Energy 1(5):16024. https://doi.org/10.1038/nenergy.2016.24

Sovacool BK, Sidortsov RV, Jones BR (2013) Energy security, equality and justice. Routledge

Sovacool BK, Burke M, Baker L, Kotikalapudi CK, Wlokas H (2017) New frontiers and conceptual frameworks for energy justice. Energy Policy 105:677–691. https://doi.org/10.1016/j.enpol.2017.03.005

Standal K, Winther T, Danielsen K (2018) Energy politics and gender. In: Hancock KJ, Allison JE (eds) The Oxford handbook of energy politics, pp 195–215. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780190861360.013.6

Standal K, Talevi M, Westskog H (2019) Engaging men and women in energy production in Norway and the United Kingdom: the significance of social practices and gender relations. Energy Res Soc Sci 60:101338. https://doi.org/10.1016/j.erss.2019.101338

Teece DJ (2010) Business models, business strategy and innovation. Long Range Plan 43(2–3):172–194. https://doi.org/10.1016/j.lrp.2009.07.003

van Bommel N, Höffken JI (2021) Energy justice within, between and beyond European community energy initiatives: a review. Energy Res Soc Sci 79:102157. https://doi.org/10.1016/j.erss.2021.102157

van der Schoor T, Scholtens B (2015) Power to the people: local community initiatives and the transition to sustainable energy. Renew Sustain Energy Rev 43:666–675. https://doi.org/10.1016/j.rser.2014.10.089

Vasileiadou E, Huijben JCCM, Raven RPJM (2015) Three is a crowd? Exploring the potential of crowdfunding for renewable energy in the Netherlands. J Clean Prod. https://doi.org/10.1016/j.jclepro.2015.06.028

Walker G, Devine-Wright P (2008) Community renewable energy: what should it mean? Energy Policy 36(2):497–500. https://doi.org/10.1016/j.enpol.2007.10.019

Westlund H, Wilhelmsson M (2021) The socio-economic cost of wind turbines: a Swedish case study. Sustainability 13(12):6892. https://doi.org/10.3390/su13126892

Local Flexibility Markets and Business Models

Felix Zornow, Saber Talari, Wolfgang Ketter, Mahoor Ebrahimi, and Miadreza Shafie-khah

1 Introduction

1.1 Motivation and Aims

Current energy systems are experiencing a transformation led by incentives to reduce greenhouse gas emissions and increase the share of renewable energy sources (RES). This way, the integration of RES into energy systems is one of core issues. However, only depending on grid investments to deal with increasing loads and integration of RES is not the way to tackle this issue, because it would be too costly (Schittekatte and Meeus 2020, p. 1; Minniti et al. 2018, p. 1).

First and foremost, flexibility is defined as the change of energy generation or consumption patterns in response to a specific signal. This flexibility is then offered as a service to support actors in the energy system. It appears that both supply and demand sources can be used as flexibility sources (Ebrahimi et al. 2022, p. 1). In this regard, upward-regulation means more generation or less consumption, and downward-regulation means less generation or more consumption, accordingly (Sánchez-Jiménez et al. 2015, p. 12).

Local flexibility markets (LFMs) are identified as platforms that coordinate and provide flexible assets. This flexibility can then be offered to the Distribution System Operator (DSO) for managing the distribution system in an efficient way preventing possible problems such as congestion (Zeiselmair and Köppl 2021, p. 1). There

F. Zornow · S. Talari · W. Ketter
Department of Information Systems for Sustainable Society, Faculty of Management, Economics and Social Sciences, University of Cologne, Cologne, Germany

M. Ebrahimi · M. Shafie-khah (✉)
School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland
e-mail: miadreza.shafiekhah@uwasa.fi

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_7

are already flexibility markets in Europe that aim to make distribution grids more efficient and decrease grid investments. Establishing a local flexibility market would offer flexibility products provided by DER and flexible demands. It also provides an access to a market platform for DER. Influential unions of DSOs and Transmission System Operators (TSO) pointed out the urgency for flexibility provision in Europe. It was also demonstrated how TSO-DSO coordination could allow both operators to access different flexibility products that assit them address system operations challenges such as congestion (Valarezo et al. 2021, p. 1).

Nevertheless, the role of the consumer becomes more critical owing to self-generation and improved information and communications technology (ICT) technology that allows better tracking and control of loads, resulting in a decreased electricity bill for the consumer (Olivella-Rosell et al. 2018, p. 4). Due to a lack of a real-world applicable business model for local flexibility markets, the relevance of this topic is emphasized.

This chapter aims to provide an overview of Local flexibility markets and their business models. Consequently, the following research question is to be answered: "What are the proposed business models for LFM, what are their drawbacks and barriers, and how can they be improved?"

1.2 Literature Review

Articles, documentation, and websites were categorized based on a concept matrix presented by Webster and Watson (2002, p. 17). Since this work's focus is to provide an overview of existing business models, their drawbacks and barriers, and possible improvements, the categorization of the concept matrix will have an upper category "local flexibility markets" with sub-categories "Business models", "Drawbacks and Barriers" and "Improvements". The sub-categories will be divided into smaller sections to provide a wide-ranging solution to the research questions.

The rest of the chapter is organized as follows. In the next section, various proposed business models for LFMs are analyzed. The third section presents the drawbacks and barriers to LFMs. The fourth section suggests how LFMs can be improved or what alternatives can be taken. The fifth section discusses this work's results and evaluates whether the objective and research question are answered. The last section concludes the chapter and gives an outlook for further future research.

2 Proposed Business Models

This section analyzes the proposed local flexibility market designs in Europe thoroughly. Due to the absence of publicly available documentation of specific projects, some projects are explored in more detail than others.

2.1 Enera

Enera is a German project coordinated by EPEX spot, EWE AG, and local TSOs and DSOs [namely Tennet DE (TSO), Avacon Netz (DSO), EWE Netz (DSO)]. It aims to coordinate the supply and demand of flexibility, help the DSOs in congestion management and minimizing the curtailment of renewable energy generation. Furthermore, the platform offers network operators a local order book, where network operators can buy flexibility to solve congestion issues. A demonstration of a local order book can be seen in Fig. 1 (Schittekatte and Meeus 2020, p. 4).

The main functions of the project include the collection of bids, market clearing, monitoring, settlement, introducing aggregation activities, network impact computations, and flexibility activation (Valarezo et al. 2021, p. 4).

The given market is a two-sided market, where TSOs and DSOs are buyers of flexibility and aggregators, and asset owners are sellers of flexibility. Moreover, the market is synchronized with the intraday market of EPEX Spot, which means the clearing period is like the intraday market (15 min), and the delivery period is 15 or 60 min. The trading happens on a different platform, even though the platform's access uses the identical API as trading on the EPEX Spot exchange. The pricing method is pay-as-bid. Bidding is a continuous process, and received bids are matched on the platform. Settlement is executed as dispatch payments, and participants are billed at the end of each month for their collected trades. The offered flexibility is devotions to change the load or production of a particular participant. When activating that flexibility, the participant's portfolio is affected by the provision of flexibility. The participant then must ensure that its portfolio is still balanced, which can be done on the intraday market. Additionally, research funds are used to continue the platform. It is to be noted that Enera is merely a pilot project (Valarezo et al. 2021, p. 11).

Fig. 1 Local order book

Local Market X	Bid		Ask	
Product	Qty	Price	Qty	Price
DE 9:00 Local X	11	41	4	39
DE 9:00 Local X	8	35	11	40
DE 9:00 Local X	3	32	7	33
DE 9:00 Local X	5	27	3	29

Regarding TSO-DSO coordination, both network operators are anticipated to exchange information bilaterally when buying flexibility to avoid conflicting activation. However, going forward, the idea is to create a mechanism that filters offers so that no such complications in activation can occur (Schittekatte and Meeus 2020, p. 8).

The project's main achievements include the development of the flex registry, which is a registry with all flexible assets and their characteristics. Moreover, a verification platform was developed that verifies the flexibility delivery. Lastly, a framework that controls the processes and interactions on the platform was presented (Sommer et al. 2020, pp. 3–5).

The project participation was voluntary, and the network operators did a prequalification to evaluate the usefulness of new aspiring participants. Additionally, there were no penalties for the non-delivery of flexibility products, which makes sense in hopes of lowering the entry barriers for new participants. Nevertheless, it would be reasonable to implement penalties in more mature flexibility markets (Schittekatte and Meeus 2020, pp. 8–9).

Moreover, it is worth noting that since October 2021, a new regulation for redispatch called Redispatch 2.0 has come into effect. This regulation allows grid operators to control renewable energy plants and CHP plants that have a capacity of 100 kW and above. These smaller assets are then included in the redispatch process. Nevertheless, the new redispatch regulation only considers generation and storage units. This regulatory framework completely ignores demand-side flexibility. To tackle this issue, a hybrid model was proposed to consider non-regulated assets (Sommer et al. 2020, p. 6).

2.2 GOPACS

GOPACS is a Dutch platform owned by the Dutch TSO and DSOs and launched in 2019 that is currently in operation. GOPACS is not a market, yet it is connected to Dutch's national energy market platform, the ETPA. Moreover, GOPACS is in contact with other market platforms (Epex Spot, Nord Pool), with ambitions to connect these platforms to GOPACS. (Valarezo et al. 2021, p. 5; https://en.gopacs.eu/).

The platform deals with congestions at all voltage levels, offering flexibility for redispatch and TSO/DSO coordination. Moreover, grid operators forecast and report congestion management needs using the platform. Trading is not executed on a different platform because it is integrated into the existing market structure. Flexibility is offered on the ETPA as a subgroup of the wholesale order book, and flexibility providers must include locational information for the offer. As the trading is executed on the ETPA, the market is two-sided. DSOs and TSOs are buyers of flexibility, and sellers of flexibility can be residential, industrial, and energy companies. The market is continuous, and the market platform carries out the settlement. The market operator is reimbursed by the flexible service providers in the form of an entry fee, a monthly fee, and a fee for every delivered MWh. Additionally, grid operators are required to pay a fee for using flexibility products. Flexibility products on GOPACS are unique. Therefore, for every purchase order, a sell order is matched even if the sell order has a higher price than the buy order. The network operator pays the difference between the orders to assure the execution. This type of product is called IDCONS (Intraday Congestion Spread). However, the bids are only matched if they are located sufficiently in the network, so the process is still cost-efficient. A procedure for this type of product can be seen in Fig. 2 (Dronne et al. 2020, p. 5; Schittekatte and Meeus 2020, pp. 4–6; Valarezo et al. 2021, p. 11).

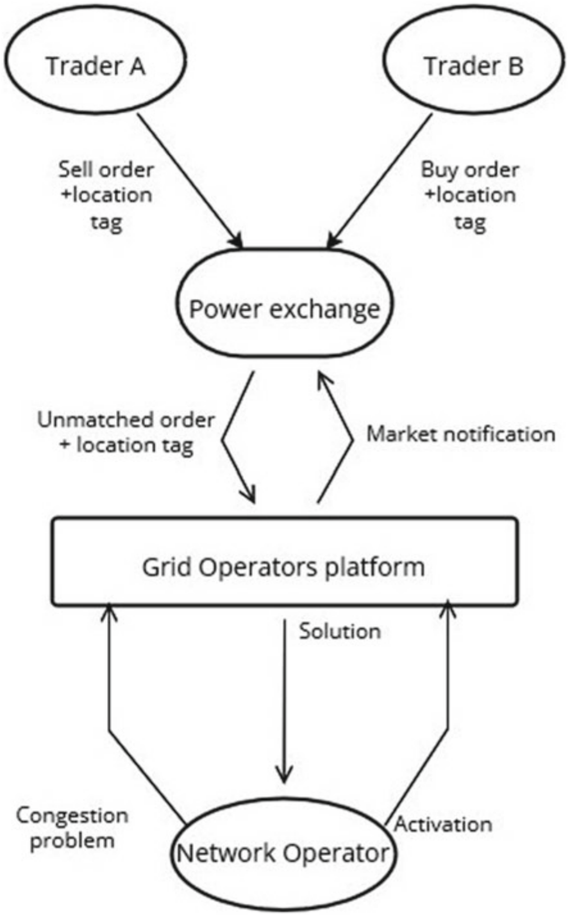


Fig. 2 IDCONS product

2.3 Picloflex

Picloflex is a marketplace based in the UK and has been operating since 2019. The key objectives of Picloflex are developing a marketplace to offer standardized flexibility products to DSOs, reduce grid reinforcement costs, and operate the system in a more efficient way. DSOs are provided with a platform where they can declare their flexibility needs based on locational information. On this platform, DSOs monitor available assets for use in the constrained zone and obtain flexibility suited for their requirements. Interestingly, the platform only offers services to DSOs and not TSOs. Aggregators, asset owners, consumers, communities, electric vehicles, and generators can offer flexibility. The provided platform is not integrated with existing energy markets (Radecke et al. 2019, p. 8; Schittekatte and Meeus 2020, pp. 4–6).

Picloflex differs from other marketplaces, since it is auction-based, and flexibility is offered with a lead time of six months to 4 years. A flexibility provider must submit prices for availability, activation, and a maximum running time. Therefore, flexible service providers are compensated for dispatch. It is also to be noted that making reservation payments and contracts with multiple services is possible in this marketplace (Valarezo et al. 2021, p. 11).

2.4 Nodes

Nodes is an international business case that aims to improve grid operation by procuring flexibility for network operators and therefore enhance congestion management options. It has been in operation since 2018 and is owned by the European Power exchange Nord Pool. Nodes has a variety of use cases across different countries, including Germany, Norway, Sweden, and the UK. In the German case (the Mitnetz case), Nodes established a project with a German DSO to test if a market-based solution could enable better local flexibility utilization for reducing congestion due to an oversupply of energy. This project aimed to reduce the curtailment of renewable energy generation. As a result, curtailment costs paid to renewable energy providers were significantly reduced, and 240 tons of carbon emissions were saved (Sarti 2020, p. 8; Valarezo et al. 2021, p. 5).

In addition, other projects like Norflex in Norway, Intraflex in the UK, and Sthlmflex in Sweden were established by Nodes. There are also incentives to create a universal approach to provide flexibility for DSOs and their interaction with flexibility markets. The project EUniversal pursues this aim in Germany, Poland, and Portugal (Sarti 2020, p. 10–11).

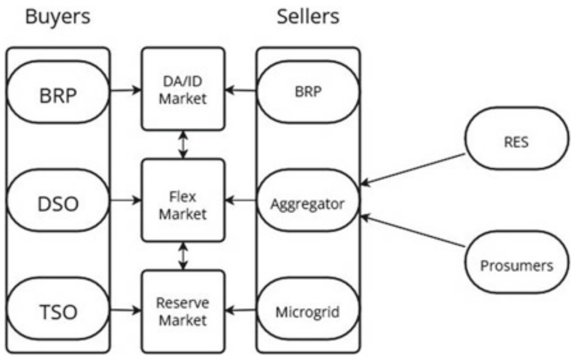


Fig. 3 Nodes market design

Nodes offers flexibility products for DSOs, TSOs, and Balancing Responsible Parties (BRP). The platform is integrated into existing energy markets so that the trading is executed on the intraday timeframe. Additional flexibility that is not required by network operators or BRPs is forwarded to other energy markets. A visual representation can be seen in Fig. 3.

The Nodes market is unique as it offers the purchase of so-called LongFlex, which enables DSOs to make availability payments to secure the possibility of receiving flexibility over a defined period. In addition, it offers the ShortFlex market, where flexibility can be acquired to solve network congestion. Furthermore, the flexibility service providers and asset owners can submit their assets to the platform, where they compete with other flexibility service providers, and thus create an order book. Flexibility products on Nodes are not standardized, as flexibility providers can modify specific parameters like order, time, and location (Sarti 2020, pp. 7–12; Schittekatte and Meeus 2020, pp. 6–7).

2.5 EcoGrid 2.0

EcoGrid 2.0 is a local flexibility market-based in Denmark that shows how households can offer flexibility services to DSOs and TSO through demand response. The project is located on the island Bornholm, and approximately 800 households participate. Every household owns a smart meter, a communication and control device, and an electric heating unit. Aggregators play a significant role in this project by controlling and optimizing an aggregation of DERs; they can operate in the whole-sale market. An overview of the EcoGrid setup can be seen in Fig. 4 (Heinrich et al. 2020, pp. 6–7).

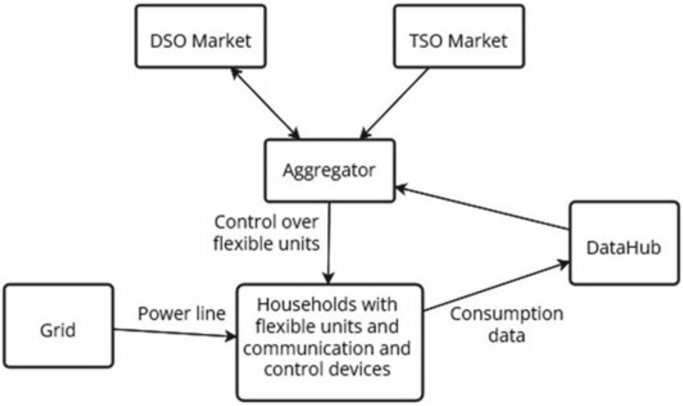


Fig. 4 Ecogrid setup

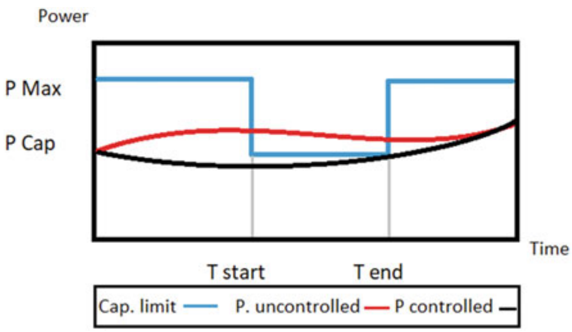
The DSO and aggregators must access the smart meter data from participants. DSOs need participants data for calculating their flexibility needs and aggregators need the data to control DERs and determine the amount of flexibility they can provide. DSOs use aggregated data, and consumers in Denmark are energy aware, thus willing to share data, making it more unlikely that data privacy concerns will arise (Heinrich et al. 2020, p. 7).

The EcoGrid 2.0 introduces two flexibility services for the DSO, the capacity limitation service and the baseline flexibility service. These services can be scheduled or conditional. Scheduled services are activated during a predetermined and regular point of time, while conditional services must be activated manually by the DSO (Heinrich et al. 2020, p. 8).

The capacity limitation service limits the power consumption of an aggregator, so his portfolio cannot exceed the consumption limit for a specific period. An example of this service can be seen in Fig. 5 (Heinrich et al. 2020, pp. 8–9).

The baseline flexibility service is distinguished by the baseline, an estimated power consumption if the aggregator did not interfere in delivering the service. In

Fig. 5 Capacity limitation service



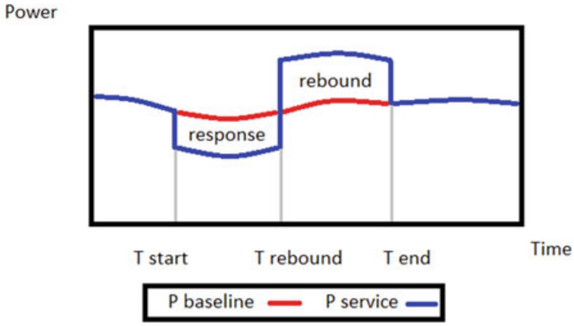


Fig. 6 Baseline flexibility service

this service, the aggregator must first change the load into one direction. Then after a specified period, he changes the load into the opposite direction for the same period. An example of this service can be seen in Fig. 6 (Heinrich et al. 2020, pp. 9–10).

The procedure of how flexibility is acquired starts with the DSO. Firstly, the DSO models the load in the network to assess the time of possible congestion. Secondly, the DSO begins an auction by providing the market operator with several service requests that might be needed. The auction must be done within a lead time of one to twelve months. The auction information is then forwarded to aggregators (without the price indicated by the DSO), who then calculates the service cost and send back a list of services they want to provide. Ultimately, the most economically beneficial service is chosen, and a standardized contract is made between DSO and aggregator. There also is the possibility that the offered service is conditional. In that case, the DSO must evaluate whether to activate the service or not. The DSO only activates the service if the activation cost is lower than the expected benefit (Heinrich et al. 2020, pp. 10–11).

2.6 Tiko

Tiko is an aggregator platform in Switzerland launched in 2014 and is still in operation today. The main goal of Tiko is to aggregate the behind-the-meter assets from Swiss households, like residential photovoltaic and electricity-based heating systems, to provide flexibility to the Swiss TSO. The flexibility the platform offers is primary and secondary balancing services for the Swiss TSO. Apart from the aggregator platform, Tiko also provides the technology used for this implementation in Germany, Belgium, France, and Austria. The platform only operates in low voltage DSO grids. The settlement for trades is firstly done on the TSO balancing market between the aggregator and the TSO, and secondly on Tiko's platform between the aggregator and the flexibility service providers. The TSO continuously acquires flexibility for the following week. Tiko generates its income from the services for the transmission grid and equipment sales, and subscriptions of customers (Valarezo et al. 2021, pp. 14–17).

The Tiko system consists of four parts: actors and sensors, gateway, Frontend, and Backend, in addition to some additional services.

- Actors and Sensors: The K-Box is a vital device for measuring and controlling. It controls and measures appliances like heat pumps, air conditioning, or EV charging stations. Measured data is forwarded to the Backend to determine the state of the device and the control decision variables. Moreover, the device is equipped with a relay that Tiko used to shift the consumption (Geidl et al. 2017, p. 6).
- Gateway: The earlier explained K-Box is connected to the M-box. The K-Box sends its data to the M-Box using the power line communication. The M-Box is an intermediate device that provides the Backend with data from the K-Box (Geidl et al. 2017, pp. 6–7).
- Backend: The primary function of the Backend is the algorithm that decides on control actions for the connected devices. Control decisions are made by analyzing various parameters. Customer comfort is guaranteed not to go beyond a specific limit. The typical behavior of the connected devices is examined using big data analysis (Geidl et al. 2017, p. 7).
- Frontend: The Frontend provides the customer with several functionalities. Firstly, the customer can visualize his historical consumption patterns via a web app or a smartphone app. Secondly, an Eco-mode allows the customer to reduce energy consumption significantly. In addition, the customer is alarmed in case energy consumption is unusual. Lastly, one can benchmark his energy consumption with other participants in the Tiko system (Geidl et al. 2017, p. 7).

Even more services are connected to the platform, including rollout and installation planning tools, a customer support portal, and an ERP system (Geidl et al. 2017, p. 8).

2.7 Equigy

Equigy is a blockchain-based initiative of European TSOs that intends to actively enable households to participate in the energy transition and generate flexibility from decentralized systems. The crowd balancing platform has projects in Germany, Italy, Switzerland, and the Netherlands. The platform allows aggregators to provide flexibility for grid balancing purposes through various consumer-based appliances, like batteries and heat pumps. Blockchain technology is responsible for validating and executing the transactions and validating the provision of flexibility services. The flexibility services the platform offers vary depending on the country of application. For instance, in the Netherlands, aFRR services, in Switzerland, FCR and RR services, in Italy, RR services, and in Germany, Redispatch services are offered. In addition to that, the platform also provides congestion management services for DSOs. The crowd balancing market is integrated into ancillary service markets from Germany, Switzerland, Italy, and the Netherlands. However, the platform can coexist with these existing markets if something fails. It is to be noted that the platform is not profitable (Fabel et al. 2021, p. 6; Niet et al. 2021, pp. 7–12; Valarezo et al. 2021, pp. 14–17; https://equigy.com/the-platform/).

2.8 *Interflex*

Interflex was a project with demonstrations in Germany, France, Sweden, Netherlands, and the Czech Republic from 2017–2019. The demonstrations focus on how the DSOs can use flexibility to solve their challenges on the distribution grid. In these demonstrations, flexibility is exclusively offered to the DSO and not to the TSO. Two kinds of approaches were used to provide. In the first approach, there were no external participants like aggregators. DSOs directly manage residential assets to activate flexibility. The German and Swedish demonstrations made use of this kind of approach. The second approach incorporates aggregators into the market setup. A market setup for the Dutch demonstration can be seen in Fig. 7 (Pourasghar Khomami et al. 2020, p. 3; Valarezo et al. 2021, p. 7).

In Interflex, there are three mechanisms for the DSO to activate flexibility.

