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Developments and Challenges in Local Electricity Markets: A Comprehensive Review

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ABSTRACT In recent years, power systems have undergone changes in technology and definition of the associated stakeholders. With the increase in distributed renewable generation and small- to medium-sized consumers starting to actively participate on the supply side, a suitable incorporation of decentralized agents into the power system is required. A promising scheme to support this shift is given by local electricity markets. These provide an opportunity to extend the liberal wholesale markets for electrical power found in Europe and the United States to the communal level. Compared to these more established markets, local electricity markets, however, neither have few practical implementations nor standardized frameworks. In order to fill this research gap and classify the types of local electricity markets, the presented paper therefore starts with the challenges that these markets attempt to solve. This is then extended to an analysis of the theoretical and practical background with a focus on these derived challenges. The theoretical background is provided in the form of an introduction to state-of-the-art models and the associated literature, whereas the practical background is provided in form of a summary of ongoing and recent projects on local electricity markets. As a result, this paper presents a foundation for future research and projects attempting to approach the here presented challenges in distribution of generation, integration of demand response, decentralization of markets and legal and social issues via local electricity markets.

INDEX TERMS Distributed generation, distribution grid, decentralized markets, local electricity markets, peer-to-peer, smart grid.

I. INTRODUCTION

A. MOTIVATION AND CONTRIBUTIONS

The power sector is undergoing a transition driven by the integration of distributed energy resources in order to electrify the other sectors, including transport, heat and industrial processes. Proliferation of grid automation and digital technologies has enabled the new design and operation of local electricity markets (LEM). These are nationally decentralized trading solutions that aim to connect consumers and generators that are in close spatial proximity. Spatial proximity is not constant as the proximity which is required for trades in a local electricity market to have a purpose is not fixed. However, it is worth highlighting that the proximity that is required is based on the problem that is to be solved, be it in the distribution or transmission grid.

Local electricity markets are a result of recent structural changes in power systems due to an increase in distributed energy resources. This comes as a result of drastic investment cost reductions in small-scale flexibility assets and production that has led to a decentralization of agents in the power system. These new agents primarily consist of end-users

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whose aim is to invest in behind-the-meter local production for self-consumption, or use local flexibility in order to react to price signals.

The use of distributed energy resources can lead to not only more efficient energy use as the production is moved closer to the consumption, but also a lower carbon footprint than conventional power production from thermal plants. Active consumers who are able to produce electricity, also referred to as prosumers, are envisioned as a central and sustainable part of the energy transition of the European Union [1]. In addition, direct power system participation of smaller-scale prosumers, e.g. small businesses or households, has become a core focus of the European Union's electricity strategy [2]. However, for prosumer integration to happen fast enough to meet climate targets, price signals and subsequently market structures must be changed in order to correctly incentivize end-users to participate actively in the power system.

Such an integration could allow for not only an expansion of renewable generation, but would also provide opportunities for future grid planning and stability. As such, the European transmission system operator network ENTSO-E highlights distributed energy resources as key assets that must be made available for the distribution and transmission system operators (DSO/TSO) using active system management techniques to access the flexibility in the distribution grid [3].

However, an increasing number of agents in the distribution grid also results in a series of challenges for the system operators, as an essential part of dealing with increased distributed energy resources consists of integrating them into the power system without compromising the security or quality of supply, such as reliability and voltage levels. Challenges with frequency balancing, congestion management, bi-directional power flow and variable renewable generation are paired with technological, social and legislative challenges such as fairness and acceptance.

In order to embrace the widespread opportunities and challenges offered by local electricity markets, the power system operators require an assessment of the existing operational models and regulatory aspect. The primary goal of this paper is to perform a comprehensive review of the technical and regulatory challenges in the implementation and modeling of local electricity market structures, and provide possible solutions to overcome these challenges.

The summary of the provided meta-review of literature review papers presented in Table 1 shows that, aside from Ref. [4], literature reviews on local markets were performed with a focus on peer-to-peer (P2P) trading mechanisms. As a result, specific challenges for local electricity markets have been underrepresented in literature reviews. This is the gap this paper aims to fill. In addition, this paper aims to build on the discovered challenges of implementation and specifically address them within the analysis of the models and implementations it provides. In summary, the contributions of this work are the following:

- An in-depth analysis of the challenges of local electricity markets (not restricted to peer-to-peer trading).
- A state-of-the-art introduction on and review of mathematical models for local electricity markets.
- An extended overview of existing local electricity market projects and implementation technologies with a focus on the outlined challenges.

These mentioned contributions stand in contrast to the previous P2P-focused literature studies on the topic of local markets. Projects and implementation of these studies have been covered in Ref. [5]. This was expanded in Ref. [6] where an Information and Communication Technology (ICT) systems review was also performed. Ref. [7] focused on centralized and decentralized market designs, whereas Ref. [8] illuminated challenges related to architectures and power routing. Furthermore, Ref. [9] reviewed papers in the virtual layer, combining the aspects of market design comparison, architectures and ICT systems. Local P2P trading ICT systems and architectures were subject to review in Ref. [10] and Ref. [11], while an extensive survey of distributed optimization models of the power system was the focal point of [12].

The presented paper is organized as follows: an overview of local electricity markets is presented in this section. Challenges of such markets are addressed in Section II. A review of modeling approaches for local electricity markets and associated distribution grid problems follows in Section III, itself followed by an overview of existing projects and their implementation in Section IV. Concluding remarks and suggestions for future work are provided in Section V.

B. INTRODUCTION TO LOCAL ENERGY AND ELECTRICITY MARKETS

Traditionally, power systems involved a top-down approach where large-scale producers and (industry) consumers made upper-level decisions and small-scale producers and consumers were involved as reactive instead of active decision makers. An increase in distributed resources in both supply and demand, however, has led to a bottom-up revolution in the energy system [13]. In particular, renewable generation has been shown to have positive impacts on local communities, e.g. through supporting rural electrification [14], [15]. As this paper will illustrate later, distribution of such resources, however, will also lead to potential challenges. For example, planning uncertainty can increase and large-scale coordination can suffer.

As mentioned previously, in the context of distributed generation, local electricity markets are a tool to decentralize the coordination of participants in a grid, by unifying participants behind a common denominator - local electricity market prices. These market prices aim to facilitate local trade, or in other words, prioritize the exchange of energy resources in smaller spatial distances over larger distances.

These local electricity markets are closely related to the empowerment of the end-consumer of electricity, and thus the

TABLE 1. Previous literature reviews on local electricity markets and related topics.

Reference	Scope	Focus
[5]	peer-to-peer (local & distributed)	projects & implementation
[6]	peer-to-peer (local & distributed)	ICT systems & implementation
[4]	local markets	market design comparison
[7]	peer-to-peer (local & distributed)	market design comparison
[8]	peer-to-peer (local & distributed)	challenges, architectures & power routing
[9]	peer-to-peer (local & distributed)	market design comparison, architectures & ICT systems
[10]	peer-to-peer (local)	ICT systems
[11]	peer-to-peer (local)	architectures & ICT systems
[12]	distributed optimization	models
this paper	local markets	challenges, models & implementation

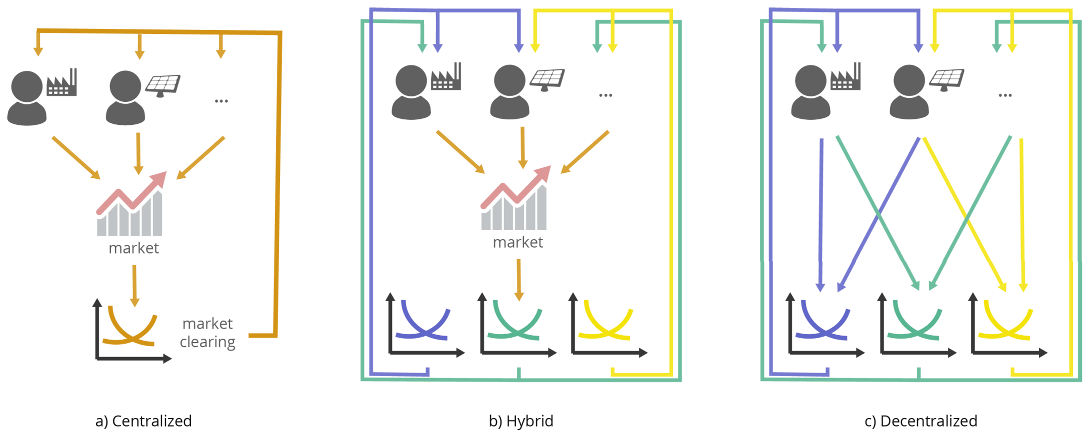


FIGURE 1. Local electricity market clearing topologies.

formation of local energy communities. The main objectives of participants in local energy trading can be defined as a reduction of energy costs, gaining (at least partial) independence from utility companies and/or protection of the environment [16]. The participation in such markets also has the potential to raise local energy production and to create jobs and stimulate economic growth in the region [17], which can be additional motivational factors. As outlined in Ref. [18], distributed investments into local generation are essential for the large-scale integration of renewable generation within power systems under liberalized markets and local electricity markets are a tool to support such issues. This is also shown in Article 16 of the ''Clean Energy for all Europeans'' package of the European Union which projects energy communities, and thus small-scale financial entities, to account for 17% of installed wind capacity and 21% of solar capacity by 2030 [19]. Furthermore, even though the characteristics of local electricity markets lie in bottom-up, i.e. grassroots, initiatives with consumer empowerment as a core pillar [20], a European Commission review of 72 EU projects related to local energy communities [21] concludes that DSOs have a central role in the development and operation of local electricity markets. Ref. [22] further postulates that TSO-DSO cooperation also plays a central role in the coordination of local electricity markets in the power system. However, and similar to wholesale markets, a single, local electricity market design does not exist.

Conceptually speaking, the interaction of agents can be separated into either peer-to-peer (directly, from participant to participant) or pool-trading (indirectly, via the aggregate of the market), with latter being the norm in implementations of wholesale markets on electricity [23].

In terms of their market-side interactions, however, there are three distinct topologies that we identify based on the literature presented below. These topologies are shown in Figure 1:

- Pool market trading (centralized)
- Hybrid market where peer-to-peer trading can be initiated via an exchange
- Full peer-to-peer trading with bilateral trades only

Refs. [7] and [24] provide an overview of the advantages and challenges of these market designs specifically for local electricity markets. In Ref. [7], the advantages of fully decentralized markets given are the higher freedom of choice for electricity consumer and producer, the empowerment of active consumers, more consideration of prosumer preferences in energy usage and the preservation of consumer/prosumer democratization. The authors in Ref. [24] commented on similar advantages, including the

TABLE 2. Comparison of local market clearing topologies.

Criterion	Centralized	Hybrid	Decentralized
Scalability	Low	$\Longleftrightarrow$	High
Transparency	Low	$\Longleftrightarrow$	High
Reliability	Low	$\Longleftrightarrow$	High
Computational cost	High	$\Longleftrightarrow$	Low
Communication cost	High	$\Longleftrightarrow$	Low
Consumer-centricity	Low	$\Longleftrightarrow$	High

mentioned democratization and consideration of individual consumer/prosumer preferences. In addition to this, both studies mention a number of challenges, including significant investments and maintenance of ICT systems and issues in the reliability of supply. Moreover, in Ref. [7], the authors comment on additional issues including scalability, computational, and power system resilience issues.

Regarding a centralized market design, the authors in Ref. [7] determine the advantages as increased cooperation among community members, higher resilience in communities, enhanced sharing of electricity and better support for grid operator services. To add to this, Ref. [24] identifies the provision of high-quality energy services as another advantage of such markets. However, a number of challenges, including fairness in energy sharing, more complexity in management specifically from the aspect of community management, ensuring consideration of individual consumer/prosumer preferences, integration and handling of data, additional complexity and transaction costs and difficulties in interactions with balancing market agents can be attributed to these centralized local markets.

As illustrated in Figure 1, hybrid market designs are positioned between decentralized and centralized market designs. The advantages range from better scalability of the ICT infrastructure, more compatibility with existing regulatory frameworks, better predictability for the grid operators and a smoother integration process into existing systems [7], [24]. In contrast, the challenges are the coordination of trades internally/externally, the integration and handling of extensive data sets, as well as and multi-market coordination.

In addition to this, Ref. [11] also compares decentralized and centralized market designs. Table 2 summarizes this qualitative survey using various criteria.

In similar manner to the selection of an adequate market topology and its nesting in the grid, another design question is also the integration into higher-level markets and the role of local electricity markets within the national market biome. This ranges from a consideration of local electricity markets as micro-grids to models of multi-market frameworks that consider hedging between markets and legal aspects of implementation via virtual power plants and balancing entities. Selection of an appropriate design is thus not a straight-forward but instead a multi-factor decision, as shown in the discussion of real projects in Section IV of this paper.

In terms of previous literature reviews, however, a clear focus on papers discussing local electricity markets via exchange-traded/auctioned peer-to-peer mechanisms can be observed. By stepping back from the focus on a specific topology, we instead aim to present local electricity markets more generally, starting with the perspective of the challenges faced, shown in Section II, the models used to overcome these challenges, as shown in Section III, and a summary of the application of these models in practice, as shown in Section IV. Conclusions followed by further work suggestions are finally presented in Section V.

II. CHALLENGES OF LOCAL ELECTRICITY MARKETS

Compared to traditional markets that usually manage large pools of participants over wide areas, local electricity markets usually show smaller pools of participants. In the electricity grid, traditional markets operate on a transmission grid level, whereas local electricity markets operate on a distribution grid level.

The necessary consideration of reactive power in the latter leads to non-linearity of the AC grid problem that requires consideration in the market model [25]. In traditional wholesale markets, these constraints are implemented via linearized DC approximations [26], leading to less complexity in the analyzed grid.

Thus, even though generally showing a smaller number of participants compared to traditional markets, local electricity markets encounter several unique challenges in fulfilling their purposes. These **purposes** of local electricity markets can be defined as the following [27]:

- Balance local demand to match intermittent supply.
- Manage congestion and transmission/distribution constraints.
- Support financial management of participants that takes into account location and network needs.
- Replace/postpone grid investments with utilization of local flexibility.

As discussed above, the **challenges** associated with local electricity markets and their implementation deviate from traditional liberalized power markets which do not need to consider the grid with such fine detail. As a result, challenges of local electricity markets are interlinked with the challenges of optimal operations of distribution grids [28]:

- Structural and cultural differences make general application of one single solution to various national grids difficult or impossible.
- Changes in power systems (more intermittent generation and more demand elasticity) might change the role of generators from a passive entity reacting to consumption to a more active role. This might increase the requirement for further grid tariffs for generators,
- Inefficient operation of storage (from a grid perspective) could lead to additional distribution cost.d
- Cost-reflective distribution grids are essential for the success of integration of electric vehicles, especially charging stations.

