D1.2: Addressing distribution grid challenges with local markets: A review

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Blockchain based ElectricitY trading for the integration Of National and Decentralized local markets

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Addressing distribution grid challenges with local electricity markets: A review

Summary

Local energy markets have recently emerge as an interesting scheme to promote and stimulate the use of locally produced renewable energy sources (e.g. solar PV rooftops). Neighboring consumers and prosumers trade surplus energy or share flexibility (e.g. Batteries, demand response, or EVs) to reduce peak demand and hence facilitate balancing operations in distribution grids. However, the interplay of local markets and distribution grids remains a not well addressed topic in the literature. In this review, this and other challenges related to the development and implementation of local markets are described along with recent literature, reports and relevant information.

1 Introduction

1.1 Motivation and background

The increase in distributed energy resources (DER) calls for structural changes in the power system. Drastic price reductions in small-scale flexibility assets and production has lead to a decentralization of agents in the power system. These new agents mostly consist of end-users who wish to invest in behind-the-meter (BTM) local production for self-consumption, or use local flexibility in order to react to price signals. The use of DER can lead to not only to more efficient energy use as the production is moved to the consumption, but also most distributed production is renewable with a lower carbon footprint than conventional power production from thermal plants. Producing consumers (prosumers) are envisioned as central and sustainable part of the energy transition of the European Union [1]. However, for prosumer integration to happen fast enough to meet climate targets, market structure and price signals must be changed to correctly incentivize end-users to participate actively in the power system.

Increasing number of agents in the distribution grid results in a series of challenges for the system operator, as an essential part of dealing with increased DER is integrating the resources into the power system without compromising security or quality of supply. Challenges with frequency balancing, congestion management, bi-directional power flow, variable renewable generation are going to increase in difficulty in the comings years. To deal with these challenges, ENTSO-E highlights distributed energy resources as key assets that must be made available for distribution and transmission system operators (DSO, TSO) using active system management techniques to acces the flexibility in the distribution grid [2].

With this context, information and communication technologies (ICT) together with DER have enabled active prosumer participation in electricity markets by connecting end-users using smart meters. Under this smart energy system regime, a historically one-way top-down electricity and information flow can evolve to a bi-directional relation where the prosumer can react to price signals and export BTM production. Local markets with coordination between end-users have risen as a natural extension to the two-way communication between retailer and end-user.

Local energy markets (LEM) are widely described in the literature as a market design feature which can integrate end-users to become more active [3]. Although LEM are mostly considered as a nano-market restricted to electricity-neighbors, they can also be considered as a dynamically changing market (web-of-cell concept) where the available peers in the market depend on the state of the grid [4]. The essence of a LEM is trade of energy between end-users where. Although the concept appears simple, there is significant complexity considering that an energy trade between two peers must be planned, executed, measured, confirmed and financed.

Peer-to-peer markets have received increasing interest in the literature, both in LEM and as a design for wholesale markets. In essence, peer-to-peer markets are markets with multi-bilateral economic dispatch (MBED), allowing for discriminatory prices between peers. This is relatively uncommon in larger wholesale markets where uniform pricing is the dominating pricing scheme. However, in local markets, peer-to-peer structures are specifically because they allow users to have independency over electricity consumption. The democratization of the energy sector is allowing consumers to actively participate in the market and have personalized criteria in the ways of consuming the commodity [5]. With free participation in electricity markets, peer-to-peer markets represent the democratization of electricity where end-users can break free from the traditional top-bottom power system that exists today. Further, the number of decentralized agents will only continue to increase due to the price development and technology related to DER. These developments in small-scale flexibility assets are key drivers of this trend. However, ICT technologies such as smart meters or intelligent controllers are required for securing the correct synchronization and operation of local energy systems both for the grid and market management. Consequently, control networks and communication between different agents or processes highly rely on the underlying IT architecture [6,].

As a consequence of the mentioned developments, a series of local market R&D projects have been deployed over the last years. The development is going in the direction of increasing interest in flexibility and integration of aggregators, DSOs and balancing products in the local market frameworks. This adds new layers of complexity compared to previous projects focusing on sharing PV production, because real-time coordination is an absolute necessity to integrate flexibility products in the local market. Products such as voltage control congestion management and reserve provision are becoming more and more important aspects in the decentralized market projects, highlighting the industries need for experience of actual implementation to evaluate potential and business cases.