- In the first mechanism, the DSO owns and directly controls flexibility assets. Batteries are mainly used to offer flexibility. In the French demonstration, the DSO directly controls a battery to solve grid congestion. In the Swedish demonstration, a central battery and a backup generator are used to make islanding possible (Dumbs et al. 2019, p. 3).

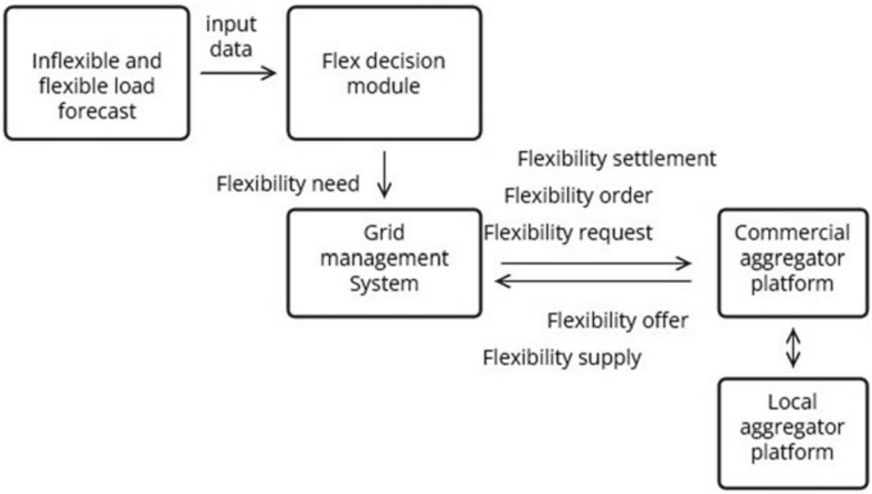


Fig. 7 Dutch interflex market setup

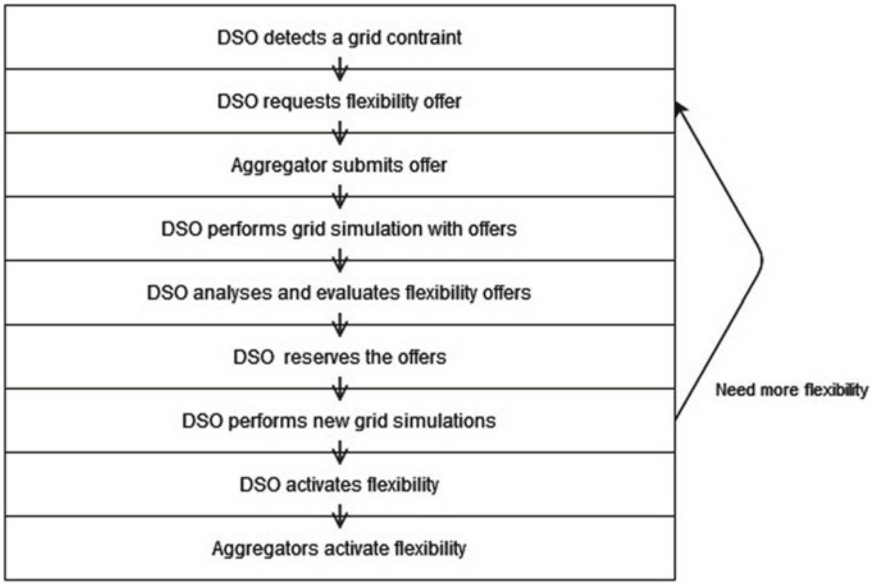


Fig. 8 Market process French demonstration

- The second mechanism depends on legal and contractual obligations, which define the use of flexibility. For example, in the German demonstration, flexibility providers are obliged to respond to DSOs signals in case of grid congestion. The flexibility in that demonstration is usually the temporal curtailment of solar energy. The DSO in Sweden has a contract with the customer to control flexibility units like heat pumps and batteries by sending signals from the system. (Dumbs et al. 2019, p. 4).
- The market response mechanism is the third mechanism to activate flexibility for the DSO. In this mechanism, the flexibility provider responds to the DSOs market demands in the form of flexibility bids activated when specific rules are satisfied. The aggregators in the French and Dutch demonstrations receive DSOs requests on their respective market platforms. Contracts with their customers allow them to control their assets using the platform. A process for the French demonstration can be seen in Fig. 8 (Dumbs et al. 2019, p. 4).

2.9 Parity Hybrid Model

2.9.1 Platform Setup

Parity is a market framework that implements a Local Energy Market (LEM) and an LFM simultaneously. Three main goals are pursued with this proposal. On the one hand, flexibility should be offered to the DSO for congestion management and voltage control. On the other hand, prosumers should be integrated into the process of providing flexibility. Lastly, prosumers should be able to trade locally produced energy among themselves. (Pressmair et al. 2021, p. 7).

The P2P energy trading takes place on a blockchain-based platform operated by the Local Energy Market Operator (LEMO). However, a LEM does not solve congestion management issues. On the opposite, it could even contribute to these issues. That's why there is an additional LFM implemented in this market. The LFM can be implemented either implicitly or explicitly. The implicit LFM does not require a separate market platform. The congestions in the grid are implicitly solved by the DSO giving off different prices for locations. The DSO forecasts where potential congestion might occur and changes the network tariff accordingly. The prosumers then must react to the price signals and adjust their consumption profile accordingly. If the prosumers respond by lowering their load at higher prices or increasing their load at lower prices, congestion can be avoided. This type of market requires the regulator to make variable grid tariffs possible. This type of market can be seen in Fig. 9 (Pressmair et al. 2021, pp. 7–8).

On the other hand, there is the explicit LFM. In this concept, the DSO buys flexibility on a different market platform. This market platform is operated by a separate entity called the Local Flexibility Market Operator, or LFMO. The flexibility for the DSO is always unconditional. This is because long-term availability payments would restrict the way the LEM operates. Prosumers of the LEM cannot assure the provision of flexibility over a longer time. The LEMO acts as an aggregator because it sells flexibility to the DSO using a BRP. After all, the LEMO is responsible for delivering the flexibility and charging the prosumer a varying fee on each trade in the LEM to achieve altered consumption patterns. A setup for the explicit LFM can be seen in Fig. 10 (Pressmair et al. 2021, pp. 7–8).

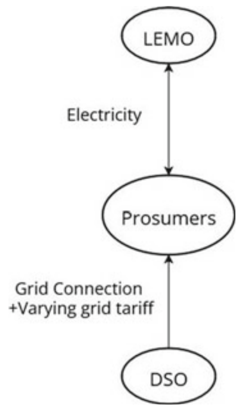


Fig. 9 LEM with implicit LFM

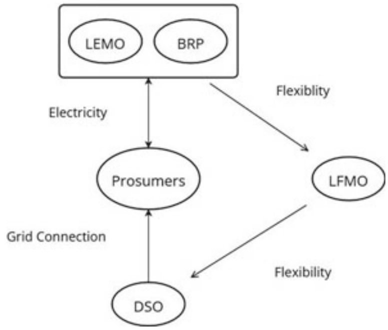


Fig. 10 LEM with explicit LFM

2.9.2 Wholesale Market Integration

The proposed model also allows the prosumer to provide ancillary services to the TSO. That is done by aggregators that acquire flexibility on the market platform. The market operator then turns the requested flexibility into prices for the prosumer. When the flexibility is activated, the market operator needs to change the price while considering price elasticity to change the consumption pattern of prosumers. Forecasting and automatic energy dispatch must be on point for a smooth operation. The market operator carries the risk of the uncertainties of delivering flexibility. Therefore, the aggregator's energy portfolio must be large and diversified to ensure safe operation in case of non-delivery (Pressmair et al. 2021, p. 10).

2.9.3 Coordination of Flexibility

There are three different types of grid operation. There is the green, yellow, and red operation state. The DSOs forecasts determine the grid state. The green state means that no constraints are forecasted. The prosumers automatically trade P2P energy. The DSO applies the usual grid tariff, and the aggregator and LEMO operate as usual. In the yellow state, the DSO forecasts some form of constraint. Here the DSO acquires flexibility from the LFM. The aggregator cannot buy flexibility in that state. However, the P2P trading among prosumers continues. The red state is only applied when the flexibility from the LFM does not solve the forecasted congestion. The DSO directly controls loads that jeopardize grid stability. In this case, the whole market platform halts. Moreover, P2P trading has also stopped (Pressmair et al. 2021, p. 10).

2.10 CoordiNet

The CoordiNet is a European project with demonstrations in Greece, Spain, and Sweden. The demonstrations pursue different goals suited to their local needs (Madina et al. 2020, p. 1).

2.10.1 Greek Demo

In Greece, the goals are to engage consumers and RES to participate actively in power systems. Moreover, reducing the costs and increasing the quality of energy by presenting innovative products and services (Madina et al. 2020, pp. 1–2).

In Greece, a multi-level and fragmented market model is used to solve congestion and voltage issues. A multi-level market model means that the DSO and TSO have separate markets for their flexibility needs. The fragmented market model only allows flexibility assets to offer their flexibility to the system they are connected to. For example, a flexible asset connected to the transmission system can only offer services for the TSO. Likewise, a flexible asset connected to the distribution system can only offer services to the DSO (Madina et al. 2020, pp. 3–4).

The essential services for the network operators are congestion management and voltage control services. The services are traded on the Day-ahead and Intra-day market (Bachoumis et al. 2019, p. 23).

Primary use cases are load and RES forecasting on transmission and distribution grids, state estimation on both grids, market platform models, and a DSO/TSO coordination platform (Madina et al. 2020, p. 4).

2.10.2 Spanish Demo

Spain's demonstration aims to provide evidence that Local Flexibility Markets integrate flexible assets of every size and location to support network operators by offering grid services (Madina et al. 2020, p. 1).

In Spain, congestion issues are solved using a local and a common market model. The local market model only considers flexibility for the DSO and disregards the central flexibility needed for the TSO. On the other hand, in the common market model, DSO and TSO can procure flexibility on a single market platform. A setup for the platform can be seen in Fig. 11 (Madina et al. 2020, pp. 3–4).

The CECRE is the Control Centre of Renewable Energies. It is the connection point between the TSO and renewable generation. The GEMAS+ is responsible for evaluating the system's state. It also calculates the power reduction in case the system must return to a safe condition. E-SIOS manages the incoming bids for the balancing markets and assures the grid's economic and consistent operation. E-SIOS and GEMAS+ needed modification for the CoordiNet project to be successfully applied (Madina et al. 2020, p. 5).

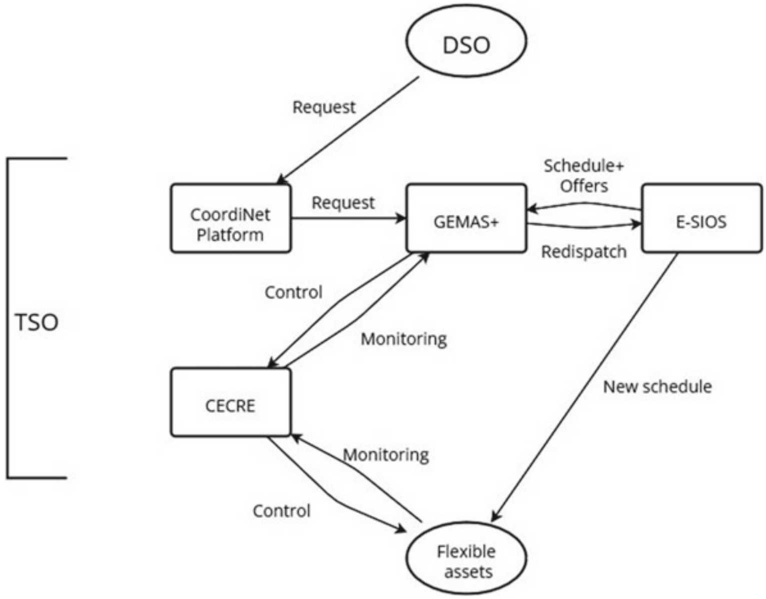


Fig. 11 CoordiNet Spanish setup

2.10.3 Swedish Demo

The Swedish demonstration intends to electrify their society for a sustainable future. Therefore, it aims to achieve the national goals for renewables and climate. It is also expected that these markets support economic growth in that area. Additionally, a P2P trading mechanism is facilitated in the Swedish demo (Madina et al. 2020, p. 2).

In Sweden, multi-level and distributed market models are used to manage congestion. The distributed market model solves flexibility needs using P2P trading. The DSO and TSO create incentives to align their objective with the participant's objectives. The market platform can be seen in Fig. 12 (Madina et al. 2020, p. 4).

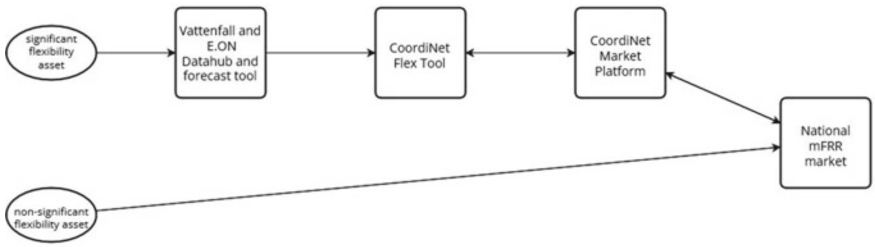


Fig. 12 Swedish setup

The Swedish setup can be split into two parts. Firstly, the market platform receives flexibility bids and ranks them in a merit order list. Secondly, the flex tool is responsible for calculating the required volume of flexibility. The market is also connected to the mFRR market. Therefore, excess flexibility is forwarded to that market (Etherden et al. 2020, p. 76).

Moreover, several lessons were learned that should be considered in a large-scale implementation of an LFM. Firstly, stakeholder engagement is crucial for the successful operation of an LFM. TSOs, DSOs, aggregators, and flexibility asset owners need to communicate and coordinate in a way that allows everybody to express their needs and to create tools and mechanisms that provide value for everyone. The second lesson learned was that the need for flexibility varies as time passes. Factors for that would be weather conditions and changes in the grid. Additionally, availability payments are essential because it assures flexibility providers to return their investments. On the other hand, only having activation bids at an early-stage project could be unattractive for flexibility providers. Finding the appropriate remuneration for availability and activation payments is also challenging. Another aspect was technical requirements. Many entry barriers were identified in that regard. For example, baseline agreements or data treatment issues were significant for DSOs and flexibility providers. Prequalification for mFRR markets was also considered too harsh and posed a barrier. The last aspect was timing in the market. The flexible assets vary because some prefer to deliver flexibility in the Day-ahead market and others prefer to deliver in the Intra-day market. Therefore, it is essential to incorporate both timeframes to maximize opportunities. The identified lessons can also be considered in different countries or projects in the EU when developing an LFM (Ruwaida et al. 2021, p. 12).

2.10.4 FLEXIMAR

The goal of the FLEXIMAR trading marketplace is to implement and provide a minimum viable energy flexibility market place prototype. This marketplace is intended for the audience consisting of individual households up to large industrial size consumers and network operators, i.e., not restricted to any predefined energy consumer classes.

An analysis in the project context indicates how the flexibility trading domain is divided to five different subdomains (Consumer/Prosumer Domain, Automated Trader Domain, Market domain, Verification domain, and Shared data domain) with their distinctive responsibilities, actors, functionalities and domain crossing information flows. Naturally, the domains would extend further and new ones discovered especially if various economical and business aspects and their respective actors would be included.

One key focus in FLEXIMAR project was on development of flexible energy resources utilization enabling management methods and systems. As part of this work, for example, an evolution path toward fully flexible, resilient, and digitalized electricity distribution networks was created focusing on the development of adaptive control and management methods as well as compatible collaborative and coordinated market schemes that can enable the improved provision of flexibility services by distribution network-connected flexible energy resources for local (distribution system operator, DSO) and system-wide (transmission system operator, TSO) needs.

Market place environment (Market domain) includes the market place collecting the submitted trade orders and executing first come first served trade matching to close trades. Also, this provides access to the information sources and messaging facilities. The information sources include machine readable current and up-to-date market information of the market movements, listing of buy and sell offer levels to all participating traders and more detailed and trader related information for the individual traders. The messaging facilities implement two-way messaging mechanism between the trading platform and the traders. The messaging includes the trade offer message reception from the traders; closed trade notifications, error messaging and market price ticker messaging (Vahedipour-Dahraie et al. 2021, p. 2).

FLEXIMAR introduced a local, flexible capacity market (LFCM), which is run on a day-ahead basis. In this way, flexibility transactions are confirmed one day before the actual delivery. In the proposed LFCM, prosumers sell their flexible capacities to the TSO and the DSO. Hence, within the LFCM, prosumers are the leading sellers, whereas the TSO and the DSO are the main buyers. The buyers are permitted to automatically control the flexible resources of prosumers if their bids are accepted. In other words, the DSO and the TSO can constantly follow their flexibility needs in real-time if they had purchased their required flexible capacities from the LFCM in the day-ahead. In real-time, the operators are allowed to activate the purchased capacities fully or partially. The operators may also decide not to activate the purchased flexible capacities if they do not need them in real-time (Shokri Gazafroudi et al. 2020, p. 3).

3 Drawbacks and Barriers

3.1 Drawbacks of Existing LFMs

Since barriers for LFMs can differentiate, this section deals with the drawbacks of specific projects.

3.1.1 EcoGrid 2.0

Authors in (Heinrich et al. 2020), pointed out that communication between flexible assets and aggregators has been inconsistent because the infrastructure for this project was based on a previous project called EcoGrid EU that are out of date. The mean absolute percentage error (MAPE) was 31% for the service delivery mean absolute percentage error. If faulty communicating participants were excluded from this calculation, the MAPE would have been 18%. Two other uncertainties influence the MAPE. Firstly, there is a baseline uncertainty when estimating the consumption profile of the participants. Different weather conditions, geographical differences among participants, and random behavior are factors of uncertainty in that regard. Secondly, the aggregator did not receive feedback about the real-time consumption of their portfolios. As a result, aggregators had to estimate the available flexibility from the weather conditions and the time of the day. While testing the realized benefit from activating 36 services, most were of little benefit. However, one activation prevented a network outage, while one activation caused a network outage. The instance where a flexibility activation caused one network outage was during a baseline service. Outages of this nature can be avoided if the baseline service duration is longer. The rebound effect was 1 h long when the outage happened. When the rebound time was extended to 3 h, outages caused by this service could be avoided (Heinrich et al. 2020, pp. 21–24).

3.1.2 Interflex

In the Interflex project, two approaches were tested: the integrated and market-based approaches. To meet every need of the DSO, both approaches must be implemented to some degree. Regulation is one of the main barriers to the integrated approach that makes the DSO the aggregator. In most European countries, the DSO is not allowed to control behind the meter assets directly. On the other hand, the market-based approach, has problems assuring that flexible assets are available when required. (Dumbs et al. 2019, p. 2).

Moreover, the risk is managed mainly by the DSO. Risk should be distributed more evenly, especially for aspects the DSO cannot control, like the inactivation of specific resources. Another challenging aspect is the creation of a market that is liquid and safe in supply (Dumbs et al. 2019, p. 5).

3.1.3 Parity Hybrid Model

The main drawbacks identified for the Parity Hybrid Model are lifestyle and administrative issues. Firstly, the lifestyle aspect, several market participants do not want to participate in the market model. Eventually, due to high complexity with a low perceived benefit. Secondly, the administrative issues, regulations impact energy market development in a major way. However, not in a positive way. Regulation presents a significant obstacle to innovation in the energy sector. Consistent policy and legal changes are required to raise interest in investment in the energy sector (Pressmair et al. 2021, pp. 14–15).

3.1.4 FLEXIMAR

Some challenges have been identified in the FLEXIMAR project. In modelling autonomous actions there are several barriers for behavior modelling. In addition, flexibility gadgets installation costs remain too much for prosumers. The ambiguity to discern prosumer motivation and double taxation in participating in grid are identified as challenges in prosumer grouping process. Furthermore, the problem in getting the right people involved and not enough monitory incentives are the identified challenges in the centrality of leader prosumers.

3.2 Barriers to the Adoption of LFMs

The following section will outline general barriers to adopting LFMs based on several categories.

3.2.1 Current Lifestyles

Firstly, adoption poses a challenge for LFM. Adoption generally begins with a small user group utilizing the new technology until more and more people embrace it. Along the adoption procedure, the participants' technology and expectations change. Therefore, the main challenge of adoption is to satisfy the changing needs and desires of the participants (Pressmair et al. 2021, p. 15).

Moreover, the participant could be disappointed in the emerging technology because their expectation were too high. Projects must keep improving and please the participants to avoid a decrease of their interest. Additionally, the concept of LFM is not popular and mature enough. Along with that goes the lack of expertise of LFMs. People do not grasp the complex nature of these markets (Pressmair et al. 2021, p. 15).

3.2.2 Administration

Existing regulation is an important restricting aspect for LFMs. New regulations are mandatory for innovation to be made in the energy sector. Because, existing regulation cannot support the new structure of LFM. The most barriers are around the aspect of regulation. In that regard, market participants like the DSO are heavily regulated. They are restricted from operating in a market or even being a market operator. Moreover, incentives are not set effectively to support LFMs. For example, energy tariffs and funding schemes are not laid out to efficiently run an LFM (Pressmair et al. 2021, p. 16).

3.2.3 Trust

Firstly, cyberattacks that endanger the grid or IoT devices are part of the trust issues of LFMs. Secondly, privacy concerns arise over the operation of LFMs. Thirdly, the reliance on these new emerging technologies could raise trust issues. Due to the immature nature of LFMs, participants must rely on unstable networks or untrustworthy technology in some cases (Pressmair et al. 2021, p. 16).

3.2.4 Technical

The first technical barrier is developing and adopting a system that fulfills every participant's requirement.

Moreover, the frictionless communication of every system component and high availability is required. The development of new algorithms are needed to optimize the operation of an LFM. However, the scarcity of data to estimate the demand represents a barrier. Lastly, the overall maturity of these markets is a significant barrier, especially for developing new technology components. That's why more real-world implementations are necessary (Pressmair et al. 2021, p. 16).

3.2.5 Standardization

With the emergence of new markets, a substantial amount of diverse technology arises. This leads to different technical requirements in numerous areas. Additionally, various business models are proposed, many without previous involvement in these markets. This makes it hard to evaluate the engagement of these markets (Pressmair et al. 2021, pp. 16–17).

3.2.6 Cost

When designing an LFM, costs need to be considered. Besides initial investment and maintenance costs, hidden costs are a significant barrier. Next up, pricing can be a limiting factor, as tariffs may become higher if grid constraints cannot be resolved. Lastly, the obtained margins are expected to be low, which makes adoption unappealing (Pressmair et al. 2021, p. 17).

3.3 Inc-Dec Gaming

The so-called inc-dec gaming bidding strategy is one drawback of the zonal market with a parallel redispatch market. In a typical environment without a market-based redispatch, energy providers bid according to their marginal cost. An example of bidding on the spot market can be seen in Fig. 13 (Hirth et al. 2019, p. 2).

However, when there is a redispatch market with the potential to increase profits, the bidding strategy changes. For example, if there is a redispatch market and the price for the equilibrium of the redispatch market is 60 €/MWh in the south of a country and 30 €/MWh in the north of a country, the bids on the spot market change. Powerplant owners do not bid according to their marginal costs anymore. Powerplant owners from the south will bid 60 €/MWh because they look forward to selling at this price on the redispatch market. In return, power plant owners from the north bid under their marginal cost at 30 €/MWh, so the spot price is 60 €/MWh. The powerplant owners from the north would then sell power in the spot market to buy it cheaper at the redispatch market. An example of this can be seen in Fig. 14 (Hirthi et al. 2019, pp. 2–3).

These types of arbitrages are common on futures markets. The prices of the two markets also equalize because the arbitrage increases the demand for redispatch. Moreover, the spot market price cannot be adjusted to two prices simultaneously (Hirthi et al. 2019, pp. 2–3).

With in-dec gaming come some undesirable consequences. Certain market actors earn higher profits. However, the higher spot market prices and redispatch costs result in a higher bill for the consumer. On the one hand, this market environment creates incentives in the south to invest in new power plants. On the other hand, it creates incentives to invest in powerplants in the north that merely exist to arbitrage and not produce any energy (Hirthi et al. 2019, p. 3).

