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Renewable and Sustainable Energy Reviews 165 (2022) 112569

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Challenges for large-scale Local Electricity Market implementation reviewed from the stakeholder perspective☆

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ARTICLE INFO

Keywords:
Stakeholder
Local Electricity Market
Framework
Market system
Deviation
Baselining
Human decisions
Market effectiveness
Data privacy

ABSTRACT

Research simulations and real-life pilots tested many different Local Electricity Market (LEM) applications and methods and have demonstrated that LEMs can solve problems in the distribution grid caused by the energy transition while allowing broader market participation. Significant progress on LEM development has been made, but challenges could nonetheless exist between LEM research and large-scale implementation.

Simulations and pilots occur in controlled environments and can, therefore, ignore LEM stakeholder requirements, making it likely that there are still challenges between LEM research and large-scale implementation. It is, therefore, essential to look at challenges between LEM research and implementation from the stakeholder's perspective while considering all requirements.

This study aims to find the existing challenges between LEM research and large-scale implementation by first determining the stakeholders of LEMs and their requirements for LEM implementation. Next, using these requirements to find state-of-the-art literature on LEMs to create an overview of these studies. Finally, to find existing challenges between LEM research and implementation, the LEMs in the overview are analyzed and compared to the stakeholder requirements and power system and market aspects four separate times.

The necessity of using a local energy market framework with a clearly defined market system, the lack of clear responsibilities for and fairness of subsequent settlement of deviations, the absence of consideration for data privacy and the reduced LEM effectiveness due to human decisions were determined to be challenges that currently stand between LEM research and large-scale LEM implementation.

1. Introduction

The electricity grid is undergoing a significant change from a central organization to a decentral organization because power generation is shifting from large and centrally placed power plants to smaller and more distributed energy resources. This shift is caused by the energy transition, where fossil fuels make way for cleaner renewable energy. Worldwide, the installed renewable energy generation capacity has been increasing for years [1]. In the Netherlands, for example, the production of green electricity has risen by 40% in 2020 [2]. However, other Distributed Energy Resources (DERs) such as Electric Vehicles (EVs), heat pumps, and batteries are making their way to consumers and will significantly increase the power consumption in the distribution grid. This shift to decentral generation and increase in local electricity consumption made, among others, the European Union (EU) calls for more local participation of prosumers in managing the electricity grid [3].

Local participation could provide electricity markets that allow the Distribution System Operators (DSOs) to address potential issues such as congestion management. In the form of a local market, a transactive energy system, an approach to energy management that combines market-based interactions with the operation of distribution grids, is a solution to facilitate the energy transition and call for participation. However, these systems come in many forms and use multiple definitions.

In this study, all different forms of transactive energy systems that operate in or address issues of the distribution grid are, for simplicity and continuity, considered local electricity markets (LEMs), which can have multiple forms and definitions. A broader definition of LEMs: LEMs allow for the trading of energy volumes by producers and consumers within the distribution grid among themselves or within existing electricity, wholesale, and balancing markets. [4].

A significant amount of research and pilots have been conducted that demonstrated various LEM capabilities. For example, in one study

☆ This document is the results of the Self-organizing Marketplace to realize a Self-Organized Sustainable Power System (AGILE) project funded by the Dutch Research Council (NWO), Netherlands.

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https://doi.org/10.1016/j.rser.2022.112569
Received 22 December 2021; Received in revised form 18 March 2022; Accepted 7 May 2022
Available online 24 May 2022
1364-0321/

Accronyms and SI Units

BRP	Balance Responsible Party
DER	Distributed Energy Resource
DSO	Distribution System Operator
EV	Electric Vehicle
LEM	Local Electricity Market
P2P	Peer-to-Peer
TSO	Transmission System Operator
kW	Kilowatt

[5] a LEM was capable of managing congested grid by including thermal overloading costs. GridFlex Heeten, a pilot in the Netherlands [6] demonstrated a LEM with a dynamic network tariff that allowed local consumers and producers to participate in the LEM regardless of available flexibility. Finally, in another study [7] a LEM brings the national balancing capabilities of the ancillary services to the distribution grid. These are examples of studies and pilots, and many more have been conducted and completed demonstrating more capabilities of LEMs.

With all these studies and pilots conducted, it seems like LEMs might be ready for real-life large-scale implementation. Meaning that LEMs can be implemented in entire regions/countries, become an integral part of existing electricity markets, and are part of the way electricity is bought and sold. For example, one study has implemented a peer-to-peer (P2P) clustering model that allows smaller LEMs to operate on a larger scale and overcomes issues such as scalability [8]. However, research can sometimes implement seamlessly in real-life on a large scale, but more often than not, unforeseen circumstances caused by real-life behavior or rules of stakeholders create new challenges that require re-evaluation and re-engineering. LEMs will likely follow a similar path for large-scale implementation because, for one, LEM research and simulation are conducted in controlled environments where participants are required, urged, or, for example, incentivized to participate. Pilots such as Gridflex Heeten or Quartierstrom [6,9] have a large and active group while it is likely that not every community will work similarly and, therefore, market participants will not always be as numerous and active.

Besides community numbers and activity, LEM participants collaborate in research simulations and pilots, but this will not be the case for real-life LEMs. Furthermore, even if people are collaborative, there is always the possibility for particular group behavior that can affect LEMs [10]. Considering the effect of market participants on LEMs, it also becomes essential to look at the impact of human decisions and their responsibility. Finally, pilots and researchers can neglect rules and regulations and operate in a sandbox environment, which is preferable for thinking outside the box. However, some rules and regulations are likely still in place when LEMs are implemented on a large scale, which will probably be gradual and not immediate. Accordingly, a LEM should be able to adapt to these conditions. The issues described above make it difficult to determine if LEMs are ready for large-scale implementation.

One can learn about this readiness by examining the challenges between LEM research and large-scale implementation and determining which challenges exist between the two, looking into potential solutions to these challenges, and determining what future LEM research should cover. As a significant number of studies and pilots have already been completed, the authors believe that by systematically analyzing the realization of stakeholder requirements in state-of-the-art LEMs, the existing challenges between research and implementation can be determined.

This study aims to find the existing challenges between LEM research and large-scale implementation by systematically reviewing and analyzing state-of-the-art LEM literature from the stakeholder's perspective. This literature review follows the following methodology: literature is selected and analyzed based on the perspective and analytically determined requirements of LEM stakeholders.

Literature reviews with a comparable topic have been conducted previously. In [11], for example, a detailed overview of current LEM methods is given, and both suggestions and future challenges of the used methods are given. However, the challenges of large-scale implementation are different and affect the used method. A comprehensive state-of-the-art LEM literature review, with a focus on PV, presented in [12] reviews current industry practices and market designs and concludes with several interesting implementation challenges of PV panels from a market algorithm perspective. However, non-industrial stakeholders and other DERs can cause different challenges and should also be included. One study mainly focuses on pilots in Denmark and the German-speaking countries of Europe and tries to determine how far along LEMs are in real-life pilot implementation [13]. Several challenges and obstacles that LEM pilots still need to face are given. Not every stakeholder and accompanying requirements are considered, and the focus is on small-scale pilot implementation. Finally, one relevant literature study with significant findings held an extensive survey among stakeholders to determine their perception of and motivation for energy flexibility of district heating [14]. However, besides being focused on district heating, which excludes most DERs, the literature on LEMs was used to create the survey while, to find the gaps between research and implementation, one can also look at LEM literature from the perspective of the stakeholders.