1.2 Meta-study & contributions

There has recently been published review articles covering similiar topics related to flexibility, peer-to-peer, consumer-centric and local markets. Articles covering existing projects related to the mentioned topics have also recently been covered. In [8], five existing peer-to-peer projects were investigated to illuminate potential aspects in future projects. Authors highlighted the need for securing business revenues streams in future projects. Similiariliy, [6] expanded the list to ten projects (of which some were the same projects) by highlighting the ICT systems and market platforms used in the projects.

Market design proposals for local electricity trading were shown in [9], where players in the market were defined, and their role, objectives and impact in different market designs. The study was extended in [10] where an extensive review on community-based and peer-to-peer markets was made, supported by a series of relevant publications from the authors. Their review focuses heavily on giving an overview of these market designs and how they should be modelled, as well as the motivation for using P2P and community markets in the future power system. A deeper dive into the model approaches and issues related to demand response, power routing algorithms and privacy concerns is presented in [11]. Finally, [12] takes a step back and gives a very general overview of P2P markets by covering the aspects in the virtual layer focusing on the variety of approaches in energy trading techniques, as well as highlighting the role of blockchain. [13] and [14] explore implementations of local energy trading via distributed ledger as a means to ensure optimal control of decentralized smart grids. Finally, [15] covers distributed methods for power system control. The authors separate the approaches into 4 categories, decentralized, distributed, hierarchical and centralized approaches. The review extensively covers power system control with the aforementioned methods and highlight the viability of these methods due to the increasing complexity and increasing amount of agents and assets in the system.

Common for the aforementioned reviews is that they all highlight a need for future research on implications of local markets, peer-to-peer markets, decentralized control and blockchain on the distribution grid. With this context, this paper provides and overview of state-of-the-art research which addresses distribution grid challenges with local markets, by making the following contributions:

- A series of distribution grid challenges with respect to distributed generation, integration of demand response, decentralization of markets, legal framework and social aspects related to local and P2P markets are addressed
- We provide an extended overview of existing local/P2P market projects specifically working on challenges related to the distribution grid, including implementation aspects
- We review state-of-the-art research addressing how grid-related challenges can be addressed in local/P2P market modeling
- We go in-depth on how ICT and blockchain technologies can function together with ancillary service provision from local markets

The rest of the paper is organized as follows: an overview of local and P2P markets plus alternatives is presented in Section 2. An overview of existing projects and how they are implemented is presented in Section 4, followed by a review of modelling approaches for local markets and distribution grid problems in Section 5. Finally, the use of blockchain and other technologies is given in Section 6 before concluding remarks and future works is given in Section 7.

2 Local Markets and Alternatives

Local markets have similarities to other forms of organizing and defining a group of consumer and prosumers. One is the definition of local *Energy Communities* which essentially assume the communal ownership or control of assets and energy management system to enable them to interact as one entity with other actors of the power system. This definition is closely associated with self-sufficiency objectives and grass root initiatives to adopt renewable energy sources. Hence, it entails active participation of the end-users in the community which is circumscribed to a geographical area. This is further defined in the EU-Winter package (Art. 16, Clean Energy for all European package, see [16]) in which energy communities are projected to account for 17% of installed wind capacity and 21% of solar by 2030. Interestingly, an European Commission review of 72 EU projects related to local energy communities [17] reveal and conclude that DSOs are central in their development and operation. The review notes that DSOs need to price a set of services and design business models that include energy communities as part of their future ecosystem. Under this definition, there is the so-called renewable energy cooperatives - (a type of energy communities) that according to a survey of the EC Joint Research Centre [18] indicates that there are at least 3500 communities of this kind of community energy initiative.

Another closely related definition and development is the concept of "energy citizenship". An overall definition of it is as follows: *"Energy Citizenship is a view of the public that emphasizes awareness of responsibility for climate change, equity and justice in relation to siting controversies as well as fuel poverty, and finally the potential for collective energy actions, including acts of consumption and the setting up of new community renewable energy projects such as energy cooperatives"*, see [19]. Similarly to energy communities, energy citizenship puts stronger focus on consumer-empowerment and the value of social innovation as mechanism to trigger a fundamental shift in consumer behaviour and hence incentivize the adoption of renewable energy facilities.