There were instances in history where market actors used this strategy, for example, in the USA and UK. However, regulation around energy markets was

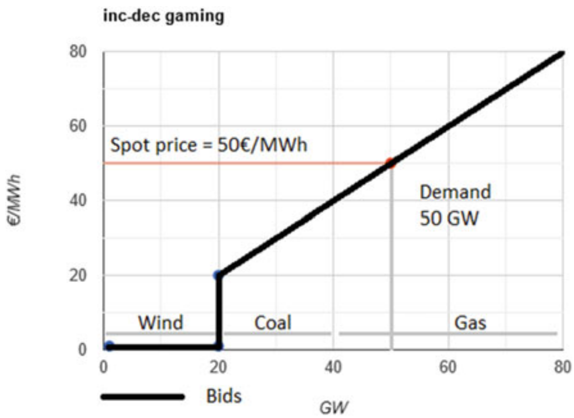


Fig. 13 Spot market bids without redispatch

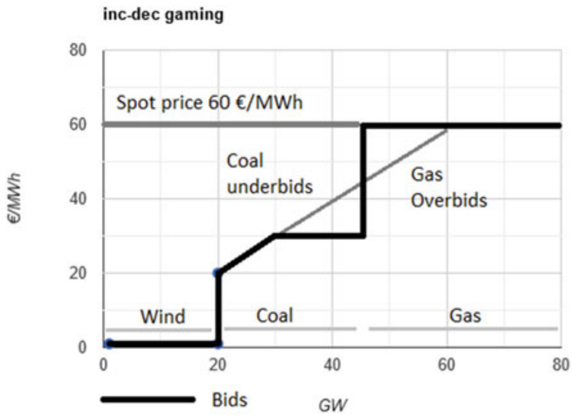


Fig. 14 Spot market bids with redispatch market

changed to prevent that from happening. It is expected that this strategy will not be used in smaller projects because using this method requires investments in analysis and prediction equipment. Nevertheless, implementing this market design on a larger scale would not be desirable (Hirthi et al. 2019, p. 3).

4 Improvements

While there are several different projects and fully operational LFMs, research is still ongoing, and many projects are still in development. Moreover, the features and efficiency of existing congestion management approaches lead to various motivations for designing an LFM. After all, it is still uncertain which is the best design. However, this question is not answered quickly, as different market designs suit other intentions. The local differences in circumstances in the energy sector in European countries create different motivations for developing an LFM (Badanjak et al. 2021, p. 6; Dronne et al. 2020, p. 11).

4.1 Countries' Different Needs for Flexibility

In the following different characteristics of four European countries are listed.

- France: In France, the depth of congestion is relatively low, while the need for new resource development is moderate. France has one TSO and one DSO. The current congestion management approach is market-based for 90 and 63 kV networks. Apart from these networks, it is connection management based. (Dronne et al. 2020, p. 13)

- Germany: In Germany, congestion is high, most of that being injection congestion. Therefore, the need for new resource development is low. Germany has four TSOs and over 800 DSOs. The current congestion management approach is cost-based. (Dronne et al. 2020, p. 13)
- United Kingdom: The UK experiences both injection and load congestion. one TSO and a few DSO operate in the UK. Congestion management is connection management based, and the need for new resource development is high. (Dronne et al. 2020, p. 13)
- Netherlands: The Netherlands has modest congestion. The need for the development of new resources is high. one TSO and 11 DSOs operate in the Netherlands. There is no market mechanism for congestion management. (Dronne et al. 2020, p. 13)

With that information, energy companies, energy markets, DSOs, and regulators could create incentives to provide flexibility suited to the country they operate in. For example, in Germany, there is high injection congestion. Therefore, mechanisms could be created that curtail in a fair and welfare maximizing way—more about that in Sect. 5.4. Additionally, incentives for smart EV charging, power to gas facilities, and electric appliances like water heaters would be attractive because that would increase downward regulation and decrease the need for curtailment.

In the UK, there is both high load and injection congestion. This means incentives that create a more significant availability of both upward and downward regulation would be reasonable. In that regard, incentives for EV and electric appliances plus residential PV could be created for the general availability of flexibility.

The same incentives could be helpful in the Netherlands because the need for new flexible assets is high in the country.

In France, the urgency for new flexibility assets is only moderate because the depth of congestion is relatively low. However, that does not mean that creating incentives in that country would be completely useless. In general, creating incentives that make society more self-sustaining should be in the interest of every nation.

4.2 LFM Design with Network Constraints

Prat et al. (2021) proposed a design of a continuous LFM with network constraints (pp. 1–6). This is especially interesting because existing approaches disregard network constraints or assume that the DSO is the market operator. However, the DSO is not permitted to act as a market operator in the EU. There are designs of continuous LFM, for example, GOPACS, ENERA, and NODES, but they do not examine network constraints when clearing markets.

4.2.1 Market Setup

The market actors (including DSOs and BRPs) send FlexOffer or FlexRequest bids in this proposed market. Moreover, these bids include price, volume, location, and whether they are upward or downward flexibility. In addition, FlexRequest can be distinct between being conditional or unconditional. Due to the continuous market, matching bids are cleared immediately, and non-matching bids end up in the order book until a matching bid appears. When two bids match, the market operator performs a network check before clearing the bids. The bids do not have to be in the same area to match. The network is checked by creating a baseline energy dispatch that looks at existing markets or approximations of load and generation (Prat et al. 2021, p. 2).

4.2.2 Network Check

Prat et al. (2021) used a DC power flow algorithm to approach the goal of designing a market clearing algorithm that incorporates network constraints (p. 2). It is noted that procured flexibility does not need to be activated. However, the network check must assure that flexibility can be activated without causing congestion. There are two aspects to consider when performing a network check. Firstly, acquired flexibility is not always fully activated, which means that any degree of activation must be assured not to cause congestion. Secondly, the former matches must be considered when checking the realizability of the ongoing match. (Prat et al. 2021, pp. 2–3).

In the following, the different options to examine the effect bids have on the network are listed.

- Individual effect: This option guarantees that every new matching bid pair will not cause congestion while being the only request activated. However, it makes sense that assuming only one matching bid is activated simultaneously, is a restricted approach for the network check (Prat et al. 2021, p. 3).
- Cumulative effect: A different approach would consider all previously matched bids. This approach requires an actor who has an overview of all the matched bids and can activate them if needed (the DSO) (Prat et al. 2021, p. 3).
- All Combinations: By considering the activation of all combinations of previously matched bids, you can guarantee that activating the currently checked bid does not cause network violations. However, this approach requires more computing power the more matched bids there are (Prat et al. 2021, p. 3).
- Unconditional requests: Lastly, unconditional requests can influence previously rejected bids. Since the acceptance of an unconditional bid changes the state of the network, previously rejected bids that would have caused congestion could

now be accepted. That means every time an unconditional request is accepted, the order book with previously rejected bids must be re-evaluated (Prat et al. 2021, p. 3).

4.2.3 Case Study

Lastly, Prat et al. (2021) simulate such a flexibility market (p. 4). The previously described market setup is applied to a bus system with 15 nodes (or buses). Each bus represents a different location in the network. Every combination of former matches is considered during the network check to guarantee that no congestion occurs. Moreover, bids can be matched partially. Once an unconditional request is accepted, the order book is re-evaluated (Prat et al. 2021, p. 4).

Prat et al. (2021) use two algorithms to accomplish this simulation, one for calculating the maximum quantity transmitted between two buses and the other for clearing the market (pp. 4–5). In the simulation, six FlexRequests are sent as a batch, and six FlexOffers come in at a time (Prat et al. 2021, p. 4).

As a result of the simulation, one offer was partially matched, and the rest was forwarded to the order book because it would have caused congestion. Another offer was rejected completely because congestion could be caused by its activation. The remaining offers were cleared normally (Prat et al. 2021, p. 4).

4.2.4 Aspects for Further Work

For the network check, a DC power flow approach was used for simplicity. However, this comes with some drawbacks, one of which is that reactive power flows must be contemplated. Moreover, Prat et al. (2021) assume, on the one hand, that the market operator knows about the baseline dispatch and, on the other hand, that for every FlexRequest, there is a location annotated (p. 5). Both assumptions require the estimation of scenarios. That is why the market clearing algorithm could be improved to be probabilistic. The allocation of reserves could also be beneficial in case a surprising event happens (Prat et al. 2021, p. 5).

Further work should also consider block offers that reach over several timeframes. Additionally, the integration of existing market structures and the exertion of market power could be examined in further work. Lastly, this proposal uses pay as bid pricing method. Other concepts, where the market operator could be reimbursed the difference between FlexRequests that are higher than FlexOffers, would be interesting to observe. The market operator's profit from this concept could be used for investments in the grid or other plans (Prat et al. 2021, p. 6).

Lastly, further work could examine how an algorithm that considers network constraints could be implemented in existing LFMs (Prat et al. 2021, p. 6).

4.3 Fair and Efficient Flexibility Markets

In many LFMs, aggregators aggregate small-scale RES and flexibility devices to help the DSO with congestion management. To change the behavior of specific flexibility devices, the aggregator remunerates them to achieve the needed consumption profile. According to the price he must pay, the aggregator offers the flexibility bids to the DSO. However, in some cases, a particular node is necessary for the trouble-free operation of the network. Therefore, aggregators near the node could increase their bids, knowing the importance of their flexibility. To counter this issue, Tsaousoglou et al. 2020) propose a market mechanism that encourages aggregators to report their honest flexibility costs and not increase their bids strategically (pp. 1–11). The typical approach for LFM optimization is social welfare maximization. Yet, this approach mistreats certain aggregators repeatedly to minimize overall costs. To tackle this issue, a fairness maximizing approach is proposed. This is done by maximizing the lowest payment for the aggregators, also called min–max fairness optimization (Tsaousoglou et al. 2020, pp. 1–2).

To implement this type of mechanism, Tsaousoglou et al. (2020) firstly introduce the system model for the distribution model, secondly formulates the problem, and thirdly present and prove a reward function (pp. 3–6). An overview of the process and communication between the DSO and aggregators can be seen in Fig. 15 (Tsaousoglou et al. 2020, p. 5).

In the first step, the DSO receives the aggregator's estimated consumption profiles for a time horizon in the future. After that, the DSO evaluates whether the network will be violated, and based on that, flexibility requests are made. Next up, the aggregator makes flexibility offers. The DSO now has to solve the min–max fairness and

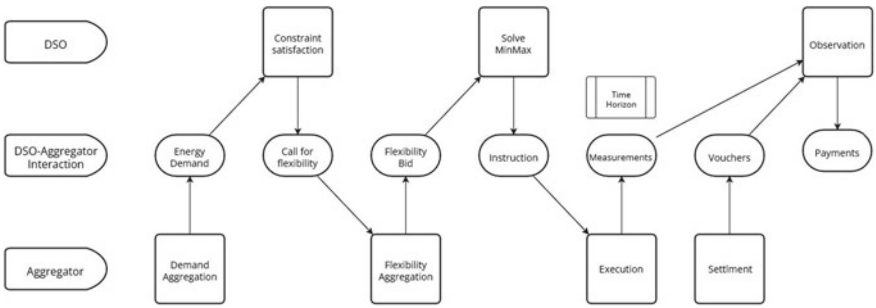


Fig. 15 Process and communication between DSO and aggregator

give instructions to the aggregators accordingly. The aggregators then change their portfolios to satisfy the instruction. Following this, the aggregator pays for its flexible devices and reports these to the DSO as a voucher. Lastly, the DSO observes all actions of the aggregators and compensates them for the provided flexibility (Tsaousoglou et al. 2020, p. 5).

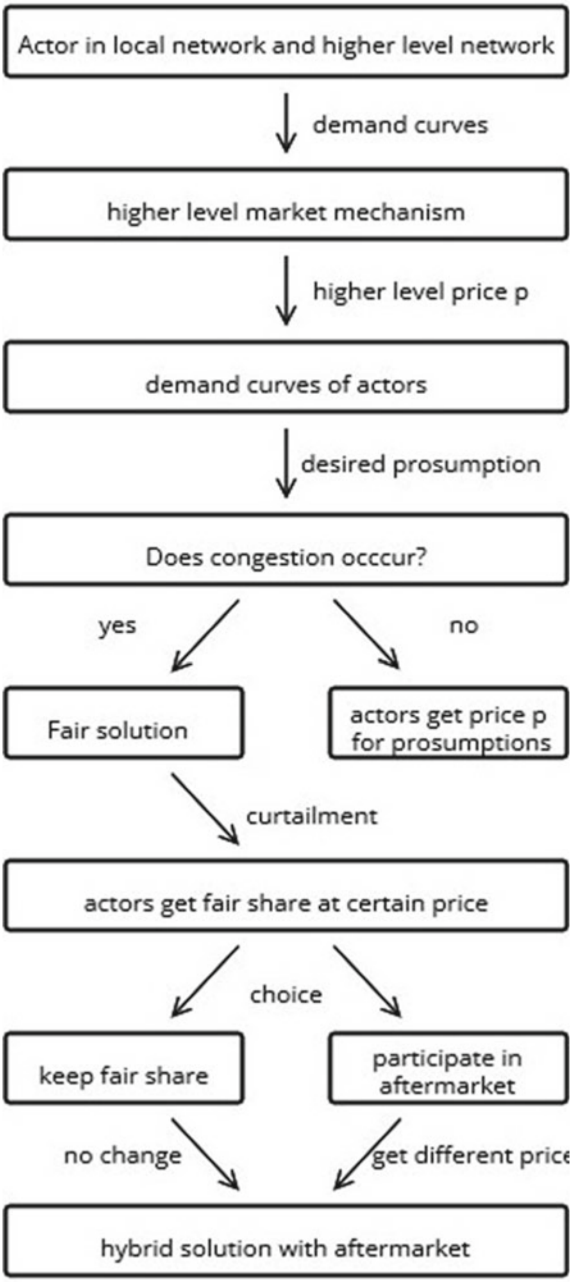
4.4 Fairness Versus Welfare

Hekkelman and Poutré (2022) propose a mechanism for local congestion management that considers fairness and welfare (p. 1). Curtailment is used as a mechanism to manage congestion. Hekkelman and Poutré (2022) describe curtailment as decreasing the prosumption of certain actors (p. 1). The most common way to design a local congestion management mechanism is to focus on welfare. Nevertheless, fairness is another vital aspect because certain actors are impacted differently. To develop a tool that considers welfare and fairness, Hekkelman and Poutré (2022) first introduce an algorithm that calculates the optimal issuance of curtailment for maximizing welfare (p. 2). Secondly, the concept of fair shares is used to create an algorithm that considers welfare and fairness. Actors can then decide whether they want to keep their fair share or participate in an aftermarket that maximizes welfare. Figure 16 shows a visualization of the processes of a hybrid congestion solution (Hekkelman and Poutré 2022, pp. 1–7).

4.5 Enera Hybrid Model

The Enera Hybrid Model considers regulated and non-regulated flexibility assets for congestion management. Under Redispatch 2.0, regulation generation and storage units are remunerated on a cost basis. However, it would be inappropriate to include the non-regulated assets in a cost-based way due to the difficulty of calculating and observing their costs. This proposal allows regulated assets to compete with non-regulated assets using different compensation schemes. Regulated assets are remunerated in a cost-based manner, while non-regulated assets are paid in a market-based way (Sommer et al. 2020, p. 13).

Fig. 16 Visualization of hybrid congestion solution



The Enera platform collects the bids from regulated flexibility assets in the first step. The bids are then shown in the local order book. Once the Redispatch 2.0 mechanism determines the dispatch measures, the dispatcher can choose to use the activation of non-regulated assets in the same area instead of the regulated asset. The flexibility from non-regulated assets is acquired in a market-based way through the Enera platform. The Enera order book provides these non-regulated alternatives only if the alternatives are less costly or impact the grid more positively than the Redispatch 2.0 solution (Sommer et al. 2020, pp. 14–15).

The implementation of this proposal is quite simple. The proposal extends the existing design of the Enera platform, and the new Redispatch 2.0 regulation is not violated. Moreover, this proposal can be applied to individual system operators identifying the potential for non-regulated flexibility assets in their area. Another upside of this proposal is that the non-regulated flexibility can be modified to suit the local need. For example, the activation duration can vary according to local conditions (Sommer et al. 2020, pp. 15–16).

A drawback of this proposal is that market-based flexibility is considered after the Redispatch 2.0 selection of flexibility potentials. This drawback can be experienced when the Redispatch 2.0 process considers the curtailment of a conventional powerplant instead of a wind farm, with market-based solutions near the wind farm. Here the best solution would be to use the market-based solution near the wind farm. However, the Redispatch 2.0 process does not consider that possibility and curtails a conventional power plant in a distant area. Another drawback would be congestion occurring in cities. Cities offer a lot of non-regulated flexibility potential. Nevertheless, regulated flexibility is not reachable for Redispatch 2.0. In a later stage, the redispatch mechanism could also consider load, so that load and generation assets can offer flexibility equally (Sommer et al. 2020, pp. 16–18).

4.6 Nodal Versus Zonal Pricing

Two main congestion management methods are used around the world. Firstly, zonal pricing, used in European electricity markets, refers to clustering electricity nodes into zones with the same prices. In reverse, nodal pricing may vary at each node depending on the congestions that occur in the grid. In that regard, producers are paid the price defined by their local node (Sarfati et al. 2019, p. 1).

4.6.1 Simulation Cases

Sarfati et al. (2019) compared nodal pricing with two types of zonal pricing (p. 1). The two types are available transmission capacity- and flow-based market coupling Zonal pricing. The three pricing methods were used on 6-node and a 24-node case study to evaluate the efficiency and profits of the participants. The 6-node system was divided into two zones with three energy producers, and the 24-bus system was divided into three zones with five energy producers. The producers are spread across different zones also to examine inc-dec gaming (Sarfati et al. 2019, p. 8).

- 6-Bus system: It was observed that the total overloading of lines was the highest in the available transmission capacity zonal pricing, followed by the flow-based market coupling zonal pricing, which had 81% less overloading. The nodal pricing had no overloading. The production cost was also the highest with the ATC zonal pricing, followed by the FBMC zonal pricing, which had 8.6% less production cost. Nodal pricing was the most efficient in that regard. Total profit was the highest for the zonal pricing with FBMC because no congestion appeared, and every producer was paid the price of the most expensive producer. In zonal pricing methods, inc-dec gaming was observed. Therefore, the market operator had positive net expenses in both zonal pricing methods. In the nodal pricing method, the market operator had negative net expenses, which means the operator made a profit (Sarfati et al. 2019, pp. 8–9).
- 24-Bus system: Similar to the 6-Bus system, the ATC zonal pricing has the highest overloading and production cost. FBMC has 76.8% reduced overloading and 14% reduced production cost. Nodal pricing is the lowest in that regard again. The market operator also makes a profit with nodal pricing and a loss with either zonal pricing method (Sarfati et al. 2019, p. 10).

Overall, it was observed that inc-dec gaming took place in both zonal approaches. This resulted in inefficiencies in production and losses for the market operator. The FBMC zonal pricing had reduced inc-dec gaming compared to ARC zonal pricing. However, its efficiency was still 2–5.3% lower than nodal pricing (Sarfati et al. 2019, pp. 10–11).

4.6.2 European Stakeholders' Arguments Against Nodal Pricing

This subsection identifies and examines European stakeholders' main arguments against nodal pricing. Moreover, possible solutions to the arguments are presented.

The first argument against nodal pricing is market power. However, it is not true that nodal pricing is more vulnerable to market power than zonal pricing. Participants in both pricing methods may exploit structural downsides in the grid. To reduce the impact of market power, mechanisms that ease market power were utilized in existing nodal markets (Eicke and Schittekatte 2022, p. 6).

Next up, it was argued that nodal pricing hinders flexibility and, therefore, the expansion of RES. In that regard, three worries can be released. First up, it was declared that nodal pricing makes continuous ID trading impossible, which is invalid. Yet it was found that auctions have several advantages. Efficient allocation, high transparency, and pooling of liquidity are some of them. It was also argued that nodal pricing mitigates demand response and energy storage. However, studies show the opposite in the US nodal market. The last point is that grid topology changes are less effective. It turns out that topology changes have a reduced impact on the nodal market. Nodal pricing itself already increases efficiency in the grid. Topology changes are possible in nodal markets but may be more challenging to handle than in the zonal approach (Eicke and Schittekatte 2022, pp. 8–9).

The following stated issue was market liquidity. There is more short-term price volatility in nodal markets than in zonal markets. This poses a risk for market participants. To mitigate that risk, market participants can hedge themselves in trading hubs. Locational risk remains but can be dealt with using specific financial instruments. However, some risk persists even with these products (Eicke and Schittekatte 2022, pp. 9–10).

Another argument is investment risk. In a nodal market, participants carry the risk of location, distributed among every participant in the zonal market. Additionally, hedging the risk connected to the area is not easy. Nevertheless, this creates incentives to invest in new locations (Eicke and Schittekatte 2022, pp. 10–11).

Complexity was also identified as an argument against nodal pricing. Next to the high computational complexity for the price calculation of every node, the pricing rule and the bidding format in Europe also contribute to the complexity of nodal pricing (Eicke and Schittekatte 2022, pp. 11–12).

The last argument is the different locational prices. The locational price can affect both consumers and generators. Firstly, the consumer can be negatively affected by a higher electricity price. However, the household energy cost only comprises 31% of the consumer's expenses. The rest is network charges, taxes, etc. Therefore, residential consumers would not be significantly affected. Industrial consumers are influenced more heavily because they pay less network tariffs and taxes. To relieve the consumer, a lower network tariff could be charged. Moreover, policy changes that aim to support industries could be created. Lastly, RES are negatively impacted by nodal pricing. In the case of high renewables generation at a node, low local prices leads to a decrease in renewable generator's revenue. To support RES, regulators could step in and increase subsidies for RES (Eicke and Schittekatte 2022, pp. 12–14).

5 Discussion

The concept of LFM is a specific domain and an emerging field that has drawn significant attention among policymakers. Nevertheless, this domain suffers from having an applicable business model in the real world.

Furthermore, each presented real-life business model is in a European country. Since European countries utilize the zonal pricing method, it makes sense that there are no implementations of LFMs in areas outside Europe. For that reason, the finding of this work can only be applied to the European region.

It is difficult for LFMs to have a one fits all solution. Local characteristics, regulations, and participant's needs differ considerably from region to region. Therefore, it is inevitable that new projects that are slightly distinct from their predecessor will arise in that domain.

Various literature and project documentation were examined to answer the research question defined in Sect. 1.2. A concept matrix with an upper category "Local flexibility markets" with sub-categories "Business models", "Drawbacks and barriers", and "Improvements" was built. Each sub-category was again divided into smaller sections that define the concepts. This work examines ten implementations of LFM that distinguish themselves from another in certain aspects. After that, specific drawbacks of concrete LFMs and general barriers to their adoption are identified. Lastly, improvements for the design of LFMs are stated, and the concept of nodal pricing is considered an alternative to the existing approach.

Consequently, it can be claimed that the objective of this research was to answer the question "What are the proposed business models for LFMs, what are their drawbacks and barriers, and how can they be improved?" was fulfilled.

However, there were several gaps and limitations to this research. These gaps and limitations are addressed in the following section.

6 Conclusion

The literature search provided a broad spectrum of results for LFM implementations, their drawbacks and barriers, and possible improvements. In this work, different design approaches were examined. The main findings were that network scopes from DSO or TSO only to DSO and TSO, flexibility products, various compensation schemes from availability to activation payments, different technical setups, and integration with existing structures are some of the aspects LFMs considerably differ in.

Next up, the critical findings for drawbacks and barriers were that technical difficulties mainly gathered around forecasting and calculation drawbacks. The next challenging aspect is regulation, which dramatically hinders new approaches from being tested and innovations from being made in the energy sector.

Lastly, the main improvements that could be addressed in existing LFMs is explicitly considering network congestion while clearing the market. Moreover, fairness and welfare are essential because they build the basis to allocate resources and remunerate participants optimally. Fairness may be even more significant than welfare when considering a large-scale implementation. When trying to make a business model attractive to many actors, it must be ensured that some actors do not earn significantly more than others. In contrast, certain actors struggle to be profitable. In the end, the nodal pricing method is suggested as an alternative to deal with congestion instead of the zonal pricing method that utilizes LFMs.

There were several gaps and limitations to this research. Firstly, the lack of critical review on existing LFMs was an identified gap in the literature. Many projects did not have literature that explicitly identified the project results or what could be specifically improved for the project. Along with that, the lack of fully operational LFMs also contributed to that. Many projects were merely in the pilot stage and discontinued after that.