This study includes stakeholders from all over the power system and does not focus on one DER specifically. The literature is found using the perspective of these stakeholders and iterated over several different times from different angles. Regulations and policies standing between LEM research/pilots and large-scale implementation are not considered as these barriers would be different per country/region or per type of LEM and, furthermore, given that EU countries have agreed to the Clean Energy for Europe package [3], regulations and policies are expected to change in line with LEM needs. This work partly builds forth on a previous study using a different methodology [15]. The main contributions of this paper are:

- A qualitatively determined list of requirements from the stakeholder requirements for LEMs
- An overview of state-of-the-art LEMs based on stakeholder requirements
- Several challenges that stand between LEM research and large-scale implementation

The paper divides as follows: first, the methodology is explained further. Second, the requirements for future LEMs from each stakeholder's perspective are defined. Third, a literature overview with LEM studies found with these requirements is given. Fourth, local electricity market frameworks are explained. Fifth, the responsibility of deviations is discussed. Sixth, the effects of consumer behavior on LEMs are elaborated. Seventh, data privacy is discussed. Finally, a discussion on the research question and conclusion will be given.

2. Methods

Fig. 1 shows a schematic overview of the methodology used for the systematic literature review. The steps are described as follows:

1. The requirements of the stakeholders are determined. These stakeholders are the DSO, the Transmission System Operator (TSO), the prosumer, and the aggregator, and all will be discussed in more detail in Section 3. Furthermore, some requirements are general and not specific to one stakeholder or are valid for all stakeholders. These requirements are described in the other requirements subsection.

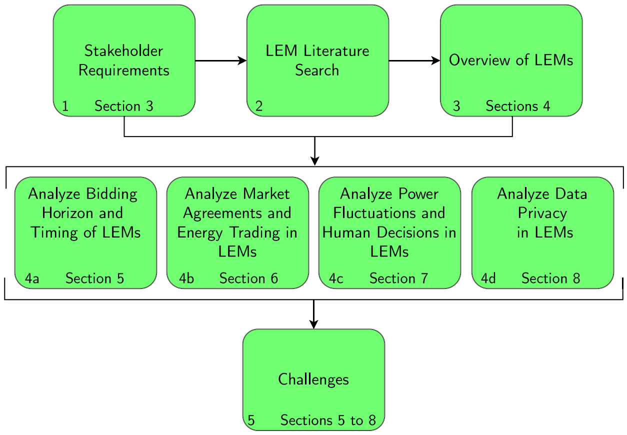

Fig. 1. Diagram showing the methodology used for the systematic literature review with the corresponding section in this paper in order of steps one to five.

2. LEM literature is found using the stakeholder requirements and comparable definitions as search terms in the IEEE and Elsevier databases to find state-of-the-art literature on LEMs. Several general LEM search terms such as smart, distribution, local, energy, flexibility, and market are also used. When discussing ancillary services in this study, the authors imply the ancillary services that handle reserve power. State of the art is determined to be from 2018 because this year gave researchers ample time to consider the EU's clean energy initiative [3]. Furthermore, the focus on challenges for large-scale implementation is from a European perspective and for large-scale implementation in the EU. However, LEM studies worldwide are still included as results from America or Asia could still be compelling and valuable for this study. This study focuses on electricity markets, but multi-energy studies can be included and validated based on their electricity market aspects. Community-based virtual power plants and microgrids are included and dissected based on their electricity market capabilities. Both LEM research and pilots are included, but LEM pilots tend to be made public by press releases and not scientific documentation. These press releases do not provide full details, so the authors have opted to only focus on scientific documentation. Extra effort is given to find scientific documentation on pilots, and pilots are included if the results have been published in a reputable scientific source such as IEEE and Elsevier.
3. An overview of state-of-the-art literature is made in Section 4 with the found literature to provide an overview and introduce LEM research that tries to satisfy the stakeholder requirements.
4. Next, while doing the literature review, various power system and market aspects of LEMs were found to be interesting in combination with the determined stakeholder requirements. These aspects of LEMs in the state-of-the-art overview are analyzed and compared to the stakeholder requirements. Where relevant, LEMs from the overview are reanalyzed on the power system and or market system aspect discussed to see the state-of-the-art on these aspects. This process is repeated four times. The LEM aspects analyzed and discussed are the bidding horizon and timing aspects in Section 5, the market agreement and energy trading aspects in Section 6, power fluctuations and human decisions in Section 7, and, lastly, data privacy in Section 8.
5. Finally, in Section 5 through 8, the remaining challenges between LEM research and implementation are determined after analyzing and comparing power system and market aspects to the stakeholder requirements and literature.

3. Stakeholder requirements

For conciseness, the authors identify four main stakeholders in LEMs most involved in exchanging local electricity/flexibility. The stakeholders considered in this study are the DSO, the TSO, the prosumers, and the aggregator. Also, a requirement section with general requirements is included as other requirements. This section will give, per stakeholder, a short elaboration on the stakeholder and determine the requirements per stakeholder. A requirement is defined as a functional or physical need that future LEMs aim to satisfy. The requirements will be summarized at the end to provide a clear overview of the determined requirements.

3.1. Transmission System Operator

The TSO operates the transmission system and is responsible for transmitting and balancing power and maintaining and developing the transmission infrastructure. The TSO is involved in the energy transition as the inconsistency and unpredictability of renewable energy, the decentralization of generation, and the increased consumption makes safely operating the transmission system difficult.

The TSO can benefit from LEMs because LEMs increase the pool of available flexibility from which the TSO can draw in the case of power imbalances. DERs contain the significant potential for providing ancillary services because DERs have three benefits over conventional generators: DERs ramp quicker, increased flexibility due to a diversity of DERs, and proximity of DERs to end-consumers reduces cable losses [16]. Therefore, future LEMs should allow participation in all the ancillary services markets, including redispatching, frequency balancing, and offering restoration reserves.

LEMs participating in the ancillary services of the TSO could, however, interfere with the DSO's operation and cause or intensify a congestion [17,18]. Hence, a requirement is that future LEMs do not cause operational conflicts between the two stakeholders.

3.2. Distribution System Operator

The DSO operates the distribution (low and medium voltage) grid and is responsible for maintaining and developing the infrastructure and ensuring that the power quality stays within the physical and regulatory limits of the distribution system. The energy transition brings large-scale generation to the distribution grid and reverses the power flow making it difficult to keep the distribution system within the regulatory operating limits. Furthermore, the energy transition brings a significant increase in power consumption due to, among others, EVs and heat pumps to the distribution grid, making component overloading a considerable problem. A LEM should help DSOs with congestion management, meaning preventing over and under voltages and reducing overloading of grid components. Furthermore, as with the TSO, the LEM should prevent operational conflicts between the two.

3.3. Aggregator

In Europe, the traditional energy supplier is divided into three roles: the energy supplier, the Balance Responsible Party (BRP), and the aggregator. Here, the energy supplier exchanges the electricity commodity with its customers (the prosumers), while the BRP is financially responsible for balancing trade volumes with the real-time energy exchange with the electricity grid. Finally, the aggregator accumulates flexibility from prosumers to sell it to the wholesale market, the TSO, or the DSO. As the authors look at exchanging electricity/flexibility through LEMs, and because the aggregator role takes care of this exchange in this triangle, the aggregator is considered to represent the combination of these three roles.

It is likely that some customers/prosumers do not want to or are not interested in participating in LEMs independently from an aggregator.

Therefore, to keep this potential flexibility available for the electricity grids and in order to allow prosumers to still benefit from participation, the aggregator should have the ability to participate in LEMs on behalf of its customers. Finally, the aggregator needs to safeguard the privacy of personal information by adhering to information, and privacy security standards [19].

3.4. Prosumer

A prosumer is a customer connected to the distribution grid that has any combination of consuming, producing, or energy storing devices at its premises. The traditional household consumer falls into this category but also customers with self-generation devices. Furthermore, the prosumer can also be seen as an EU citizen that must get more access to electricity markets directly or via some energy community. The prosumer is currently not involved in the electricity market but has a considerable flexibility potential expected to grow soon.

Prosumers must be able to participate in LEMs to use the full flexibility potential of prosumers. Therefore, inclusivity is an essential requirement for this stakeholder. The authors refer to equal access to the electricity markets for all players regardless of energy volumes exchanged with inclusivity. This access could be handled by themselves or through an aggregator. This way, the prosumer should gain access to the wholesale market, the DSO, and the TSO ancillary services. Finally, privacy is also a significant concern for prosumers and crucial for the trustworthiness of the markets and should be considered.