All in all, these two definitions (energy communities and energy citizenship) have been used interchangeably under different notions (usually related to problem context, research perspective or others). Recently, these are being grouped or used within the umbrella of local electricity markets. Hence, local electricity markets take different forms. For example, [10] classifies local P2P markets as follows :

- *Full P2P market*: Consumers and prosumers (peers) negotiate directly with each other and settle a price and amount. This is not restricted to a geographical area.

- *Community-based market*: Assumes that a community manager oversees trading activities within the community. It also might act as an aggregator or intermediary to procure or trade with retail or other external energy markets.
- *Hybrid P2P market*: envisions a combination of the previous two. Here there might be communities that trade among each other or there are individuals that engage on independent trading decisions based on market opportunities.

Similarly, in [3]

Integrating the end-user in the future power system boils down to providing as precise price signals as possible assuming a market setup. A perfect dynamic tariff which reflects the true cost of using the grid is in all likelihood not achievable. Based on [2], an overview of methods to access flexibility is described in Table 1. To access the flexibility, an integrated market platform with flexibility accessible by both the TSO and the DSO is highlighted as a preferable outcome.

Table 1: Analysis of methods to access flexibility

Method	Description	Advantages	Drawbacks
Connection agreement	Fixed agreements with specific actors	Specialized actors, detailed agreements, coordination with SO	High market entry barriers, static - slow adaptation
Flexibility market	Location based flexibility markets	Low market entry barrier, dynamic, high competition,	High coordination demand, bad liquidity in some areas
Tariff	Price signals implicitly triggering flexibility	Easy to implement, synergy with local markets	Sub-optimal price signals, fairness issues, social resistance
Rule-based	Rule-based curtailment based on technical solutions	Reliable, easy to implement	Potentially unfair, inflexible high market entry barrier

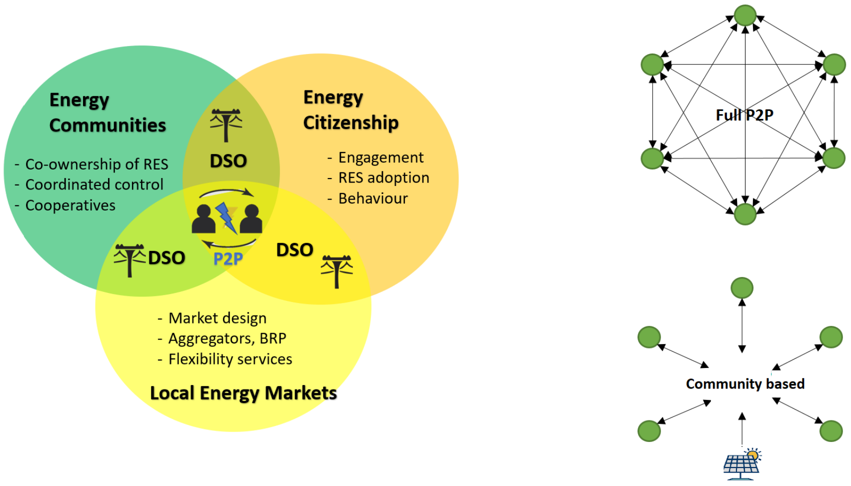

Figure 1: Energy communities and definitions of local electricity markets and P2P trading schemes.

3 Challenges of Local Markets

In energy systems, local markets are decentralized trading solutions that aim to connect consumers, generators and prosumers that are in close spatial proximity. Compared to traditional markets that usually manage large pools of participants over wide areas, these markets usually show smaller pools of participants. In the electricity grid, traditional markets operate on transmission grid level, whereas local markets operate on distribution grid level. The necessary consideration of reactive energy in latter leads to non-linearity of the AC grid problem that requires to be considered in the market model [20]. In traditional markets, these constraints are traditionally implemented via linearized DC approximations [21], leading to less complexity of the analyzed grid.

Thus, even though generally showing a smaller number of participants compared to traditional markets, local markets encounter several unique challenges in fulfilling their purposes. These **purposes** of local markets can be defined the following [22]:

- 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 grid investments with investments in local flexibility.

As discussed above, the **challenges** associated with local markets and their implementation deviate from traditional liberalized power markets.