Another important aspect is that achieving the large-scale implementation of such markets and fulfilling the main goals

TABLE 3. Challenges of local markets.

Challenge	Tag	Source
Changes in line losses	A	[29], [30]
Changes in voltage levels	A	[29], [30]
Changes in power quality	A	[29], [30]
Changes in fault current levels	A	[29], [30]
Changes in requirements for protection systems	A	[29], [30]
Potential reduction in system reliability and thus more need for flexibility	A	[29], [30]
Lack of studies on system loadability and voltage security under distributed generation	A	[31]
Risk of increasing electricity cost	A C D E	[32]–[35]
Potential waste of resources	A	[32]
Less choice of supply	A	[32]
Negative environmental effects	A	[32]
Increase of computational complexity	A B	[36]–[39]
Physical vulnerabilities due to cyber-vulnerabilities	A	[40], [41]
Non-unified, location-dependent incentives process could impede investments	A	[42], [43]
No "all-in-one" solution for stakeholder incentives	A B D E	[17], [42]–[49]
Distributed generation is more susceptible to structural, regulatory, social and technical changes than centralized generation	A	[50]
Requirement of coordination and potential of resulting conflicts	A C	[51]–[55]
Similar tariffs might lead to different outcomes locally	A B D	[33], [45], [46], [56]
Forecasts of individuals are more error-prone than forecast of aggregates	B	[57], [58]

TABLE 3. *(Continued.)* Challenges of local markets.

Correlation of behavior and subsequent control issues due to wrong (price) signals	B	[59], [60]
Different tariffs in different parts of the distribution grid can lead to transmission system issues	B	[44]
Requirement of real-time control	B C	[61], [62]
Requirement to upgrade existing meters and software for energy flow management	B C D	[11], [63]–[65]
Requirements for multi-period models brings threat of computational intractability	B	[66], [67]
No "all-in-one" solution for all types of demand response	B	[58]
Response to price signal might vary depending on the individual	B	[68], [69]
Requirement for new consumer-centric/prosumer-centric algorithmic solutions on trading and optimization	C E	[5], [11], [17], [49], [70]–[74]
Fairness for all market participants in terms of, e.g., equal benefit, consumer roles and rights, access, energy sharing due to size differences, distribution of taxes and fees	C D E	[5], [11], [33], [46]–[48], [72]
Real-time markets may lead to lower energy prices, price volatility, uncertainty amongst consumers and imbalances of demand and supply	C	[75], [76]
Changes of traditional roles and responsibilities, market-structural factors such as cost and risks, product definitions and communication of demand-side effects	C	[11], [77]
Markets are required to be robust to systemic changes such as carbon prices, feed-in-tariffs for renewables, etc.	C	[78]
Data security, data privacy, data access and associated responsibilities	C D E	[11], [17], [41], [46], [49], [54], [55], [55], [63], [64], [71], [72], [79]–[82]

TABLE 3. ***(Continued.)*** **Challenges of local markets.**

Scalability issues of communication devices	C	[4], [11], [55], [71], [83]
Metering without a centralized authority needs to be reliable and trusted	C E	[55], [72]
Data storage infrastructure and management	C	[55]
Addressing of different consumer objectives, such as profit maximization, decarbonization or supply security	C E	[11], [16]
Relationships within local markets as well as between existing markets, and other emerging entities remain unclear	C D E	[4], [45], [46], [49]
Interoperability between communication technologies	C	[4], [55], [64]
Rigid energy market regulations	D	[7], [33], [45], [84], [85]
Need to protect elderly, socially disadvantaged, and price sensitive customers	D E	[16], [46], [55], [86]
Enforcement of law, as digital contracts may not be appropriately regulated	D	[64]
Legal integration into the legal framework for distribution and transmission networks	D	[33]
Stakeholders in current market framework might lobby against changes	D	[87]
Encouragement of participation	E	[47], [48], [72]
Maintaining trust is a constant process that requires adequate data security and involvement in such	E	[55], [72], [80]
Entrance barriers might be too high for voluntary participants	E	[88]
Dealing with conflicting stakeholder interests, expectations and preferences	E	[5], [16], [17], [72]–[74]
Different market topologies might affect participants differently	E	[4], [5], [11]

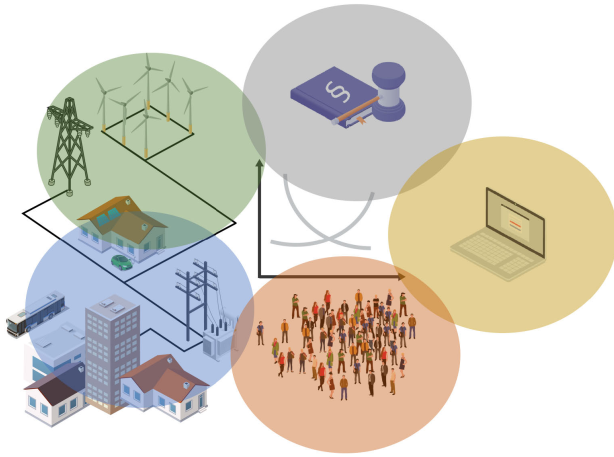


FIGURE 2. **Identified main challenges.**

of optimizing grid operation (and thus fulfilling sub goals such as reducing CO2 emissions) also requires adequate remuneration of the involved stakeholders (ranging from end consumers and prosumers to grid operators and traditional large-scale generators). Neglecting either of these aspects in the design could lead to a potential disparity between the goals of local electricity markets and the policies utilized to implement them [89].

Based on this, the main sources of challenges in establishing and operating local electricity markets were identified to be the five factors as shown in Figure 2:

A- optimal utilization of distributed supply
B-optimal utilization of demand response
C-efficient and secure operation and technical implementation of localized markets
D-existing and emerging legal boundaries
E-socioeconomic aspects and human interaction

Table 3 summarizes these challenges in the order of their appearance in the following subsections.

A. DISTRIBUTION OF GENERATION

One goal of implementing local electricity markets is to enable distribution of generation. This means installing, generally smaller, capacities in a larger number of locations in the grid. The goal is to better utilize local resources (e.g. available wind and solar capacities) and decrease distribution and transmission cost.

Specifically, Ref. [32] lists several goals of distributed generation:

1. liberalization of electricity markets
1.1. peak shaving
1.2. reliability and power quality support
1.3. substitution of transmission and distribution capacities
1.4. ancillary service support
2. environmental concerns

2.1. combined heat and power generation
2.2. efficient use of cheaper generation forms

Enforcing such a distribution of generation has a variety on impacts on the operation of the grid. Ref. [29] and subsequently Ref. [30] categorize them as changes in line losses, changes in voltage levels, changes in power quality (voltage flicker and harmonics), changes in fault current levels, changes in requirements of protection systems and a potential reduction in system reliability.

In regards to these technical constraints, system loadability and voltage security have been underrepresented in studies regarding distributed generation [31].

As mentioned in Ref. [32], distributing generation can further pose several structural challenges. One of these is that distributed generation shows a higher per kW price than localized generation. In general, wasting resources due to localized economic inefficiency is a challenge in the distribution of generation. In addition, energy security could be threatened due to lower diversification of generation resources. Furthermore, power quality can be negatively affected in various ways such as system frequency effects due to household appliances and changes in power flows from the different grid levels (traditionally, the flow is unidirectional from transmission to distribution grid, but with decentralized generation this flow would be bidirectional and changing continuously). In addition to these general problems of all forms of decentralized generation, Ref. [32] also illustrates challenges that could be imposed by a decentralization of specifically thermal generation: less supply choices of primary fuel sources and thus potential negative environmental impacts.

As described in Ref. [36], distributing such generation thus requires adequate locational price/cost signals such as locational network and energy prices. These should remunerate the balancing/grid-responsible parties whilst fulfilling the fairness principles of deregulated markets. Applied in practical settings, implementation of such locational signals can however lead to a dramatic increase in computational complexity [37]. This is especially important considering multi-energy systems which could further amplify this computational complexity on a local level [38].

In addition to that comes the potential of issues within adequate communication of these signals. The implementation of ICT as a virtual layer in microgrids is fundamental to ensure controllability and observability of the physical processes. Appropriate data flows require appropriate collection, transmission, processing and storage of information and market signals in order to allow generators to be updated and react accordingly. However, such ICT also increase the risk to cyber-vulnerabilities. Resulting incidents caused deliberately or by accident could lead to negative physical consequences such as power outages, equipment destruction, ineffective operational decisions, voltage and frequency instability, unintentional islanding and load curtailment [40], [41].

Furthermore, varying localized ''soft cost'' such as permission/inspection/interconnection cost can distort installation incentives and lead to generation capacities being installed in sup-optimal locations [42]. As further discussed in Ref. [43], these wrong incentives might even impede installation of beneficial local capacity. This also shows a larger problem with distributed generation - it is susceptible to external effects, not only through regulatory or political factors but also through behavioristic or technological factors [50]. On an aggregated, national level these changes might have a less severe impact than on the local level.

In combination with demand response, distributed generation can also offer potential for local coordination and offer congestion relief [51]. Issues in coordination would thus lead to congestion issues in systems that are designed on the premise of this form of congestion relief. This is also shown in Ref. [52], which analyzes a number of European projects on decentralized generation, of which all consider demand response via local households at least to a certain degree.

A trait similarly shared with demand response is the question of adequate remuneration of the grid providers, which mostly comes in the form of tariffs. The impact of these tariffs can vary locally and lead to distortion of investments in capacities [56].

B. INTEGRATION OF DEMAND RESPONSE

Similar to distributed generation, i.e. the supply side, the demand side can also be affected by a smaller pool of participants. As such, forecasts of individual demand sources can be error-prone, thus localized markets should allow for a certain degree of aggregation [57]. This is especially important considering that end-consumers can be vastly inhomogeneous, further amplifying this error [58].

In contrast to this, large-scale aggregation can also lead to a loss of accuracy in terms of control. Particularly on transmission grid levels, centralized price signals can lead to control issues on the distribution grid level, especially considering the control of deferrable loads. For example, Ref. [59] illustrates how centralized price signals lead to correlated behavior in electrical vehicles. Another example is provided by Ref. [60] that shows how central price signals cause synchronization of water heater startups and thus lead to load kickbacks. In a local electricity market, these effects also have to be considered as well when aggregating demand response.

Utilizing price signals dependent on time or special incentives (i.e. tariffs) is a common tool to implement decentralized price signals. However, different rules in various distribution grids can lead to coordination problems within the transmission grids [44].

Furthermore, considering demand response effects of residential appliances in an appropriate manner requires methods to utilize algorithms capable of performing real-time control [61]. Therefore, local electricity markets have to be designed with operational speed in mind. This is a challenge that stands in conflict with the goal of appropriately modeling the non-linearities of AC power flows, which usually leads to higher computational complexity. This problem is amplified by models considering storage units and/or electric vehicles requiring multi-period-optimization, thus further increasing the complexity of those problems [39]. This problem is particularly highlighted by Ref. [66] that illustrates how utilities under storage (specifically electric vehicles, local batteries or storage heaters) show the highest financial benefits. However, such problems are computationally highly intractable and could therefore lead to problems finding global optima and thus the most beneficial outcomes [67].

This problem of computational complexity is further amplified by the fact that different forms of demand response require different measures. Ref. [58] illustrates this and shows, for example, how time of use pricing can support storable loads but curtailable loads require dynamic load capping.

Another factor is the behavioristic component of demand response. For example, users can show different price responses [68]. Again, in systems with fewer participants such as local electricity markets these effects could be amplified over the aggregated wholesale markets. This is especially challenging considering that wrong assumptions and thus wrong incentives set by the demand response manager (e.g. the local electricity market provider) could lead to adverse effects and push demand response providers towards behavior contrary to the desired goals [69].

C. DECENTRALIZATION OF MARKETS

Designing functional local electricity markets does not only require coping with the previous requirements on computational complexity and modeling the specific components in appropriate manner, but also requires functional interaction of these components. Key components of a local electricity market are the microgrid setup, the grid connection, the ICT system, the market and pricing mechanism, the energy management trading systems and the regulation behind them. To what extent these components are fulfilled depends on the roles market participants take and how they execute them [90].

Because of the computational complexity of such markets, advanced trading algorithms are required to manage and coordinate the conduction of both trading and demand response [70]. According to Ref. [49], trading schemes can only be considered successful if they supply at least 50% of people's energy needs for the duration of implementation.

Furthermore, a two-way communication infrastructure requires an ambitious architecture with several market layers [11], [71]. The implementation of such an infrastructure comes with high investment costs, which can be a deterrent for the development of local electricity markets. Additionally, transaction fees for such an infrastructure may provide an extra cost in the case of adopting certain ICT technologies [11], [55], [63]–[65], [71]. In addition to this, there is also a need for appropriate schemes for the distribution of taxes and fees for local energy trading [46]. The question arises whether taxes or fees should still to be covered by the supplier or rather by the energy community itself. This also incorporates the

TABLE 4. Overview of challenges addressed in the model approach literature.

Source	Addressed Challenge				
	A	B	C	D	E
[93]	x	x	x		
[70]	x	x	x		x
[94]	x	x	x		
[95]	x	x	x		
[96]	x	x	x		
[97]	x	x	x	x	
[98]	x		x		
[62]		x			
[99]	x		x		
[100]					x
[101]		x			
[102]	x	x	x		
[103]	x		x	x	
[104]	x	x	x		
[105]	x	x	x	x	
[48]	x	x	x		x
[106]	x	x	x		
[107]	x		x		
[108]			x		
[109]	x	x			
[110]	x		x		
[111]	x	x	x		
[112]		x	x		
[113]	x	x	x		
[114]	x	x	x		
[115]	x	x	x		
[116]		x	x		
[117]			x		
[118]	x	x	x	x	
[119]		x	x	x	
[120]	x	x		x	
[121]		x		x	x
[122]	x	x	x	x	
[123]	x	x	x	x	
[124]			x		
[125]					x
[81]	x	x	x		x
[126]	x		x		
[127]			x		
[128]	x		x		
[47]			x		x
[129]	x		x		
[130]			x		
[131]		x	x		
[132]	x	x	x		
[133]	x		x		

TABLE 4. ***(Continued.)*** **Overview of challenges addressed in the model approach literature.**

[118]	x		x		
[134]	x		x		
[135]	x	x			
[136]	x	x			
[137]	x	x	x		
[138]	x	x	x		
[139]	x	x	x		
[140]	x	x			
[141]	x	x	x		
[142]	x	x	x		
[86]	x	x	x	x	
[143]	x	x	x		
[144]	x	x	x		
[145]	x	x	x		
[146]	x		x		x
[147]	x		x	x	

risk of increasing marginal cost, i.e. additional cost per kWh sold [33], [34].