3.5. Other requirements

Other requirements for LEMs are based on other parties or are general requirements not specific to one stakeholder or valid for all. Due to the increase of market participants and the subsequent increase of deviations from agreed-upon bids/flexibility, all stakeholders need a precise determination of responsibility for the caused deviations. Furthermore, LEMs should be economically viable for all parties involved. Also, the market-clearing and transactions should be fair and explainable such that all stakeholders understand and feel confident to trade leading to faster adoption by DSOs and aggregators [20]. LEMs should be adaptable because developments and changes must be possible in the future [11]. Finally, LEMs should be resilient to human decisions such as market abuse and negative emergent/group behavior as this would reduce the effectiveness and trustworthiness of LEMs for all stakeholders [10,20].

A summary of the requirements per stakeholder can be found in Fig. 2

4. Literature overview

An overview of LEM literature that tries to satisfy stakeholder requirements can be made using the abovementioned requirements. The literature is found using the method described in Section 2, which resulted in forty-six LEM studies worldwide. The LEMs are divided into three categories: transactive and inclusive, congestion and ancillary services, privacy, responsibility, and others. These are the properties and requirements most often satisfied by the studied LEMs or give an example of a wide variety of applications. If a study is included in a particular category, it does not mean its requirements are limited to that category.

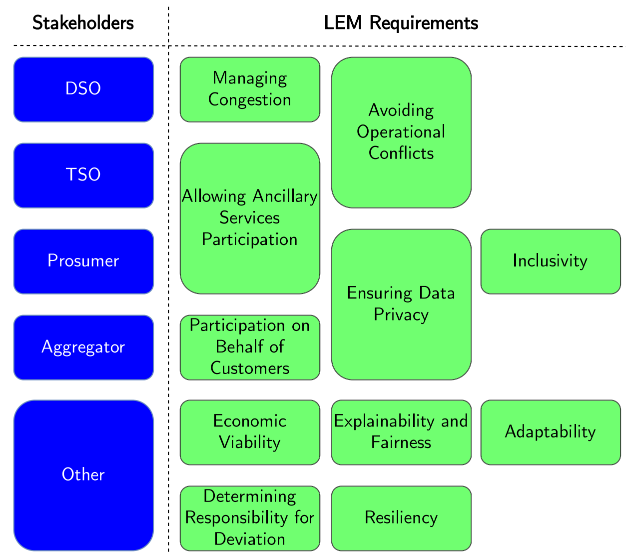

Fig. 2. Summary of LEM requirements per stakeholder.

4.1. Transactive and inclusive

Liu et al. [21] present a LEM that allows participants to adjust bids based on prices, but the LEM includes an undisclosed capacity limit allowing only more significant consumers and producers to participate. Both Haghighat et al. [22] and Masood et al. [23] demonstrate a LEM for aggregators aimed at alleviating grid congestion, where the LEM of Masood et al. takes extra steps to prevent peaks caused by flexibility. Azizi et al. [24] present an energy mechanism that uses the losses caused by each transaction as a criterion to match peers that want to trade energy.

Some LEMs focus specifically on inclusivity. In Andriopoulos et al. [25] a LEM is shown that centers on giving small-time participants access to a day-ahead market. Chen et al. [26] presents a LEM that allows prosumers to self-learn the optimal bidding strategy to participate in several decentral LEMs. In Oprea et al. [27], several LEM algorithms are demonstrated and compared to see which gives prosumers the best market performance indicators such as social welfare and DER penetration.

P2P is also a common type of LEM. In the paper of Okwuibe et al. [28] a double-sided auction and a P2P energy market, currently used in a German field test (RegHEE), with a short gate closure time based on blockchain is presented. Perger et al. [29] and Baez-Gonzalez et al. [30] demonstrate a P2P LEM for prosumers where Perger et al. uses linear optimization and characterizes prosumers on their willingness to pay for local energy. Furthermore, in Zhang et al. [31] a two-settlement(hourly and event-driven) P2P LEM is presented for price certainty in the market and an increased trade volume energy from DERs.

4.2. Congestion and ancillary services

Numerous studies present LEMs capable of congestion management while allowing prosumers to participate. In both Marzband et al. [32] and Asrari et al. [33] such a LEM is presented. A different approach is presented in Leeuwen et al. [34] and Coraldesi et al. [35]. The LEMs presented in these studies allow prosumers to alleviate grid congestion by bidding on a rolling horizon.

In Kok et al. [36] a method called Fast Locational Marginal Pricing is presented that allows prosumers to join a LEM that balances supply and demand within the grid constraints. In Nakayama et al. [37] an inclusive LEM capable of congestion management is presented that uses blockchain technology. Four other examples of inclusive LEMs capable of managing grid congestion have been presented in Zhang et al. [38], Faia et al. [39],He et al. [40], and Asrari et al. [41]. In Lezama et al. [42] an inclusive LEM is presented.

Others focus not only on electricity and change LEMs to local energy markets. Thermostatically controlled loads are used by Chakraborty et al. [43] to reduce congestion and cap local electricity prices. Furthermore, in Chen et al. [44] a local energy market is presented that combines heating flexibility with electricity flexibility to provide the DSO with congestion management while considering the TSOs constraints.

Some studies present LEMs focusing on ancillary services. The LEM presented by Oskouei et al. [45] allows industrial parks to participate in the ancillary services considering the capacity of components. Agostini et al. [46] present two models that allow DERs to participate in the ancillary services, but a DER is removed from the pool if its participation threatens the operation of the DSO.

Du et al. [47] present a LEM that allows DSOs to bid into the ancillary services markets on behalf of prosumers. Comparable to [47], Arkhangelski et al. [48] present a LEM that allows prosumers with batteries to participate in the ancillary services with a local aggregator. The LEM of Dabeshvar et al. [49] allows prosumers not only to participate in the ancillary services but also the day-ahead market.

Several LEMs studied can manage congestion, allowing prosumers to participate and bid in the ancillary services. In Farrokhseresht et al. [50] a LEM is proposed that requires prosumer to send bids to the DSO, which will then place bids on behalf of the participants in the traditional electricity markets and the ancillary services. Hou et al. [51] present a LEM that allows EVs to participate in the ancillary services, and the LEM also includes a rolling horizon for a day-ahead scheduling market aimed at congestion management. Similarly, Zhou et al. [52] presents a LEM that allows a local P2P market to participate in the ancillary services and provide local balancing. Schwidtal et al. [53] elaborate on an Italian pilot called UVAM that uses local flexibility for congestion management and the ancillary services.

4.3. Privacy, responsibility, and others

Privacy is a consideration for several studies. For example, Bedoya et al. [54] propose that individual prosumers can host data storage to ensure their privacy. The LEM presented in Jalali et al. [55] goes further and does not allow participants to see each other's bids by introducing an independent economic entity that settles the market privately. Morstyn et al. [56] shows a P2P energy framework that allows prosumers to retain control of bids and negotiations and gives individual decision-making in order to increase the privacy of participants. Finally, in Dukovska et al. [57] a P2P LEM is presented that uses a distributed approach to improve the privacy of participants and minimizes the electricity procurement costs.

Responsibility for flexibility or causing a deviation is also a stakeholder requirement addressed in several studies. In Saxena et al. [58] a LEM is presented that allows bidders to react to market prices and adjust bids with a negotiation strategy to maximize social welfare by, first, estimating the deviation and subsequent costs and, secondly, adjusting the profiles to minimize these costs. Adrian et al. [59] demonstrate an algorithm that optimizes the home energy management system of prosumers to obtain bids that the aggregator can use for local and wholesale markets. This aggregator is responsible for the deviation and actively tries to prevent deviations and acts when deviations still occur.