Regulation is another aspect that hinders the adoption of LFM. Therefore, the regulation also represents a limitation to the research on this topic. As regulation restricts the development of new mechanisms and designs for LFMs, it also makes research difficult because new regulators frameworks would also promote the development of LFMs, resulting in further research in this domain.

In the end, it will be interesting to see how the adoption of LFMs will play out in the future. Whether large-scale and fully operational projects create an applicable business model that will be determined by regulators and stakeholders' engagement.

For further studies, improving LFMs by considering fairness and network constraints in the market design would be compelling. As the need for integration of RES and congestion management rises, LFMs will also gain attention. The concept of nodal pricing also seems like an attractive concept. However, the EU does have a very rigorous view on that topic. For that reason, nodal pricing will probably not be adopted into European energy markets (Table 1).

Table 1 Concept matrix

References	Local flexibility markets										
	Business models										
	Enera	GOPACS	Picloflex	Nodes	EcoGrid 2.0	Tiko	Equigy	Interflex	Parity hybrid model	CoordiNet	FLEXIMAR
Bachoumis (2019)										✓	
Dronne et al. (2020)		✓									
Dumbs et al. (2019)								✓			
Eicke and Schittekatte (2022)											
https://equigy.com/the-platform/							✓				
Nicholas et al. (2020)										✓	
Fabel et al. (2021)							✓				
Geidl et al. (2017)						✓					
https://en.gopacs.eu/		✓									
Heinrich et al. (2020)					✓						
Hekkelman and Poutré (2022)											
Hirth et al. (2019)											
Madina et al. (2020)										✓	
Niet et al. (2021)							✓				

(continued)

Table 1 (continued)

References	Local flexibility markets										
	Business models										
	Enera	GOPACS	Picloflex	Nodes	EcoGrid 2.0	Tiko	Equigy	Interflex	Parity hybrid model	CoordiNet	FLEXIMAR
Prat et al. (2021)											
Pressmair et al. (2021)									✓		
Pourasghar Khomami et al. (2020)			✓	✓							
Radecke et al. (2019)										✓	
Sánchez-Jiménez et al. (2015)											
Sarfati et al. (2019)				✓							
Sarti (2020)	✓	✓	✓	✓							
Schittekatte and Meeus (2020)	✓										
Sommer et al. (2020)											
Tsaousoglou et al. (2020)	✓	✓	✓	✓		✓	✓	✓			
Vahedipour-Dahraie et al. (2021)											✓
Shokri Gazafroudi et al. (2020)											✓
Ebrahimi et al. (2022)											

(continued)

Table 1 (continued)

References	Local flexibility markets								
	Drawbacks and barriers			Improvements					
	Drawbacks of LFMs	Barriers to adoption	Inc-dec gaming	Countries' different needs for flexibility	LFM design with network constraints	Fair and efficient flexibility markets	Fairness versus Welfare	Enera hybrid model	Nodal versus zonal pricing
Bachoumis (2019)									
Dronne et al. (2020)				✓					
Dumbs et al. (2019)	✓								
Eicke and Schittekatte (2022)									✓
https://equigy.com/the-platform/									
Nicholas et al. (2020)									
Fabel et al. (2021)									
Geidl et al. (2017)									
https://en.gopacs.eu/									
Heinrich et al. (2020)	✓								
Hekkelman and Poutré (2022)							✓		
Hirth et al. (2019)			✓						
Madina et al. (2020)									
Niet et al. (2021)									

(continued)

Table 1 (continued)

References	Local flexibility markets								
	Drawbacks and barriers			Improvements					
	Drawbacks of LFMs	Barriers to adoption	Inc-dec gaming	Countries' different needs for flexibility	LFM design with network constraints	Fair and efficient flexibility markets	Fairness versus Welfare	Enera hybrid model	Nodal versus zonal pricing
Prat et al. (2021)					✓				
Pressmair et al. (2021)	✓	✓							
Pourasghar Khomami et al. (2020)									
Radecke et al. (2019)									
Sánchez-Jiménez et al. (2015)									✓
Sarfati et al. (2019)									
Sarti (2020)									
Schittekatte and Meeus (2020)								✓	
Sommer et al. (2020)						✓			
Tsaousoglou et al. (2020)									
Vahedipour-Dahraie et al. (2021)									
Shokri Gazafroudi et al. (2020)		✓					✓		
Ebrahimi et al. (2022)		✓				✓	✓		

References

Badanjak D, Pandžić H (2021) Distribution-level flexibility markets—a review of trends, research projects, key stakeholders and open questions. Energies 14:6622. https://doi.org/10.3390/en14206622

Bachoumis T, Dratsas P, Kaskouras C, Sousounis MC, Torres LV, García AIM, Vlachos I, Dimeas A, Trakas D, Botsis A, Sideratos G, Voumvoulakis M (2019) D5.1—Demonstrator analysis & planning. https://coordinet-project.eu/publications/deliverables

Dronne T, Roques F, Saguan M (2020) Local flexibility markets for distribution network congestion-management: which design for which needs? Chaire European electricity markets/working paper #47

Dumbs C, Jarry G, Willems M, Gross T, Larsen A, Wagner T (2019) Market models for local flexibility procurement: interflex' experience and main challenges. In: 25th international conference on electricity distribution

Ebrahimi M, Gazafroudi AS, Laaksonen H, Shafie-Khah M (2022) Two-layer game-based framework for local energy flexibility trading. IEEE Access 10:68768–68777. https://doi.org/10.1109/TPWRS.2019.2944200

Eicke A, Schittekatte T (2022) Fighting the wrong battle? A critical assessment of arguments against nodal electricity prices in the European debate

Equigy: https://equigy.com/the-platform/

Etherden N, Ruwaida Y, Johansson S (2020) D4.5—Report on lessons learned, bug fixes and adjustments in products and routines within the Swedish demo. https://coordinet-project.eu/publications/deliverables

Fabel Y, Zeiselmair A, Spindler R, Bogensperger A (2021) Vergleich aktueller Plattform-Projekte in der Energiewirtschaft und die Rolle der Dezentralisierung. In: 12. Internationale Energiewirtschaftstagung an der TU Wien IEWT 2021

Geidl M, Arnoux B, Plaisted T, Dufour S (2017) A fully operational virtual energy storage network providing flexibility for the power system. In: 12th IEA Heat Pump Conference

GOPACS project: https://en.gopacs.eu/

Heinrich C, Ziras C, Syrri ALA, Bindner HW (2020) EcoGrid 2.0: a large-scale field trial of a local flexibility market center for electric power and energy, Technical University of Denmark

Hekkelman B, Poutré HL (2022) Fairness vs welfare: a hybrid congestion aftermarket. In: Proceedings of the thirteenth ACM international conference on future energy systems (e-Energy '22). Association for Computing Machinery, New York, NY, USA, pp 93–104. https://doi.org/10.1145/3538637.3538843

Hirth L, Maurer C, Schlecht I, Tersteegen B (2019) Strategisches Bieten in Flex-Märkten; Energiewirtschaftliche Tagesfragen 69. Jg. Heft 6

Madina C, Gomez-Arriola I, Santos-Mugica M, Jimeno J, Kessels K, Trakas D, Chaves JP, Ruwaida Y (2020) Flexibility markets to procure system services. In: CoordiNet Project. 2020 17th international conference on the European energy market (EEM). https://doi.org/10.1109/eem49802.2020.9221890

Minniti S, Haque N, Nguyen P, Pemen G (2018) Local markets for flexibility trading: key stages and enablers. Energies 11:3074. https://doi.org/10.3390/en11113074

Niet Irene A, Dekker R, bvan Est R (2021) Seeking public values of digital energy platforms. Sci Technol Hum Values 1–24

Olivella-Rosell P, Lloret-Gallego P, Munné-Collado I, Villafafila-Robles R, Sumper A, Ødegaard Ottessen S, Rajasekharan J, Bremdal BA (2018) Local flexibility market design for aggregators providing multiple flexibility services at distribution network level. Energies 11:822. https://doi.org/10.3390/en11040822

Pourasghar Khomami H, Fonteijn R, Geelen D (2020) Flexibility market design for congestion management in smart distribution grids: the Dutch demonstration of the interflex project. In: IEEE PES innovative smart grid technologies (ISGT) conference, The Hague, The Netherlands,

Oct 25–28 2020, pp 1191–1195). [9248970] Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/ISGTEurope47291.2020.9248970
Prat E, Herre L, Kazempour J, Chatzivasileiadis S (2021) Design of a continuous local flexibility market with network constraints. In: 2021 IEEE Madrid PowerTech, pp 1–6
Pressmair G, Kapassa E, Casado-Mansilla D, Borges CE, Themistocleous M (2021) Overcoming barriers for the adoption of local energy and flexibility markets: a user-centric and hybrid model. J Clean Prod 317:128323
Radecke J, Hefele J, Hirth L (2019) ZBW—Leibniz Information. Centre for Economics, Kiel, Hamburg
Ruwaida Y, Chaves-Avila JP, Etherden N, Gomez-Arriola I, Gurses-Tran G, Kessels K, Madina C et al (2021) TSO-DSO-customer coordination for purchasing flexibility system services: challenges and lessons learned from a demonstration in Sweden. IEEE Trans Pow Syst 1–13. https://doi.org/10.1109/tpwrs.2022.3188261
Sánchez-Jiménez M, Stamatis K, Kollau M, Stantcheva M, Busechian E, Hermans P, Guzeleva D, Abrandt GE, Friedl W, Mandatova P, Stromback J (2015) SGTF-EG3 report: regulatory recommendations for the deployment of flexibility
Sarfati M, Hesamzadeh MR, Holmberg P (2019) Production efficiency of nodal and zonal pricing in imperfectly competitive electricity markets. Energy Strateg Rev 24
Sarti R (2020) NODES white paper: paving the way for flexibility
Schittekatte T, Meeus L (2020) Flexibility markets: Q&A with project pioneers. Util Policy 63:101017
Shokri Gazafroudi A, Shafie-Khah M, Prieto-Castrillo F, Corchado JM, Catalão JPS (2020) Monopolistic and game-based approaches to transact energy flexibility. In: IEEE transactions on power systems, vol 35, no 2. https://doi.org/10.1109/TPWRS.2019.2944200
Sommer H, Gertje J, Wilken J, Neumann C (2020) enera – Improving redispatch thanks to flexibility platform experience. https://projekt-enera.de/blog/improving-redispatch-thanks-to-flexibility-platform-experience/
Tsaousoglou G, Giraldo JS, Pinson P, Paterakis NG (2021) Mechanism design for fair and efficient DSO flexibility markets. IEEE Trans Smart Grid 12(3):2249–2260. https://doi.org/10.1109/TSG.2020.3048738
Vahedipour-Dahraie M, Rashidizadeh-Kermani H, Shafie-Khah M, Siano P (2021) Peer-to-Peer energy trading between wind power producer and demand response aggregators for scheduling joint energy and reserve. IEEE Syst J 15(1):705–714. https://doi.org/10.1109/JSYST.2020.2983101
Valarezo O, Gómez T, Chaves-Avila JP, Lind L, Correa M, Ulrich Ziegler D, Escobar R (2021) Analysis of new flexibility market models in Europe. Energies 14:3521. https://doi.org/10.3390/en14123521
Webster J, Watson RT (2002) Guest editorial: analyzing the past to prepare for the future: writing a literature review, vol 11. https://web.njit.edu/~egan/Writing_A_Literature_Review.pdf
Zeiselmair A, Köppl S (2021) Constrained optimization as the allocation method in local flexibility markets. Energies 14:3932. https://doi.org/10.3390/en14133932

Generation-Side and Demand-Side Player-Centric Tradings in the LEM: Rule-Empowered Models and Case Studies

M. Imran Azim, Amin Shokri Gazafroudi, and Mohsen Khorasany

1 Introduction

1.1 Background

In recent years, feed-in-tariff (FiT) scheme and demand response (DR) program have been introduced to incentivise prosumers—electricity consumers who have local generation at their premises (Parag and Sovacool 2016)— and DR participants—electricity consumers who sell their right to buy power willingly (Melendez et al. 2019). However, both FiT and DR are managed exclusively by centralised entities with marginal inputs and flexibilities from engaging players, resulting in insignificant financial returns (Azim et al. 2022). As such, the dissatisfaction rate among both FiT and DR customers has been getting higher over the past few years. This has also caused some of them to drop out from these programs (FiT plummeted: ABC News 2022; Demand response customer insights report 2022). To this end, the concept of local energy market (LEM) has emerged in recent times with a mission to empower sustainable energy management in a participant-focused manner to expedite the vigorous presence of diversified players (Gazafroudi et al. 2021).

A LEM is a sub electricity market that facilitates local energy management and trading at customers' level following a set of consensus-based rules and regulation (Tsaousoglou et al. 2022). It aims at speeding up the integration of locally pro-

M. I. Azim (✉) · M. Khorasany
Department of Electrical and Computer Systems Engineering, Monash University, Clayton 3068, Australia
e-mail: imran.azim@monash.edu

M. Khorasany
e-mail: mohsen.khorasany@monash.edu

A. S. Gazafroudi
OLI Systems GmbH, Harthausen 67376, Germany

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_8

duced clean energy into the distribution network without compromising the safe operation (Lin et al. 2022). The execution of LEM is primarily driven by electricity customers, e.g., prosumers and consumers, to enlarge their benefits (Gazafroudi et al. 2021). Thus, it is fundamentally contrasting to some other mechanisms, such as distributed resource management systems (DERMS) and advanced distribution management systems (ADMS) (LEM project: Powerledger 2022). Player-centric peer-to-peer (P2P) energy trading is one of the fruitful facets of LEM that enables players, both prosumers and consumers, to negotiate and trade energy frequently between each other to become independent energy contractors and financial gainers (Capper et al. 2022). Some of the remarkable positive aspects of P2P trading include flexible participation, energy expense reduction, social attributes, local supply and demand matching, peak demand shaving, energy operational and transport costs diminishing, reserve (generation and storage) requirement minimisation, energy losses paring down, low-voltage (LV) distribution network viability, power grid resilience betterment, and privacy safeguard (Azim et al. 2022).

In general, player-centric trading can be performed in two levels following a hybrid market structure: information sharing level and physical network level (Javed et al. 2022). The information sharing level manages smart contracts—computerised transaction protocols to arrange terms and conditions of P2P trading without an intermediary service—using an advanced distributed ledger technology, blockchain for example, to guarantee security, privacy, and transparency (Khan et al. 2021). Apart from this, it is also responsible to settle bilateral/multi-lateral financial transactions among multifarious LEM participants in the most cost-effective and flexible manners (Khorasany et al. 2022). In contrast, physical network level supports the LV distribution network—where players are connected physically—and accountable for actual P2P energy dispatch while technical constraints are maintained repeatedly (Ullah and Park 2021).

1.2 Types of Trading in the LEM

Confirming to the nature of energy dispatch in the physical network, player-centric P2P trading in the LEM could be of two types: generation-side player-centric (also termed as P2P kilowatt) trading and demand-side player-centric (also termed as P2P negawatt) trading (Jing et al. 2019).

In generation-side player-centric trading, LEM players exchange their available energy (difference between local energy generation and energy demand) among themselves at negotiated prices unlike the FiT scheme to receive better economic rewards while the participation flexibility is ascertained. On top of it, consumers without any local energy generation can still join in the LEM to purchase the clean energy at reduced prices (Azim et al. 2019). Assume LEM player 1 has 5 kW local power generation at a given time interval. It consumes 1 kW, and thus contains 4 kW available power to trade in the LEM. On the other hand, suppose each of LEM player 2 and LEM player 3 has 2 kW of power shortage at the same time period. Once

P2P price negotiation is finalised on a secured trading platform in near real-time arrangement, LEM player 1 exports 4 kW into the LV distribution network while both LEM player 2 and LEM player 3 consume 2 kW each from the same power network.

On the contrary, in demand-side player-centric trading, LEM players dictate their energy consumption scheduling with a view to balancing supply and demand in the LEM. In other words, they exploit P2P mechanism to decide when to decrease energy demand flexibly at mutually agreed prices as opposed to DR strategy. In this form of trading, LEM players may or may not have locally produced energy and must possess some controllable loads to play with their power demand periodically (Azim and Tushar 2021). Suppose two LEM players are scheduled to use 5 kW of power each at a given time period. However, LEM player 2 requires 2 kW more power at that time although the power supplier of the LV distribution network can only provide them with 10 kW (in total) at the time-off-use (ToU) price. Assume LEM player 1, LEM player 2 and the power supplier communicate to strike a deal on the trading platform. LEM player 1 agrees to give up 2 kW usage to enable LEM player 2 to consume 2 kW more from the power network.

1.3 Contributions

This chapter demonstrates the concepts of generation-side and demand-side P2P tradings—which are player-centric in nature—in the LEM, and their deployment suitability in an LV distribution network. Appropriate frameworks are developed to model both types of P2P tradings in a player-centric fashion by dint of a set of LEM rules pertaining to storage operational constraints; local power export and import limits; and lucrative LEM transaction price determination. Rule-based mechanisms are prioritised in this chapter as they provide the market solution quickly without requiring rigorous computational analysis. Additionally, their implementation in a software environment is real-world compatible, scalable, and cost-effective. To end with, a case study is conducted on a typical LV distribution network containing LEM players to evaluate their financial gains received in the proposed trading models compared to business-as-usual (BAU). The simulation results confirm that proposed generation- and demand-side tradings outperform existing FiT and DR mechanisms in terms of providing economic benefits to participating LEM players.

2 Proposed Trading Models in the LEM

2.1 Distribution Network Model

Assume an LV distribution network whose buses' set is represented by $\mathcal{BS} = \{1, 2, \cdots, BS\}$. Also, assume the sets of branches that connect all buses are signified by $\mathcal{BH} = \{1, 2, \cdots, BH\}$. The branch connecting bus b and bb, where $b; bb \in \mathcal{BS}$, is indicated by $(b, bb) \in \mathcal{BH}$. Let complex power and voltage of each bus in the LV network be symbolised by $S_b = P_b + jQ_b$ and $V_b = | V_b | e^{j\theta}$. Here, $P_b; Q_b \in \mathbb{R}$ refer to active and reactive power of each bus $b \in \mathcal{BS}$ respectively.

The complex power flow through $(b, bb) \in \mathcal{BH}$ is denoted as $S_{b,bb} = P_{b,bb} + jQ_{b,bb}$, where $P_{b,bb}; Q_{b,bb} \in \mathbb{R}$ denote active and reactive power flow through (b, bb) respectively. The voltage difference between bus b and bus bb is calculated as:

$$V_b - V_{bb} = Z_{b,bb}\, I_{b,bb};\ \forall (b, bb) \in \mathcal{BH} \tag{1}$$

where $Z_{b,bb} = R_{b,bb} + jQ_{b,bb}$. Here, $R_{b,bb}; n_{b,bb} \in \mathbb{R}$ are resistance and reactance of (b, bb) respectively.

The current flow $I_{b,bb}$ through (b, bb) is determined as:

$$I_{b,bb} = \left(\frac{S_{b,bb}}{V_b}\right)^*;\ \forall (b, bb) \in \mathcal{E} \tag{2}$$

Adopting (2) in (1) and considering the magnitude squared, the following relationship is formed:

$$| V_{bb} |^2 = | V_b |^2 + | Z_{b,bb} |^2 \, | I_{b,bb} |^2 - \left(Z_{b,bb}S^*_{b,bb} + Z^*_{b,bb}S_{b,bb}\right) \tag{3}$$

The complex power is balanced at each bus bb; $\forall bb \in \mathcal{BS}$, as follows:

$$S_{bb} = \sum_{bbb:(bb,bbb)\in\mathcal{E}} S_{bb,bbb} - \sum_{b:(b,bb)\in\mathcal{E}} \left(S_{b,bb} - Z_{b,bb} \, | I_{b,bb} |^2\right) + Y^*_{bb} \, | V_{bb} |^2 \tag{4}$$

where $Y_{bb} = G_{bb} + jB_{bb}$. Here, $G_{bb}; B_{bb} \in \mathbb{R}$ refer to conductance and susceptance of each bus bb respectively.

Using (4) and (2) on the basis of real variables, the LV network branch flow model (Farivar and Low 2013), $\forall b; bb \in \mathcal{BS}$ and $\forall (b, bb) \in \mathcal{E}$, is described as:

$$P_{bb} = \sum_{(bb,bbb)\in\mathcal{E}} P_{bb,bbb} - \sum_{(b,bb)\in\mathcal{E}} \left(P_{b,bb} - R_{b,bb} \, | I_{b,bb} |^2\right) + G_{bb} \, | V_{bb} |^2 \tag{5}$$

$$Q_{bb} = \sum_{(bb,bbb)\in\mathcal{E}} \beta_{bb,bbb} - \sum_{(b,bb)\in\mathcal{E}} \left(Q_{b,bb} - X_{b,bb} \, | I_{b,bb} |^2\right) + B_{bb} \, | V_{bb} |^2 \tag{6}$$

$$| V_{bb} |^2 = | V_b |^2 - 2\left(R_{b,bb}P_{b,bb} + X_{b,bb}Q_{b,bb}\right) + \left(R_{b,bb}^2 + X_{b,bb}^2\right) I_{b,bb} \quad (7)$$

2.2 LEM Players' Model

Suppose some of considered LV network buses accommodate LEM players and the set of their buses is implied by $\mathcal{PBS} \subset \mathcal{BS}$. Let the set of the players be indicated by $\mathcal{PR}$ and u stands for the index of each LEM player, where $u \in \mathcal{PR}$. It is assumed that each LEM player's bus contains only one LEM player without a loss of generality. Thus, the total number of LEM players' buses $| \mathcal{PBS} |$ is equal to the total number of LEM players $| \mathcal{PR} |$, i.e., $| \mathcal{PBS} | = | \mathcal{PR} |$. Assume each LEM player u can be equipped with both uncontrollable (base) and controllable loads (flexible), local generation systems, and storage systems. Let $\mathcal{F}$, $\mathcal{G}$, and $\mathcal{H}$ be sets of LEM players with loads only, local generation systems, and local generation systems and storage systems respectively at any time $\tau \in \mathcal{TM}$, where $\mathcal{F}, \mathcal{G}, \mathcal{H} \subset \mathcal{PR}$.

Let $P_u^b(\tau)$ and $P_u^c(\tau)$ be base and controllable loads of each LEM player u at a given time instant τ. The summation of $P_u^b(\tau)$ and $P_u^c(\tau)$ is the total power demand of each LEM player u, which is denoted by $P_u^{pd}(\tau)$ such that $P_u^{ld}(\tau) = P_u^b(\tau) + P_u^c(\tau); \forall u \in \mathcal{PR}; \forall \tau \in \mathcal{TM}$. The locally generated power of each LEM player u at time τ is symbolised by $P_u^{lg}(\tau); \forall u \in \mathcal{G}, \mathcal{H} \subset \mathcal{PR}$. Note that $P_u^{lg}(\tau) = 0, \forall u \in \mathcal{F} \subset \mathcal{PR}$. Suppose $P_u^{cg}(\tau); \forall u \in \mathcal{H} \subset \mathcal{PR}$ and $P_u^{dg}(\tau); \forall u \in \mathcal{H} \subset \mathcal{PR}$ represent charged and discharged power of the storage system of each LEM player u at time τ, that are bounded by maximum capacity of charging $\kappa_u; \forall u \in \mathcal{H} \subset \mathcal{PR}$, and minimum capacity of discharging $-\kappa_u; \forall u \in \mathcal{H} \subset \mathcal{PR}$, respectively. The storage charging/discharging operation is handled by the state-of-charge (SoC) $\lambda_u(\tau); \forall u \in \mathcal{H} \subset \mathcal{PR}$—which is managed by maximum capacity of storage $\overline{\lambda_u}$. The mathematical expressions are as follows:

$$\begin{aligned} &\lambda_u(\tau) - \lambda_u(\tau-1) - \left(\zeta^{cg} \times c_u(\tau) \times P_u^{cg}(\tau) \times \Delta\tau\right) \\ &- \left(\frac{d_u(\tau) \times P_u^{dg}(\tau) \times \Delta\tau}{\zeta^{dg}}\right) = 0;\ \forall u \in \mathcal{H},\ \forall \tau \in \mathcal{TM} \end{aligned} \quad (8)$$

$$0 \le \lambda_u(\tau) \le \overline{\lambda_u};\ \forall u \in \mathcal{H},\ \forall \tau \in \mathcal{TM} \quad (9)$$

$$0 \le \left(P_u^{cg}(\tau) \times \Delta\tau\right) \le \kappa_u;\ \forall u \in \mathcal{H},\ \forall \tau \in \mathcal{TM} \quad (10)$$

$$-\kappa_u \le \left(P_u^{dg}(\tau) \times \Delta\tau\right) \le 0;\ \forall u \in \mathcal{H},\ \forall \tau \in \mathcal{TM} \quad (11)$$

where $\Delta\tau$ indicates the time length. The charging and discharging efficiencies of the storage system are represented by ζ^{cg} and ζ^{dg} respectively. Note that $P_u^{cg}(\tau), P_u^{dg}(\tau) = 0; \forall u \in \mathcal{F}, \mathcal{G} \subset \mathcal{PR}$. $c_u(\tau)$ and $d_u(\tau)$ are binary variables of each

LEM player u at time τ related to storage charging and discharging to evade simultaneous charging and discharging such that $c_u(\tau) + d_u(\tau) \leq 1$.