Similar to the real-time issues with demand response, the markets themselves have real-time components. This comes as a result of traditional electricity markets showing a larger pool of participants, allowing for variable but pre-announced prices, which is not possible in local electricity markets [62]. Trading in local electricity markets usually takes place in smaller time frames. Interactions are thus either in a day-ahead timescale (1-hour intervals) or in real-time (5- to 15-minute intervals). Real-time markets may provide a lower average price of energy which can make it more attractive compared to day-ahead models. However, real-time processing leads to a higher volatility in prices [75]. This could cause uncertainty for consumers. Non-volatile prices in real-time markets lead to an imbalance of demand and supply as naturally the demand for energy increases if the price is low [76].

As Ref. [77] discusses, establishing markets also requires a degree of standardization that could deviate from the real grid topology and situation. The paper specifically mentions the following crucial aspects: roles and responsibilities, market-structural factors such as cost and risks, product definitions and communication of demand-side aspects. Local electricity market design should be general enough to support a wide variety of real-life systems on these aspects. In addition, the markets need to be designed to be adjustable enough to support interaction with policy makers. This means that operation of markets needs to be robust to the introduction of carbon pricing, feed-in tariffs for renewable energy, regulation and subsidies [78].

Effective coordination between TSOs and DSOs is of importance for the stability of the grid and should thus be a core aspect of market decentralization. Examples of challenges in this area are the sharing of measurements and forecasts, coordination under emergency situations, coordinated power quality support and coordination of balancing services [53], [55]. Design of local electricity markets has to support those mechanisms, but also aim to keep the privacy of the involved private parties and thus reduce the unnecessary sharing of information. Sharing this information also requires appropriate systems that allow for the coordination of the decentralized, independent systems that local electricity markets entail [54].

These systems have to support data security in order to support the functionality of the market. According to Ref. [80], potential threats include impersonation, data manipulation, eavesdropping, privacy breaches, disputes and denial-of-service. Appropriate privacy and security measures have to ensure a reduction in the risk of these threats to a level that allows reliable operation of the local electricity markets and the distribution grids behind them. In relation to this, the required two-way communication network also raises questions of such privacy and security, i.e. responsibilities and data access, to avoid issues caused by non-transparent energy markets. In particular, security vulnerabilities may include submission of fake contracts, double spending of energy or money, modification of transactions and denial-of-service attacks on the system [63], [79].

A central component of local electricity markets is thus a sophisticated ICT infrastructure that ensures this security whilst establishing transparency and connection points for the market participants. This can be technically challenging to implement for an increasing number of participants, in particular in centralized local electricity market structures [4], [11], [55], [71], [83]. Implementation of a control and trading system requires several key features. Latency in emergency cases, the probability of delivering the information in a given deadline, the capability of the system to combat ambient conditions or the scalability of the network are some of them [55], [91]. Moreover, local electricity markets may require big-data storage applications. Deciding how the data is stored and who owns it can be a challenge in itself [55].

Related to this technical implementation of local markets, Ref. [64] highlights the interoperability between new and existing market solutions deployed throughout the energy sector. A core challenge within design of the ICT systems is to what extend allow interaction. Such interoperability may refer to both the development of new communication standards between, for example, different blockchain protocols, as well as to the interaction of different systems or techniques. In addition to this, the adoption of hardware must also be compatible with the ICT layer deployed [55].

Considering local markets as decentrally operating microgrids allows for decentralized coordination between these local market entities instead of traditional wholesale markets, which might result in similar challenges to local markets arising on the wholesale market as well [86].

D. LEGAL FRAMEWORK OF IMPLEMENTATION

EU Directive 2019/944 [2] allows consumers to unite as ''citizen energy communities'' and exchange energy on a local level. This directive authorizes member states to allow citizen energy communities to act as distribution system operators either under the general scheme or as ''closed distribution system operators''. The provisions of this directive on citizen energy communities only clarify those aspects of distribution system operation that are likely to be relevant for citizen energy communities.

However, due to the still restrictive regulations of the energy market and the more recently published directive, business models for energy sharing via local electricity markets are still very rarely put into commercial practice [84].

Similar to the previously discussed demand response in Section II-B, no ''one-size-fits-all'' solutions can be established in respect to local energy trading [45]. As a result, the provisions adopted in the current EU directive [2] remain relatively open to interpretation. Although the role and responsibility of prosumers and local electricity markets is to a large extent clarified by this directive, further demand for regulatory clarification remains. The Council of European Energy Regulators [33] argues that existing market principles such as unbundling, consumer rights or cost-sharing principles applicable to energy networks could theoretically be circumvented by the introduction of citizen energy communities.

Given that local electricity trading predominantly takes place in local electricity markets, integration into national law on grid regulation will be crucial in order to enable local electricity markets within energy communities [7], [33], [85].

Moreover, specification of market design concepts is crucial in terms of establishing the legal framework. As such, appropriate incentives for flexibility have to be elaborated on [45], [46]. As already discussed in Section II-A and Section II-B, these incentives can be conflicting.

By EU regulation [2], smart consumption and production meters must be able to communicate supply-demand load matching within short time steps in order to identify conditions for self-consumption and assign an energy value for billing purposes. According to the previously discussed challenges in demand response (Section II-B) and market decentralization (Section II-C), local electricity markets may require upgrades to existing meters and software for managing the flow of electricity. Thus, regulations need to clarify who is responsible for such upgrades [63], [79].

Hence, the protection of vulnerable, i.e. elderly, socially disadvantaged, and price-sensitive [55] consumers in the context of local energy trading remains a somewhat challenging task [46]. As Energy Communities can link production and supply more closely, it is necessary to maintain the same consumer rights for participants in energy communities. Discrimination should be prevented, thus ensuring democratization of energy [5]. Consequently, consumers can neither be forced, nor prevented from joining an energy community as long as they meet the technical requirements. They have to be authorized to choose or change their supplier at will and to be informed accordingly about the conditions of supply. In particular, active consumers should be aware that they are responsible for their imbalances stated in Section II-A and Section II-B [33], [45], [46].

In the case of decentralized local electricity markets, the enforcement of law if a promised energy service is not delivered can pose a challenge as digital contracts (e.g. smart contracts) may not be appropriately regulated [64]. In line with the challenges mentioned in Section II-C, the adopted ICT must ensure data portability, an appropriate quality of service, and data protection for customers must be ensured. Other market players must not be disadvantaged under any circumstances [11], [33], [46], [64], [71], [81]. The current legislative environment might also limit the integration of technologies that do not provide sufficient flexibility (e.g. permissionless blockchains), as they might not provide flexibility to manipulate private data [64].

Furthermore, the given regulatory framework can significantly limit the profitability of local trading. There are two ways to implement the proposed market concepts: Either the regulation must be fundamentally changed so that the specific assumptions of the proposed concepts can be implemented, or the market concept must be adapted so that it fits into the regulatory framework. Changes in the regulatory framework carry the risk that pure electricity consumers have to bear higher expenses due to increased self-consumption rates. This has the result that in most models, the total fixed grid costs are distributed amongst lower grid consumption, which primarily affects pure consumers [35].

Member states are free to allow Energy Communities to own the grid infrastructure itself. In such a case, an appropriate legal integration into the legal framework for distribution and transmission networks has to be ensured [33].

Another potential challenge to the implementation of decentralization in the electricity grid is shown in Ref. [87] which outlines that stakeholders profiting from existing regulatory implementation barriers could be incentivized to use their lobbying powers to uphold the status quo in order to maintain their current business models.

As mentioned above, there are further challenges concerning the relationship between local electricity markets, existing electricity markets, and other emerging entities such as DSO [45], [46]. Fundamentally, the reorganization of the highly regulated energy industry is a challenging task. To disrupt the status quo, results from a wide range of implemented case studies from around the world are required [84].

E. SOCIAL ASPECTS

The main system design challenge in local electricity markets is to develop schemes and business models that encourage participants to contribute and trade energy with one another [47], [48], [72]. In order to motivate people to participate in a local energy trading paradigm, various social and behavioral aspects must be taken into account. On the one hand these include people's values, opinions and emotions [16]. On the other hand interests and expectations also need to be considered [48], [74]. These may differ and conflict with each other. Similarly, they can also differ within the groups of prosumers and consumers themselves. As people's willingness to participate depends on these aspects, the design and implementation of new local energy trading schemes and business models discussed in Section II-C has to be consumer- as well as prosumer-centric and take into account both groups' interests and expectations [5], [17], [48], [72], [73]. The heterogeneity of prosumers' preferences must also be taken into account [73]. Although different preferences should be separately considered, heterogeneous prosumer preferences do not automatically have to differ regarding common objectives at the local energy exchange [16].

For both prosumers as well as consumers, cost factors play a major role. Economic benefit is considered the primary motivation for participation in a local energy exchange [17], [74]. This is also reflected in the fact that the relevance of locally generated energy seems to appear insignificant if it incurs higher costs for the users [17]. As described in Section II-D, payment procedures need to be secure and easily manageable in order to be accepted by the public [74].

Besides economic growth, additional incentive values for participation in local energy trading need to be defined [17] such as providing equal benefits to all prosumers [47]. Participation has to be rewarded at any time regardless of whether the participant acts solely as a buyer or in addition as a seller [48]. Moreover, consumers are by definition less engaged than prosumers as their interaction is unidirectional instead of bidirectional. For most prosumers, autonomy, personal and business image play a more significant role than consumptional needs. For consumers, this is not the case [74]. Local energy trading necessitates the prosumers relying on each other for trading electricity. Without a centralized authority the trust between users and their trust in the technology needs to be constantly maintained. Aside from guaranteeing users' security and privacy, discrimination needs to be avoided and equal access for all users needs to be enabled [72], [80]. This is not only limited to the involved processes and software, but also includes the hardware side as well. For example is smart meter validity necessary to ensure trust in the market as these are the main providers of the input data from the participants side [55].

Another factor is the operational complexity mentioned in the previous sections. Increasing technical complexity can also affect the willingness of participation. Under voluntary participation the need for additional investments into technology and the variations caused by intermittent renewable generation might lead to complications that might provide too high an entrance barrier [88].

Further findings show that people are more likely to participate in localized trading schemes that operate at the region/city level and that involve their local council. Project framing needs to emphasize anonymity of consumer data [49]. The selection of an appropriate data-management technology will determine the level of anonymity of the participants. Insufficient data management can be a drawback for businesses due to commercially sensitive data [55]. Public blockchains offer pseudonyms and limit the possibility of analyzing the identity behind the addresses [92]. However, this may also contradict the common way that DSOs deal with distribution grids, where customers are identified and physical entities - people - are responsible for energy consumption [55], [64].

In addition to this can the chosen design of a local market, as introduced previously and shown in Figure 1, lead to differing challenges on the socioeconomic side. This is especially concerned with the differentiation in centralization and decentralization.

Centralized markets maximize a single objective function, e.g. mutual economic benefit and profit maximization, reduction and minimization of energy generation, consumption or cost minimization of greenhouse gas emissions, system efficiency, reliability, stability and congestion management improvement, system loss reduction, minimization of voltage and frequency deviations, increased supply security for each participant and/or maximization of social welfare. Thus, centralized topologies are not necessarily ideal to implement in local electricity markets with a heterogeneous nature in which the participants' objectives deviate strongly from each other. In addition to that could the previously mentioned cyber-attacks potentially more damaging in such centralized topologies, caused by the collection of data in single central platforms. This in turn could negatively affect user trust. Moreover, the influence of large members in the market could lead to an unfair and biased energy sharing [11].

In decentralized markets, uncoordinated interaction could lead to a competition amongst the participants causing price imbalances and market inefficiencies [11]. As discussed previously, in addition to the interaction within the local electricity market itself, the interaction with existing energy markets is also essential for local electricity markets to function. According to Refs. [5] and [4], this interaction specifically deserves further attention in future literature and its effects on individual prosumers might not be fully mapped today.

III. MODELING APPROACHES

This chapter explains the most common models of local electricity markets with a focus on the introduced challenges. The reviewed literature is related to grid representation, decentralization of markets, cooperative/competitive games, distributed control, demand response, uncertainty and related technologies. The considered papers and their relation to particular challenges are shown in Table 4.

NOMENCLATURE

Indexes	
i	generation/demand unit
b	bus
j	market participant
t	period
Variables	
P	active power
Q	reactive power
δ	voltage angles
V	voltage magnitude
x	market participant decision
y	market clearing decision
λ	inequality constraint dual variable
μ	equality constraint dual variable
S	storage state
Functions	
C	generation cost/consumption utility function
C'	purchase cost/sales profit function
P^B	bus injection
P^L	line load
MC	market clearing function
H	inequality grid constraints
G	equality grid constraints
$\mathcal{Q}$	Lagrangian relaxation
Sets	
I	generation/demand units
Additional notation	
$\underline{\cdot}$	lower limits
$\bar{\cdot}$	upper limits

A. GRID REPRESENTATION

In its simplest form, the operational problem within the grid is to match demand and supply under minimization of cost, whilst enforcing line limits:

$$\max_{P} \sum_{i \in I} C_i^d(P_i) - C_i^g(P_i) \tag{1a}$$

$$\text{s.t.} \quad \underline{P}_i \leq P_i \leq \bar{P}_i \quad \forall i \tag{1b}$$

In problem (2) the objective shown in (1a) is to maximize system welfare by adjusting active power under a (most often convex) cost function. The limits of the active power are provided in (2b). In traditional optimal power flow (OPF) problems, demand is considered as inelastic, i.e. $\underline{P}_i = \bar{P}_i$ for a demand unit i. In this case, the utility function of such demand units is not considered in the objective, leading to $C_i^d(P_i) = 0$ and the objective being a traditional generation cost minimization problem. In local electricity markets however, utilizing demand response could be achieved via a utility function (i.e. a negative cost function). Consumption would then be represented via negative limits on the active power, i.e. lower limits of $\underline{P}_i < 0$ and upper limits of $\bar{P}_i \leq 0$. A prosumer could then be implemented either via splitting the unit up into an individual consumer or producer, or allowing negative lower limits and positive upper limits with an adequate cost function. The advantage of this utility function definition is that it allows for representation of market participants of several sizes and types. Aggregates of several consumers, producers or prosumers are as possible as granularity to a per-household or even per-device level. In addition to that this formulation allows for the addition of other technical specifications such as the later discussed state equations for storage devices. The described problem is convex if the cost function is convex.