These challenges can be overlapping with the challenges of optimal operations of distribution grids [23]:

- 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.
- cost-reflective distribution grids are essential for the success of integration of electric vehicles, especially charging stations of such.

Another important aspect is that achieving the large-scale implementation of such markets and fulfilling the main goals 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 those aspects in the design could lead to potential disparity between the goals of local markets and the policies utilized to implement those [24].

Section	**Challenge**	**Reference**
3.1	Changes in line losses;	[25, 26]
3.1	Changes in voltage levels;	[25, 26]
3.1	Changes in power quality;	[25, 26]
3.1	Changes in fault current levels;	[25, 26]
3.1	Changes in requirements for protection systems;	[25, 26]
3.1	Potential reduction in system reliability;	[25, 26]
3.1	Potential waste of resources;	[27]
3.1	Less choice of supply;	[27]
3.1	Negative environmental effects;	[27]
3.2	Forecasts of individuals are more error-prone than forecast of aggregates;	[28]
3.2	Correlation of behavior and subsequent control issues due to wrong (price) signals;	[29, 30]
3.2	Requirements for multi-period models brings threat of computational intractability;	[31, 32]
3.3	Development of a P2P trading algorithm;	[12]
3.3	Requirement of innovative scheduling and optimization techniques;	[12]
3.3	Real-time markets may lead to...	

	...a lower energy price;	[33, 34]
	...a certain degree of price volatility;	[33, 34]
	...uncertainty among consumers;	[33, 34]
	...an imbalance of demand and supply;	[33, 34]
3.3	Changes of roles and responsibilities;	[35]
3.3	Changes in market-structural factors such as cost and risks, product definitions and communication of demand-side effects;	[35]
3.3	Markets are required to be robust to changes such as carbon prices, feed-in-tariffs for renewables, etc.;	[36]
3.3	Information security and privacy requirements;	[37, 38]
3.3	An increasing growth of a market leads to higher computation and communication overheads;	[9]
3.3	High investment cost for information and communication infrastructure;	[14]
3.3	Interaction of local markets with existing markets;	[9]
3.3	Centralized/community-based P2P markets include...	
	...high barriers for a large-scale implementation;	[9, 14, 39]
	...higher communication costs due to a constant information exchange between peers and coordinator;	[14]
	...inadequate addressing of different consumer objectives;	[14]
	...risk of cyberattacks due to centrally collected data of participants;	[14, 39]
	...possibly unfair and biased energy sharing due to big member's influence;	[14]
3.3	Decentralized P2P markets include...	
	...possible price peaks due to competition among participants;	[39]
	...possible price convergence issues;	[14]
	...a sophisticated architecture with several market layers;	[14, 39]
	...a two-way communication system;	[14]
3.4	Rigid energy market regulations;	[40]
3.4	National law might hamper a comprehensive regulation;	[10, 41]
3.4	No appropriate incentives for flexibility;	[42, 43]
3.4	Reduction of system costs with concurrent increase in flexibility;	[44]
3.4	Response of local consumption to efficient price signals;	[44]
3.4	Higher balancing risk for prosumers;	[44]
3.4	Schemes for the distribution of taxes and fees for P2P energy trading not established;	[43]
3.4	Risk of higher costs in the course of electricity sales;	[44]
3.4	Data security, privacy, access and responsibilities;	[45, 46]
3.4	Need to protect vulnerable customers;	[43]
3.4	Ensuring equal consumer rights for participants;	[44]
3.4	Awareness of active consumers of their responsibility in case of imbalances;	[44]
3.4	If energy communities become owners of the grid infrastructure, challenges arise concerning...	
	...risk of duplication of assets;	[44]
	...ensuring economic efficiency;	[44]
	...harmonisation of regulation with the legal framework for distribution system operators;	[44]
	...consideration of the general grid usability in operation;	[44]
	...ensuring an appropriate quality of service for customers;	[44]
	...risk of discrimination against other market players;	[44]
3.4	Stakeholders in current market framework might lobby against changes	[47]
3.5	Encouraging participants to trade energy with one another;	[48–50]
3.5	Dealing with conflicting interests;	[48]