2.2.1 Model for Generation-Side Player-Centric Trading

According to the local power generation; power consumption; and storage usage, available power $P_u^{pa}(\tau)$ and power shortage $P_u^{ps}(\tau)$ of each LEM player u are calculated as:

$$\begin{aligned} P_u^{pa}(\tau) = & \left(P_u^{lg}(\tau) - (d_u(\tau) \times P_u^{dg}(\tau))\right) \\ & - \left(P_u^{ld}(\tau) + (c_u(\tau) \times P_u^{cg}(\tau))\right);\ \forall u \in \mathcal{PR},\ \forall \tau \in \mathcal{TM} \end{aligned} \tag{12}$$

$$\begin{aligned} P_u^{ps}(\tau) = & \left(P_u^{ld}(\tau) + (c_u(\tau) \times P_u^{cg}(\tau))\right) \\ & - \left(P_u^{lg}(\tau) - (d_u(\tau) \times P_u^{dg}(\tau))\right);\ \forall u \in \mathcal{PR},\ \forall \tau \in \mathcal{TM} \end{aligned} \tag{13}$$

Let $\alpha_y(\tau)$ and $\alpha_z(\tau)$ be the prices declared by each LEM generation-side seller $y \in \mathcal{SG} \subset \mathcal{PR}$ and each generation-side buyer $z \in \mathcal{BG} \subset \mathcal{PR}$ to sell $P_y(\tau)$, where $P_y(\tau) \leq P_u^{pa}(\tau)$; $y, u \in \mathcal{PR}$, and buy $P_z(\tau)$, where $P_z(\tau) \leq P_u^{ps}(\tau)$; $z, u \in \mathcal{PR}$, power at a trading period τ respectively. All participating sellers and buyers are assumed to announce their trading quantities and prices at the start of every LEM intervals.

For a bilateral generation-side LEM transaction in $\mathcal{SG} \cup \mathcal{BG}$, each seller $y \in \mathcal{SG}$ can trade as long as it has available power to sell, i.e., $P_y(\tau) \neq 0$. Similarly, each buyer $z \in \mathcal{BG}$ with power shortage can trade in the LEM, i.e., $P_y(\tau) \neq 0$. The LEM transaction price between each seller and each buyer is defined as the average value of $\alpha_y(\tau)$ and $\alpha_z(\tau)$ to reward both of them substantially (Azim et al. 2019). As such, the quantity $\beta_{a|y,z}^{gs}(\tau)$ for ath LEM transaction, where $a \in \mathcal{GS}$ (set of generation-side transactions), is determined as:

$$\beta_{a|y,z}^{gs}(\tau) = \min\left\{P_y^{(a)}(\tau), P_z^{(a)}(\tau)\right\};\ \forall a \in \mathcal{GS},\ \forall y \in \mathcal{SG},\ \forall z \in \mathcal{BG},\ \forall \tau \in \mathcal{TM} \tag{14}$$

Further, the price $\alpha_{a|y,z}^{gs}(\tau)$ for ath LEM transaction is expressed as:

$$\alpha_{a|y,z}^{gs}(\tau) = \frac{\alpha_y^{(a)}(\tau) + \alpha_z^{(a)}(\tau)}{2};\ \forall a \in \mathcal{GS},\ \forall y \in \mathcal{SG},\ \forall z \in \mathcal{BG},\ \forall \tau \in \mathcal{TM} \tag{15}$$

Note that $\beta_{a|y,z}^{gs}(\tau)$ is bounded by the maximum power export limit $P_b^{ex}(\tau)$; $\forall b \in \mathcal{PBS}, \forall \tau \in \mathcal{TM}$ and maximum power import limit $P_b^{im}(\tau)$; $\forall b \in \mathcal{PBS}, \forall \tau \in \mathcal{TM}$. Further, $\alpha_{a|y,z}^{gs}(\tau)$ is limited by the ToU price $\alpha^{rd}(\tau)$ and FiT rate $\alpha^{ft}(\tau)$ such that $\alpha^{ft}(\tau) < \alpha_{a|y,z}^{gs}(\tau) < \alpha^{rd}(\tau)$; $\forall \tau \in \mathcal{TM}$.

During no generation-side trading periods in the LEM, i.e., when there are no local available power, both sellers and buyers purchase electricity from the grid at

ToU prices. The total electricity cost to each LEM player $u \in \mathcal{PR}$ for a given period $\mid \mathcal{TM} \mid$ is:

$$\iota_u^{gs} = \sum_\tau \Big[\alpha^{rd}(\tau) \times \beta^{rd}(\tau) \times \Delta\tau - \sum_z \alpha^{gs}_{\cdot|z}(\tau) \times \beta^{gs}_{\cdot|z}(\tau) \times \Delta\tau + \sum_y \alpha^{gs}_{\cdot|y}(\tau) \times \beta^{gs}_{\cdot|y}(\tau) \times \Delta\tau\Big];\ \forall u \in \mathcal{PR} \tag{16}$$

where $\beta^{rd}(\tau)$ signifies the power each LEM player u purchases from the grid at the ToU price $\alpha^{rd}(\tau)$ at time τ. $\beta^{gs}_{\cdot|y}(\tau)$ and $\beta^{gs}_{\cdot|z}(\tau)$ denote traded power of each LEM player u with each seller y and each buyer z at prices $\alpha^{gs}_{\cdot|y}(\tau)$ and $\alpha^{gs}_{\cdot|y}(\tau)$ respectively.

In the existing BAU, sellers export their available power to the LV distribution network at the FiT rate. Any power shortage is compensated by the grid at the ToU prices. Hence, the equivalent total electricity cost to each LEM player $u \in \mathcal{PR}$—if traded equivalent LEM quantities at FiT and ToU prices becomes:

$$\iota_u^{ft} = \sum_\tau \Big[\alpha^{rd}(\tau)\left(\beta^{rd}(\tau) \times \Delta\tau + \sum_y \beta^{gs}_{\cdot|y}(\tau) \times \Delta\tau\right) - \sum_z \alpha^{ft}(\tau) \times \beta^{gs}_{\cdot|z}(\tau) \times \Delta\tau\Big];\ \forall u \in \mathcal{PR} \tag{17}$$

Since generation-side LEM framework aims at benefiting players more than that of the existing BAU billing mechanism, the electricity cost reduction for each LEM player $u \in \mathcal{PR}$ is evaluated as:

$$\overline{\iota_u^{gs}} = \iota_u^{ft} - \iota_u^{gs} = \sum_\tau \Big[\sum_z \left(\alpha^{gs}_{\cdot|z}(\tau) - \alpha^{ft}(\tau)\right) \times \beta^{gs}_{\cdot|z}(\tau) \times \Delta\tau + \sum_y \left(\alpha^{rd}(\tau) - \alpha^{gs}_{\cdot|y}(\tau)\right) \times \beta^{gs}_{\cdot|y}(\tau) \times \Delta\tau\Big];\ \forall u \in \mathcal{PR} \tag{18}$$

where $(\sum_\tau \sum_z (\alpha^{gs}_{\cdot|z}(\tau) - \alpha^{ft}(\tau)) \times \beta^{gs}_{\cdot|z}(\tau) \times \Delta\tau)$ is the profit of each LEM seller. On the other hand, the saving of each LEM buyer is represented by $(\sum_\tau \sum_y (\alpha^{rd}(\tau) - \alpha^{gs}_{\cdot|y}(\tau)) \times \beta^{gs}_{\cdot|y}(\tau) \times \Delta\tau)$.

A MATLAB script is provided in Appendix I to calculate the benefit of a generation-side LEM seller and a generation-side LEM buyer.

2.2.2 Model for Demand-Side Player-Centric Trading

The net power demand $P_u^{nt}(\tau)$ of each demand-side LEM player $u \in \mathcal{PR}$ at time τ is as follows:

$$P_u^{nt}(\tau) = P_u^{ld}(\tau) - P_u^{lg}(\tau) - (d_u(\tau) \times P_u^{dg}(\tau)) + (c_u(\tau) \times P_u^{cg}(\tau)); \ \forall u \in \mathcal{PR}, \ \forall \tau \in \mathcal{TM} \tag{19}$$

If $P_u^{nt}(\tau) < 0$, the LEM player u has excess generation and does not participate in demand-side LEM. It is self-sufficient—no need for demand-side LEM—in case of $P_u^{nt}(\tau) = 0$. In contrast, it needs to buy power shortage $P_u^{ps}(\tau)$ from the grid if $P_u^{nt}(\tau) > 0$. This is where demand-side LEM finds its application to reduce the energy cost (Azim and Tushar 2021). Suppose a LEM player buys energy at ToU prices but it is required to pay higher prices during supply-restricted scenarios when its power demand exceeds a pre-defined threshold (Integrated system plan 2020). Let each LEM player $u \in \mathcal{PR}$ be satisfied at the ToU price $\alpha^{lw}(\tau)$ as long as its power shortage $P_u^{ps}(\tau)$ is not higher than the maximum power usage limit $P_u^{lw}(\tau)$, i.e., $P_u^{ps}(\tau) \leq P_u^{lw}(\tau)$, at time τ. In case of $P_u^{ps}(\tau) > P_u^{lw}(\tau)$, LEM player u needs to buy power at a higher price $\alpha^{hg}(\tau)$ compared to $\alpha^{lw}(\tau)$, i.e., $\alpha^{hg}(\tau) > \alpha^{lw}(\tau)$.

Let $\mathcal{SD}$ and $\mathcal{BD}$ be the sets of demand-side LEM sellers and buyers respectively, where $\mathcal{SD}, \mathcal{BD} \subset \mathcal{PR}$. Each LEM seller $u \in \mathcal{SD}$ has a power shortage of $P_u^{ps}(\tau) \leq P_u^{lw}(\tau)$ and cutbacks its power demand by $P_u^{rc}(\tau)$ upon request. On the other hand, each LEM buyer $u \in \mathcal{BD}$ possesses a power shortage of $P_u^{ps}(\tau) > P_u^{lw}(\tau)$ and buys extra power of $P_u^{ic}(\tau)$ via demand-side LEM. Power decrease and increase limits are bounded by $P_u^{rc}(\tau) \geq 0$ and $P_u^{ic}(\tau) \leq \overline{P_u^{max}}$ (maximum bought power limit) respectively. The modified power shortage of each demand-side LEM seller is written as:

$$P_u^{psy}(\tau) = P_u^{ps}(\tau) - P_u^{rc}(\tau); \ \forall u \in \mathcal{SD}, \ \forall \tau \in \mathcal{TM}, \ \text{if } P_u^{ps}(\tau) \leq P_u^{lw}(\tau) \tag{20}$$

Likewise, the modified power shortage of each demand-side LEM buyer is represented as:

$$P_u^{psz}(\tau) = P_u^{lw}(\tau) + P_u^{ic}(\tau); \ \forall u \in \mathcal{BD}, \ \forall \tau \in \mathcal{TM}, \ \text{if } P_u^{ps}(\tau) > P_u^{lw}(\tau) \tag{21}$$

where $P_u^{psz}(\tau)$ and $P_u^{psz}(\tau)$ amounts of power are bought by each LEM seller and each LEM respectively at any given time period τ.

Each LEM seller $u \in \mathcal{SD}$ seeks to boost the difference between $\alpha^{hg}(\tau)$ and $\alpha^{lw}(\tau)$ prices to enlarge its revenue. In contrast, the gap between $\alpha^{hg}(\tau)$ and $\alpha^{lw}(\tau)$ prices is sought to be dwarfed by each LEM buyer $u \in \mathcal{BD}$ to diminish the expense notably. Hence, demand-side LEM trading price $\alpha^{ds}(\tau)$ is defined as the middle value of $\alpha^{hg}(\tau) - \alpha^{lw}(\tau)$ to incentivise both sellers and buyers (Azim et al. 2021).

$$\alpha^{ds}(\tau) = \frac{\alpha^{hg}(\tau) - \alpha^{lw}(\tau)}{2}; \ \forall \tau \in \mathcal{TM} \tag{22}$$

The LEM buyer pays $\alpha^{ds}(\tau)$ to the contracted LEM seller to consume power at $\alpha^{lw}(\tau)$ price In the demand-side LEM, a LEM player acts either as a seller or a buyer simultaneously at various trading instants. Therefore, the energy expenditure of each LEM player u for a given period of $\mid \mathcal{T} \mid$ is computed as:

$$\iota_u^{ds} = \sum_{\tau}\Big[\Big[\Big(P_u^{psy}(\tau) \times \Delta\tau \times \alpha^{lw}(\tau)\Big) - \Big(P_u^{rc}(\tau) \times \Delta\tau \times \alpha^{ds}(\tau)\Big)\Big] \tag{23}$$
$$+ \Big[\Big(P_u^{psz}(\tau) \times \Delta\tau \times \alpha^{lw}(\tau)\Big) + \Big(P_u^{ic}(\tau) \times \Delta\tau \times (\alpha^{ds}(\tau) + \alpha^{lw}(\tau))\Big)\Big]\Big];\ \forall u \in \mathcal{PR}$$

If a LEM player u wishes to purchase the equivalent amount of energy from the grid during a supply-constrained circumstance, the equivalent energy cost becomes:

$$\iota_u^{dr} = \sum_{\tau}\Big[\Big[\Big(P_u^{psy}(\tau) \times \Delta\tau \times \alpha^{lw}(\tau)\Big) - \big(P_u^{rc}(\tau) \times \Delta\tau \times \alpha^{rc}(\tau)\big)\Big] \tag{24}$$
$$+ \Big[\Big((P_u^{psz}(\tau) - P_u^{ic}(\tau)) \times \Delta\tau \times \alpha^{lw}(\tau)\Big) + \Big(P_u^{ic}(\tau) \times \Delta\tau \times \alpha^{hg}(\tau)\Big)\Big]\Big];\ \forall u \in \mathcal{PR}$$

where $\alpha^{rc}(\tau)$ symbolises the monetary gain offered by the grid to cut down the flexible demand at any energy-restricted period.

The monetary reward to each demand-side LEM player u is determined as:

$$\overline{\iota_u^{ds}} = \iota_u^{dr} - \iota_u^{ds} = \sum_{\tau}\Big[\big[P_u^{rc}(\tau) \times \Delta\tau\,\big(\alpha^{ds}(\tau) - \alpha^{rc}(\tau)\big)\big] \tag{25}$$
$$+ \big[P_u^{ic}(\tau) \times \Delta\tau\,\big(\alpha^{hg}(\tau) - (\alpha^{lw}(\tau) + \alpha^{ds}(\tau))\big)\big]\Big];\ \forall u \in \mathcal{PR}$$

A MATLAB script is provided in Appendix II to calculate the benefit of a demand-side LEM seller and a demand-side LEM buyer.

3 Case Studies

This section describes some numerical results to emphasise both financial and physical performances of the proposed generation- and demand-side LEM mechanisms. In particular, it is demonstrated that the designed LEM trading frameworks can minimise substantial portions of the electricity expenditures to all engaging players while maintaining voltage profiles of the power network within the prescribed margins.

Figure 1 depicts the single-line diagram of a typical three-phase 0.415 kV (LV) distribution network containing 34 single-phase energy user' buses, i.e., 102 buses in total for the entire three-phase system. The distribution sub-station, responsible for power supply, is represented by bus 1. The prescribed voltage limit of this network is ranged between 0.9 pu and 1.06 pu. Voltage values greater than 1.06 pu and less than 0.9 pu are tagged as over-voltage and under-voltage phenomena respectively.

It is assumed that 30 energy users'—labelled as prosumers—of the studied network located at buses 5–14 have solar photovoltaic (PV) systems ranging from 3 kW_p to 6.6 kW_p and some of them are also assumed to have battery energy storage systems (BESSs) that range from 5 kWh to 10 kWh, but the uses of BESSs are totally

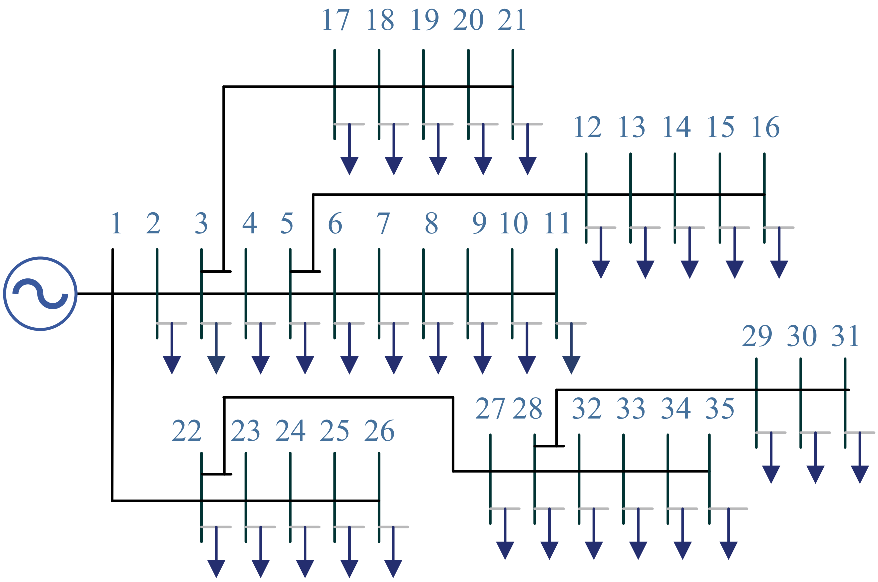


Fig. 1 A single-line diagram of a typical 0.415 kV distribution network in Australia (Azim et al. 2020)

decided by the LEM players. That means, for a given day, they may choose to use BESSs while on the other day they may not considering the fact of the operational degradation. In general, total local supply from solar PV and BESS is found to be less than the total power demand. Thus, the rest of the required power supply is considered to come from the distribution sub-station.

3.1 Case Study on Generation-Side Player-Centric Trading

In this case study, it is assumed that all 30 energy users of the studied LV network located at buses 5–14 are interested to take part in the proposed generation-side LEM trading. Note that LEM players may or may not choose to install/connect/use BESSs for the trading purposes depending upon their energy status and preference. Nonetheless, these LEM players are assigned with a unique identity pursuant to the sequence they are connected in the network. For instance, player 1; player 2; and player 3 are located at phase a; phase b; and phase c of bus 5 respectively. Similarly, following the network sequence, phase a; phase b; and phase c of bus 14 contain player 28; player 29; and player 30 respectively.

While ToU tariff is varied between 15 ¢/kWh and 35 ¢/kWh during off-peak; shoulder; and peak times, a fixed FiT rate of 10 ¢/kWh is considered in this study. The LEM trading price is altered between the FiT and ToU prices so that players receive

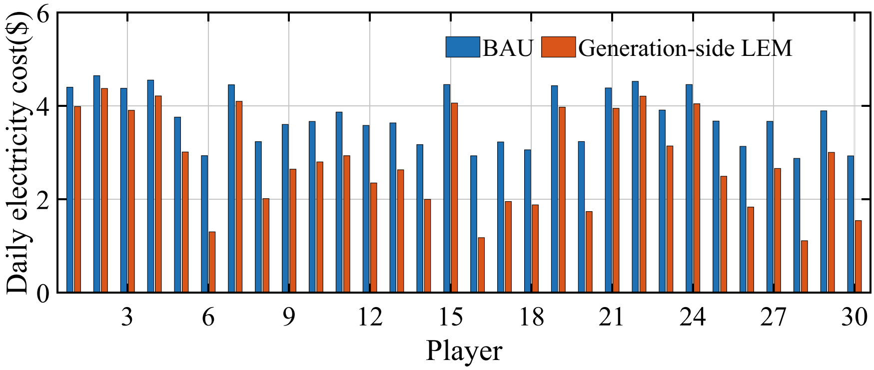


Fig. 2 Daily electricity cost comparison between BAU and proposed generation-side LEM for all players in Australian dollars

monetary gains. Every 30 minutes apart, the participating LEM players execute the proposed generation-side trading on OpenDSS-interfaced MATLAB platform and the monetary gains are compared with BAU (power is sold/bought via FiT/ToU rate). Also, the three-phase voltages of the studied LV network is checked to demonstrate the deployment suitability of the financial generation-side LEM trading.

The electricity costs of all generation-side LEM players, in Australian dollar (AUD), over the course of 24 hours are captured in Fig. 2. As is observed from Fig. 2, player 6 (located at phase c of bus 6); player 8 (located at phase b of bus 7); player 13 (located at phase a of bus 9); player 25 (located at phase a of bus 13); and player 29 (located at phase b of bus 14) incur electricity bills around \$2.93; \$3.23; \$3.63; \$3.67; and \$3.89 respectively as per BAU. The proposed generation-side LEM trading facilitates these players to lower their energy costs nearly to \$1.3; \$2.01; \$2.63; \$2.49; and \$3 respectively, causing approximately 55.57%; 37.69%; 27.6%; 32.14%; and 22.83% reduction in their respective daily energy bills—which are impressive figures. Other generation-side LEM players also diminish their energy expenditures notably by joining in the proposed generation-side LEM model, verifying the proposed generation-side LEM trading as a financially-viable strategy.

The implication of the proposed generation-side LEM trading model on three-phase voltages of the studied LV network, shown in Fig. 1, is demonstrated in Figs. 3, 4 and 5. The phase voltages step up during solar PV periods, in which local penetration is conducted through generation-side LEM trading. At around 12 pm, the peak local penetration is observed, leading to maximum phase voltage rise in the network. For instance, the maximum voltages are recorded as 1.034 pu (as per Fig. 3); 1.031 pu (as per Fig. 4); 1.046 pu (as per Fig. 5) at phase a; phase b; and phase c respectively. Importantly, these values are within the prescribed upper voltage limit, which is defined as 1.06 pu. Besides, all phase voltages are also with the acceptable upper voltage margin at other geration-side LEM trading slots such as 10 a.m.; 11 a.m.; 1 p.m.; 2 p.m.; and 3 p.m. Thus, there is no over-voltage problem

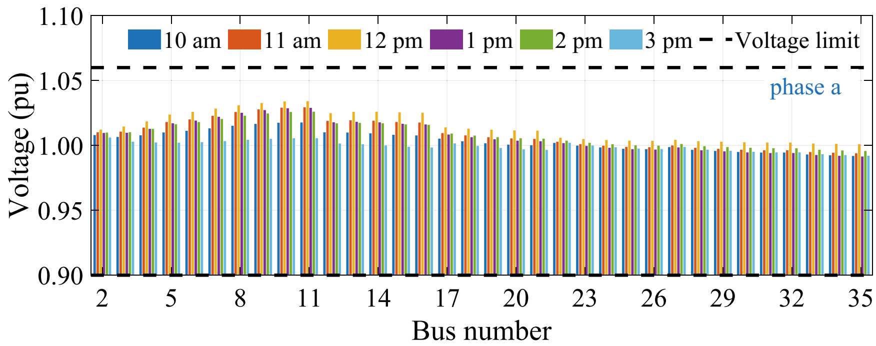


Fig. 3 Bus voltages of phase a of the studied LV distribution network at different generation-side LEM trading slots

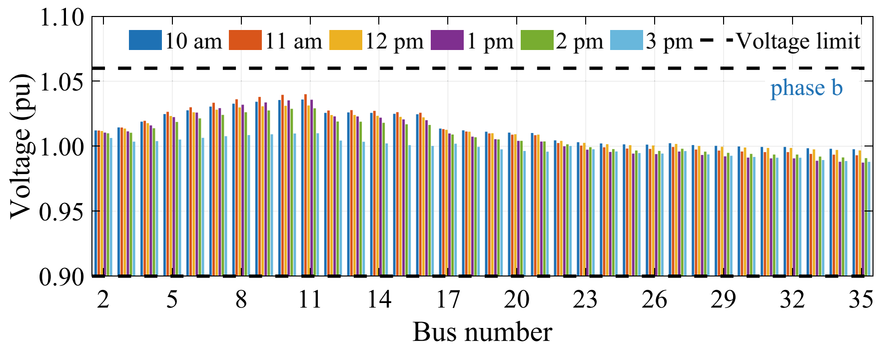


Fig. 4 Bus voltages of phase b of the studied LV distribution network at different generation-side LEM trading slots

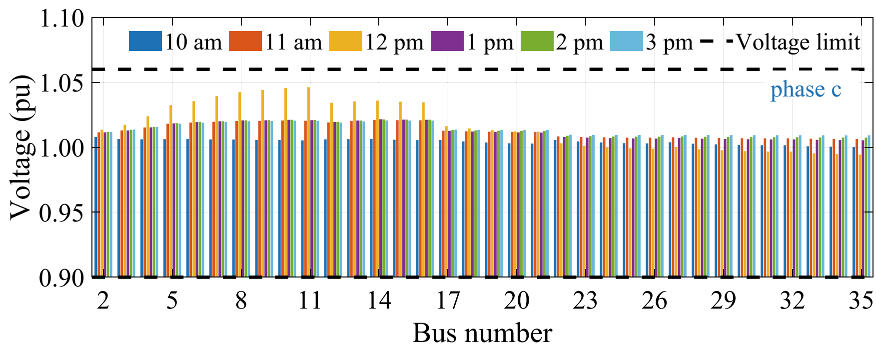


Fig. 5 Bus voltages of phase c of the studied LV distribution network at different generation-side LEM trading slots

in the studied LV network and the proposed generation-side LEM trading is safe for the network to deploy.