One of the key goals of local electricity markets is the alleviation of challenges within the power grid, specifically low-voltage grids. As such, most models that implement and/or analyze local electricity markets consider a form of (distribution) grid, are mostly implemented as an OPF problem.

A popular form of such an OPF is provided by the DC OPF representation, where voltage magnitudes are approximated to one, and reactive power and transmission losses are neglected. This is a common representation in transmission grid problems.

$$\min_{P,\delta} \sum_{i \in I} C_i(P_i) \tag{2a}$$

$$\text{s.t.} \quad \underline{P}_i \leq P_i \leq \bar{P}_i \quad \forall i \tag{2b}$$

$$P_b^B(\delta_b) = \sum_{i \in I_b} P_i \quad \forall b \tag{2c}$$

$$\underline{P}_{b_1,b_2}^L \leq P_{b_1,b_2}^L(\delta_{b_1}, \delta_{b_2}) \leq \bar{P}_{b_1,b_2}^L \quad \forall b_1, b_2 \tag{2d}$$

The objective of this optimization problem, shown in (2a), is, as in (1a), maximizing system welfare, as well as incorporating voltage angles. In addition to the previous constraint on active power limits it also considers Kirchhoff's equations. The balance within a bus b is enforced by (2c) and the line flow limits are enforced by (2d). In this problem, both bus balance P^B and line balance P^L are kept as convex functions.

The shown DC OPF is also often referred to as DC approximation, due to it being an approximation of the AC reality, which does not consider additional grid aspects such as reactive loads, line resistance and voltage magnitudes. The convexity of problem (2) makes such as DC approximation of the OPF problem a popular choice. Moreover, the DC OPF problem represents a linearization of the nonlinear AC OPF problem. The linearity and convexity have led to the DC OPF being the basis for most literature on power markets considering the grid, as they make finding the equilibrium points a tractable problem and are thus able to ensure fairness. A solution to a non-linear and non-convex problem is by definition a local solution, meaning that it cannot be ensured that it is the optimal point for all participants.

As previously mentioned, local electricity markets specifically aim to solve problems in low voltage grids, which would require incorporation of the same model components that lead to non-convexities in the power flow equations. Some papers solve this dilemma by decoupling the market clearing problem from the power flow problem and solving both separately, with others accepting this decoupling of the problem as a premise and not incorporating power flow equations into their model at all. However, some literature sources still rely on a form of AC OPF:

$$\min_{P,Q,\delta,V} \sum_{i \in I} C_i(P_i) \tag{3a}$$

$$\text{s.t.} \quad \underline{P}_i \leq P_i \leq \bar{P}_i \quad \forall i \tag{3b}$$

$$\underline{Q}_i \leq Q_i \leq \bar{Q}_i \quad \forall i \tag{3c}$$

$$\underline{\delta}_b \leq \delta_b \leq \bar{\delta}_b \quad \forall b \tag{3d}$$

$$\underline{V}_b \leq V_b \leq \bar{V}_b \quad \forall b \tag{3e}$$

$$P_b^B(V_b, \delta_b) = \sum_{i \in I_b} P_i \quad \forall b \tag{3f}$$

$$Q_b^B(V_b, \delta_b) = \sum_{i \in I_b} Q_i \quad \forall b \tag{3g}$$

The optimization problem now has two additional decision variables - the voltage magnitude and the reactive power. All of the four decision variables have their respective limits enforced via (3b) to (3e). Kirchhoff's equations are represented via the bus balance constraints for active power in (3f) and (3g) respectively. These AC power flow equations are the contributors of the non-convexity of the AC OPF problem, as they usually depend on a sine/cosine formulation of the voltage angles. Further information on variations of power flow equations and the optimal power flow can be found in the more comprehensive study provided in Ref. [148]. These include, for example, formulations considering storage or uncertainty, which are both aspects that play considerable roles in local electricity market models.

The non-convexities in this problem lead to solutions being local instead of global, meaning that it cannot be ensured that a found solution is actually welfare-optimal. This is a problem that has led to adequate pricing issues in examples such as AC locational marginal prices [37], and is a significant hurdle in terms of fair remuneration.

Thus, when disregarding the type of non-convex AC OPF problem, most of the papers utilize a form of convex approximation of the AC OPF, with the previously introduced DC power flow approximation or the second-order conic relaxation [149] as popular examples. The reason for this approximation is that a non-convex representation stands in direct contrast to fairness. This results in a majority of the main technical/computational challenges of solving real grid problems, discussed in Section II, contradicting the main social challenge of fair distribution of resources. This will be further discussed in the subsequent subsection on market clearing, using the more general notation of H and G as a representation of the chosen grid constraints.

Local electricity markets empower investments in renewable generation and flexibility in the distribution grid, but also impose new challenges with respect to quality of supply onto the DSO. Peer-to-peer trading and local electricity markets have received significant attention in state-of-the-art research, using mathematical models to ensure fairness, market efficiency and incentives for distributed energy resources. After a market is cleared and transactions are established in the financial (virtual) layer, its effect will be imposed on the physical layer. An important next step is to incorporate grid challenges into the mathematical formulation, either directly or indirectly, ensuring that the imposed impact on the physical layer is feasible and does not cause further issues, as presented in Section II.

The literature discussing grid challenges related to local electricity markets is shown in Table 5. In addition, the sources are presented below.

TABLE 5. Literature on grid related challenges.

Paper	AC PF	DC PF	Congestions	Voltages	Tariffs	Policy
[93]	x		x	x		
[70]					x	x
[94]	x		x	x		
[95]	x		x	x		
[96]	x		x	x	x	
[97]	x		x	x		
[98]	x		x	x	x	
[62]		x	x	x		
[102]		x	x	x		x
[105]			x			x
[107]	x		x	x		
[108]		x	x			
[109]		x	x			
[110]		x	x			
[112]		x	x			
[115]			x		x	x
[116]	x		x	x		
[117]	x		x	x		
[119]		x	x		x	
[120]			x		x	
[121]			x		x	x
[122]			x		x	x
[81]		x	x			
[128]	x			x		
[129]	x		x	x		
[133]	x			x		
[134]	x		x	x		
[137]			x			
[138]	x		x	x		
[139]	x		x	x		
[140]			x			
[141]	x		x	x		
[142]	x		x	x		
[86]	x	x	x	x		
[143]		x	x			
[144]	x		x	x		
[145]	x		x	x		
[146]	x		x	x		
[147]	x		x	x		

1) LITERATURE, FOCUS: POWER FLOW

Modeling the AC power flow (AC PF) problem or parts of it has been performed in a series of studies. It should be noted that, unlike the AC OPF problem, the AC PF problem does not attempt to optimally dispatch distributed energy resources, but analyses the distribution grid impact of the market clearing decisions. An approach for the DSO to access flexibility through a local electricity market is suggested in Ref. [116]. The suggested model clears the local electricity market and performs an AC PF analysis of the instance to investigate potential congestions. The aggregator is then responsible for finding a new dispatch in the local electricity market. Using auctions-based trading, Ref. [95] utilizes a local peer-to-peer market clearing with post clearing analysis of a low voltage network. The analysis focuses on investigating network problems that a financially attractive peer-to-peer market can introduce. Simulations performed on a low-voltage network show that voltage limits are violated using a local peer-to-peer market. In addition, losses are increased by 4.1%. Similarly, [147] has developed a decision support tool for prosumers, using a computationally efficient piecewise linearized bidding curve with low computational requirements. Further, bids are matched by the DSO, ensuring that the grid constraints are satisfied. In Ref. [98], storage decisions are included into the local electricity market problem via a multi-period AC OPF. The market is established via locational marginal pricing and is cleared centrally, thus bringing the problem closer to a centralized dispatch problem than a liberalized local electricity market implementation. In Ref. [107], a collaborative Nash bargaining game over a multi-period AC power flow is implemented. The model uses various approximations such as a second order conic representation of the non-convexities in the power flow, which is a decomposition technique aiming to separate the optimal power flow and the bidding problem as well as using a Lagrangian relaxation approach for the state constraints. An unbalanced 3-phase power flow model was used in [142] in order to add details on phase-level. A Stackelberg game is formulated in [146]. Unique to the formulation is that the non-cooperative game, privacy measures and distributed energy resources are included alongside the grid constraints in the upper level of the problem.

In the distribution system, local flexibility can be made available to the DSO by using price signals from grid tariffs. In Ref. [97] the authors suggest a combination of power flow simulations and the aforementioned grid tariffs. The suggested approach clears the market, solves the power flow problem and then adds network tariffs to the conducted trades. In addition, the model adds a power loss factor as well as penalization terms for all agents. Community-based and decentralized peer-to-peer approaches are compared in [96], where the authors highlight that the different market schemes impact voltage levels significantly. This is done using distributed optimal power flow, extracting distributed locational marginal prices as a result of the grid constraints. Ref. [128] assesses network power losses associated with peer-to-peer trading through an analysis of the physical layer. Losses occurring under peer-to-peer conditions are estimated by a simulation model utilizing an effective nodes-per-area concept, and compared with existing losses in non-peer-to-peer systems.

Distributed optimal power flows have been investigated in [117], as the method shows synergy with the distributed nature of local electricity markets. Such a distributed approach is also reviewed as a promising method of ensuring proper voltage control with decentralized control in Ref. [133]. However, as discussed in Ref. [94], the implementation of such distributed models requires radical changes in market design primarily due to technical and market design barriers.

Moreover, DC power flow approaches with exogenous cost allocations are used to avoid congestions [119]. Based on the Newton method, Ref. [62] addresses challenges related to congestions and distribution grid expansion. A DSO pricing approach based on distributed locational marginal pricing is presented in [102], where linearized power flow constraints are considered.

B. MARKET REPRESENTATION

In a market setting, there is no welfare-maximizing agent (or *benevolent dictator*) that has direct control of each producer/consumer/prosumer and tries to minimize the global cost function (i.e. maximize the welfare). Instead, either a market operator (as in traditional electric power markets)/community manager or the market participants themselves (as in modern peer-to-peer markets) set their bids in order to obtain a market clearing result and produce/consume accordingly. This means that market participants submit their respective bids under usually imperfect information on aspects such as the other participants cost/utility functions and are remunerated accordingly.

In its generalized form, a centralized, traditional electricity market clearing can be presented via utilizing H and G to represent the inequality and equality constraints of the previously introduced grid problems:

$$\min_{x_i \forall i \in I_j} \sum_{i \in I_j} C_i'(x_i, y) \quad \forall j \tag{4a}$$

$$\min_{y} \sum_{i \in I} MC_i(x, y) \tag{4b}$$

$$\text{s.t.} \quad \begin{aligned} H(x, y) &\leq 0 \\ G(x, y) &= 0 \end{aligned} \tag{4c}$$

The objective functions in (4a) represent the individual profit maximization/cost minimization problem of the market participants - i.e. a consumer minimizing their cost or a prosumer/producer maximizing their profits. Each participant j supplies a bid x to the market, whereas most commonly these aspects are prices or power. Often in local electricity markets, these participants hold a single unit, thus $\text{card}(I_j) = 1$, but they can also be demand/supply/hybrid aggregators that hold a number of units $\text{card}(I_j) > 1$. In a centralized market, these units are coordinated via a central decision maker, the market operator/community manager, whose objective is the cost minimization within the market as depicted in (4b).

This operator has a separate market clearing function for each participant. This function MC could, for example, be assumed as $MC = C$ in case of perfect information. Additionally, it could be a minimization of imports to the grid or a minimization of assumed cost functions. The clearing results, which could be a clearing price or a clearing quantity on power will then in turn affect the individual player problems, leading to the optimization being a so-called Nash game.

Another potential representation is a market that refrains from using a dedicated decision maker to yield the market clearing results but instead clears the market in decentralized manner (i.e. peer-to-peer):

$$\min_{x_i, y_i \forall i \in I_j} \sum_{i \in I_j} C_i'(x_i, y) \quad \forall j \tag{5a}$$

$$\text{s.t.} \quad \begin{aligned} H(x, y) &\leq 0 \\ G(x, y) &= 0 \end{aligned} \tag{5b}$$

In this case, the intermediary of a market operator/community manager is removed, leading to the players directly influencing the market clearing parameters of other players y^i whilst relying on all of the other players' decisions. An example of a peer-to-peer market implementation would be price and power quantity bids in form of vector x_i and accepted quantities from other players in the form of vector y_i. A visual comparison of centralized and decentralized market clearings is provided in Figure 3.

The main reason for such a decentralized model would be to reduce the requirement for information centralization, as there is no need for a central market clearing entity that is informed about the specifications of the players. Nonetheless, the trade-off between an accurate grid representation and fairness is still inherited in this formulation. Additionally, both the centralized and decentralized problem have multiple objectives that further complicate the optimization. This will be discussed in the subsequent subsection on the representation of competition.

The papers related to the market design are displayed in Table 6 and will be introduced below.

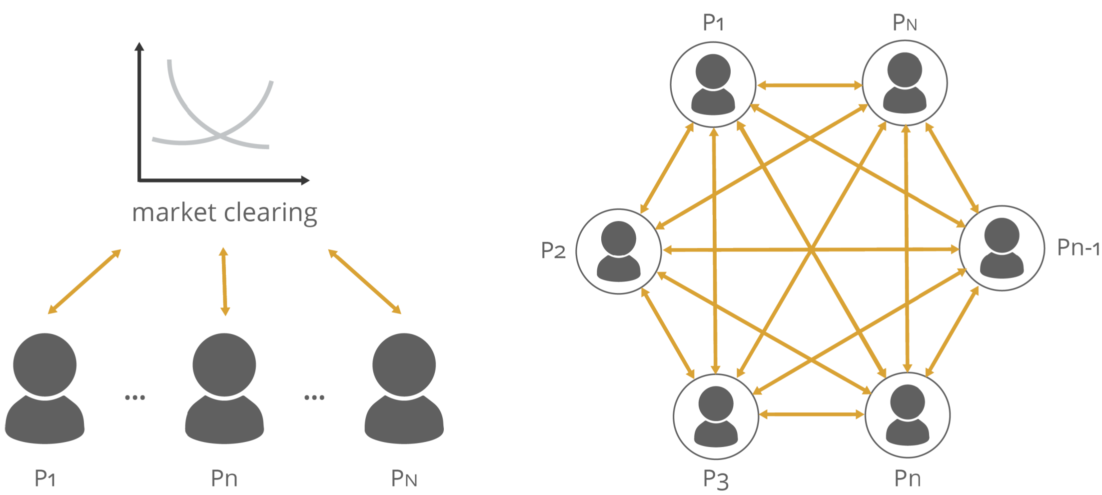
TABLE 6. Literature on market challenges.