Some of the studied LEMs are also able to avoid operational conflicts. For example, in Lampropoulos et al. [60] a LEM is proposed that includes several conditions that prevent an operational conflict. The LEM can enter a mode of operations specifically for congestion management that ensures that ancillary services bids in upwards/downwards direction contributing to the congestion are canceled.

Other LEMs allow aggregators to participate on behalf of the prosumers, which is the case in the LEM presented by Crespo-Vazquez et al. [61] where the LEM that allows a smart service energy provider to participate in the national wholesale and ancillary services on behalf of the prosumers.

Several LEMs studied have the economic viability of at least one of the stakeholders as one of the performance indicators for the presented LEMs. Meißner et al. [62] presented a LEM that is able to stay under network constraints without requiring curtailment, and the costs of achieving this were lower than the average feed-in costs of a German region. Another example of economic viability in LEMs is presented in Fonteijn et al. [63]. In the presented LEM, the prices for flexibility are based on the financial risks of overloading and outages, so when overloading occurs, the DSO activates flexibility for the price it would have to pay in component degradation and or outage costs. In Movahednia et al. [64] the economic viability of market participants is used as one of the performance indicators.

Local marginal pricing has been proven to work in various general electricity markets and is transparent, simple, and understandable. In Pinto et al. [65] a LEM is presented that uses locational marginal pricing to clear the market. Another interesting method for simplicity is presented in Li et al. [66]. This study shows, a LEM shifts the complexity to the creation of bids and thus keeps the market process and price updates transparent and explainable.

5. Local electricity market framework

IIn this section, the bidding horizon and timing aspects of LEMs are analyzed and compared to the ancillary services participation, congestion management, and inclusivity stakeholder requirements and how the LEMs in the overview are addressing these requirements.

5.1. Bidding horizons

The bidding horizon, or duration and schedule of bids, are an important aspect of electricity markets. The studied LEMs are classified based on the used bidding horizons, ignoring bid deadlines, where the authors consider event-driven, short-term, and hourly as bidding horizons using the following definitions:

- Hourly: Bids have a duration of at least one hour, and the settlement periods follow a consecutive fixed schedule. Comparable to the wholesale day-ahead market.
- Short-Term: Bids have a duration shorter than one hour, and the settlement periods follow a consecutive fixed schedule. Comparable to the wholesale intraday market.
- Event-driven: Bids can follow a schedule but are activated real-time based on an event, regardless of the bidding horizon. Comparable to the secondary ancillary services.

Fig. 3 shows the relative occurrence of the three stakeholder requirements most often satisfied in the included LEMs, and from Fig. 3 it becomes clear that LEMs in the overview are most often capable of congestion management. An interesting trend occurs if one looks at the bidding horizons of LEMs capable of either, or both, congestion management and ancillary services participation.

Some studies combine, for example, a day-ahead (hourly) market with an intraday (short-term) market, and therefore it is possible that a study is classified as being, in this example, both short-term and hourly.

Fig. 4(a) shows the occurring bidding horizons for LEMs that are capable of congestion managing but do not allow for participation in the ancillary services. From Fig. 4(a) it seems that LEM algorithms capable of congestion management do so on an hourly and or short-term basis.

Fig. 4(b) shows the occurring bidding horizons for LEMs that allow ancillary services participation. Note that most of these are also capable of congestion management. A clear shift to event-driven bidding horizons occurs when ancillary services are involved. The LEMs focusing

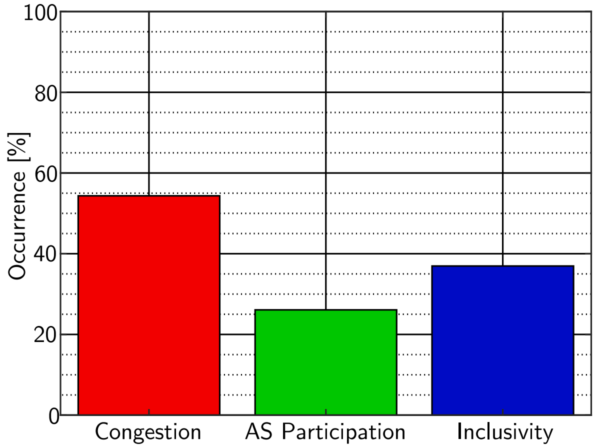

Fig. 3. Occurrence of the congestion management, ancillary services participation, and inclusivity stakeholder requirements. For data, see Table 1 in Appendix.

on ancillary services participation are all event-driven as these have to abide by the event-driven bidding horizons of the ancillary services. The LEMs also capable of congestion management often have an hourly or short-term aspect of managing the congestion by scheduling consumption and production.

Figs. 4(a) and 4(b) seem to suggest that congestion management requires an hourly and or short-term approach and ancillary services participation requires an event-driven approach. Congestion management is often addressed with a scheduling aspect in the form of, for example, a day-ahead market or a receding horizon, and final adjustments made event-driven in local balancing effort. Participation in the ancillary services requires an event-driven algorithm, which is how the ancillary services are regulated.

5.2. Framework

Considering the stakeholder requirements, both the capability of congestion management and ancillary services participation are necessary for future distribution grids. As congestion management and ancillary services are on different timescales, it is challenging for large-scale (real-life and in entire regions/countries) implementation to implement stakeholder requirements while being explainable simultaneously, another stakeholder requirement, as joining the two in one LEM algorithm could be difficult and complex. Therefore, to implement a LEM capable of congestion management and ancillary services participation, the authors believe that, considering the stakeholder requirements, a LEM framework is required.

Several studies in the literature overview have implemented such a framework. In [38], for example, prosumers first negotiate and trade bids among themselves in a P2P market to maximize the social welfare, and this is followed by an event-driven market that controls the voltage and manages congestion. Another example is a market framework where participants send a bid to an agent, which then places bids on behalf of the participant in a local P2P market but also in the national day-ahead and intraday markets [65]. Comparable frameworks can be found in [35,49,50,52,56,60,61]. Finally, a consortium existing of Dutch key players in the Dutch energy chain has developed the Universal Smart Energy Framework (USEF) that sets communication and trading protocols for most stakeholders to allow the use of flexibility for congestion management and ancillary services [67].

In the LEM frameworks presented in the papers mentioned above, the overall trend seems to be one LEM with some form of scheduling, another LEM for short-term adjustments based on situational changes, and one LEM for flexibility that can be used for local balancing or the ancillary services. However, variations exist between the presented frameworks, which vary on capabilities, structure, and objective, making it challenging to present a representative picture of all frameworks in one image. However, to give a visualization of a LEM framework, a generalized schematic is given in Fig. 5. The presented LEM frameworks either let the prosumer (households and citizens) bid directly in the various LEMs or send information to the aggregator (including BRP and energy supplier) who bids on behalf of prosumers. The various available LEMs also vary, but the four in Fig. 5 are four examples mentioned in the previously mentioned frameworks which could work alongside one another. Finally, the DSO can check the network constraints for the intraday and day-ahead markets, and both the DSO and TSO can request flexibility when required. The various LEMs in Fig. 5 are an example, and a selection of these LEMs or a variation with different LEMs could be possible.

5.3. Market system

The aforementioned LEM frameworks can incorporate several LEMs and, therefore, satisfy the requirements for congestion management and ancillary services participation. These frameworks are presented as a complete solution with fixed capabilities, organization, and market system or the way the framework distinguishes between LEMs. However, adaptability is a vital stakeholder requirement because, as stated, the implementation of the various LEMs will be gradual, the optimal LEM could vary per region or type of connection, and LEMs will be changed and updated to improve the LEMs. Therefore, local energy market frameworks should consider adaptability and arrange the market system so LEMs can be varied and individually implemented, operated, and updated.