3.5	Maintaining trust between users without a centralized authority;	[48]
3.5	Managing the security and privacy of users;	[48]
3.5	Managing network congestion when the number of users becomes large;	[48]
3.5	Avoiding discrimination at virtual P2P energy networks (e.g. equal access);	[48]
3.5	Designing consumer-centric/prosumer-centric P2P energy-trading schemes/business models;	[48, 51]
3.5	Trading scheme has to be beneficial for the prosumers at any time they participate irrespective of their roles (buyers or sellers);	[49]
3.5	Designing an easy manageable procedure of payment;	[52]
3.5	Meeting expectations;	[52]
3.5	Heterogeneity of prosumers' preferences and overlapping segmentation;	[53]
3.5	Heterogeneity of prosumers' preferences;	[54]
3.5	Creating target group addressing products;	[54]
3.5	Finding added values to participate;	[51]
3.5	Locally generated energy versus price level;	[51]
3.5	Increasing economic benefits;	[55]
3.5	Offering trading schemes that provide a high proportion of peoples' total energy needs;	[56]
3.5	Offering trading schemes that operate at the region/city level;	[56]
3.5	Motivating local councils to assume a responsible role within the energy trading;	[56]
3.5	Guaranteeing anonymity;	[56]
3.5	Counteracting the public's association of the term Blockchain with the term Bitcoin;	[56]
3.5	Finding a way that all prosumers benefit equally;	[50]
3.1, 3.2	Increase of computational complexity;	[57–59]
3.1, 3.3	Requirement of coordination and potential of resulting conflicts;	[37, 60–62]
3.2, 3.3	Requirement of real-time control;	[63, 64]
3.2, 3.4	Imminent necessity of upgrading existing meters and software for energy flow management;	[45]
3.3, 3.4	Current regulatory framework can limit the profitability;	[65]
3.3, 3.4	Effective management of purchases from multiple suppliers;	[44]
3.3, 3.4	Relationship between P2P energy trading markets, existing electricity markets, and other emerging entities remain unclear;	[42, 43]
3.3, 3.4	Lack of tangible real P2P case studies around the world;	[40]

Table 2: Challenges of Local Markets

Based on this, the crucial challenges for success of establishing and operation local markets in Table 2 were formulated. These will subsequently be expaned on below.

3.1 Distribution of Generation

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

Specifically, Ref. [27] 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 distribution of generation has a variety on impacts on the operation of the grid. Ref. [25] and subsequently Ref. [26] categorize them as a 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.

As mentioned in Ref. [27], decentralizing generation can further pose several structural challenges. One of these is that decentralized generation shows a higher per kW price than centralized generation. In general, wasting of resources due to localized economic inefficiency is a challenge in 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. [27] also illustrates challenges that could be imposed by a decentralization of specifically thermal generation: less choices between primary fuel sources and potential negative environmental impacts.

As described in Ref. [57], 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 deregulized markets. Applied in practical settings, implementation of such locational signals can however lead to a drastic increase in computational complexity [58].

In combination with demand response, distributed generation can also offer potential for local coordination and offer congestion relief [60]. 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. [61], 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.

3.2 Integration of Demand Response

Forecasts of individual demand sources can be error-prone, those localized markets should allow for a certain degree of aggregation of such [28].

Contrary to this, large-scale aggregation can also lead to a loss of accuracy in terms of control. Especially 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. [29] illustrates how centralized price signals lead to correlated behaviour in electrical vehicles. Another example is provided by Ref. [30] that shows how central price signals cause synchronization of water heater startups and thus lead to load kickbacks. In a local market, these effects have to be considered as well when aggregating demand response.

Considering demand response effects of residential appliances in appropriate manner, however, requires methods to utilize algorithms capable of performing real-time control [63]. Therefore, local 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 [59].

This problem is especially highlighted by Ref. [31] 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 and could therefore lead to problems finding global optima and thus the most benefitial outcomes [32].

3.3 Decentralization of Markets

Designing functional local markets does not only require coping with the previous requirements on computational complexity and modeling the specific components in appropriate manner. It also requires functional interaction of those components. Key components of a local market are microgrid setup, grid connection, information and communication system, market and pricing mechanism, energy management trading systems and regulation. To what extend these components are fulfilled depends on the roles market participants take and how they execute these [66].