Paper	Centralized market clearing	Decentralized market clearing	Balancing products	Demand response
[93]	x			
[70]		x		
[94]		x		
[95]		x		
[96]	x	x		x
[97]	x			
[98]	x		x	
[62]	x			x
[99]		x		
[100]	x			
[101]	x			
[102]		x		
[103]	x		x	x
[104]	x			
[105]		x		x
[48]	x			
[107]	x			
[108]		x		
[109]	x		x	x
[110]	x			x
[111]	x		x	x
[112]	x	x	x	x
[113]		x		x
[114]	x			x
[115]	x			x
[116]	x			
[117]	x			x
[118]	x			x
[119]	x			
[120]	x			x
[121]	x			x
[122]	x			
[123]	x		x	x
[124]		x		
[125]	x			x
[81]	x	x		x
[128]			x	
[129]		x		
[131]		x		x
[132]		x		
[118]			x	
[134]	x			
[135]	x			
[136]	x			x
[137]		x		x
[138]	x		x	x
[139]	x			x
[140]	x			x
[141]	x			x
[142]	x			
[143]		x		
[144]	x			x
[145]	x			
[146]	x	x		x
[147]		x		

1) LITERATURE, FOCUS: CENTRALIZED MARKET CLEARING

Centralized market clearings provide a method to share sensitive information about utility functions of each agent with only a central entity, the market operator or community manager. In Ref. [105], the authors prove that centralized energy communities can achieve similar market clearings as a fully decentralized peer-to-peer market under the assumption of a supervisory node with access to utility functions of all involved agents. Both were found to be viable approaches in Ref. [96], which however found centralized community-based approaches ensured DSO interests to a greater extent. Other advantages of such centralized energy collectives are the adaptability to the existing market design as well as future market designs in terms of balancing, wholesale and ancillary service provision [105]. The role of the community operator would therefore be to supervise and ensure convergence to optimality of trades inside the community as well as acting on behalf of the community with other markets such as flexibility or ancillary service markets.

Ref. [150] defines the need for less information flow between the market operator/community manager and the peers, but also highlights the need for coordination



a) Centralized market clearing with uniform pricing

b) Decentralized P2P market clearing with discriminatory pricing

FIGURE 3. Centralized and decentralized market clearing.

from a supervisory node to lower costs and increase self-consumption inside the community. Another aspect often ignored in local electricity market research is the necessity for coordination in intraday markets due to uncertainty in load and distributed generation in the local electricity market. In Ref. [123], a local intraday market is suggested to handle deviations from the scheduled demand and production, coordinated by a central market clearing entity. A similar multi-market model approach is shown in Ref. [103], where a local electricity market is positioned within a wholesale electricity market. The main hurdle for implementation is the computational complexity, which stems from the necessity of a two-stage stochastic program scenario generation as each market has its own clearing period that provides updated information on uncertainties. Local trades are prioritized for the intraday market. In order to ensure scalability, this paper utilizes scenario reduction techniques. Further approaches considering community managers are also shown in Refs. [151], [152].

2) LITERATURE, FOCUS: DECENTRALIZED MARKET CLEARING

As discussed above, in markets with decentralized market clearings, information is not sent to a supervisory node but is performed in a multi-bilateral fashion between agents in the system. This poses challenges for the DSO as it is demanding to influence the flexibility and transactions to facilitate healthy operation of the grid. A full peer-to-peer market design with complete multi-bilateral energy dispatch was designed in Ref. [108]. In addition, Lagrangian relaxation and the alternating direction method of multipliers (further introduced below in Section III-D) are recommended in [7], due to their ability to define to maintain privacy and split the problem into one subproblem per asset or agent. Here, end-users share only their volume and willingness to pay for electricity, keeping asset information and similar aspects private. Note that this method is not fully decentralized, as there is still a supervisory node.

Auction-based approaches are also viable methods for clearing local electricity markets, as they scale well compared to computationally comprehensive optimization methods such as optimal power flow or location marginal pricing based methods. Auction-based approaches benefit from the fact that the market clearing follows an automated set of rules and can be solved in a distributed fashion by the involved agents. Continuous double auctions have been demonstrated in Ref. [153], where trading with a shared electric energy storage in an energy community is proposed. In Ref. [94], zero intelligence trading algorithms were investigated to match buyer and seller bids in local peer-to-peer markets, also allowing for a lack of market supervisor. Iterative continuous double auctions have also been applied on energy trading in microgrids [154]. The use of local electricity markets with peer-to-peer transactions, based on continuous double auctions together with blockchain technology, was suggested for charging of plug-in hybrid electric vehicles in Ref. [131] where sensitive information about the vehicles would remain private. Integration of flexible resources into electricity markets using continuous double auctions in a prediction-integration strategy optimization model is suggested in Ref. [155]. Similarly, Ref. [126] proposes a comparative analysis of various auction mechanisms and bidding strategies for solar electricity trading. The economic efficiencies and impacts of the different strategies on market conditions are simulated through a case study, considering participants in a microgrid at varying photovoltaics penetration levels. Ref. [113] proposes a framework that allows for continuous auctions in order to match distributed demand and supply in a microgrid. The model utilizes a distributed peer-to-peer approach with the goal of profit maximization of its agents, whilst minimizing information-sharing. Clustering is suggested in Ref. [100] as an approach to increase efficiency of a market clearing heuristic solving the auction problem of a local power exchange. The paper aims to ensure optimal fairness in a non-convex problem (i.e. a problem where finding the optimal global fairness solution is "NP-hard"). An attempt to incorporate information asymmetry into local electricity markets is presented in Ref. [156]. To do so it uses a utility function formulation and explores both centralized and decentralized local electricity markets. In addition, it analyses the issue of privacy. The model is non-convex and thus scalability is again an issue here.

A common theme of the mentioned studies is that grid concerns are not specifically included, indicating open research avenues on integration of DSO requests in decentralized local electricity market clearing.

C. COMPETITION REPRESENTATION

The previously introduced market representation implements a model under competition in which every participant aims to individually maximize their respective results. Disregarding the form of competition (Cournot, Stackelberg, Bertrand), the players will only focus on their individual outcome when making their bidding/consumption/generation or any other decision. In literature, it is common to focus on the decisions yielding the Nash equilibria, i.e. the x and y values where none of the participants can further reduce their cost. Assuming the dual variables of the grid inequality and equality constraints are denoted as λ and μ respectively allows to reformulate the Karush-Kuhn-Tucker conditions for the Nash game:

$$\frac{\partial Q(x, y, \lambda, \mu)}{\partial x_i} = 0 \quad \forall i \tag{6a}$$

$$\frac{\partial Q(x, y, \lambda, \mu)}{\partial y} = 0 \tag{6b}$$

$$0 \leq \lambda \perp H(x, y) = 0 \tag{6c}$$

$$G(x, y) = 0 \tag{6d}$$

$$\mu \in \mathbb{R}, \lambda \in \mathbb{R}^+ \tag{6e}$$

In general, for a feasible problem and convex functions, this problem will converge to a Nash equilibrium solution, i.e. to a point where no participant can decrease their cost. Further information on Karush-Kuhn-Tucker and related optimality conditions (included non-convex cases) can be found in Ref. [157].

In contrast to competitive models stand cooperative models. In traditional wholesale power markets, such models are less prevalent, which can not only be explained by the large number of participants but also by the goals of the competitive markets to ensure profits for its participants in order to sustain additional ventures such as future investments and R&D into the right products for the market. An illustrative example of the difference between cooperative and competitive models can be found in Figure 4. In the cooperative case, a central entity (e.g. community manager) minimizes the total cost of the agents, whereas in the competitive case all agents minimize their individual costs.

On smaller scales, i.e. in local electricity markets, cooperative market models are more prevalent. This can not only be explained due to a lower number of competitors but also due to the goal of collaborative markets that is to ensure optimal fairness for all its participants. In such a model, the market is cleared for the welfare-maximizing solution and the participants are remunerated according to maximum fairness. The reason is that the fairest solution might not be the welfare-maximizing solution. An example is that of a monopolist which in a competitive market would be able to extract a higher profit/lower cost by utilizing their market power to influence prices. A welfare-optimizing market under fair cooperation would thus remunerate the monopolist not utilizing their market power to do so but instead choosing the welfare-maximum with an accordingly higher share of the end result.

The cooperative approach is less standardized than the competitive approach, as many methods, such as Shapley and Harsanyi values, are intractable for larger problems, thus only allowing for limited scalability. Some local electricity market model designs oversee this hurdle and only conceptualize small systems, whilst others specifically approach this limitation via approaches to increase computational performance.

Within local decentralized markets, an established technique to approach collaboration instead of fair distribution is via bargaining solutions. The Nash bargaining game is a common way to implement this:

$$\min_{x,y} \prod_j \Big(\sum_{i \in I_j} C_i(P_i) - \sum_{i \in I_j} C_i'(x_i, y) \Big) \tag{7a}$$

$$\text{s.t.} \quad \begin{aligned} H(x, y) &\leq 0 \\ G(x, y) &= 0 \end{aligned} \tag{7b}$$

$$\text{where} \quad P \subseteq x \tag{7c}$$

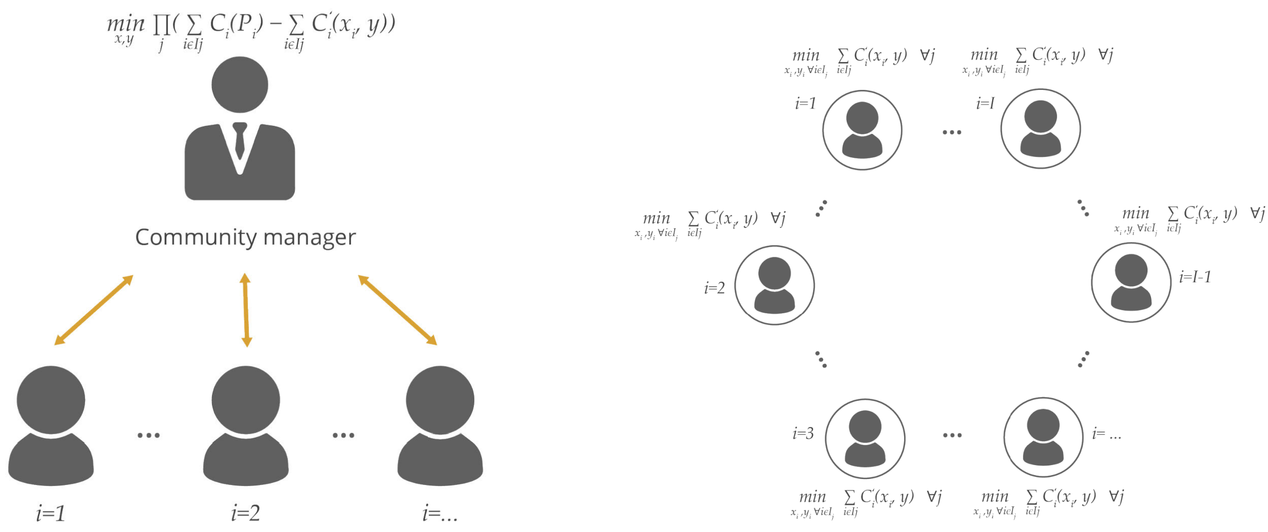
The bargaining solution given in (7a) is thus the product of the system cost under cooperation C minus the system cost under competition C' over each player.

However, not all solutions of local electricity markets require information-sharing entities to decide on market results. In fact, peer-to-peer markets are often specifically designed to minimize information sharing and allow for decentralized optimization principles. This does not only provide advantages in data security, it also supports the scalability of such optimization techniques. This will be discussed in the following subsection on distributed optimization.

Table 7 summarizes the solution approaches for the models presented in literature. In addition, they are described in detail below.

1) LITERATURE, FOCUS: COOPERATIVE GAMES

Since individual agents' interests are not explicitly considered in the centralized approach, this approach is often used



(a) Cooperative game (b) Competitive game

FIGURE 4. Comparison of objective function structures in cooperative and competitive games.

for benchmark models that provide the system welfare optimum. An optimal matching of stochastic load and local generation is presented in Ref. [62]. In Ref. [118], it was found that decentralized batteries lead to almost 20% of savings compared to one centralized battery in a localized peer-to-peer market. Similarly, Refs. [115], [120] found that best-case coordination of flexible assets in a neighborhood could reduce peak loads. Ref. [101] analyzed the impact of risk-neutral and risk-averse agents in local electricity markets.

As described previously, aggregators are market entities designed to deal with centralized control. They are able to coordinate end-users in markets as well as interact directly with the DSO. In Ref. [116], the DSO performs an AC PF analysis after each market clearing and informs the aggregator if congestions or voltage problems arise. In that case, the aggregator is forced to change their generation schedule in order to avoid congestions. A decentralized market for distribution system flexibility is suggested in [142], where aggregators fulfill the role of flexibility providers and manage the individual prosumer assets while coordinating with the DSO. Because the market design allows for opt-in from the end-user side, fairness issues and implementation challenges are reduced.