Though the local energy market frameworks in this study are presented as fixed, it is unknown if the authors have considered adaptability and can arrange the market system within the framework. Nevertheless, future research needs to consider the market system a set of operation boundaries and regulations within the frameworks to which LEMs should abide to ensure cooperation between LEMs. These boundaries and regulations should set time aspects such as the bidding deadlines and bidding horizon and the capabilities and objectives of LEMs. For example, in Fig. 6, within the framework of the European national electricity markets, there is also a market system that separates the day-ahead, intraday, and ancillary services based on objectives, deadlines, and bidding horizons. The TSO also has a clearly defined market system in the ancillary services separating the frequency containment reserve, automated frequency restoration reserve, and the manual frequency restoration reserve.

This type of clearly described market system should be brought to the distribution grid and incorporated within the LEM framework. However, it is not simple to bring the wholesale electricity markets to the distribution grids as these are designed for different energy volumes and number of participants, and therefore, more research is required into bringing a market system to the distribution grid. In [68] a possible solution is given. Herein a LEM framework is presented that on one side bids into the wholesale day-ahead and intraday markets and on the prosumer side has a separate two-stage P2P LEM. It might be possible to participate in the wholesale markets but have a separate market mechanism in the distribution grid by funneling bids through an aggregator or other market operator.

Finally, the market system should also ensure that operational conflicts between TSO and DSO are avoided. Meaning, for example, that flexibility offered in the ancillary services should not cause or intensify congestion in the distribution. Therefore, avoiding operational conflicts between the DSO and TSO should be an integral part of the LEM framework's market system. One way this can be done is by implementing a constraint to the market-clearing that ensures that the traded energy volume does not violate the grid constraints [36]. Another possibility is by communicating power flow constraints between the TSO and DSO so these constraints can be considered in the electricity markets [50].

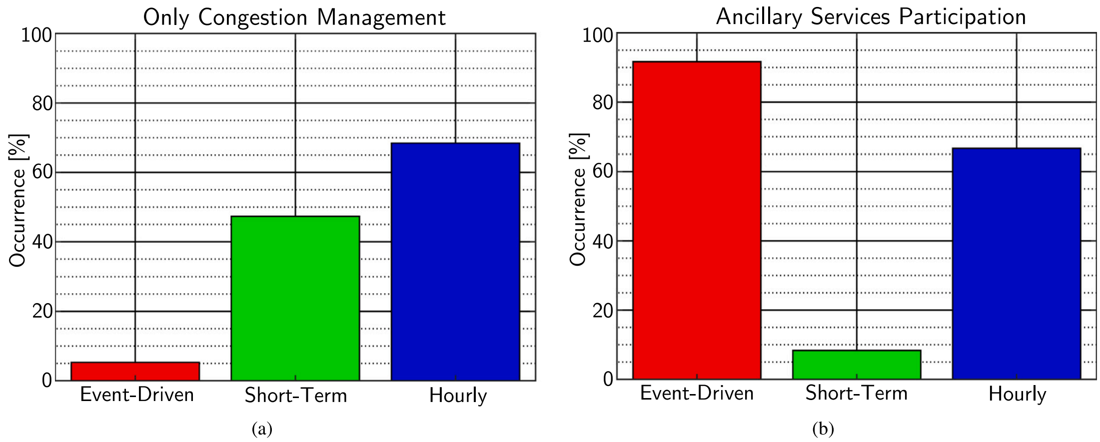

Fig. 4. Relative occurrences of event-driven, short-term, and hourly bidding horizons in (a) only congestion managing and (b) ancillary services participating LEMs. For data, see Table 1 in Appendix.

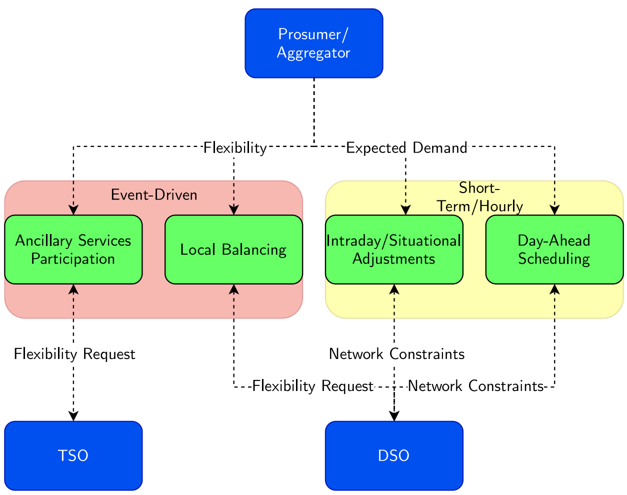

Fig. 5. Generalized schematic of a framework containing several local electricity markets with different capabilities and bidding horizons.

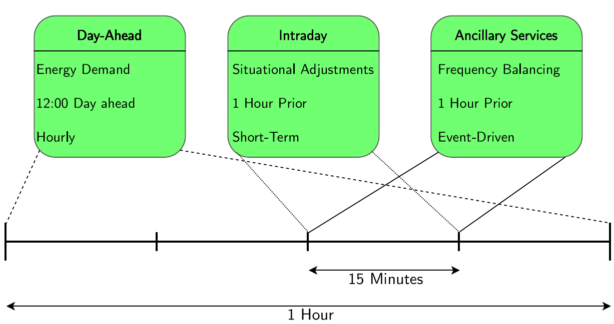

Fig. 6. Example of the market system within the framework of several national electricity markets in Europe where the objective, deadline, and bidding horizons create a clear distinction between the markets.

6. Handling of deviations

In this section, LEMs' market agreements and energy trading aspects are analyzed and compared to the responsibility of deviation, economic viability, and explainability and fairness stakeholder requirements and how the LEMs in the overview address these requirements.

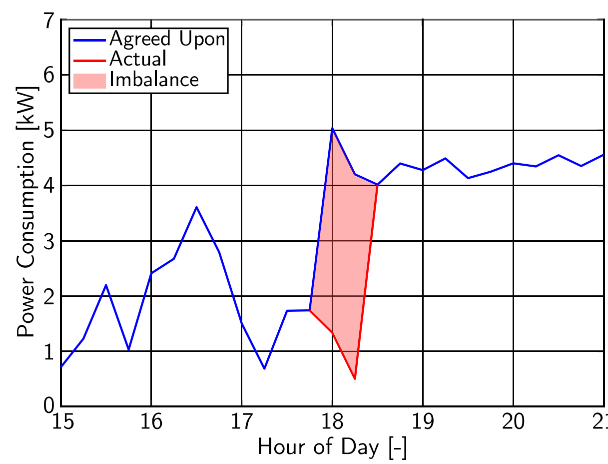

Fig. 7. An example of deviation caused by an EV arriving half an hour later than anticipated.

6.1. Responsibility

Deviation in electricity markets means moving away from and not abiding by a previously agreed upon bid of an energy or power quantity during a delivery period. An example of a deviation created using the model from [69], in which an EV that was supposed to arrive at 18:00 but arrives at 18:30 is shown in Fig. 7. Between 18:00 and 18:30, the actual consumption is 3.7 kW lower than the actual agreed-upon consumption because the EV has not arrived, causing a deviation in the delivery period.

A clear advantage of simulating markets is that participants' willingness to provide flexibility can be programmed and will be high and constant, which will not be the case for large-scale (real-life and in entire regions/countries) implementation, where provided flexibility will vary. There will be a limit to the number of devices consumers are willing to provide flexibility with within LEMs. When they please, consumers will do some activities, such as cooking dinner or making coffee, and these activities cannot be planned. It is thus likely that participants will not be able to abide by an agreed-upon consumption profile and, consequently, cause a deviation.

However, even if participants would abide, uncertainty will ensure a mismatch in planned and actual consumption and or production. Furthermore, as previously discussed, prosumers (households and citizens) should have the ability to participate independently or let aggregators (including BRP and energy supplier) join on their behalf. Also, a hybrid model could exist, where the prosumer independently offers flexibility but is dependent on the aggregator for all other energy consumption. All are different participation models, likely with other responsibilities complicating clear determination and distinction further. Therefore, LEMs must be able to clearly determine the responsibility and consequences of causing deviations before large-scale implementation is likely.