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 markets [64]. Trading and interaction on the market can either be in a day-ahead timescale (1 hour intervals) or in real-time (5 to 15 minutes intervals). Real-time markets may provide a lower average price of energy which makes it more attractive compared to day-ahead models; however, real-time processing leads to a higher volatility of prices [33]. This could cause uncertainty for consumers. Involatile 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 [34].

As Ref. [35] discusses, establishing markets 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. 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 adjustable enough to support interaction with policy makers in its design. This means, that operation of markets needs to be robust to introduction of carbon pricing, feed-in-tariffs for renewable energy, regulation and subsidies [36].

Working coordination between TSOs and DSOs is of importance for the stability of the grid and thus should 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 [62]. Design of local markets has to support those mechanisms, but also aim to keep the privacy of the involved private parties and thus reduce unnecessary sharing of information.

Sharing this information also requires appropriate systems that allow for the coordination of the decentralized, independent systems that local markets are [37]. These systems have to support data security in order to support functionality of and ensure trust in the market. According to Ref. [38], potential threats include impersonation, data manipulation, eavesdropping, privacy breaches, disputes and denial-of-service. Appropriate privacy and security measures have to assure reducing the risk of these threats to a level that allows reliable operation of the local markets and the distribution grids behind those. A central component of P2P markets is thus a sophisticated communication and information infrastructure that ensures this security whilst establishing transparency and connection points for the market participants. An appropriate information and communication infrastructure is one the one hand technically challenging to implement, especially if the amount of market participants increases [39]. On the other hand, the implementation of such an infrastructure comes with high investment costs, which can be a deterrent factor for the development of local markets [14]. Increasing communication requirements in large local markets lead to accurate communication and information systems being required for wide-scale application. In addition, the computational complexity of such markets requires the development of advanced trading algorithm to manage and coordinate the conduction of trading [12].

In addition to the interaction within the local market itself, the interaction with existing energy markets is essential for the implementation of local energy markets. According to Ref. [9], this interaction deserves further attention by future literature.

According to the communication and participant's interaction in local markets, two different design choices can be distinguished - centralized and distributed models (with hybrid versions combining both approaches inbetween). Centralized markets are managed by a coordinator/mediator who connects prosumers and consumers, whereas in a distributed market the peers interact directly with each other [9, 39, 67]. Each model brings chances and challenges that have to be considered when setting up a local energy market.

A centralized or community-based local market with a coordinator who mediates between the market participants lacks in terms of large-scale implementation due to the complex communication structure that cannot manage a large amount of participants' interaction [9, 14, 67]. This furthermore leads to higher costs because information has to be processed constantly between the coordinator and other participants. In addition, the objective of centralized markets is one-dimensional and therefore not ideal to implement in local markets with a heterogenous nature in which the participant's objectives deviate strongly from each other [14]. Market segmentation could solve both of these issues [9, 14, 67]. The previously mentioned cyberattacks could be potentially more damaging in centralized topologies, due to the collection of data on one central platform and the influence of big members in the market could lead to an unfair and biased energy sharing. Centralized optimization models also lack in potential of scalability. An increase of participants in the market would therefore even jeopardize an existing communication system infrastructure [14].

These challenges do not (at all or at this magnitude) occur in distributed energy markets in which consumers, prosumers or aggregators of such communicate amongst each other without the coordination of a third party. However, this uncoordinated interaction could lead to a competition among the participants which causes price imbalances and market inefficiencies. Furthermore, the communication infrastructure in distributed models is more complex and requires an ambitious architecture with several market layers which enables the large-scale extension of these models. Hence, the implementation of a distributed/decentralized market scheme is more difficult in both computational and information-sharing perspective [14].

3.4 Legal Framework of Implementation

The European Union Directive (EU) 2019/944 [68] allows consumers to unite as "citizen energy communities" and exchange energy peer-to-peer. This directive authorises 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 rigid regulations of the energy market and the more recently published directive, business models for energy sharing via local markets are still very rarely put into practice [40].

According to Ref. [42], no "one-size-fits-all" solutions can be established in respect to local energy trading. The provisions adopted in the current EU directive [68] remain relatively open to interpretation. Although the role and responsibility of prosumers and local energy markets is to a large extent clarified by this directive, further demand for regulatory clarification remains. The Council of European Energy Regulators [44] 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 markets, integration into national law on grid regulation will be crucial to enable local markets within energy communities [10, 41, 44].