2) LITERATURE, FOCUS: COMPETITIVE GAMES

In Ref. [158], local generation and consumption coordination is implemented using a game-theoretic approach. The paper finds that that sparsity in peer behavior resulted in higher savings and lower peak loads. Flexibility assets are coordinated using a local peer-to-peer market in Ref. [159], where end-users in a neighborhood coordinate their consumption under a subscribed capacity network tariff design. By implementing a local electricity market, end-users can rent subscribed capacity from other agents in order to reduce neighborhood peak loads. Further, Ref. [132] proposes a general framework for implementing an electricity market structure with large distributed energy resources. The framework enables consumers to participate directly in the market and aims to be profitable for the prosumers, as well as maximizing the expected profit of the distributed energy resources by analyzing uncertainties. Complementarity models using the Karush-Kuhn-Tucker conditions can be extended to Stackelberg games by introducing a two-level approach. This is performed in Ref. [9] where a Stackelberg formulation (sometimes referred to as MPEC, math program with equilibrium constraints) is used to optimally design grid tariffs in order to avoid high peak loads from the prosumers in the market. A Stackelberg approach is also used in Ref. [135], where a bilevel game where consumers react to prosumers within a non-cooperative peer-to-peer market is designed. The paper is based on a logarithmic formulation of utility curves and a welfare-maximization approach for market clearing. Similarly, in Ref. [104], a Stackelberg market clearing model for local electricity trading in a microgrid is proposed. Sellers are assumed to be taking the role of leaders and buyers the role of followers. The paper shows that under consideration of the taken assumptions by the players, i.e. the buyers basing their decisions on the sellers' as well as rational, selfish players with access to full information, the proposed market model finds the unique Nash equilibrium. A Nash game for a sharing mechanism between prosumers that utilizes auctions is proposed in Ref. [125]. It provides a proof for the Nash equilibrium of the game existing and being unique in addition to being socially optimal. Further, Ref. [48]

TABLE 7. Literature on model-approach challenges.

Paper	Optimization	Auctions	Cooperative	Competitive	Scalability	Uncertainty
[93]	x		x			
[70]		x		x		
[94]	x	x		x		
[95]		x		x		
[96]	x	x	x	x		
[97]	x			x		
[98]	x			x		x
[62]	x	x	x			x
[99]	x	x		x	x	
[100]	x	x		x	x	
[101]	x	x		x		
[102]	x	x		x		
[103]	x		x		x	
[104]	x			x		
[105]	x		x			
[48]			x			
[107]	x	x	x		x	
[108]	x		x			
[109]	x			x		x
[110]	x			x		x
[111]	x			x		x
[112]	x			x		x
[156]	x	x			x	x
[113]	x	x		x		
[114]	x			x		x
[115]	x		x			
[116]	x		x			
[117]	x			x		
[118]	x		x			
[119]	x			x		
[120]	x		x			
[121]	x			x		
[122]	x			x		
[123]	x		x			x
[124]	x			x	x	
[125]	x	x	x			x
[81]	x	x		x	x	
[126]		x				
[127]				x	x	x
[47]				x		
[129]	x			x		
[130]				x	x	
[131]	x	x		x		
[132]				x		x
[133]	x			x		
[118]	x			x		
[134]	x		x		x	
[135]	x			x		
[136]	x			x		
[137]	x	x	x			
[138]	x					x
[139]	x		x		x	
[140]	x		x			x
[141]	x		x			
[142]	x			x		
[86]	x		x			
[144]	x		x			x
[145]	x			x		x
[146]	x	x		x		
[147]		x		x		

demonstrates a collaborative game within a local electricity market. It solely focuses on the socio-economical impacts of such and disregards other factors such as uncertainty of supply or the underlying grid. In their analysis the authors find that a coalitional game can provide the required financial incentives for customers of electricity to participate in local exchange of energy. The authors in Ref. [47] utilize a motivational psychology framework in order to design a decentralized local electricity market trading scheme which aims to increase user participation. A game-theoretic approach is applied in order to validate the scheme. In this context, Ref. [127] evaluates how automated negotiation strategies regarding energy exchange contracts can increase system efficiency and fairness through the proposed negotiated allocations. The approach is also robust to uncertainty in demand and generation.

A comprehensive cost recovery approach is used in Ref. [121] where the leader (DSO) scales and chooses between three grid tariff structures to minimize peak loads from end-users in a non-cooperative game. Similarly, Ref. [99] models a local energy system behind a feeder (i.e. without network constraints) where both electricity and hydrogen can be traded. The model is a hybrid between Bertrand and Cournot models, where every agent maximizes their own benefits. The model also includes privacy considerations and discussions. In addition, the model mentions that due to its location in the distribution grid, the number of participants could potentially be large. Thus, the model focuses on adequate sizing. This is demonstrated by the included case studies, which involve a hundred households competing over 24 hours. A day-ahead market framework using EV aggregators to provide congestion management service is presented in [137]. In addition to solving congestion management challenges in a local market, a data traffic operator is suggested for efficient data traffic management between market participants.

D. DISTRIBUTED OPTIMIZATION

Distributed optimization is the optimization of an entire system via the optimization of its components. This has the advantage that individuals can optimize their respective results and coordinate with each other within the system via external inputs. In local electricity markets, a common technique to implement distributed optimization is the Alternating Direction Method of Multipliers (ADMM). This method is a combination of dual decomposition and the augmented Lagrangian method. The objective function of a local electricity market problem suited for the ADMM can be represented by the following:

$$\min_{x,y} \sum_{j} \sum_{i \in I_j} C_i'(x_i, y) + \sum_{i \in I} MC_i(x, y) \tag{8}$$

The ADMM updates the dual values step-wise via primal descent and dual ascent until both primal and dual problems are converged. The method only requires equality constraints, but inequalities can be incorporated into the augmented Lagrangian relaxation. For the sake of notational simplicity, further information on the algorithm will be omitted but can be found in the comprehensive review on this technique presented in Ref. [160]. The main advantage of ADMM is the ability to solve a centralized problem in a distributed fashion. Semantically speaking, the problem can be described as each agent individually optimizing their assets (local computation) to meet the request from the community manager, and the market operator/community manager coordinating their results via the dual variables of the constraints. This allows for specific asset data and the utility function of each agent to remain private. Additional techniques for distributed optimization exist and can for instance be found in Ref. [161]. Nonetheless, it can be stated in general that problem convexity, and thus a convex grid representation, is key for such global optimization methods. Equally, this convexity is a focus for further additions to the grid and/or bidding problem, some of which will be discussed below.

1) LITERATURE, FOCUS: DISTRIBUTED OPTIMIZATION

ADMM algorithms have been widely described in the literature due to their capability of solving convex problems by splitting them into more tractable problems. This is demonstrated by Ref. [134] where scalability and privacy issues are highlighted as advantages of ADMM. A consensus version of the method is showcased in Ref. [119], where a competitive equilibrium can be achieved in a distributed manner. A unified formulation for consensus ADMM under different market designs is presented in Ref. [124], where the market design can be conveniently changed by changing the utilized communication links. The authors also claim faster convergence and better resilience to asynchronous behaviors. ADMM is used to combine the DC OPF formulation with trading in Ref. [129], where an integrated blockchain-based energy management platform for bilateral trading which optimizes the energy flows in a microgrid is designed. The optimization problem is broken down by the ADMM and a smart contract executes the role of a virtual aggregator. A similar approach is investigated in Ref. [162], where a consensus + innovation approach to solve the local electricity market clearing is used. Compared to ADMM, this approach was found to converge faster for peer-to-peer coordination within a microgrid. Ref. [110] uses a centralized market to deal with demand responses expressed as utility functions and generation uncertainty. The paper achieves this by utilization of a Value at Risk formulation and an iterative algorithm (based on ADMM) for the distributed optimization. An alternative to the ADMM-based distributed optimization approaches can be found in [139], where a retail market mechanism for distribution grids under high penetration of distributed renewable generation is suggested, using a novel coordination algorithm. The authors argue that their algorithm not only requires less computational resources than ADMM, but also enhances privacy preservation over it. This is due to the framework not requiring sharing of dual values representing their distance between the agents optimal points. A bi-level problem is formulated in Ref. [114], where an energy-sharing model is implemented considering prosumer willingness to trade. The multi-agent framework allows the model to be solved in a distributed iterative way rather than by formulating an equilibrium problem with equilibrium constraints (EPEC), as there the model does not require an objective function in the upper level.

E. ADDITIONAL MODEL COMPONENTS

As illustrated later in Section IV, topology, market types, participants, sizes and many other aspects of local electricity market implementations differ internationally, certain modeling components are shared amongst the various models and implementations. Some of these will be discussed here.

A common aspect is the connection to balancing the local grid via exports/imports from a larger network. This is the most common trait shared amongst the models, as most of the models do not aim to implement microgrids but instead aim to solve local problems nested in larger national/regional grids. Some models solve this via bi-level models such as the aforementioned Stackelberg games. In the notation shown below, however, the simplest implementation would be via an import/export agent i with a cost function C_i similar to the purchasing/selling price of a national/regional market (for example intraday wholesale market prices) and unlimited import/export capacities of $\underline{P}_i$ and $\bar{P}_i$. In most models, this import/export agent is also integrated into the market operator/community manager, as the profit maximization of such an agent in this way is not considered part of the competition.

Another common model component is a state constraint in the form of:

$$S_{i,t} = S_{i,t-1} - P_{i,t} \tag{9}$$

Here, t denotes the specific period and S the state of the storage device. In addition, many models often consider degradation cost of the batteries and charging inefficiencies as the power stored will not be equal to the power discharged. Nonetheless, even this simple formulation can create problems in model scalability. This is a general problem in such models and is also an active research topic within the field of multi-period optimal power flows (see Ref. [39] for further information).

A third example of an additional aspect would be uncertainty in parameters. In local electricity markets, this could, for example, mean uncertainty in wholesale prices (thus on the cost functions C), on the limits of the generation units $\underline{P}$ and $\bar{P}$ or similarly on the availability of demand flexibility. As both possibilistic and probabilistic as well as hybrid methods have found their way into power system analysis, no defacto standard for inclusion of uncertainty in local electricity markets can yet be identified. However, a growing literature base of such models can be expected in the future. This is due to the discussion on forecast accuracy in Section II which outlines how uncertainty increases in smaller scales.

1) LITERATURE, FOCUS: GRID TARIFFS

An alternative to modeling grid constraints is implicitly modeling the grid or the potential grid impact. As discussed previously, an all-in-one solution is unachievable for real-world problems. Specifically, grid tariffs are often challenged in terms of fairness and comprehensiveness for the customer [163]. A Stackelberg game incorporating grid tariffs is suggested in Ref. [121]. The leader (DSO) scales and chooses between three grid tariff structures to minimize peak loads in the distribution grid. Similarly, Ref. [122] designed an optimal cost-recovery based grid tariff with the goal of minimizing peak imports from an energy community. A more direct approach is considered in Ref. [119], where network charges are allocated based on electrical distance to reduce stress on the grid in a local electricity market.

2) LITERATURE, FOCUS: UNCERTAINTY MODELING

An intraday local electricity market is suggested in Ref. [123] as a mechanism to deal with uncertainty in prices, demand and photovoltaic production. The intraday market is represented as the second stage in a two-stage stochastic program, where deviations from the day-ahead market position can be corrected in the intraday market. The same idea is extended to a three-stage model in Ref. [136], which describes a multi-stage local electricity market formulation. The focus of the paper is the coordination between storage, demand response and other flexible resources over longer time frames. Uncertainty is also considered in Ref. [155], which uses a special form of a neural network trained via a random update based on the Moore-Penrose inverse instead of gradient descent, in order to find the optimal bidding strategy in an uncertain peer-to-peer market for electricity. The model reinforces its initial assumption based on prior literature: a profit-maximizing agent is able to make continuous profits via peer-to-peer trading. Ref. [143] similarly introduces an optimization model for small-scale agents in smart energy systems with multi market participation under uncertainty, which increases the profit potential for end-users in electricity markets. Ref. [144] shows that robust operation planning of unbalanced three-phase microgrids hedges against a worst-case realization of uncertainties and performs better in terms of average cost.

In addition, Ref. [109] aims to unify scheduling decisions under uncertainty with peer-to-peer trading of intermittent renewables, with a focus on the scheduling decisions. It considers a multi-period problem that implements electric vehicles and local storage. It also considers forecasting errors, with most uncertainties being represented in Gaussian form. Moreover, by coordinating centrally as a community, mitigation of uncertainty in load, renewable generation and prices can be achieved by allowing local electricity market trading inside the community under cooperative game theory. This is demonstrated in Ref. [140].

A bi-level formulation of an upper level wholesale market and a lower level local electricity market is demonstrated in Ref. [112]. The upper level market facilitates trade between large generators (thermal plants, hydropower plants, wind power plants), while the lower level market facilitates trade between distributed generation, electric vehicles and demand response units. The model utilizes a scenario formulation to implement uncertainty. Ref. [111] discusses coordination of demand response and uncertain generation in the form of wind power via a competitive peer-to-peer reserve market. The model considers uncertainty in the form of a Conditional Value at Risk formulation. Within a bi-level problem, the wind plant operators purchase demand response in order to prevent higher losses on the balancing market. Risk aversity among prosumers is also discussed in Ref. [130], where bilateral contract networks are utilized for energy trading within centralized local electricity markets. Both real-time and forward markets are assessed with utility-maximizing preferences.

3) LITERATURE, FOCUS: INFORMATION AND COMMUNICATION TECHNOLOGIES

As mentioned in Section II, a key factor in the practical implementation of local electricity market models is the data and information exchange. One of the most common proposed technologies to ensure the communication between parties in local electricity markets is distributed ledgers, i.e. blockchain.

A considerable number of papers explore distributed ledger technologies as the core enablers for automatized market platforms [64], [164]–[166]. In the context of local electricity markets, the literature principally focuses on the technical ICT features of blockchain [65], [167]–[170]. For example, Ref. [171] determines the cryptography mechanism to allow for a secure trading system. The paper proposes the utilization of asymmetric encryption to resist security attacks in bi-lateral markets and secure the settlement of monetary transactions. Other sources pay more attention to scalability issues or the definition of contracts between agents. In Ref. [172] the authors explore Merkle Trees to reduce the number of transactions and allow the entry of more participants. By using this particular configuration, Ref. [172] proposes a demand response market capable of balancing the system by implementing incentives and penalty rates which enforce the demanded flexibility levels.

Ref. [167] suggests real-time bidding to guarantee the privacy of bids before the clearing of the market is performed. This approach combines sealed quotations with aleatory strings. The latter is used as a private key for automatic verification of the real bid. By the adoption of this system, Ref. [167] aims to enforce confidentiality and trust among participants. In a more recent study, Ref. [168] also employs sealed quotations, but applied to an electric vehicle focused trading platform. The paper proposes blockchain as the communication layer for direct monetary transactions between charging and discharging vehicles. This is in line with Ref. [170] where the authors implement a market platform where participants are rewarded when they charge their vehicle during peak loads caused by renewable energy. With a wider perspective of the utility of blockchain, Ref. [169] presents the technology as the facilitator for bidding, contracting, and settling economic transactions within a community supplied by renewable solar energy. The author argues that blockchain should be carefully implemented due to its associated financial risks, high requirements for computational resources and associated transaction cost.