Deviation or imbalance is mentioned in the studied literature and addressed in several of the LEMs in the overview. In [50] prosumers send bids to the DSO that bids on behalf of the prosumers in the national electricity markets, including the existing imbalance market. The DSO is responsible for the caused deviations.

Another study presents a different approach where LEMs are used to reduce the imbalance of the national electricity markets, and if this is not possible, the national imbalance price is paid by the responsible market operator [42]. These two studies considered deviations with a top-down approach where the national imbalance is brought to LEMs.

In [49] a local event-driven balancing market is implemented to alleviate and address the local imbalance caused by the LEM. In this study, each micro-grid is responsible for the imbalance caused by deviating from their day-ahead bids and can counteract deviations from themselves or others in the event-driven balancing market. The imbalance price is determined similarly to national imbalance prices.

Finally, in [60] a methodology is presented where the aggregator constantly calculates the deviation caused during the current settlement period, and power is adjusted accordingly to try and re-balance the portfolio. If the deviation was not solved, the aggregator is held responsible and is required to pay for the caused deviation determined using the methodology for determining the national imbalance prices.

The local imbalance price in these studies seems to be determined using a comparable method to the national imbalance price. There are differences in the way of dealing with deviations as some try to deal with national imbalances while others implement markets or systems to prevent a local imbalance. Interestingly, the studies seem to place the responsibility of the caused deviation on the aggregator.

As described above, there are three models of participation ranging from fully independent prosumers to participation on behalf of the prosumers by the aggregator. For each model, the responsibility should be clearly and fairly determined for all parties, even though the models could have different requirements and applications.

It is, however, a future challenge to implement a precise determination and distinction of responsibility in LEMs as, currently, responsibility is not implemented in most LEMs in the overview. Therefore, future LEM research should focus more on the responsibility question and its consequences as it is vital for the aggregator and prosumer and the fairness and economic viability. For all future solutions, however, it is essential to determine who is responsible for deviations and the magnitude of these deviations.

6.2. Baselining

Determining the deviation per participant is not as simple as in the national electricity market. This is especially the case when flexibility is involved, as offering flexibility means intentionally deviating from the load profile.

Several factors contribute to the difficulty of determining the deviation from the expected consumption, or baseline, during a settlement period of prosumers. These are factors such as a limit in flexible devices, uncertainty of predictions, and the bidding in several LEMs all happening behind one smart meter.

An example shown in Figs. 8(a) and 8(b), created using the same data as in Fig. 7 but with a different household load from 18:00 onwards, shows the impact uncertainty could have. In this example, the EV arrives at 18:00, but the household consumption after 18:00 is more significant than expected. For a market operator, who would only see the total consumption, it is challenging to discern if the EV is charging with more power or if the household consumption is more significant than anticipated. If it was agreed that the EV would be charging at 3.7 kW, one would need an accurate baseline of the household consumption to determine if the agreement was met.

Baselining, determining the baseline, is not mentioned in the studies included in the literature overview, likely due to the extra complexity, and baselining is, therefore, not considered in the presented LEMs. However, several baselining methods apply to LEMs, and a detailed description of baselining methods can be found in [70]. It is necessary, however, to highlight a few in this section.

- Window Before, where one takes the last power measurement before delivering flexibility and uses this measurement as the baseline, is a commonly used method to determine the baseline.
- Historical Data uses historical data to determine what the baseline would have been based on averaging recent measurements. Several variants of historical data were used for an economic assessment to see if historical data would be beneficial for prosumers [71]. Baselines based on historical data can be financially attractive for all parties involved, but the market organizers had to share profit, and the data had to be artificially biased for better results.
- Machine learning can also be used to determine the baseline. In [72] a data-driven method is proposed to estimate the baseline of prosumers that offer flexibility. The method reduces the error rate significantly and is thus more accurate than standard methods such as window before and using historical data.

Determining the baseline with either the window before method or using historical data is transparent and explainable, but the accuracy depends on the magnitude and frequency of flexibility [70]. Machine learning, however, is complex and opaque because a machine-learned model taught itself the connection and relation between input and output. This makes it nearly impossible to understand the exact working of the model from the outside, which does not help with being explainable for market participants.

It seems that with the current baselining methods, there is a trade-off between simplicity, accuracy, and transparency, necessitating further research. One study even suggests that baselining is not suited for LEMs and that capacity limitation, reducing one's consumption to a certain agreed-upon point, is a more realistic option for large-scale implementation [20]. Extra metering could also be an option, but this is a delicate balance between metering accuracy, data requirements, and implementation costs [73].

In any case, a significant gap between LEM research and large-scale implementation that could affect the methods and effectiveness of a LEM is the responsibility and determination of deviations. Therefore, if one wants to implement a LEM, a solution must be found for these issues. Otherwise, the implementation will not be successful because explainability and fairness will be neglected, and responsibility for deviation cannot be determined.

7. Affecting market effectiveness

In this section, power fluctuations and human decision aspects of LEMs are analyzed and compared to stakeholder requirement of resiliency to human decisions such as market abuse and, on a system level, negative emergent/group behavior and how the LEMs are addressing these requirements in the overview. So far, the focus in this study has been on problems where participants were assumed to be obedient and dutiful. This will certainly not be the case in real life, and operational disruptions caused by emergent behavior and market abuse will affect LEMs. Emergent behavior is caused by the complexity of the electricity system and is behavior that comes from the system as a whole, not from individual parts. For example, in Italy, where interdependencies between power stations and internet nodes caused the shutdown of one power station to cascade into the separation of Italy's northern and southern electricity grid [74].

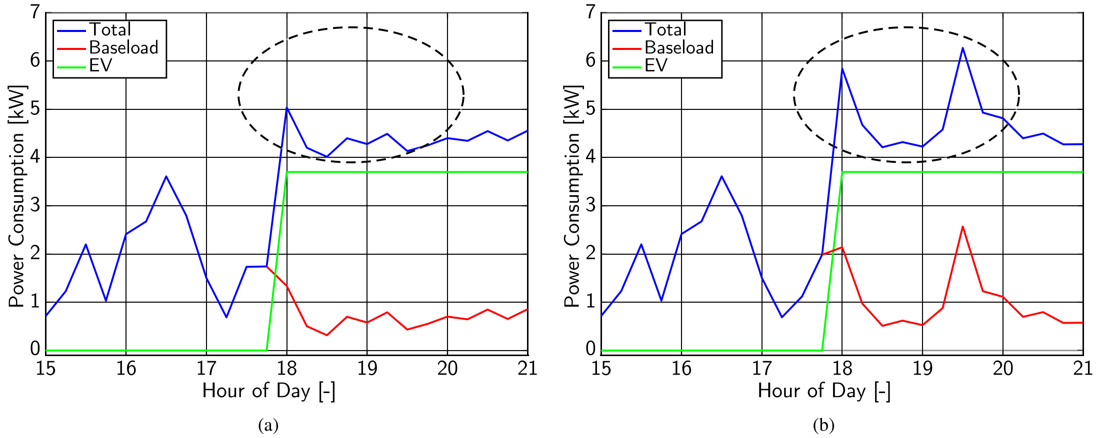

Fig. 8. Example of unpredictability altering the expected household profile (a) into an unexpected household profile (b).

7.1. Market abuse and emergent behavior

Market abuse can take place in the form of economic abuse such as insider dealing, market manipulation, and misrepresentation of information [75] but also in well-known forms such as monopolies or cyber-attacks. One study, for example, shows that by injecting undetectable errors in LEM algorithms, a cyber attack can influence the local marginal prices and give financial benefits to the attackers [76]. However, market abuse is such a well-studied topic for which papers can be easily found in all databases explaining all the various types of abuse and solutions that it warrants a separate literature study.

Nevertheless, most studies in the literature overview do not consider the possibility and effects of market abuse and emergent behavior. Therefore, with the determined stakeholder requirements, a gap between LEM research and large-scale implementation can still be recognized when taking the effects of emergent behavior and market abuse on the operation of LEMs into account.