3.2 Case Study on Demand-Side Player-Centric Trading

This case study assumes that 18 energy users located at buses 5–10 of the studied LV network are willing to join in the proposed demand-side LEM trading. Similar to generation-side LEM trading, demand-side LEM players are also provided with a unique identity in accordance with their physical location in the LV network. For example, phase a; phase b; and phase c of bus 5 accommodate player 1; player 2; and player 3 respectively. Whereas, player 16; player 17; and player 18 are located at phase a; phase b; and phase c of bus 10 respectively following the network sequence.

In this case study, ToU tariff is also altered between 15 ¢/kWh and 35 ¢/kWh during off-peak; shoulder; and peak times while keeping FiT rate as a flat one (10 ¢/kWh). However, the ToU tariff is considered to be 1.6 times higher if the energy users consume more than the pre-defined rated amount during a supply-restricted scenario. It is also assumed that demand-side LEM players have some sorts of controllable loads that may include washing machine; refrigerators; air conditioners; dish washers; and cloth dryers for example, and agree to sacrifice their rights to buy energy to benefit other players in the community as a whole.

Nonetheless, the proposed demand-side LEM trading is performed every 30 min apart on OpenDSS-interfaced MATLAB platform, and economic benefits are compared with BAU (power is sold/bought via FiT/ToU rate and an centralised incentive is given for demand reduction when requested). Further, the three-phase voltages of the studied LV network is also analysed to understand the effect of financial demand-side LEM trading on an actual distribution network.

Figure 6 exhibits energy usage expenditures of all engaging demand-side LEM players, in Australian dollar (AUD) for the period of 24 h. Without the proposed demand-side LEM trading, players 2 (located at phase b of bus 5); 4 (located at phase a of bus 6); 8 (located at phase b of bus 7); 13 (located at phase a of bus 9); and 18 (located at phase c of bus 10) receive \$4.85, \$7.74, \$5.82, \$5.65 and \$9.2 daily electricity bills respectively as per BAU. With the proposed demand-side LEM trading, these figures plummet to \$3.58, \$6.61, \$4.63, \$4.58 and \$8.13 respectively, resulting in striking figures of approximately 26.19%; 14.6%; 20.45%; 18.94%; and 11.63% cutback in their respective every day electricity costs. Other participating players are also able to attain economic gains with the help of the proposed demand-side LEM trading as displayed in Fig. 6. As such, the proposed framework is financially beneficial for all involving LEM players.

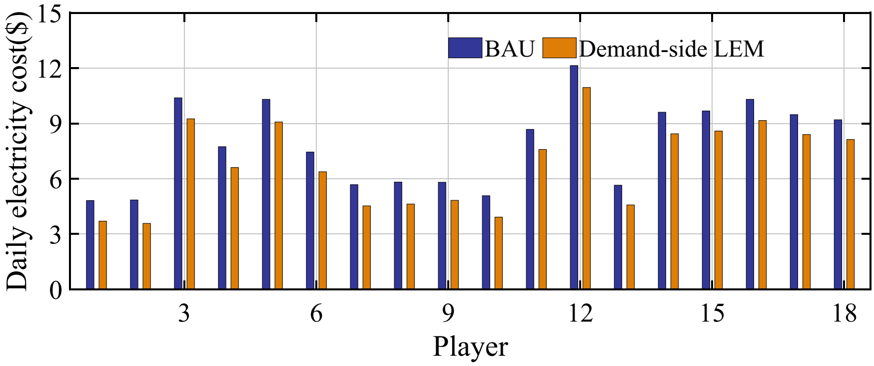


Fig. 6 Daily electricity cost comparison between BAU and proposed demand-side LEM for all players in Australian dollars

Figures 7, 8 and 9 illustrate how the proposed demand-side LEM trading impact the phase voltages the studied LV network shown in Fig. 1. Without a loss of generality, one high and one low demand-side LEM trading instant (occurred at 7 p.m. and 10 p.m. respectively) are chosen for model validation and the changes in the voltage magnitudes of phase a; phase b; and phase c—owing to the change in power demand induced by the proposed demand-side LEM trading—are depicted in Figs. 7, 8 and 9 respectively. The demand-side LEM players experience greater falling-off in phase voltages during the high demand-side trading slot in contrast with that of the low demand-side trading slot as increased amounts of power is consumed at some nodes. Nevertheless, the proposed demand-side LEM trading ascertains the voltage drop within the prescribed margin, i.e., 0.9 pu. Hence, it is felicitous for real deployment on an actual LV network.

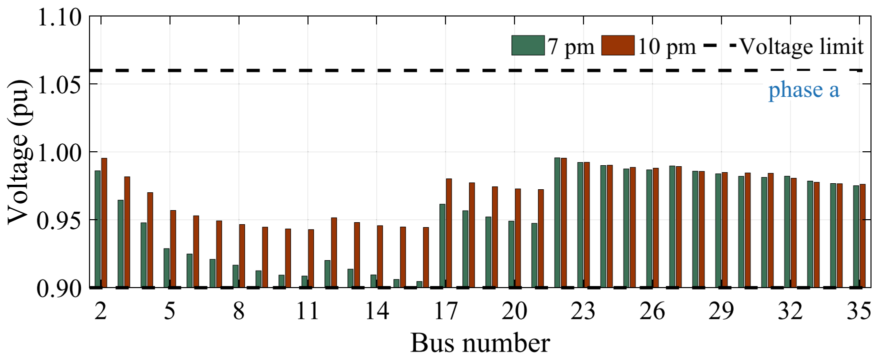


Fig. 7 Bus voltages of phase a of the studied LV distribution network at different demand-side LEM trading slots

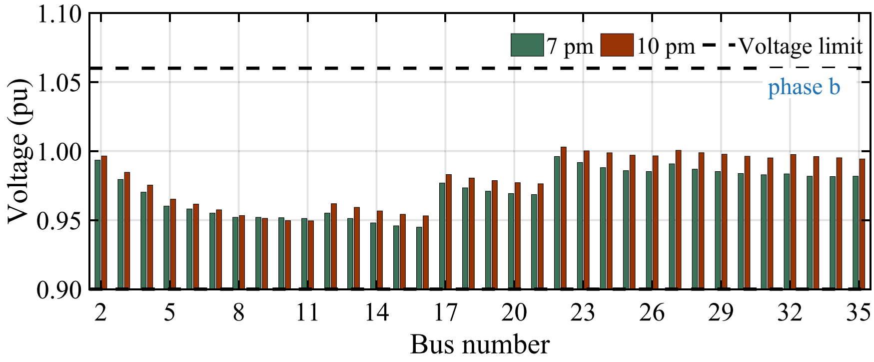


Fig. 8 Bus voltages of phase b of the studied LV distribution network at different demand-side LEM trading slots

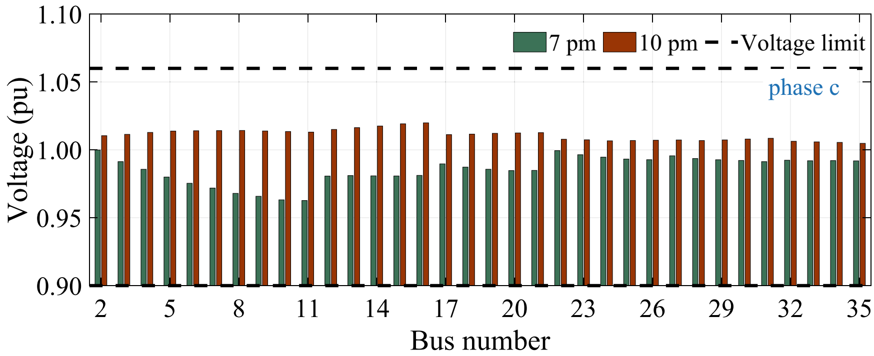


Fig. 9 Bus voltages of phase c of the studied LV distribution network at different demand-side LEM trading slots

4 Conclusion

Generation-side and demand-side player-centric tradings—driven by efficacious rules—have been presented in the chapter. To begin with, mathematical formulations have been demonstrated to model rule-based trading among different LEM participants in a connected LV distribution network in a player-centric manner; in which financial interests of all LEM players have been taken care of considering the local power export and import limits. Diverse case studies have been illustrated to analyse the performance of the proposed LEM frameworks in contrast with BAU. It has been found that the proposed generation-side LEM model not only incentivises involving sellers more than the FiT scheme but also facilitates buyers to scale down their energy costs as opposed to the FiT. Further, the proposed demand-side LEM model has been able to lower significant portions of electricity expenditure of all participating LEM players compared to the centralised DR method.

The proposed LEM models can be extended to develop a coordinated and uniform framework that can enable both generation-side and demand-side player-centric tradings simultaneously in the LEM while changing local power export and import limits dynamically. Besides, the incorporation of energy retailers' financial interests in the LEM modelling would be interesting to authenticate the real-world applicability.

Appendix I

Generation-Side LEM Trading Example

Suppose player 1 has 5 kWh solar PV generation and 1 kWh energy demand at a given time slot. On the contrary, player 2 has 4 kWh power demand at the same trading slot. If ToU and FiT prices are 25 ¢/kWh and 10 ¢/kWh respectively, calculate: (a) generation-side LEM trading quantity and price; (b) earning and expense with generation-side LEM trading; and (c) profit and saving compared to BAU.

MATLAB Code

```
% Inputs
player_1_generation=5; %kWh
player_1_demand=1; %kWh
player_2_demand=4; %kWh
tou_price=25; %c/kWh
fit_rate=10; %c/kWh
% Generation-side LEM
player_1_excess_generation=player_1_generation-player_1_demand; %kWh
trading_quantity=min(player_1_excess_generation, player_2_demand); %kWh
trading_price=(tou_price+fit_rate)/2; %c/kWh
BAU_equivalent_quantity=trading_quantity; %kWh
earning_player_1_LEM=(trading_quantity*trading_price); %c
expense_player_2_LEM=(trading_quantity*trading_price); %c
earning_player_1_BAU=(BAU_equivalent_quantity*fit_rate); %c
expense_player_2_BAU=(BAU_equivalent_quantity*tou_price); %c
profit_player_1=profit_player_1_LEM-profit_player_1_BAU; %c
saving_player_2=saving_player_2_BAU-saving_player_2_LEM; %c
% Outputs
trading_quantity=4kWh
trading_price=17.5c/kWh
earning_player_1_LEM=70c
expense_player_2_LEM=70c
```

```
profit_player_1=30c
saving_player_2=30c
```

Appendix II

Demand-Side LEM Trading Example

Suppose both player 1 and player 2 have 5 kWh energy demand each at a given supply-restricted time slot and 5 kWh is the maximum threshold. But player 2 requires 2 kWh more energy demand due to some reasons. If lower and higher ToU prices are 25 ¢/kWh and 40 ¢/kWh respectively and demand reduction incentive is 4 ¢/kWh, calculate: (a) demand-side LEM trading quantity and price; (b) expense with demand-side LEM trading; and (c) saving compared to BAU.

MATLAB Code

```
% Inputs
player_1_demand=5; %kWh
player_2_demand=5; %kWh
player_2_extra_demand=2; %kWh
tou_price_low=25; %c/kWh
tou_price_high=40; %c/kWh
reduction_incentive=4; %c/kWh
% Demand-side LEM
trading_quantity=player_2_extra_demand; %kWh
trading_price=(tou_price_high-tou_price_low)/2; %c/kWh
modified_demand_player_1=player_1_demand-trading_quantity; %kWh
modified_demand_player_2=player_2_demand+trading_quantity; %kWh
BAU_equivalent_quantity=trading_quantity; %kWh
expense_player_1_LEM=(modified_demand_player_1*tou_price_low)-(
        trading_quantity*trading_price); %c
expense_player_2_LEM=(player_2_demand*tou_price_low)+(trading_quantity
        *(tou_price_low+trading_price)); %c
expense_player_1_BAU=(modified_demand_player_1*tou_price_low)-(
        BAU_equivalent_quantity*reduction_incentive); %c
expense_player_2_BAU=(player_2_demand*tou_price_low)+(
        BAU_equivalent_quantity*tou_price_high); %c
saving_player_1=expense_player_1_BAU-expense_player_1_LEM; %c
saving_player_2=expense_player_2_BAU-expense_player_2_LEM; %c
% Outputs
trading_quantity=2kWh
trading_price=7.5c/kWh
```

```
expense_player_1_LEM=60c
expense_player_2_LEM=190c
saving_player_1=7c
saving_player_2=15c
```

References

Azim MI, Pourmousavi SA, Tushar W, Saha TK (2019) Feasibility study of financial P2P energy trading in a grid-tied power network. In: Proceedings of the IEEE power & energy society general meeting, Atlanta, USA, pp 1–5

Azim MI, Tushar W (2021) P2P negawatt trading: a potential alternative to demand-side management. In: Proceedings of the IEEE power & energy society ISGT Asia, Brisbane, Australia, pp 1–5

Azim MI, Tushar W, Saha TK (2020) Regulated P2P energy trading: a typical Australian distribution network case study. In: Proceedings of the IEEE power & energy society general meeting, Montreal, Canada, Aug 2020, pp 1–5

Azim MI, Tushar W, Saha TK (2021) Cooperative negawatt P2P energy trading for low-voltage distribution networks. Appl Ener 299:117300

Azim MI, Tushar W, Saha TK, Yuen C, Smith D (2022) Peer-to-peer kilowatt and negawatt trading: a review of challenges and recent advances in distribution networks. Renew Sustain Ener Rev 169:112908

Capper T, Gorbatcheva A, Mustafa MA, Bahloul M, Schwidtal JM, Chitchyan R, Andoni M, Robu V, Montakhabi M, Scott IJ et al (2022) Peer-to-peer, community self-consumption, and transactive energy: a systematic literature review of local energy market models. Renew Sustain Ener Rev 162:112403

Demand response customer insights report (2022). https://arena.gov.au/assets/2018/08/demand-response-consumer-insights-report.pdf

Farivar M, Low SH (2013) Branch flow model: relaxations and convexification-Part I. IEEE Trans Pow Syst 28(3):2554–2564

FiT plummeted: ABC News (2022). https://www.abc.net.au/news/2021-09-29/solar-feed-in-tariff-energy-australia-tesla-battery/100498592

Gazafroudi AS, Khajeh H, Shafie-khah M, Laaksonen H, Corchado JM (2021) Local market models. In: Local electricity markets, pp 79–90

Gazafroudi AS, Khorasany M, Razzaghi R, Laaksonen H, Shafie-khah M (2021) Hierarchical approach for coordinating energy and flexibility trading in local energy markets. Appl Ener 302:117575

Integrated system plan (2020). https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en&hash=6BCC72F9535B8E5715216F8ECDB4451C

Javed H, Irfan M, Moazzam S, Hafiz AM, Jumshed A, Vishal D, Guerrero JM (2022) Recent trends, challenges and future aspects of P2P energy trading platforms in electrical based networks considering blockchain technology: a roadmap towards environmental sustainability. Front Ener Res 10:1–20 Mar

Jing Z, Pipattanasomporn M, Rahman S (2019) Blockchain-based negawatt trading platform: conceptual architecture and case studies. In: Proceedings of the IEEE power & energy society GTD Asia, Bangkok, Thailand, pp 68–73

Khan SN, Loukil F, Ghedira-Guegan C, Benkhelifa E, Bani-Hani A (2021) Blockchain smart contracts: applications, challenges, and future trends. Peer-to-peer Netw Appl 14(5):2901–2925

Khorasany M, Gazafroudi AS, Razzaghi R, Morstyn T, Shafie-khah M (2022) A framework for participation of prosumers in peer-to-peer energy trading and flexibility markets. Appl Ener 314:118907

LEM project: Powerledger (2022). https://www.powerledger.io/media/lem-do-you-want-to-do-a-project-with-us
Lin B, Chen J, Wesseh PK (2022) Peak-valley tariffs and solar prosumers: why renewable energy policies should target local electricity markets. Ener Policy 165:112984
Melendez KA, Subramanian V, Das TK, Kwon C (2019) Empowering end-use consumers of electricity to aggregate for demand-side participation. Appl Ener 248:372–382 Aug
Parag Y, Sovacool BK (2016) Electricity market design for the prosumer era. Nat Ener 1(4):16032
Tsaousoglou G, Giraldo JS, Paterakis NG (2022) Market mechanisms for local electricity markets: a review of models, solution concepts and algorithmic techniques. Renew Sustain Ener Rev 156:111890
Ullah MH, Park J-D (2021) Peer-to-peer energy trading in transactive markets considering physical network constraints. IEEE Trans Smart Grid 12(4):3309–3403 Jul

A Market-Based Mechanism for Local Energy Trading in Integrated Electricity-Heat Networks

Sara Haghifam, Hannu Laaksonen, and Miadreza Shafie-khah

Nomenclature

Acronyms

CHP	Combined Heat and Power
DG	Dispatchable Generator
DHS	District Heating System
DSO	Distribution System Operator
EB	Electric Boiler
ED	Electric Demand
EDS	Electrical Distribution System
HD	Heat Demand
HES	Heat Exchanger Station
HS	Heat Station
IEHN	Integrated Electricity-Heat Network
LEM	Local Energy Market
Power-to-Heat	P2H
Power-to-X-to-Power	P2X2P
PV	Photovoltaic System
WT	Wind Turbine

S. Haghifam (✉) · H. Laaksonen · M. Shafie-khah
School of Technology and Innovations, Flexible Energy Resources, University of Vaasa, Vaasa, Finland
e-mail: sara.haghifam@uwasa.fi

H. Laaksonen
e-mail: hannu.laaksonen@uwasa.fi

M. Shafie-khah
e-mail: miadreza.shafiekhah@uwasa.fi

M. Shafie-khah and A. S. Gazafroudi (eds.), *Trading in Local Energy Markets and Energy Communities*, Lecture Notes in Energy 93,
https://doi.org/10.1007/978-3-031-21402-8_9

Sets and Indices

ch	CHP indices
dg	DG indices
eb	EB indices
ed	ED indices
hd	HD indices
i, j	Set of nodes in EDS
ij	Indices of lines in EDS
n	Set of nodes in DHS
nm	Indices of pipelines in DHS
pv	PV indices
t	Time indices
wt	WT indices
Ω_{CHP}	Set of CHPs connected to set of nodes
Ω_{DG}	Set of DGs connected to set of nodes
Ω_{EB}	Set of EBs connected to set of nodes
Ω_{ED}	Set of EDs connected to set of nodes
Ω_{HD}	Set of HDs connected to set of nodes
Ω_{HES}	Set of HESs connected to set of nodes
Ω_{HS}	Set of HSs connected to set of nodes
Ω_{PV}	Set of PVs connected to set of nodes
Ω_{hR}, Ω_{hS}	Set of return/supply pipelines in DHS
$\Omega_{hR-B}^{n}, \Omega_{hR-E}^{n}$	Set of return pipelines beginning/ending at node n
$\Omega_{hS-B}^{n}, \Omega_{hS-E}^{n}$	Set of supply pipelines beginning/ending at node n
Ω_{WT}	Set of WTs connected to set of nodes
Ω_{e}	Set of lines in EDS

Parameters

b_{ij}, g_{ij}	Susceptance/conductance of line ij in EDS (ohm^{-1})
C_W	Specific heat capacity of water (J/g °C)
H_{HD}	Heat demand of DHS (kW)
HPR	Heat-to-power ratio of CHPs
HV_{gas}	Heat value of natural gas (kWh/m^3)
L_{nm}	length of pipelines in DHS (km)
m	Mass flow rate of nodes in DHS (kg/s)
m_R, m_S	Mass flow rate of return/supply pipelines in DHS (kg/s)
$P_{CHP}^{max}, P_{CHP}^{min}$	Maximum/minimum generated power of CHPs (kW)
$P_{EB}^{max}, P_{EB}^{min}$	Maximum/minimum generated power of EBs (kW)
P_{ED}	Electric demand of EDS (kW)

P_{ij}^{max}	Maximum capacity of line *ij* in EDS (kW)
Q_{DG}, Q_{PV}, Q_{WT}	Maximum quantity offers of DGs/PVs/WTs in LEM (kW)
T_{Amb}	Ambient temperature (°C)
T_R^{max}, T_R^{min}	Maximum/minimum temperature of return pipelines in DHS (°C)
T_S^{max}, T_S^{min}	Maximum/minimum temperature of supply pipelines in DHS (°C)
V_{nom}	Nominal voltage (V)
$\lambda_{DG}, \lambda_{PV}, \lambda_{WT}$	Offer prices of DGs/PVs/WTs in LEM (€/kWh)
λ_{gas}	Natural gas price (€/m^3)
λ_g	Locational marginal price of PCC (€/kWh)
$\eta_{CHP-E}, \eta_{CHP-H}$	Electricity/heat efficiency of CHPs (%)
η_{EB-H}	Heat efficiency of EBs (%)
ϑ	Maximum voltage variation (%)
κ	Heat transfer coefficient of pipelines in DHS (W/cm °C)

Variables

G_{CHP}	Gas flow to CHPs (m^3)
H_{CHP}	Output heat of CHPs (kW)
H_{EB}	Output heat of EBs (kW)
P_{CHP}	Output power of CHPs (kW)
P_{DG}	Offer of DGs in LEM (kW)
P_{EB}	Output power of EBs (kW)
P_g	Imported electricity from upstream grid (kW)
P_{PV}	Offer of PVs in LEM (kW)
P_{WT}	Offer of WTs in LEM (kW)
T_R, T_S	Return/supply temperature of nodes in DHS (°C)
$T_{R,in}, T_{S,in}$	Return/supply temperature at inlet of pipelines in DHS (°C)
$T_{R,out}, T_{S,out}$	Return/supply temperature at outlet of pipelines in DHS (°C)
V	Voltage magnitude (V)
ΔV	Voltage deviation (V)
α, β	Dual Variables or shadow prices (€/kWh)
θ	Voltage angle (rad)

1 Introduction

In recent years, a lack of fossil fuel sources and their irreversible environmental damages have led to a marked increase in the exploitation of renewable energy resources in power distribution systems (Zhang et al. 2021). Although the high penetration of renewable energies can overcome the above-mentioned challenges, the stochastic and intermittent nature of these units drives the need for flexibility in the electricity sector (Bernath et al. 2021). As one of the pragmatic and new solutions for flexibility provision at the distribution level, the coupling of different energy sectors, including the EDSs and DHSs, in the form of IEHNs has attracted more attention in the past few years (Zhang et al. 2020). To establish an IEHN via the sector-coupling concept, the presence of P2X2P, more specifically P2H, conversion technologies in the energy systems is required (Kirkerud et al. 2017; Skov et al. 2021). Combined heat and power (CHP) plants (Ahn et al. 2021), electric boilers (EBs) (Du et al. 2022), and electric heat pumps (EHPs) (David et al. 2017) are the most prevalent P2H elements in IEHNs.