The studies in Ref. [15], [158], [172] extend the application of blockchain to automatic activation of electric devices (specifically appliances and HVAC systems). By the combination of smart controllers and blockchain, Ref. [15] proposes that the operations of the devices are dictated by a smart contract. The communication of the signals is made through blockchain and aims to ensure optimal information access for participants.

Another line of research in the literature about blockchain applications in local electricity markets is the linkage between power system control models (e.g. voltage control) with market clearing model. Ref. [65] deploys a blockchain ledger to send signals from the market clearing model to the power flow analysis algorithm to technically analyze the impact on the distribution network. With a similar objective, Ref. [168] shows AC power flows results that validate the viability of the trading outputs. Alternatively, Ref. [15] directly introduces grid constraints in the market model to determine the energy transactions.

IV. LOCAL MARKET IMPLEMENTATION

In recent years, numerous Research and Development (R&D) projects implementing local electricity markets have been deployed internationally. Central to these R&D projects is the specification of the contribution of such a local electricity market, whether be it energy, flexibility or both combined [173].

Another central characteristic is the topology. This comes due to local electricity markets also aim to establish marketplaces to acquire end-users' resources to offer flexibility to potential flexibility buyers, e.g. distribution system operators, transmission system operators, aggregators and balancing responsible parties. As discussed above, this can be conducted centrally or decentrally, with or without the involvement of a mediator such as a local electricity market operator or an aggregator.

This section enumerates key R&D projects in the European power system addressing the challenges presented in Section II. Further, it explores the projects based on the modeling aspects presented in Section III. The frame of this section is set at completed or on-going research and demonstration projects applied in a real-life environment. These projects fall into a technology readiness level (TRL, as defined by the European Commission) between 5 and 8, with the purpose to validate and demonstrate the key developments in real-life environments and thus can be defined as ''close-to-market-ready'' products [174].

A. CHALLENGES ADDRESSED

Here, the R&D projects are mapped to the specific challenges as shown in Section II.

1) DISTRIBUTION OF GENERATION

Wide-scale deployment of distributed generation in electric grids can be a cause of operational challenges including examples such as line overloading, voltage disturbance, increased line loss and bidirectional power flow. As mentioned in Section II, one of the key advantages of implementing local electricity markets is to provide grid services through demand response. Among all such grid services, congestion management can be identified as the most common priority for most of the R&D projects. This is followed by voltage management and reduction in line losses.

Coordinating self-consumption or collective self-consumption can also be identified as one of the key operational challenges. Such issues related to balancing of generation and demand appears due to the intermittence of renewable electricity generation, which in turn affects the hosting capacity of the local grid itself. Some of the local electricity market R&D projects, aimed at local balancing and maximization of locally generated electricity consumption, thus aim to indirectly enhance the hosting capacity of the distribution grid. The projects *Quartierstrom* [175], *LAMP* [90] and *NRGcoin* [176] are peer-to-peer based market examples which focus on local balancing of locally generated electricity. *Piclo* [177], *Vanderbron* [178] and *sonnenCommunity* [179] are examples of projects which utilize hybrid market structures to match electricity supply and demand. When not all the local electricity market participants are located within the same sub-station network, a common approach is to assign the market/network operator the obligation to resolve phase imbalance issues. With the exception of *StoreNet*, within the considered R&D projects this issue was not discussed.

Further, forecasting of renewable energy resources is one of the key aspects to facilitate integration of intermittent renewable energy sources. In a liberalized power market, the traditional system approach for dealing with the potential of forecasting errors is the implementation of sequential market structures such as day-ahead, intraday, local flexibility and ancillary service markets. The project *Smart4RES* [180] approaches this problem on a local level by improving the performance of renewable energy forecasting but also the value chain incorporating data science approaches in grid and market applications. One of the use cases investigated in the project is to analyze the impact of uncertainty associated in renewable generation while providing flexibility to the DSO which, in turn, supports congestion management [181].

2) INTEGRATION OF DEMAND RESPONSE

In addition to local generation facilities, there is a variety of demand resources connected to distribution networks that potentially could offer flexibility in local markets. The scale of these resources ranges from residential to industrial. Available technologies incorporate storage, heat pumps, electric transport and power-to-gas/heat plants. Even though most of the real-life projects are explicitly technology-neutral, certain demonstration projects focus on different technologies for demand resources. Project *InterFlex* [182] does so with six demonstration sites in five EU countries. Each of the demonstration sites implements different demand response schemes utilizing a variety of available assets in order to access flexibility through direct DSO control or a local flexibility market [183]. The project *SINTEG New 4.0: ENKO* [184] tests medium scale loads ranging from electric vehicles to heat/electric storage, combined with heat plants and local industrial demand. In the project *ENKO*, local loads are controlled using a flexibility platform in order to avoid curtailment of renewable energy.

Further, energy storage is also indicated by literature as a key flexible resource [185] and thus further increases its participation in electricity and flexibility markets, improving the smart grid operation with high penetration of renewable resources [186]. Certain R&D projects are therefore entirely focused on energy storage. To provide an example, project *StoreNet* [187] explores a market platform for procuring flexibility from end-users storage facilities to serve the DSO's needs for congestion and voltage management. In addition, it evaluates business cases for end-users conducting energy arbitrage over time [188]. Further, project *sonnenCommunity* provides a peer-to-peer energy trading platform to prosumers, similar to projects like *Piclo* and *Vandebron*, with a special emphasis on storage. To add to this, project *INVADE* [189] explores a cloud-based flexibility management platform with the purpose of managing a wide range of storage facilities. These include mobile assets such as electric vehicles, and centralised facilities such as battery energy storage in substations or on residential level, as well as shiftable loads in form of flexible heating.

3) DECENTRALIZATION OF MARKETS

As described previously, local electricity market structures aim to involve existing and/or develop new actors in the current electricity market. This comes along with the introduction of new, modified roles of traditional participants. R&D projects on local markets thus focus on designs of local electricity markets in a way to make the underlying business model compatible with aforementioned market actors under proper coupling with existing central electricity markets and systems. In order to reduce the risks associated with local market uncertainty and thus decrease revenue volatility and stabilize value propositions for end-users' assets, it is advantageous for end-users providing flexibility to have (indirect) access to multiple markets ranging from a local level to national level. The project *ENERA Epex Spot* [190] is an example of this structure which investigates flexibility markets operated in parallel with a central wholesale market across an intraday time horizon.

As described above, proper TSO-DSO coordination is another key aspect that needs to be incorporated into the design of local electricity markets. As such, this coordination is particularly important for local electricity markets deployed to relieve local grid congestion and provide balancing and ancillary services using the flexibility of end-users' assets. Project *SmartNet* considered this and explored different TSO-DSO coordination schemes used to obtain ancillary services from distributed resources on low and medium voltage level [191]. Two out of the five TSO-DSO coordination schemes tested in the project made use of a local flexibility market with the DSO as operator to solve the local congestion management and conduct balancing on local level. Project *GOPACS* is initiated by the Dutch TSO and four DSO partners and develops market-based mechanisms to alleviate grid congestion [192], [193]. *GOPACS* also investigates an intermediary platform utilized for TSO-DSO coordination used to avoid double activation of the same end-users' assets. In the UK, the TSO-DSO operated pilot project *Power Potential* [194] explores the provision of reactive power support and dynamic voltage control for the transmission grid from the perspective of distributed energy resources connected to the distribution grid through TSO-DSO coordination as shown in Ref. [195]. The dedicated service providers in this project are dynamically selected through day-ahead auctions and receive payment for availability and activation of flexible resources [196].

Aligned with DSO/TSO coordination, the interaction of local electricity markets with existing markets is also attempted by R&D projects. Such interaction requires a definition of timescale and sequences as well as a clear definition of products traded. In this context, most of the local electricity market R&D projects focus on trading within an intraday time frame. This can be attributed to its closeness to real-time operation and the resulting reduced chance of forecasting errors. Although prevalent in theoretical models, there are few projects which combine multiple time frames, such as day-ahead and intraday markets. The project *PEBBLES*, specifically aimed at local balancing of locally generated power, allows energy trading in both these markets to reduce the effect of forecasting errors [197]. Projects like *Piclo* [177] and *PicloFlex* [198] provide trading opportunities with lead time ranging from an intraday time frame to months in advance.

As discussed above, the digitalized nature of local electricity markets also exposes end-users to cyber threats imposed by new platforms and mechanisms. Blockchain-enabled energy trading is gaining momentum in local electricity market projects due to its tamper-proof nature and elimination of the need for a trusted intermediary. The projects *Quartierstrom* [175], *LAMP* [90], *NRGcoin* and *PEBBLES* [199] are examples of blockchain-based local electricity market projects.

4) LEGAL FRAMEWORK OF IMPLEMENTATION

Most of the R&D projects identified follow the EU guidelines as described in Section II. Some of the projects, specifically *Piclo* [177], *Vanderbron* [178] and *SonnenCommunity* [179] are approaching peer-to-peer energy sharing business models from a regulatory perspective. As such they provide analysis on existing policies and regulatory frameworks at national levels. For most EU countries, however, national energy policy and regulations are not yet supportive or well-defined enough to allow for implementation of most local electricity market models. Hence, most of the shown real-world projects are designed as test beds and aim for the disseminated results to provide input to shape the future regulatory framework. Ref. [84] specifically presents the obstructions in current regulatory frameworks with a focus on the Portuguese energy market after analyzing the peer-to-peer energy sharing business model of the project *Community S* [200].

Further, network tariffs specific to local electricity markets also receive attention from a regulatory framework perspective. On the local level such tariffs are usually lower compared to system level and mostly reflect partial usage of networks based on geographic proximity of demand and generation. The project *Quartierstrom* [175] proposes one such local network tariff as an incentive to maximize local consumption at a community level.

As a cross-comparison study of several projects, the project *INTERRFACE* [201] has investigated the regulatory aspects of TSO-DSO coordination related to flexibility markets. This specifically concerned four projects in Europe: *PicloFlex* [198], *ENERA* [190], *GOPACS* [192] and *NODES* [202]. Based on this, *INTERRFACE* identifies gaps in the existing regulation at the national and EU level that, in future, could further be explored to update the network codes for TSO-DSO better coordination.

5) SOCIAL ASPECTS

One of the advantages of the local electricity market is the possibility to address heterogeneous preferences of consumers and prosumers in a more individualistic manner compared to traditional markets. Specifically dealing with this participant-wise product differentiation, the project *NRGcoin* [176] proposes the use of smart contracts in a local market in order to facilitate trade between renewable electricity producers and local consumers. The project is designed with the goal to enable end-users to express preferences of local, emission-free energy and reduce volatility for the end consumers. Another project, *Energy Collective* [203], deploys consensus-based pricing, i.e. pricing depending upon individual user preferences in a local market environment.

As described in Section II, data security and privacy significantly impacts the willingness of participation. This can be used to explain the large share of local market implementation projects concerned with security-related technologies such as blockchain. Contrary to this, however, few projects explicitly deal with the consumer response to such privacy measures or the general system design from a behavioristic or socioeconomic point of view. In conclusion, it can be stated that such analysis deserves further attention in the published outcome of R&D projects.

To summarize the findings listed here, Figure 5 illustrates R&D in the context of the challenges described in Section II.

B. MODELING APPROACH

Here, the R&D projects are mapped to their specific model components as shown in Section III.

1) MARKET TOPOLOGY

Solutions built around a central entity responsible for managing the local market can be identified as the most common topology found in the literature on R&D projects. Based on this it can be observed that the R&D projects with a centralized topology are matured and projects considering such also focus on additional characteristics such as ICT structure, scalability, optimality of market design, development of business models, synergies with existing markets and cyber security. As discussed in Figure 1, such central entities appear both in centralized or hybrid market forms.

In contrast to these topologies, fully decentralized market topologies employed in local electricity markets with bilateral trading are still nascent. Local electricity markets that require energy or flexibility trading with external markets, e.g. wholesale, balancing and ancillary service markets, adopt either centralized or hybrid market topologies due to easier coordination with existing markets. In contrast, decentralized market topologies are instead mostly focused on privacy and consumer preference issues. Naming specific projects, *EMPOWER* implements a centralized topology [204], *Vandebron* [178] provides an example of a hybrid market topology and *Quartierstrom* [175] falls under the decentralized category. From the given literature it can be observed that local electricity market projects with focus on flexibility trading possess market structures with a central entity responsible for aggregating flexibility from small-scale end-users to trade with external flexibility buyers. The project *iPower* is a local flexibility market project which evaluates both centralized and hybrid market topologies where a DSO submits flexibility requirements and aggregators bid flexibility from end-users. In this project, the ICT platform itself fulfills the role of a central matchmaking entity [205], [206].

2) GRID REPRESENTATION

As discussed, integration of grid constraints into the market design is another crucial aspect of local electricity markets. Currently, R&D projects consider grid constraints either explicitly through mathematical formulation in their market clearing or implicitly through solving power flow equation separately to validate market positions.

The project *SmartNet* tested a range of network models under one market clearing algorithm in order to analyze the computational tractability of such. It proposes a simplified DC model for the transmission network along with a convex relaxed model such as a second-order cone programming model for the distribution network [208].

The project *DOMINOES* assigns the DSO as technical validators for the market dispatch. As such their role is to perform grid analysis. Hence, the network model is only indirectly considered in the market clearing algorithm [209].