One study offers insight into the reduction of market effectiveness that applying various bidding strategies can have on LEMs and shows that some bidding strategies can reduce the amount of energy traded, making the LEM less effective [77]. Similarly, a reduction in effectiveness and an increase for individual market participants could also be achieved by strategic curtailment of renewable energy in LEMs [78].

False data injection attacks, where participants intentionally temper equipment to send false information to the market operator, are another way market effectiveness can be reduced by reducing the profits of prosumers, potentially reducing incentives to participate in LEMs [79]. Some studies even propose new effective methods to commit such an attack, and others also propose methods to recognize such attacks with machine learning [80,81].

However, on a system level, emergent behavior can also reduce the effectiveness of LEMs. One study, for example, showed that some market algorithms are susceptible to catastrophic consumer synchronization where a small price change can lead to large load fluctuations [82].

7.2. Effectiveness

An example is created using, again, data from [69] to visualize the before-mentioned market abuse and emergent behavior effects on LEMs. Fig. 9 shows three consecutive days of the transformer load when no LEM is present for reference (green line), a transformer load when a simulated marginal pricing LEM [69] is present (blue line), and when the same LEM is presented but affected by simulated market abuse and emergent behavior (red line).

The affected line is a manufactured example but at several moments shows how a LEM could be affected. The difference between the simulated and affected load, for example, during day one at noon, could

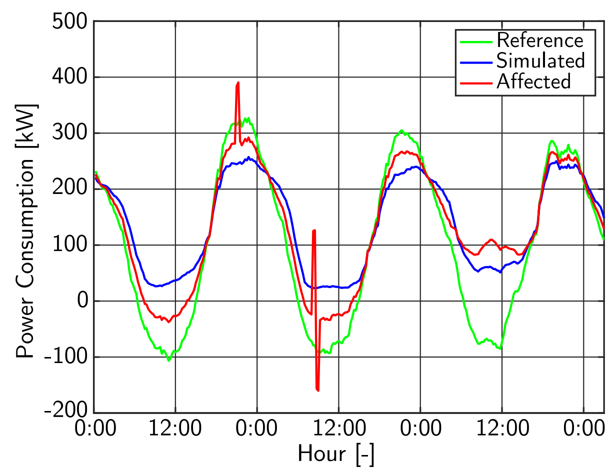

Fig. 9. Transformer load when no LEM is present for reference (green), a transformer load when a simulated marginal pricing LEM is present (blue), and when the same LEM is presented but affected by human decisions such as market abuse or emergent behavior (red).

be an effect various bidding strategies can have at reducing the traded electricity [79]. The peak at 23:00 on day one could be caused by EVs synchronizing [82] due to a slight price dip. The peak and drop on day two at 10:00 could be an example of market manipulation [75]. Finally, the higher consumption of the affected load at noon on the third day could be an example of strategic curtailment [78].

Given the number of ways that can reduce the effectiveness of LEMs, it is likely that future LEM implementations need to be able to deal with reduced effectiveness. Therefore, researchers and engineers working on LEMs should consider this reduction and ensure that LEMs are still effective enough under certain circumstances. Especially because the economic margins are already small, and as shown in [79], the incentives to participate can be reduced. Possibly even to such an extent that people do not find it attractive to participate anymore, reducing the effectiveness of LEMs even more. Furthermore, potential detection algorithms, such as presented in [83], might not be simple additions later and need to be integrated during the development.

As LEM studies often neglect market abuse and emergent behavior, LEM effectiveness could pose a problem for future implementation. However, the authors recognize that another challenge lies in combining market abuse and emergent behavior solutions with the other stakeholder requirements. The problem of not having a baseline and its uncertainty is already an issue of trustworthiness and responsibility. Combining this with preventing and detecting market abuse and emergent behavior increases the complexity of determining the difference between right and wrong. Furthermore, the simplicity of LEMs must still be considered as making LEMs too complex to understand for prosumers will reduce the willingness to participate.

Therefore, some challenges between LEM research and large-scale implementation still exist. The first challenge is the inclusion and understanding of the implications of reduced effectiveness caused by emergent behavior and or market abuse. Furthermore, the effects that these problems have on other challenges such as the requirement of a market framework and lack of baseline or stakeholder requirements such as simplicity could be problematic.

8. Data privacy

In this section, data privacy in LEMs is analyzed and compared to the stakeholder requirement of privacy to see how the LEMs in the overview address this requirement.

The sharing of smart meter data to LEMs is vital for the operation of smart grids, but sharing this data can expose privacy-sensitive information about prosumers [84]. Ensuring that this privacy-sensitive data is misused by involved parties or falls into the wrong hands is essential for the LEM's trustworthiness. Studies and books exist that give methods as to how smart meter data can be used to predict, among others, household behavior, socio-demographic information, and energy usage patterns [85,86].

These works could be used maliciously if smart meter data falls into the wrong hands. Therefore, data privacy must be taken seriously and is a critical stakeholder requirement. Several LEMs in the state-of-the-art overview consider data privacy by implementing a privacy protection step. For example, in [57] privacy is taken into account in the communication requirements by limiting the communication to a central coordinator. In [54] privacy is part of operating the market decentrally and therefore allowing participants to host their own data storage to ensure privacy. Another way privacy can be implemented in a LEM is by allowing participants to set their individual preferences for autonomy and privacy [56]. Finally, one of the LEMs presented has implemented a step in the middle that ensures that participants cannot see each other's bids and the information is not shared with the DSO [55]. It is good that these studies considered privacy because most studies in the overview have not. However, privacy seems to have been more of an additional step than fundamental during the design in the studies mentioned above, while there is a method or step-wise approach to address privacy throughout the design process.

From a LEM perspective, privacy by design means proactively considering and including privacy into the (LEM) design, the market-clearing, and the communication network's operation. Privacy to design has seven foundational principles [87] that can be applied to LEMs as follows :

1. Proactive not reactive: privacy measures in place should anticipate and prevent data breaches or unintended data sharing.
2. Privacy by default: private data should automatically be kept private, meaning, for example, that the required data for LEMs be minimized by design.
3. Embedded Privacy in Design: privacy should be the default in the information technology (IT) system that stores and carries all the data from participants to the market operator.
4. Full Functionality: implementing privacy measures should not reduce any functionality of the LEM or compete with other market aspects such as security.
5. End-to-End Security: every step in the process which encounters data should be scrutinized for data breaches, confidentiality, and integrity, which means for LEMs that every step between the smart meter and final billing should be secure.
6. Visibility and Transparency: involved stakeholders should be open about their data usage and protection practices. Furthermore, there should be independent verifications.
7. Respect for User Privacy: participants' respect and interests should be of the utmost importance to the involved stakeholders. For example, by asking for consent for data usage and giving the option to give complaints when participants feel their data is not being treated well.

That privacy by design can be implemented in LEMs is shown by Gridflex Heeten, which uses USEF as part of its market mechanism [88]. USEF is designed with privacy by design in mind [84]. Several measures have been designed to ensure privacy. Some examples are: all data related to consumption is handled as personal data, an IT system is designed following the embedded privacy in design principle, and a data protection impact assessment is in place.

USEF and Gridflex Heeten are professional implementations. Some of the privacy by design foundational principles (regarding consent forms and IT systems, for example) might be less applicable to simulations and models and, therefore, are less relevant for researchers. Furthermore, privacy is also social and subjective, and the data that someone is willing to provide in a marketplace can vary from participant to participant. Utilities would argue that the more data they receive, the better their service, potentially lower costs. Privacy preferences could also vary significantly per region or government.

Considering the difference between professional and scientific implementations and the social and subjective aspect of privacy, it is not easy to put the privacy challenge between the current state of the art and large-scale implementation of LEMs in a scientific perspective.

Nevertheless, considering data privacy is still important. LEMs will likely not be able to access all available data from prosumers, and researchers should consider this. Privacy can be an afterthought, but privacy by design already has the seven foundational principles, of which some could undoubtedly be exciting guidelines in the design process of LEMs. Researchers from the EU should undoubtedly consider the effects of the General Data Protection Regulation on LEMs, as this regulation is already in effect [89].