In general, P2H solutions require techno-economic interactions with two local energy sectors, namely power and heat. Nevertheless, these kinds of interactions add new challenges to the optimal operation of IEHNs due to the lack of a suitable coordination platform (Bloess et al. 2018). To cope with this issue and implement sector-coupling at the distribution level, proposing an appropriate market-based framework is of great importance. Accordingly, local market-based solutions for sector-coupling have received widespread attention over the last few years. The following literature review highlights some important studies in this area:

A decentralized optimization method has been raised in Cao et al. (2019) to model a LEM for the coordinated operation of the EDS and DHS in the form of an IEHN. In the suggested framework, EDS and DHS are able to be operated independently by solving optimal power and thermal flows, respectively. A LEM has been designed in Chen et al. (2019) to investigate the energy trading within an IEHN and in the presence of multiple strategic players. In the provided framework, locational marginal prices of electricity and heat achieved from optimal power and thermal flows have been exploited to settle the considered market. A bi-level optimization model has been presented in Chen et al. (2021) for clearing a LEM and modeling its interaction with the wholesale electricity market. Accordingly, at the upper level, the DSO settles the LEM and determines locational marginal prices, while at the lower level, the wholesale market clearing, as well as the DSO's interaction with this market, are specified. A linear optimization-based approach has been developed in Brolin and Pihl (2020) to model a LEM enabling the integration of the EDS and DHS at the distribution level. The market-clearing process has been conducted from a central operator's perspective to maximize consumers and producers' surplus. A novel market-based platform has been introduced in Huynh et al. (2022) to couple the EDS and DHS and facilitate the utilization of P2H and storage technologies at the local level. The primary goal of this research work is to develop innovative market orders that respect energy system integration. A LEM mechanism has been suggested in Wang et al. (2022) to provide the possibility of peer-to-peer power and heat energy trading and investigate the cooperative behaviors among peers. In this study, each peer is able to promote its own profit by determining the joined coalition and its role as a seller or buyer of heat and electricity within this coalition. In the end, a fully decentralized market-based framework has been employed in Davoudi and Moeini-Aghtaie (2022) that supports peer-to-peer energy trading among several price-maker agents at the distribution level. To determine the optimal strategy of participated agents in the designed LEM and improve their net profit, a linear optimization model has been utilized in this study.

Due to the importance of establishing an efficient market-based environment for coupling of electricity and heat sectors at the local level, this chapter tends to model a LEM that enables the integration of EDSs and DHSs through CHPs and EBs, as fundamental P2H conversion technologies. The design of the considered LEM is based on a centralized one-sided auction-based energy trading process which is settled by the DSO with the objective of social welfare maximization. To this end, the schematic structure of the designed LEM, as well as the mathematical model for the market clearing process, are expressed in more detail in Sect. 2. The implementation of a case study and its discussions are provided in Sect. 3. Finally, the work is concluded in Sect. 4.

2 Methodology

As briefly mentioned in the previous section, the main purpose of the current chapter is to design a LEM for facilitating energy trading within integrated energy networks. Before delving into the mathematical model of the proposed market-based framework, its overall structure and regulations are described.

In this work, the considered LEM is designed based on a centralized one-sided auction format. In this case, it is assumed that a central operator is responsible for the operation of the IEHN at a specific time through the complete exchange of energy and information among two electricity and heat sectors. Hence, in order to identify the market settlement point, all participants are required to submit their bids/offers to the LEM operator. Furthermore, it is presumed that the clearing mechanism of the LEM is according to the one-sided auction method, in which only production offers are considered in the negotiation procedure (Khorasany et al. 2018). As a result, since multiple energy carriers are traded simultaneously in the presented market-based platform, each offer contains specific information, including the type of energy, quantity as well as valuation of the offer, the delivery time, and location of the injected energy to the network. On the other hand, the pricing system of the LEM is uniform, in which all players are paid at the same market clearing price regardless of their submitted offers. This clearing price is set at the offer price of the most expensive supplier chosen for providing the service (Kahn et al. 2001).

The schematic structure of the presented LEM platform for the integration of the EDS and DHS is illustrated in Fig. 1. According to the figure, the DSO as a central operator is responsible for the LEM clearing and meeting the IEHN's demands in the presence of both networks' technical constraints. To this end, the DSO firstly collects offers from the existing market participants like dispatchable generators (DGs), wind turbines (WTs), and photovoltaic systems (PVs). Then, considering the locational marginal price of the PCC, as well as the operational condition of the available CHPs and EBs, this entity attempts to settle the market and determine accepted offers as well as distribution locational marginal prices for the optimal scheduling of the IEHN. The electric demand (ED) of the system is procured from DGs, WTs, PVs, CHPs, and the upstream grid, while the heat demand (HD) is procured from CHPs and EBs.

As stated above, the DSO as the market operator clears the suggested LEM platform with the objective of social welfare maximization (Haghifam et al. 2022), which is equal to the total energy cost minimization in this study. The mathematical formulation of the mentioned objective function is expressed by Eq. (1). In this equation, the first term is related to the cost of imported electricity from the upstream grid. The second, third, and fourth terms are related to the marginal costs of the LEM participants. In the end, the fifth term is related to the operating cost of the CHP units.

$$Min \sum_{t} \left\{ P_g(t)\lambda_g(t) + \sum_{dg} P_{DG}(dg, t)\lambda_{DG}(dg, t) \right.$$

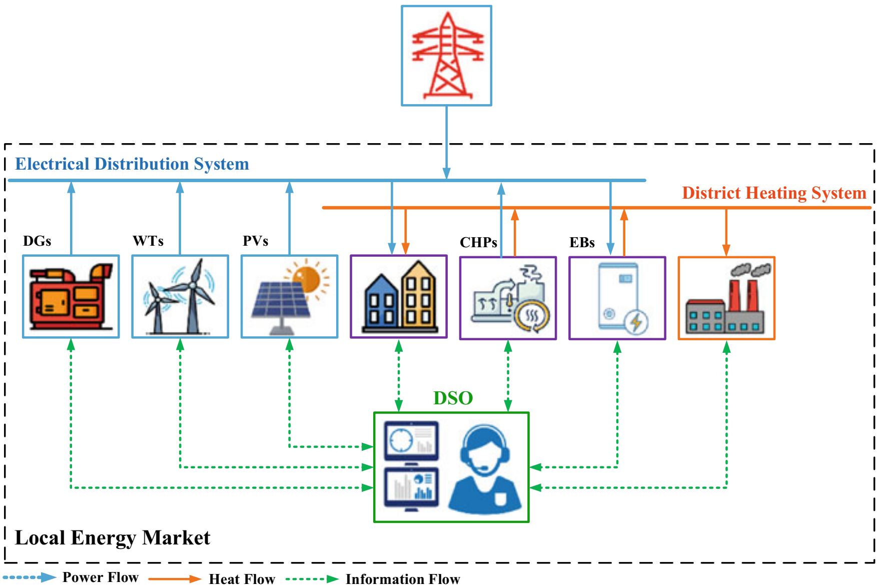


Fig. 1 Schematic structure of the proposed LEM framework

$$+\sum_{wt} P_{WT}(wt,t)\lambda_{WT}(wt,t) + \sum_{pv} P_{PV}(pv,t)\lambda_{PV}(pv,t)$$
$$\left. + \sum_{ch} G_{CHP}(ch,t)\lambda_{gas}(t) \right\} \quad (1)$$

The considered objective function is subject to a set of linear technical as well as operational constraints, as follows:

$$P_g(t) = \sum_{j:(i,j)\in\Omega_e} \left\{ V_{nom}\left[\Delta V(i,t) - \Delta V(j,t)\right] g_{ij} - V_{nom}^2\left[\theta(i,t) - \theta(j,t)\right] b_{ij} \right\}, \alpha(i,t)$$
$$\forall i = 1, t \quad (2)$$

$$\sum_{dg:(dg,i)\in\Omega_{DG}} P_{DG}(dg,t) + \sum_{wt:(wt,i)\in\Omega_{WT}} P_{WT}(wt,t)$$
$$+ \sum_{pv:(pv,i)\in\Omega_{PV}} P_{PV}(pv,t) + \sum_{ch:(ch,i)\in\Omega_{CHP}} P_{CHP}(ch,t)$$
$$- \sum_{eb:(eb,i)\in\Omega_{EB}} P_{EB}(eb,t) - \sum_{ed:(ed,i)\in\Omega_{ED}} P_{ED}(ed,t)$$
$$= \sum_{j:(i,j)\in\Omega_e} \left\{ V_{nom}\left[\Delta V(i,t) - \Delta V(j,t)\right] g_{ij} - V_{nom}^2\left[\theta(i,t) - \theta(j,t)\right] b_{ij} \right\}, \alpha(i,t)$$
$$\forall i \neq 1, t \quad (3)$$

$$-P_{ij}^{max} \leq \left\{ V_{nom}\left[\Delta V(i,t) - \Delta V(j,t)\right] g_{ij} - V_{nom}^2\left[\theta(i,t) - \theta(j,t)\right] b_{ij} \right\}$$
$$\leq P_{ij}^{max}, \quad \forall (ij) \in \Omega_e, t \quad (4)$$

$$-\vartheta V_{nom} \leq \Delta V(i,t) \leq \vartheta V_{nom}, \quad \forall i,t \quad (5)$$

$$V(i,t) = V_{nom} + \Delta V(i,t), \quad \forall i,t \quad (6)$$

$$-\pi \leq \theta(i,t) \leq \pi, \quad \forall i,t \quad (7)$$

Equations (2)–(7) demonstrate technical constraints of the EDS that model the linear AC power flow in this work (Santos et al. 2017). Accordingly, the power balance of the electricity sector is expressed by Eqs. (2) and (3), and their dual variables or shadow prices are specified after the colon. The LEM clearing price or distribution locational marginal price of electricity is achieved from the shadow prices of the power balance constraints (O'Neill et al. 2005). Moreover, the power flow in distribution lines, as well as voltage deviation of nodes, are limited by Eqs. (4)

and (5), respectively. Also, Eq. (6) represents the voltage magnitude of nodes. Finally, the voltage angle of each node is restricted by Eq. (7).

$$0 \le P_{DG}(dg, t) \le Q_{DG}(dg, t), \quad \forall dg, t \tag{8}$$

$$0 \le P_{WT}(wt, t) \le Q_{WT}(wt, t), \quad \forall wt, t \tag{9}$$

$$0 \le P_{PV}(pv, t) \le Q_{PV}(pv, t), \quad \forall pv, t \tag{10}$$

$$G_{CHP} = P_{CHP}(ch, t)/HV_{gas}\eta CHP - E(ch), \quad \forall ch, t \tag{11}$$

$$H_{CHP}(ch, t) \le P_{CHP}(ch, t)HPR(ch)\eta_{CHP-H}(ch), \quad \forall ch, t \tag{12}$$

$$P_{CHP}^{\min}(ch) \le P_{CHP}(ch, t) \le P_{CHP}^{\max}(ch), \quad \forall ch, t \tag{13}$$

$$P_{EB}^{\min}(eb) \le P_{EB}(eb, t) \le P_{EB}^{\max}(eb), \quad \forall eb, t \tag{14}$$

$$H_{EB}(eb, t) = P_{EB}(eb, t)\eta_{EB-H}(eb), \quad \forall eb, t \tag{15}$$

On the other hand, Eqs. (8)–(15) display operational constraints of the existing energy resources in the IEHN. In this regard, inequalities (8), (9), and (10) restrict DGs, WTs, and PVs' offers in the LEM to their maximum quantity offers, respectively. The relation between the gas flows to the CHP units and their output powers is determined by Eq. (11). Furthermore, the relation between the output heat and the output power of CHPs is defined by Eq. (12). Ultimately, the CHPs' output powers are confined to their minimum and maximum values by Eq. (13) (Li et al. 2022). As stated, EBs are P2H elements that consume electricity to produce thermal energy. In this context, the power consumption of these units is limited by Eq. (14), and their generated heat is displayed by Eq. (15) (Wu et al. 2021).

DHSs contain supply pipelines that transfer hot water from heat sources to HDs, and return pipelines that return back cold water from HDs to heat sources (Tan et al. 2022). Normally, these networks are controlled in four different modes, including constant-flow-constant-temperature, constant-flow-variable-temperature, variable-flow-constant-temperature, and variable-flow-variable-temperature. Equations (16)–(25) depict technical constraints of the DHS that model the constant-flow-variable-temperature strategy in this work (Pan et al. 2017). Notably, as non-linear hydraulic terms are eliminated in the considered model, the ultimate thermal model is linear.

$$\sum_{ch:(ch,n)\in\Omega_{CHP}} H_{CHP}(ch, t) + \sum_{eb:(eb,n)\in\Omega_{EB}} H_{EB}(eb, t)$$

$$= C_W m(n,t)\{T_S(n,t) - T_R(n,t)\}, \quad \forall n \in \Omega_{HS}, t \tag{16}$$

$$\sum_{hd:(hd,n)\in\Omega_{HD}} H_{HD}(hd,t) = C_W m(n,t)\{T_S(n,t) - T_R(n,t)\}, \beta(n,t)$$
$$\forall n \in \Omega_{HES}, t \tag{17}$$

$$T_{S,out}(nm,t) - T_{Amb}(t) = \left\{T_{S,in}(nm,t) - T_{Amb}(t)\right\} e^{\frac{-\kappa L_{nm}}{C_W m_S(nm,t)}}, \quad \forall nm \in \Omega_{hS}, t \tag{18}$$

$$T_{R,out}(nm,t) - T_{Amb}(t) = \left\{T_{R,in}(nm,t) - T_{Amb}(t)\right\} e^{\frac{-\kappa L_{nm}}{C_W m_R(nm,t)}}, \quad \forall nm \in \Omega_{hR}, t \tag{19}$$

$$T_S^{\min} \le T_S(n,t) \le T_S^{\max}, \quad \forall n, t \tag{20}$$

$$T_R^{\min} \le T_R(n,t) \le T_R^{\max}, \quad \forall n, t \tag{21}$$

$$T_{S,in}(nm,t) = T_S(n,t), \forall nm \in \Omega^n_{hS-B}, n, t \tag{22}$$

$$T_{R,in}(nm,t) = T_R(n,t), \forall nm \in \Omega^n_{hR-B}, n, t \tag{23}$$

$$\sum_{nm\in\Omega^n_{hS-E}} \left\{m_S(nm,t)T_{S,out}(nm,t)\right\} = T_S(n,t) \sum_{nm\in\Omega^n_{hS-B}} m_S(nm,t), \quad \forall n, t \tag{24}$$

$$\sum_{nm\,\in\,\Omega^n_{hR-E}} \left\{m_R(nm,t)T_{R,out}(nm,t)\right\} = T_R(n,t) \sum_{nm\,\in\,\Omega^n_{hR-B}} m_R(nm,t), \ \forall n, t \tag{25}$$

Accordingly, Eqs. (16) and (17) show the heat balance of the system in heat stations (HSs) that are equipped with heat sources and heat exchanger stations (HESs) that are modeled as HDs, respectively (Li et al. 2015). The dual variable or shadow price of Eq. (17) is presented after the colon that specifies the LEM clearing price or distribution locational marginal price of heat. The temperature drop caused by heat loss in supply and return pipelines is represented by Eqs. (18) and (19), respectively. Inequalities (20) and (21) restrict the temperature of nodes in supply and return pipelines. Equations (22) and (23) ensure that the inlet temperature of supply and return pipelines is equal to the nodes' temperature. Finally, according to Eqs. (24) and (25), the nodes' temperature is computed as the mixture temperature of mass flows entering the nodes.

3 Case Study

In this section, the LEM clearing model is applied to an IEHN, including a 13-node EDS (Ali et al. 2012) and a 4-node DHS. The single-line diagram of this integrated system is depicted in Fig. 2.

Accordingly, the EDS contains two DGs, one WT, and one PV at nodes 10, 13, 12, and 9, respectively. The EDS nodes 6 and 8 are connected to the HS of the DHS, which is equipped with one CHP and one EB. The maximum quantity offers of the LEM participants as well as technical specifications of the existing P2H elements are provided in Tables 1 and 2, respectively.

Offer prices of the available market participants, as well as locational marginal prices of PCC, are illustrated in Fig. 3. The electric and heat demand profiles of the

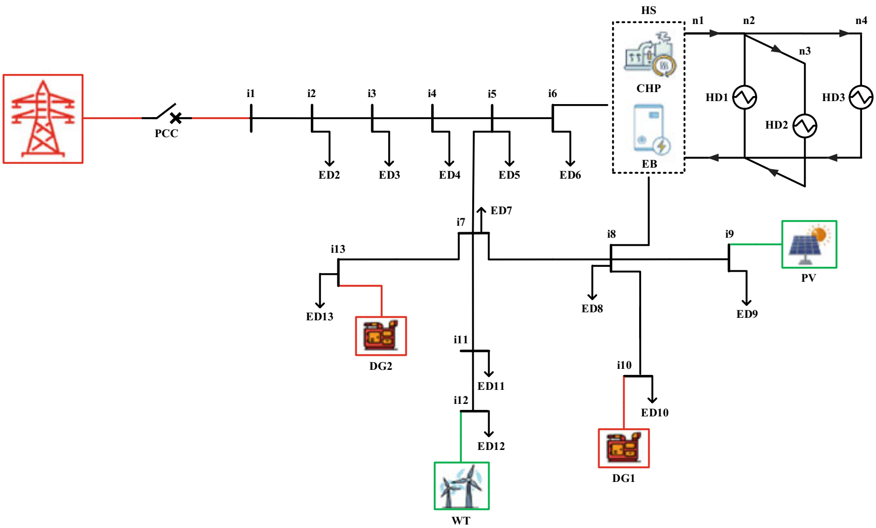


Fig. 2 Studied IEHN

Table 1 Maximum offers of LEM participants

# Unit	Maximum quantity offers (kW)
DG 1	3000
DG 2	2000
WT	2000
PV	1500

Table 2 Characteristics of P2H units

# Unit	Minimum power (kW)	Maximum power (kW)	Heat efficiency (%)	Electricity efficiency (%)	Heat-to-Power ratio
CHP	200	2000	55	45	1
EB	0	500	80	–	–

studied IEHN are displayed in Fig. 4. Furthermore, the peak demand of the system in each node is expressed in Table 3.

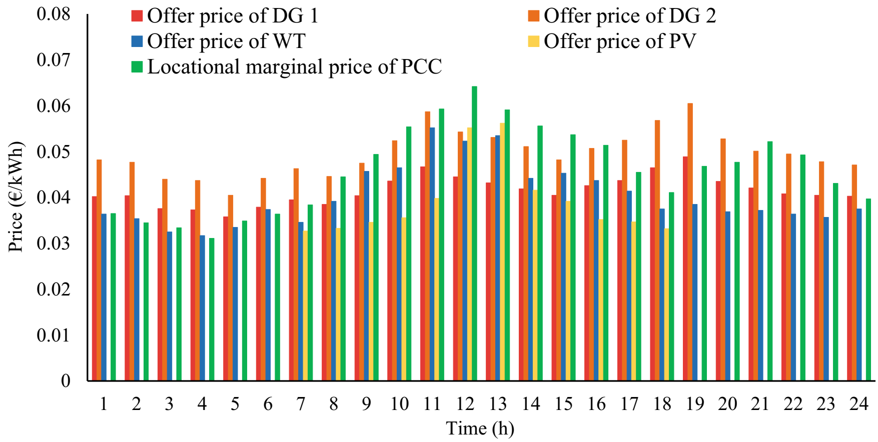


Fig. 3 Prices in the LEM clearing process

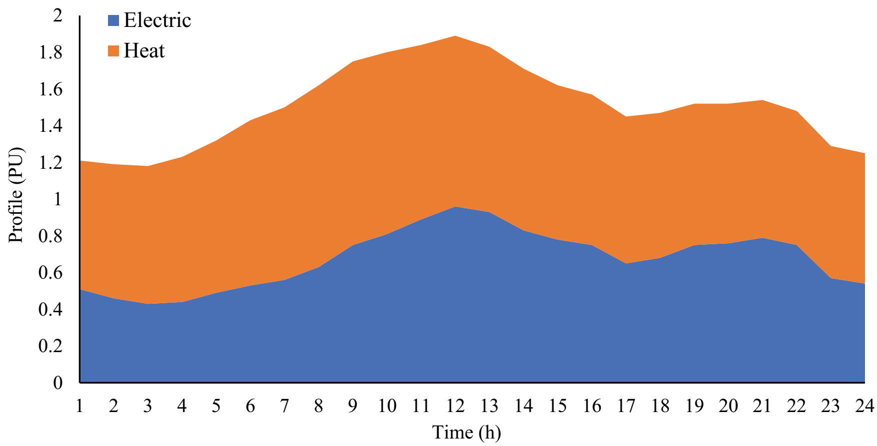


Fig. 4 Demand profiles of the IEHN

Table 3 Peak demand of the IEHN

# Node	1	2	3	4	5	6	7	8	9	10	11	12	13
Electric demand (kW)	0	890	628	1112	636	474	1342	920	766	662	690	1292	1124
Heat demand (kW)	0	450	400	450	–	–	–	–	–	–	–	–	–

On the other hand, it is assumed that the temperature of supply pipelines in the DHS varies between 60 and 100 °C, while the temperature of its return pipelines varies between 20 and 60 °C. In addition, the ambient temperature is 10 °C, specific heat capacity of water is 4.182 J/g °C, and heat transfer coefficient of pipelines is 0.00455 W/cm °C (Shabanpour-Haghighi and Seifi 2016).

In the end, the natural gas price is considered a three-tariff price, and the heat value of natural gas is presumed to be 11.7 kWh/m^3.

Accepted offers of the LEM participants, namely DGs, WT, and PV, as well as the output power of P2H elements, namely CHP and EB, are demonstrated in Fig. 5. In this figure, the DSO's imported electricity from the upstream grid is displayed as well. Notably, the line graph shows the system's whole ED during the studied day.

As shown, the entire produced and imported powers have procured the required powers of the EB and ED. On the other hand, based on Figs. 3 and 5, since the offer prices of WT and PV are lower than the offer prices of DGs and locational marginal prices of PCC in most hours of the day, their maximum quantity offers have been accepted in the LEM clearing process.

The output heat of P2H elements, i.e., CHP and EB, are depicted in Fig. 6. Similarly, the line graph shows the system's whole HD during the studied day.

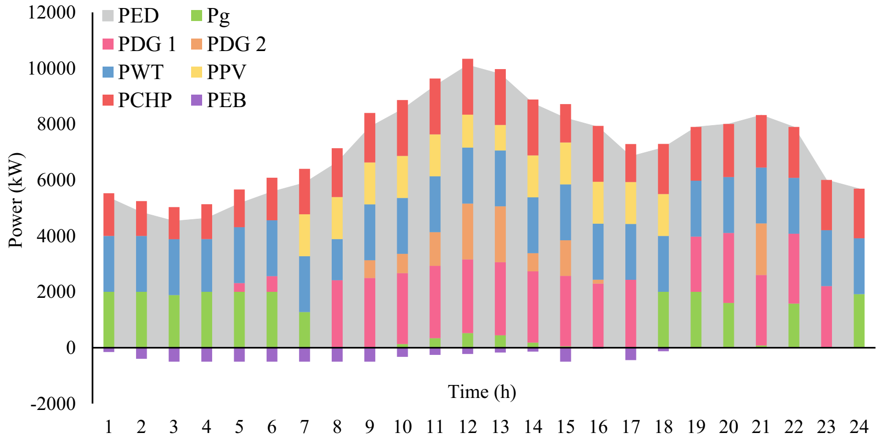


Fig. 5 Optimal operating points of power resources in the LEM

Based on the DHS modeling in the previous section and Fig. 6, it is observed that the generated heat at each hour has procured not only the HD but also heat loss in supply and return pipelines. Also, since the electricity price is low in the early hours of the day, the DSO has preferred to transform the power to heat by the available EB and satisfy the peak HD of the system.

The amount of gas consumption by the available CHP unit in the IEHN, as well as the three-tariff natural gas price, are depicted in Fig. 7. Clearly, during the peak of electric and heat demands, the considered CHP has consumed the highest amount of gas.

Temporal and spatial variation of distribution locational marginal price of electricity in the LEM clearing procedure is presented in Fig. 8.

The generic temporal analysis shows that by increasing the ED, the distribution locational marginal price is increased as well. On the other hand, according to the spatial analysis, the increase in the ED during peak hours leads to congestion in the EDS, which changes the LEM clearing price at different nodes.