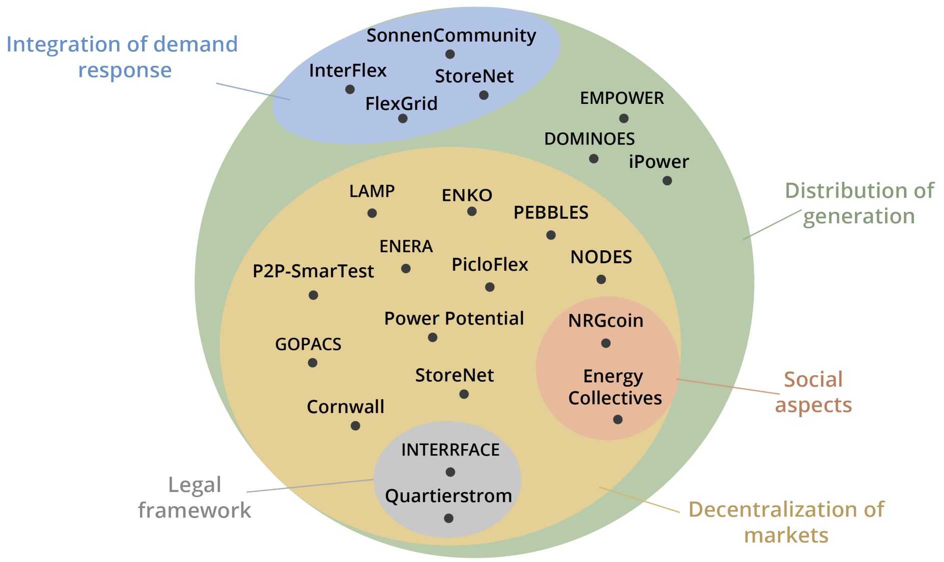


FIGURE 5. **Challenges addressed in R&D projects.**

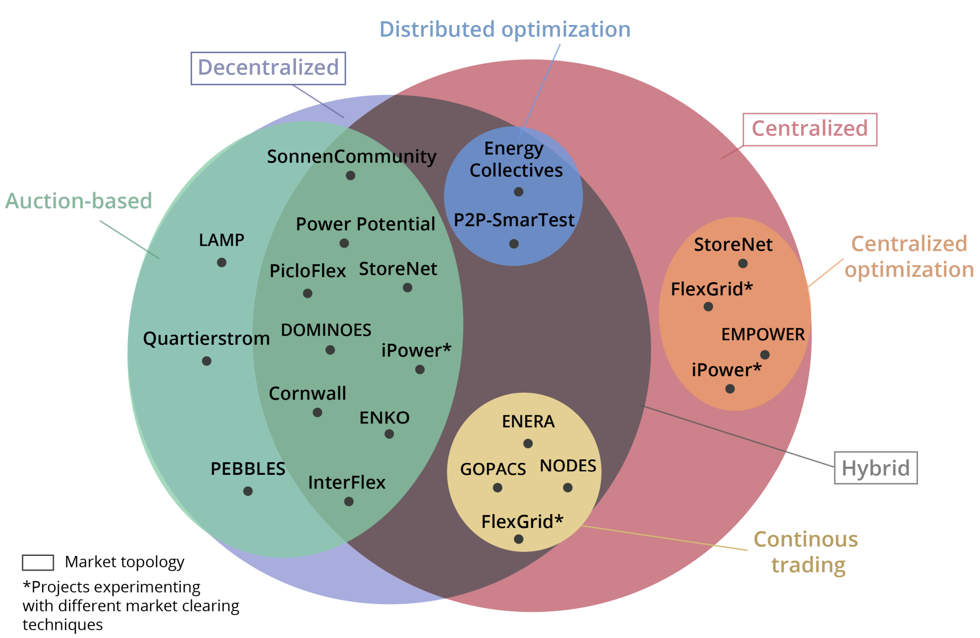


FIGURE 6. **Model components utilized in R&D projects.**

The project *PEBBLES* enforces restrictions in the matching algorithm allowing a maximum volume which can be submitted/retrieved by individual participants in order to impose the capacity boundaries of the underlying grid assets. These restrictions are dynamic and depend on the underlying grid topology and the forecasts of renewables and electric loads [197].

FLEXGRID instead envisions a local flexibility market architecture consisting of two sequential markets, each with its own market clearing approach with underlying grid constraints. The first stage implements a day-ahead local flexibility market using a convex relaxation of the AC OPF and the second stage implements continuous trading where an AC OPF is performed to validate the matched bids [210].

3) MARKET CLEARING

As discussed previously, the literature does show no clear trend pointing towards centralized or decentralized market clearing mechanisms as the definitive standard in implementation of local electricity markets. The project *EMPOWER*

TABLE 8. Key representative local market R&D projects.

Project Name	Stakeholders	Challenge(s)	Grid services	Market topology	Grid representation	Market clearing methods	Objective/ Outcomes
iPower (Denmark)	Buyer: DSO Seller: Aggregator	A	CM,VM	Centralized & Hybrid	OPF & AC power flow	Centralized optimization & auction-based	Control scheme and market mechanism to mobilize flexibility from end-user to DSO by utilizing demand response.
InterFlex (Europe)	Buyer: DSO Seller: Aggregator, large prosumer	A, B	CM	Hybrid	Network analysis run separately by DSO	Auction-based	Tools and process for local flexibility market to solve the existing and future grid constraints
EMPOWER (Europe)	Buyer: DSO Seller: Aggregator, prosumer	A	CM	Centralized	DSO flexibility requests in constraints	Centralized optimization	Cloud based ICT platform and user app to facilitate local market.
Quartierstrom* (Switzerland)	Buyer: Prosumer, Consumer Seller: Prosumer, Producer	A, C, D	LB	Decentralized	Not available	Auction-based	Bilateral trading of locally produced solar energy for local consumption.
Energy Collective (Denmark)	Buyer: Prosumer, Consumer Seller: Prosumer, Producer	A, C, E	LB, CM	Hybrid	Not available	Distributed optimization-based	Deployment of local market with provision of consumer preferences.
NRGcoin* (Europe)	Buyer: Prosumer, Consumer Seller: Prosumer, Producer	A, C, E	LB	Decentralized	Not available	Not available	Smart contract based trading platform, consideration of wholesale market structure, support for local renewable consumption.
SonnenCommunity (Germany)	Buyer: Prosumer, Consumer Seller: Prosumer, Producer	A, B	LB	Hybrid	Not available	Auction-based	Trading platform replicating the role of energy supplier who links consumers and producers with storage system on focus.
LAMP* (Germany)	Buyer: Prosumer, Consumer Seller: Prosumer, Producer	A, C	LB	Decentralized	Not available	Auction-based	Bilateral trading of local solar energy within neighbors in microgrid.
P2P-SmarTest (Europe)	Buyer: Aggregator, Microgrid trader Seller: Microgrid trader, prosumer	A, C	CM,VM	Hybrid	Line congestion incorporated in the optimization problem as cost function	Distributed optimization-based	Control and ICT architecture for microgrid to facilitate peer-to-peer trading in energy market and ancillary service market.
DOMINOES (Europe)	Buyer: DSO, Supplier, TSO Seller: Aggregator, prosumer	A	CM	Hybrid	Network analysis run separately by DSO	Auction-based	Market platform that enables prosumers to engage with other prosumers and also with different central market actors.
PEBBLES* (Germany)	Buyer: DSO Seller: Prosumer	A, C	CM	Decentralized	Grid assets boundaries limit on participants' bid size	Auction-based	Energy trading platform with congestion management functionalities embedded in matching algorithm.
SmartNet (Europe)	Buyer: TSO, DSO Seller: Aggregator	A, C	CM, VM, LLR	Hybrid	DC model and convex relaxation model	Auction-based	Different DSO-TSO coordination schemes to procure ancillary services from distributed resources in distribution network.
ENERA (Germany)	Buyer: DSO, TSO(in future) Seller: Aggregator	A, C	CM	Hybrid	Network analysis run separately by DSO	Continuous trading, pay-as-bid	Market-based congestion management through regional, "on-demand" flexibility market covering regional distribution area.
NODES (Europe)	Buyer: DSO, TSO (in future) Seller: Aggregator	A, C	CM	Hybrid	Network analysis run separately by DSO	Continuous trading, pay-as-bid	Marketplace to tap additional flexibility potential for enhancing congestion management to improve grid operation.
GOPACS (Netherlands)	Buyer: TSO, DSO Seller: Aggregator	A, C	CM	Hybrid	Network analysis run separately by DSO	Continuous trading, pay-as-bid	Development of integrated TSO-DSO coordination platform to procure flexibility time-frame to avoid congestion.
Piclo Flex (UK)	Buyer: DSO Seller: Aggregator, large prosumer	A, C	CM,VM	Hybrid	Network analysis run separately by DSO	Continuous trading, pay-as-bid	Development of marketplace for multiple DSOs to procure flexibility.
Cornwall [210] (UK)	Buyer: DSO Seller: Aggregator, large prosumer	A, C	CM	Hybrid	Network analysis run separately by DSO	Auction-based	Virtual marketplace to procure flexibility services from homes and businesses to serve the need of DSO and TSO in coordination.
StoreNet (Ireland)	Buyer: DSO Seller: Aggregator, prosumer	A, B	CM,VM	Centralized	AC power flow	Centralized optimization	Market platform to procure flexibility from end-users storage facilities through aggregator to serve DSO's need.
FlexGrid (Europe)	Buyer: DSO, TSO Seller: Aggregator, prosumer	A, B	CM,VM	Centralized	Convex relaxed AC OPF and AC power flow	Pay-as-bid, Auction-based	Automated trading platform for all market actors, grid management platform for DSO/TSO, flexibility aggregation tool for aggregators.
Power Potential (UK)	Buyer: DSO, TSO Seller: Aggregator, large prosumer	A, C	VM	Hybrid	Network analysis is done separately by TSO-DSO in coordination	Auction-based	Market platform for reactive power support and dynamic voltage control for transmission grid from distributed energy resources connected in the distribution grid through TSO-DSO coordination.

CM: Congestion Management, VM: Voltage Management, LB: Local Balancing, LLR: Line Loss Reduction.
* Projects implementing blockchain technology.

applies a centralized market clearing platform that selects flexibility providers based on an optimization problem formulated to serve the DSO requests at minimum cost [204].

The project *PEBBLES* implemented an auction based market matching algorithm using blockchain to settle contracts [197]. *P2P-SmarTest* [211] instead applies a dual decomposition theory based peer-to-peer trading mechanism and presents a comparative analysis between cooperative and non-cooperative approaches [212]. The *Nodes* Market project [202], [213] as well as *Enera* [190] and *GOPACS* [193] are focused on intraday time frames and thus implement continuous trading similar to European wholesale electricity markets.

Thus, the literature shows the choice of the market clearing approach in the R&D projects being based on the objectives and structure of the chosen local market design. The literature suggests centralized market clearing approaches to be prioritized in projects where trust-worthy relations exist between end-users and the chosen local market clearing entity and where scalability is not a crucial concern due to a limited number of participants. Opposing to this are projects with emphasis on limited sensitive data sharing among market participants on one hand and scalability on the other hand more incentivized to instead make use of decentralized market clearing approaches.

Figure 6 summarizes these insights and illustrates the enumerated R&D project based on market topology and market clearing methods.

In similar manner, Table 8 provides an overview of the previously listed European R&D projects on local electricity markets.

V. CONCLUSION AND FUTURE WORK

This paper presents a comprehensive review on the topic of local electricity markets, with a specific focus on recent literature and on the challenges of their modeling, implementation, analysis and management. To achieve this, the paper starts with an introduction to the topic and an analysis of previous literature studies that show a lack of literature on local electricity markets that extend beyond peer-to-peer implementation. Focusing on a more general level and including all three identified topologies - centralized, hybrid and decentralized local electricity markets, the paper then categorizes the challenges associated with local electricity markets. These challenges are classified into five areas: distribution of generation, integration of demand response, decentralization of markets, the legal framework of implementation and the associated social aspects.

Next, the paper introduces modeling approaches via a technical summary of analysis and operational models whilst pointing to specific recent literature examples. These examples are also classified into various categories, for example based on the applied market clearing mechanisms, the physical grid or other technical specifications such as the consideration of uncertainty and balancing markets/services. The resulting chapter on modeling offers an overview of the theoretical side of local electricity market implementation, analysis and administration and thus provides a starting point for prospective model users and researchers alike. The practical aspects of such local electricity markets are then discussed in the final part of the paper, which introduces numerous European projects realizing local electricity markets. Similar to the theoretical models, these practical projects are also categorized by their main focus and further put into relation to the previously derived challenges in order to present a mapping of the project landscape.

In summary, the provided literature and the challenges derived from it lay the foundation for future work on local electricity markets. The identified topics with a lack of literature where the challenges of integration of uncertainty, coordination of grid and local electricity market resources, practical scalability of theoretical approaches (specifically for hardly tractable problems such as multi-period problems) and standardization and generalization of methods and topologies, the latter we attempt to provide the foundation for with this paper.

We further found that **distribution of generation** in local electricity markets has been modelled and analyzed extensively in literature. However, this is done often in a simplified manner ignoring the complexity of combining both in-depth market and in-depth grid representations. In this context, specifically the trade-off between fairness (as caused by convex market formulations) and accurate grid representation (implemented via non-convex grid constraints) can be identified as a basis for future research.

On the topic of **integration of demand response**, simplified market models might limit the practical applicability of technical research, as both the financial and technical aspects must be considered in tandem. We showed that few studies consider both the AC power flow aspects of the quality of supply while also simulating a competitive local electricity market. The reason for this we found to lie in the associated computational complexity. Most notably, this effect increases when considering three-phase modeling of low-voltage grids.

Handling risk and uncertainty associated with the **decentralization of markets** can also be observed as an underrepresented topic in research. Risk related to sunk costs and non-optimal operation and uncertainty in load/generation and market commitments leads to more technical challenges which provide a potential starting point for future research. The complexity of such models is only amplified by the consideration of TSOs and DSO interactions, another potential source of risk and uncertainty.

In our literature we found real life demonstration of local electricity markets to show strong inclination towards centralized and hybrid topologies over fully decentralized. With a strong foundation of theoretic literature on frameworks for fully decentralized markets, a research gap can be identified in applying such in practical settings.

Further has congestion management been observed as the primary grid service at the center of most practical implementations. Providing multiple grid services e.g. voltage management, line loss reduction and power quality support might thus be of interest for future local flexibility market projects. From the perspective of the **legal framework of implementation**, however, many of the questions of the regulatory responsibilities are yet to be cleared. Topics such as defining responsible parties for additional grid services considering more uncertainty in e.g. local bilateral contracts and regulating rights for behind-the-meter control could become an important topic in a more decentralized power grid and be at the core of the practical implementation of local electricity markets.

Similarly, on the topic of reliability, legal and technical aspects not only merge but **social aspects** also become a key component in such highly automated real-time systems as local electricity markets are. Considering these aspects, there is need for both long-term studies on behavioural changes and adjustments to local electricity markets, as well as the core principles of traditional markets - ensuring fairness and non-discrimination.

In conclusion it can be stated that the paper provides a general analysis of the research on local electricity markets, incorporating quantitative as well as qualitative aspects whilst structuring and classifying the available literature with a strong focus on the derived challenges. In contrast to the majority share of previous literature studies listed in the introduction, the main focus of this paper does not lie specifically on peer-to-peer markets and Information and Communication Technologies, thus distinguishing it from the bulk of research on the topic. Albeit it introduces and discusses these topics, it takes a more holistic view and instead focuses on the localization and thus more on associated aspects such as the physical grid or social aspects.

Thus, the paper provides a starting point for future research into establishing local electricity markets both in theory and in practice.

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