9. Discussion

The goal of this study was to find the existing challenges between LEM research and large-scale implementation. A literature overview was made using state-of-the-art LEM research and pilots. The state-of-the-art LEMs from this overview were systematically analyzed with the determined stakeholder requirements (see Fig. 2) and power system and market aspects. This process was repeated four times for four aspects: bidding horizons, market agreements, human decisions, and data privacy. This methodology identified several challenges between LEM research and implementation.

The main challenges found are fourfold. First is the necessity of a LEM framework including multiple LEMs operating on different timescales that should have a system that ensures adaptability while avoiding operational conflicts between the TSO and the DSO. Second is the determination of the baseline and subsequent handling of deviations and responsibility of bids. Third, the lack of awareness and inclusion in studies of the reduced effectiveness of LEMs caused by human decisions. Finally, future research should consider the data privacy concerns of participants more thoroughly by taking privacy by design principles into account.

The above-defined challenges were derived from the perspective of the most involved stakeholders in exchanging local electricity/flexibility. Additional challenges could appear when including other sectors, such as information technology, that are not directly involved in energy exchange. Other challenges could also become apparent when including heat or other energy sources into local electricity/energy markets. The various regulations and policies in countries/regions have not been considered. However, these could be a barrier for implementation depending on the type of LEM, country/region, and moment in time, as, in Europe at least, the regulations and policies need to

Table 1
Overview of LEM classification Section 4. From left to right: Congestion Management, Ancillary Services Participation, Inclusivity, Event-Driven, Short-Term, and Hourly.

		Congestion Mgmt.	AS. Participation	Inclusivity	Event-Driven	Short-Term	Hourly
Adrian	[59]	Green	Red	Green	Red	Red	Green
Agostini	[46]	Red	Green	Green	Green	Red	Red
Andriopoulos	[25]	Red	Red	Green	Red	Red	Green
Arkhangelski	[48]	Red	Green	Green	Green	Red	Red
Asrari	[41]	Green	Red	Green	Red	Green	Red
Asrari	[33]	Green	Red	Green	Red	Red	Green
Azizi	[24]	Red	Red	Red	Green	Red	Red
Baez-Gonzalez	[30]	Red	Red	Green	Red	Green	Red
Bedoya	[54]	Green	Red	Green	Red	Green	Red
Chakraborty	[43]	Green	Red	Green	Red	Red	Green
Chen	[26]	Red	Red	Green	Green	Green	Red
Chen	[44]	Green	Red	Green	Red	Red	Green
Corinaldesi	[35]	Green	Red	Green	Red	Green	Red
Crespo-Vasquez	[61]	Red	Green	Green	Green	Red	Green
Daneshvar	[49]	Red	Green	Red	Red	Green	Green
Du	[47]	Red	Green	Green	Green	Red	Red
Dukovska	[57]	Red	Red	Green	Red	Green	Red
Faia	[39]	Green	Red	Green	Red	Red	Green
Farrokhseresht	[50]	Green	Green	Green	Green	Red	Green
Fonteijn	[63]	Green	Red	Red	Red	Green	Red
Haghighat	[22]	Green	Red	Red	Red	Red	Green
He	[40]	Green	Red	Green	Red	Red	Green
Hou	[51]	Green	Green	Green	Green	Red	Green
Jalali	[55]	Green	Red	Red	Red	Green	Green
Kok	[36]	Green	Red	Green	Red	Green	Green
Lampropoulos	[60]	Green	Green	Green	Green	Red	Green
Leeuwen	[34]	Green	Red	Green	Red	Green	Red
Lezama	[42]	Red	Red	Green	Red	Red	Green
Li	[66]	Red	Red	Green	Red	Red	Green
Liu	[21]	Red	Red	Red	Green	Red	Red
Marzband	[32]	Green	Red	Green	Red	Red	Green
Masood	[23]	Green	Red	Red	Red	Red	Green
Meißner	[62]	Green	Red	Red	Red	Green	Green
Morstyn	[56]	Green	Green	Green	Green	Red	Green
Movahednia	[64]	Red	Red	Green	Red	Red	Green
Nakayama	[37]	Green	Red	Green	Red	Red	Green
Okwuibe	[28]	Red	Red	Green	Green	Red	Red
Oprea	[27]	Red	Red	Green	Red	Green	Red
Oskouei	[45]	Red	Green	Red	Green	Red	Green
Perger	[29]	Red	Red	Green	Red	Red	Green
Pinto	[65]	Red	Red	Red	Red	Red	Green
Saxena	[58]	Red	Red	Red	Red	Green	Red
Schwidtal	[53]	Green	Green	Red	Green	Red	Red
Zhang	[38]	Green	Red	Green	Green	Green	Red
Zhang	[31]	Red	Red	Green	Green	Red	Green
Zhou	[52]	Green	Green	Green	Green	Red	Green

accommodate the Clean Energy for Europeans package [3]. Finally, given the European focus of this study, the challenges' applicability could vary outside Europe. Nevertheless, the challenges found still are relevant, even outside Europe, for future LEM research and pilots.

This work is relevant for researchers' future work into LEMs as it gives LEM aspects and properties that need further research to facilitate its implementation on a large scale better. The same applies to the conductors of pilots with the extra opportunity of having access to actual human behavior and their decisions, giving the exciting possibility of seeing the real effects of human decisions on LEMs. Furthermore, this work is significant because it is different in methodology from previously conducted comparable literature studies [11–14], as the authors iterated over the literature four times from four different angles (see steps 4a-d Fig. 1), and therefore found different challenges. In fact, several studies agree on the necessity of a LEM framework to support various LEMs [35,38,49,50,52,56,60,61,65,67].

10. Conclusion

This study aimed to find the existing challenges between LEM research and large-scale implementation by systematically reviewing and analyzing state-of-the-art LEM literature from the stakeholder's perspective. The following challenges were identified:

1. It was determined that a LEM framework containing at least two LEMs, one for scheduling and one for event-driven balancing/ancillary services participation, is required to allow for both congestion management and ancillary services participation. Within this framework, a market system that allows for the adaptability of LEMs and is integrally capable of avoiding operational conflict should be clearly defined.
2. The responsibility of caused deviations and the subsequent settlement of deviations was discussed and determined to be still a significant challenge to which future research must find a realistic and practical solution. Especially, the difficulty of determining the baseline consumption/production creates uncertainty for settlements in LEMs.
3. It was determined that human decisions, in the form of market abuse and, on a system-level, emergent behavior, likely reduce the effectiveness of LEM. The solutions to this problem are difficult to combine with other stakeholder requirements such as simplicity and responsibility.
4. Data privacy consideration was also determined to be important for future LEMs, but the extent of this importance depends on the LEM implementation and on social and subjective aspects. Future researchers and developers should at least consider some

of the foundational principles of privacy by design and be aware that not all smart meter data will be available.

The challenges could guide future work to find solutions to aid large-scale LEM implementation. This work could include developing a market system for the distribution grid level, looking at various types of responsibility and baselining, and the effects of human decisions on LEM effectiveness. Furthermore, with the solutions to these challenges known, it is possible to look at the business case of LEMs and their stakeholders. In any case, the state-of-the-art LEMs in this study show promise for the future, but LEMs must at least overcome the determined challenges before large-scale implementation is likely.

CRediT authorship contribution statement

Sjoerd C. Doumen: Conceptualization, Methodology, Software.

Declaration of competing interest

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

Acknowledgment

The authors would like to thank the Dutch Research Council's (NWO) research program Complexity–Programmable Self-organization for funding this study, which is part of the Self-organizing Marketplace to realize a Self-Organized Sustainable Power System (AGILE) project.

Appendix. Literature data

Table 1 contains the data for all LEMs included in the state-of-the-art overview used to create Figs. 3 and 4.

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