To better investigate the spatial level, distribution locational marginal prices of the EDS nodes at hours 12 and 21 are represented in Fig. 9.

Based on Fig. 9, at hours 12, distribution locational marginal prices at nodes 1 to 4 are equal to locational marginal prices of PCC. Due to the congestion in line 4–5, the rest of the nodes' marginal prices have been affected by the offer prices of the LEM participants. In this context, PV as a marginal producer has determined distribution locational marginal prices at nodes 5–9 and 11–13. The marginal price of node 10 has resulted from offer price of DG 1, which is located at this node. The important point here is that while the offer price of DG 1 is lower than the offer price of PV, this unit has not been able to affect other nodes' marginal prices due to the congestion

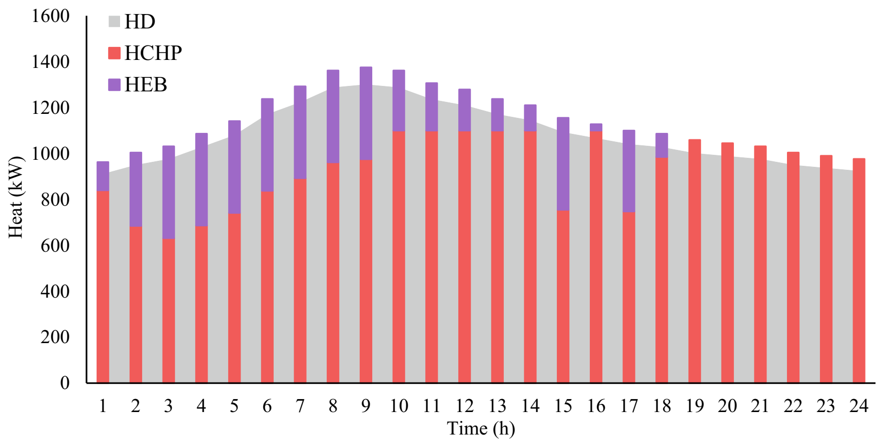


Fig. 6 Optimal operating points of heat resources in the LEM

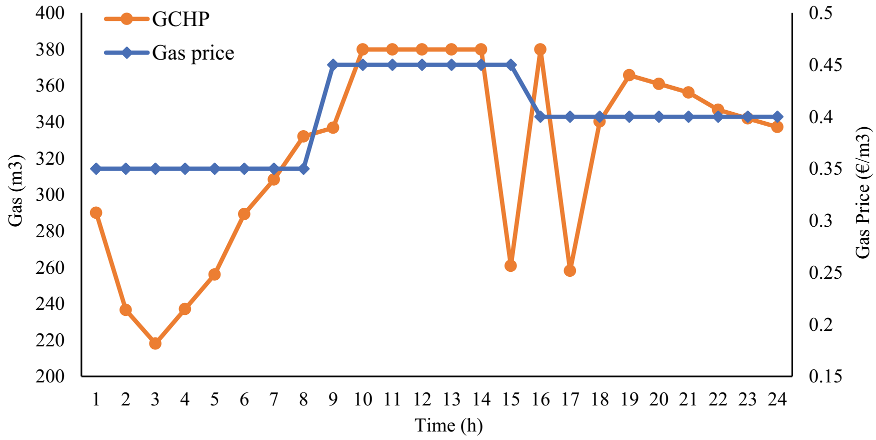


Fig. 7 CHP's gas consumption and natural gas price

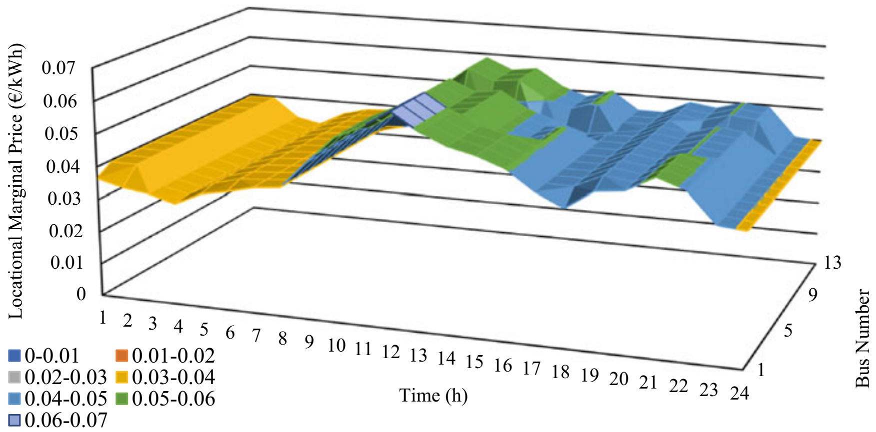


Fig. 8 Variation of distribution locational marginal price of electricity

in line 8–10. Similarly, at hour 21, distribution locational marginal prices at nodes 1–4 are equal to locational marginal prices of PCC. Because of the congestion in line 4–5, distribution locational marginal prices at nodes 5–9 and 11–13 have been determined by DG 2 as a marginal producer. Also, because of congestion in line 8–10, DG 1 has only been able to impact the marginal price of node 10.

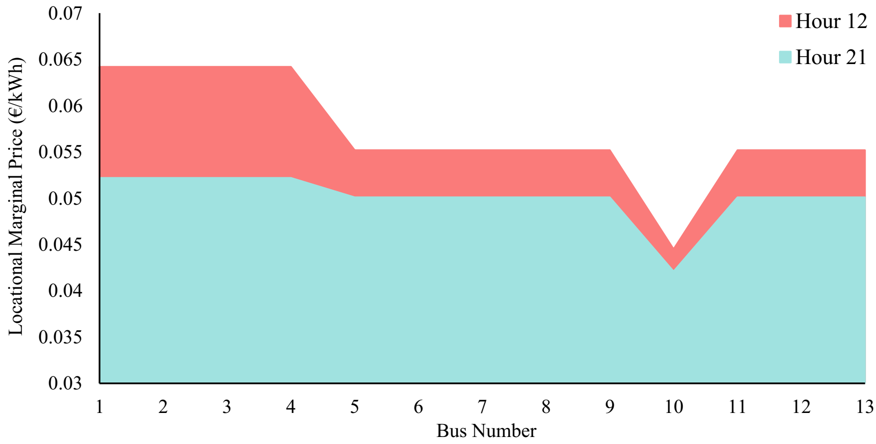


Fig. 9 Distribution locational marginal prices at hours 12 and 21

4 Conclusion

The high penetration of renewable energies has increased the need for flexibility in power distribution systems. Recently, the coupling of EDSs and DHSs in the form of IEHNs has been raised as one of the promising solutions for flexibility provision. Nonetheless, establishing IEHNs and optimally operating them requires the development of an appropriate and practical market-based mechanism. In this context, this chapter modeled a LEM for the integration of the EDS and DHS at the distribution level. The considered LEM was cleared by the DSO using a centralized one-sided auction to maximize social welfare. Then, the suggested LEM clearing model was applied to an IEHN under the technical constraints of both EDS and DHS. Output results specified that distribution locational marginal prices are affected by a set of factors, including the topology as well as demands of the network.

Acknowledgements Sara Haghifam would like to acknowledge the Fortum and Neste Foundation that supports research, education, and development in natural, technical, and economical sciences within the energy industry.

Appendix—GAMS Code

```
sets
t        Time              /t1*t24/
g        Upstream grid     /g1/
dg       DGs               /dg1*dg2/
wt       WT                /wt1/
pv       PV                /pv1/
ch       CHP               /ch1/
eb       EB                /eb1/
i        BusE              /i1*i13/
slack    Slack             /i1/
n        BusH              /n1*n4/
pS       pipSupply         /pS1*pS3/
pR       pipReturn         /pR1*pR3/
;
*---------------------------------------------------------------------------*
set
UpstreamgridConnectE(i,g)  / i1 . g1 /
DGsconectE(i,dg)  / i10 . dg1  i13 . dg2 /
WTconectE(i,wt) / i12 . wt1 /
PVconectE(i,pv)  / i9 . pv1 /
CHPconectE(i,ch)  / i6 . ch1 /
CHPconectH(n,ch)  / n1 . ch1 /
EBconectE(i,eb)  / i8 . eb1 /
EBconectH(n,eb)  / n1 . eb1 /
;
*---------------------------------------------------------------------------*
Table CHPdata(ch,*)
;
Table EBdata(eb,*)
;
Table OfferDGs(dg,t,*)
;
Table OfferWT(wt,t,*)
;
Table OfferPV(pv,t,*)
;
*---------------------------------------------------------------------------*
table BusDataE(i,*)
;
table LoadE(t,*)
;
parameter Eload
;
Eload(t)=sum(i,  BusDataE(i,'peakE')* LoadE(t,'demandE'))
;
display Eload
;
*---------------------------------------------------------------------------*
alias (i,j)
;
set conexE
/ i1  . i2
  i2  . i3
  i3  . i4
  i4  . i5
  i5  . i6
  i5  . i7
  i7  . i8
  i7  . i11
  i7  . i13
  i8  . i9
  i8  . i10
  i11 . i12 /
;
conexE(i,j)$(conexE(j,i))=1
```

```
;
Table branchE (i,j,*)
            g         b          limit
i1  . i2
i2  . i3
i3  . i4
i4  . i5
i5  . i6
i5  . i7
i7  . i8
i7  . i11
i7  . i13
i8  . i9
i8  . i10
i11 . i12
;
branchE(i,j,'b')$(branchE(i,j,'b')=0)=branchE(j,i,'b');
branchE(i,j,'g')$(branchE(i,j,'g')=0)=branchE(j,i,'g');
branchE(i,j,'Limit')$(branchE(i,j,'Limit')=0)=branchE(j,i,'Limit');
branchE(i,j,'b')$conexE(i,j)=branchE(i,j,'b');
branchE(i,j,'g')$conexE(i,j)=branchE(i,j,'g');
*---------------------------------------------------------------------------*
table BusDataH(n,*)
        peakH
n1
n2
n3
n4
;
table LoadH(t,*)
;
parameter Hload
;
Hload(t)=sum(n, BusDataH(n,'peakH')*LoadH(t,'demandH'))
;
*---------------------------------------------------------------------------*
table nodeH(n,t)
;
table pipSupply(pS,t)
;
table pipReturn(pR,t)
;
*---------------------------------------------------------------------------*
table landagrid(t,*)
;
*---------------------------------------------------------------------------*
Table landagas(t,*)
;
*---------------------------------------------------------------------------*
positive variables
Pg
Pdg
Pwt
Ppv
Peb
Pchp
Heb
Hchp
Gchp
Voltage
TemS
TemR
TemSOu
TemROu
TemSIn
TemRIn
variables
```

```
Pij
deltaV
teta
ObjFun
;
*---------------------------------------------------------------------------*
teta.up(i,t)=pi;
teta.lo(i,t)=-pi;
teta.fx(slack,t)=0;
pij.up(i,j,t)$((conexE(i,j)))=1*branchE(i,j,'Limit');
pij.lo(i,j,t)$((conexE(i,j)))=-1*branchE(i,j,'Limit')
;
*---------------------------------------------------------------------------*
scalars
Vnom          //
epsilon       //
TemA          //
TemSMin       //
TemSMax       //
TemRMin       //
TemRMax       //
Cw            //
Landa         //
HVgas         //
lenPip        //
;
*---------------------------------------------------------------------------*
equations
ObjectiveFunction
Eq1
Eq2
Eq3
Eq4
Eq5
Eq6
Eq7
Eq8
Eq9
Eq10
Eq11
Eq12
Eq13
Eq14
Eq15
Eq16
Eq17
Eq18
Eq19
Eq20
Eq21
Eq22
Eq23
Eq24
Eq25
Eq26
Eq27
Eq28
Eq29
Eq30
Eq31
Eq32
Eq33
Eq34
Eq35
Eq36
Eq37
Eq38
```

```
;
*----------------------------------------------------------------------------*
ObjectiveFunction..ObjFun=e=sum(t,  sum(g, Pg(g,t)*landagrid(t,'GridPrice'))
                          + sum(dg, Pdg(dg,t)*OfferDGs(dg,t,'landaDG'))
                          + sum(wt, Pwt(wt,t)*OfferWT(wt,t,'landaWT'))
                          + sum(pv, Ppv(pv,t)*OfferPV(pv,t,'landaPV'))
                          + sum(ch, Gchp(ch,t)*landagas(t,'GasPrice'))  )
;
*----------------------------------------------------------------------------*
Eq1(i,j,t)$conexE(i,j)..Pij(i,j,t)=e=Vnom*(deltaV(i,t)-deltaV(j,t))*branchE(i,j,'g')
                            -(Vnom**2)*branchE(i,j,'b')*(teta(i,t)-teta(j,t));
Eq2(i,t)..deltaV(i,t)=l=epsilon*Vnom;
Eq3(i,t)..deltaV(i,t)=g=-epsilon*Vnom;
Eq4(i,t)..Voltage(i,t)=e=Vnom+deltaV(i,t);
Eq5(i,t)$(ord(i)=1)..sum(g  $ UpstreamgridConnectE(i,g),  Pg(g,t))
              =e=sum(j$conexE(i,j),  Pij(i,j,t))
;
Eq6(i,t)$(ord(i)>1)..sum(dg  $ DGsconectE(i,dg),  Pdg(dg,t))
                +sum(wt $ WTconectE(i,wt),  Pwt(wt,t))
                +sum(pv $ PVconectE(i,pv),  Ppv(pv,t))
                +sum(ch $ CHPconectE(i,ch),  Pchp(ch,t))
                -sum(eb $ EBconectE(i,eb),  Peb(eb,t))
                -(BusDataE(i,'peakE')*LoadE(t,'demandE'))
                =e=sum(j$conexE(i,j),  Pij(i,j,t))
;
*----------------------------------------------------------------------------*
Eq7(dg,t)..Pdg(dg,t)=l=OfferDGs(dg,t,'DGmax');
Eq8(dg,t)..Pdg(dg,t)=g=OfferDGs(dg,t,'DGmin');
Eq9(wt,t)..Pwt(wt,t)=l=OfferWT(wt,t,'WTmax');
Eq10(wt,t)..Pwt(wt,t)=g=OfferWT(wt,t,'WTmin');
Eq11(pv,t)..Ppv(pv,t)=l=OfferPV(pv,t,'PVmax');
Eq12(pv,t)..Ppv(pv,t)=g=OfferPV(pv,t,'PVmin')
;
*----------------------------------------------------------------------------*
Eq13(ch,t)..Gchp(ch,t)=e=Pchp(ch,t)/(HVgas*CHPdata(ch,'EtaECHP'));
Eq14(ch,t)..Hchp(ch,t)=l=Pchp(ch,t)*CHPdata(ch,'HPR')*CHPdata(ch,'EtaHCHP');
Eq15(ch,t)..Pchp(ch,t)=l=CHPdata(ch,'PCHPmax');
Eq16(ch,t)..Pchp(ch,t)=g=CHPdata(ch,'PCHPmin');
Eq17(eb,t)..Heb(eb,t)=e=Peb(eb,t)*EBdata(eb,'EtaHEB');
Eq18(eb,t)..Peb(eb,t)=l=EBdata(eb,'PEBmax');
Eq19(eb,t)..Peb(eb,t)=g=EBdata(eb,'PEBmin')
;
*----------------------------------------------------------------------------*
Eq20(n,t)$(ord(n)=1)..sum(ch  $ CHPconectH(n,ch),  Hchp(ch,t))
                 +sum(eb $ EBconectH(n,eb),  Heb(eb,t))
                 =e=Cw*nodeH(n,t)*(TemS(n,t)-TemR(n,t));
Eq21(n,t)$(ord(n)>1)..(BusDataH(n,'peakH')*LoadH(t,'demandH'))
                 =e=Cw*nodeH(n,t)*(TemS(n,t)-TemR(n,t));
Eq22(n,t)..TemS(n,t)=l=TemSMax;
Eq23(n,t)..TemS(n,t)=g=TemSMin;
Eq24(n,t)..TemR(n,t)=l=TemRMax;
Eq25(n,t)..TemR(n,t)=g=TemRMin;
Eq26(pS,t)..TemSOu(pS,t)-TemA=e=(TemSIn(pS,t)-TemA)*exp(-(Landa*lenPip)/(Cw*pipSupply(pS,t)));
Eq27(pR,t)..TemROu(pR,t)-TemA=e=(TemRIn(pR,t)-TemA)*exp(-(Landa*lenPip)/(Cw*pipReturn(pR,t)));
Eq28(pS,n,t)$(ord(n)=2  and ord(pS)=2)..TemSIn(pS,t)=e=TemS(n,t);
Eq29(pS,n,t)$(ord(n)=2  and ord(pS)=3)..TemSIn(pS,t)=e=TemS(n,t);
Eq30(n,t)$(ord(n)=2)..sum(pS   $  (ord(pS)=1),   TemSOu(pS,t)*pipSupply(pS,t))=e=TemS(n,t)*(sum(pS   $  (ord(pS)=2),
pipSupply(pS,t))
                                                   +sum(pS $ (ord(pS)=3),  pipSupply(pS,t))
                                                   +nodeH(n,t))
;
Eq31(pR,n,t)$(ord(n)=2  and ord(pR)=1)..TemRIn(pR,t)=e=TemR(n,t);
Eq32(n,t)$(ord(n)=2)..     TemR(n,t)*sum(pR     $     (ord(pR)=1),     pipReturn(pR,t))=e=sum(pR     $     (ord(pR)=2),
TemROu(pR,t)*pipReturn(pR,t))
                                             +sum(pR  $ (ord(pR)=3),  TemROu(pR,t)*pipReturn(pR,t))
                                             +TemR(n,t)*nodeH(n,t)
;
```

```
Eq33(pS,n,t)$(ord(n)=1  and ord(pS)=1)..TemSIn(pS,t)=e=TemS(n,t);
Eq34(pS,n,t)$(ord(n)=3  and ord(pS)=2)..TemSOu(pS,t)=e=TemS(n,t);
Eq35(pS,n,t)$(ord(n)=4  and ord(pS)=3)..TemSOu(pS,t)=e=TemS(n,t);
Eq36(pR,n,t)$(ord(n)=1  and ord(pR)=1)..TemROu(pR,t)=e=TemR(n,t);
Eq37(pR,n,t)$(ord(n)=3  and ord(pR)=2)..TemRIn(pR,t)=e=TemR(n,t);
Eq38(pR,n,t)$(ord(n)=4  and ord(pR)=3)..TemRIn(pR,t)=e=TemR(n,t)
;
*---------------------------------------------------------------------------*
Model LEM  /all/;
option optca=0 , optcr=0;
option mip=cplex;
Solve LEM  use mip min  ObjFun;
execute_unload "LEM.gdx"
;
```

References

Ahn H, Miller W, Sheaffer P, Tutterow V, Rapp V (2021) Opportunities for installed combined heat and power (CHP) to increase grid flexibility in the US. Energy Policy 157:112485

Ali A, Mohsen D, Farzad R, Majid D (2012) Optimal DG placement in distribution networks using intelligent systems. Energy Power Eng 2012

Bernath C, Deac G, Sensfuß F (2021) Impact of sector coupling on the market value of renewable energies–a model-based scenario analysis. Appl Energy 281:115985

Bloess A, Schill W-P, Zerrahn A (2018) Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl Energy 212:1611–1626

Brolin M, Pihl H (2020) Design of a local energy market with multiple energy carriers. Int J Electr Power Energy Syst 118:105739. https://doi.org/10.1016/j.ijepes.2019.105739

Cao Y, Wei W, Wu L, Mei S, Shahidehpour M, Li Z (2019) Decentralized operation of interdependent power distribution network and district heating network: a market-driven approach. IEEE Trans Smart Grid 10(5):5374–5385. https://doi.org/10.1109/TSG.2018.2880909

Chen Y, Wei W, Liu F, Sauma EE, Mei S (2019) Energy trading and market equilibrium in integrated heat-power distribution systems. In: 2019 IEEE power & energy society general meeting (PESGM), p 1. https://doi.org/10.1109/PESGM40551.2019.8973984

Chen H et al (2021) Local energy market clearing of integrated ADN and district heating network coordinated with transmission system. Int J Electr Power Energy Syst 125:106522. https://doi.org/10.1016/j.ijepes.2020.106522

David A, Mathiesen BV, Averfalk H, Werner S, Lund H (2017) Heat roadmap Europe: large-scale electric heat pumps in district heating systems. Energies 10(4):578

Davoudi M, Moeini-Aghtaie M (2022) Local energy markets design for integrated distribution energy systems based on the concept of transactive peer-to-peer market. IET Gener Transm Distrib 16(1):41–56

Du X, Ma X, Liu J, Wu S, Wang P (2022) Operation optimization of auxiliary electric boiler system in HTR-PM nuclear power plant. Nucl Eng Technol

Haghifam S, Dadashi M, Laaksonen H, Zare K, Shafie-khah M (2022) A two-stage stochastic bilevel programming approach for offering strategy of DER aggregators in local and wholesale electricity markets. IET Renew Power Gener

Huynh T, Schmidt F, Thiem S, Kautz M, Steinke F, Niessen S (2022) Local energy markets for thermal-electric energy systems considering energy carrier dependency and energy storage systems. Smart Energy 6:100065. https://doi.org/10.1016/j.segy.2022.100065

Kahn AE, Cramton PC, Porter RH, Tabors RD (2001) Uniform pricing or pay-as-bid pricing: a dilemma for California and beyond. Electr J 14(6):70–79

Khorasany M, Mishra Y, Ledwich G (2018) Market framework for local energy trading: a review of potential designs and market clearing approaches. IET Gener Transm Distrib 12(22):5899–5908

Kirkerud JG, Bolkesjø TF, Trømborg E (2017) Power-to-heat as a flexibility measure for integration of renewable energy. Energy 128:776–784
Li Z, Wu W, Shahidehpour M, Wang J, Zhang B (2015) Combined heat and power dispatch considering pipeline energy storage of district heating network. IEEE Trans Sustain Energy 7(1):12–22
Li Y, Wang J, Zhang Y, Han Y (2022) Day-ahead scheduling strategy for integrated heating and power system with high wind power penetration and integrated demand response: a hybrid stochastic/interval approach. Energy 253:124189
O'Neill RP, Sotkiewicz PM, Hobbs BF, Rothkopf MH, Stewart WR Jr (2005) Efficient market-clearing prices in markets with nonconvexities. Eur J Oper Res 164(1):269–285
Pan Z, Guo Q, Sun H (2017) Feasible region method based integrated heat and electricity dispatch considering building thermal inertia. Appl Energy 192:395–407
Santos SF, Fitiwi DZ, Shafie-Khah M, Bizuayehu AW, Catalão JPS (2017) Optimal sizing and placement of smart-grid-enabling technologies for maximizing renewable integration. In: Smart energy grid engineering. Elsevier, pp 47–81
Shabanpour-Haghighi A, Seifi AR (2016) Effects of district heating networks on optimal energy flow of multi-carrier systems. Renew Sustain Energy Rev 59:379–387
Skov IR, Schneider N, Schweiger G, Schöggl J-P, Posch A (2021) Power-to-X in Denmark: an analysis of strengths, weaknesses, opportunities and threats. Energies 14(4):913
Tan J, Wu Q, Zhang M (2022) Strategic investment for district heating systems participating in energy and reserve markets using heat flexibility. Int J Electr Power Energy Syst 137:107819
Wang N, Liu Z, Heijnen P, Warnier M (2022) A peer-to-peer market mechanism incorporating multi-energy coupling and cooperative behaviors. Appl Energy 311:118572. https://doi.org/10.1016/j.apenergy.2022.118572
Wu Q, Tan J, Zhang M, Jin X, Turk A (2021) Chapter 6—Adaptive robust energy and reserve co-optimization of an integrated electricity and heating system considering wind uncertainty. In: Wu Q, Tan J, Jin X, Zhang M, Turk A (eds) Optimal operation of integrated multi-energy systems under uncertainty. Elsevier, pp 145–170. https://doi.org/10.1016/C2020-0-01519-7
Zhang M, Wu Q, Wen J, Pan B, Qi S (2020) Two-stage stochastic optimal operation of integrated electricity and heat system considering reserve of flexible devices and spatial-temporal correlation of wind power. Appl Energy 275:115357
Zhang M, Wu Q, Wen J, Lin Z, Fang F, Chen Q (2021) Optimal operation of integrated electricity and heat system: a review of modeling and solution methods. Renew Sustain Energy Rev 135:110098