Further, 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 [42, 43], as they can be opposing. On one hand it is important to reduce overall system cost while increasing flexibility, not only for the participants within the local energy community but beyond. On the other hand, local consumption should still respond to effective market price signals. Within large bidding zones, the most cost-efficient operation of generation hast to be ensured. Prosumers have to cover their own demand even if self-generation is currently not possible. In such times, high market prices are also more frequent. These suppliers are also likely to face a higher balancing risk [44].

In addition to this, there is also a need for appropriate schemes for the distribution of taxes and fees for local energy trading [43]. The question arises whether taxes or fees should still to be covered by the supplier or rather by the energy community itself. As such, suppliers are exposed to the risk of additional marginal cost, i.e. additional costs per kWh sold [44].

By regulation, 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. Hence, local markets may require upgrades to existing meters and software for managing the flow of electricity, and thus regulations need to clarify who is responsible for such upgrades. [45, 46].

Related to the previously outlined question of data security, the required two-way communication network also raises questions of such security and privacy, 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, possible Denial-of-Service attacks on the P2P system [45, 46].

Hence, the protection of vulnerable customers in the context of local energy trading remains a quite challenging task [43]. As Energy Communities can link production and supply more closely, it is necessary to maintain the same consumer rights for participants in energy communities. Thus, 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 [44].

The given regulatory framework can significantly limit the profitability of local trading. Taking Germany as an example, 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. In particular, the current regulation allows for a large arbitrage potential for prosumers with a battery storage, but does not provide an incentive to trade electricity locally. In this case, marginal costs exceed wholesale prices, while taxes and charges remain constant. A change in the regulatory framework carries the risk of distribution effects at the expense of pure electricity consumers due to very high self-consumption rates of prosumers (with storage) who avoid using the grid. Therefore, the total fixed grid costs must be distributed to lower grid consumption, which mainly affects pure consumers [65].

As with other transactions, concurrent electricity purchases from several suppliers must be managed effectively with clear contractual agreements and data transparency [44].

Furthermore, member states are free to allow Energy Communities to own the grid infrastructure itself. In such a case, further challenges will arise. For example, duplication of assets must be avoided, economic efficiency and appropriate regulation in line with the legal framework for distribution system operators must be ensured. In particular, general grid usability during operation has to be considered in addition to local optimization tasks. Furthermore, an appropriate quality of service and data protection for customers must be ensured. Other market players must not be disadvantaged under any circumstances [44].

As mentioned above, there are further challenges concerning the relationship between local energy markets, existing electricity markets, and other emerging entities such as DSO [42, 43]. Fundamentally, the reorganization of the highly regulated energy industry is a challenging task that may only be tackled with the results of a wide range of implemented case studies around the world. This could provide a sufficient number of advantages and generate enough to disrupt the status quo within which traditional energy market models are designed [40].

Another potential challenge for implementation of decentralization in the electricity grid is shown in Ref. [47] 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.

3.5 Social aspects

In order to motivate people to participate in a local energy trading paradigm, various social and behavioral aspects must be taken into account [53].

The willingness to participate depends on peoples' interests and their expectations. In local energy trading, differentiation between consumers and prosumers is necessary. While a consumer is just that - buying and consuming energy - a prosumer not only consumes but also produces energy (e.g. via rooftop solar panels) and offers the surplus to interested parties on the market [52].

The design and the implementation of new local energy trading schemes and business models have to be consumer- as well as prosumer-centric and take into account both groups interests and expectations [48,49,51]. Participation has to be rewarded at any time regardless of whether the participant acts solely a buyer or as a seller as well, whereas the roles can be changing dynamically [49].

Main objectives of participants in local energy trading can be defined as reduction of energy costs, gaining (at least partial) independence from utility companies and/or protection of the environment [53]. The participation in such markets further has the potential to raise local energy production and to create jobs and stimulate economic growth in the region [51], which can be additional factors of motivation.

In general, economic benefit is considered the primary motivation for participation in a local energy exchange [51,52]. This is also reflected by the fact that the relevance of locally generated energy seems to appear insignificant if it incurs higher costs for the users [51]. On the other hand, behavioral adaptation in the consumption of energy, such as time-adjusted use, may increase the economic benefits in the framework of localized energy trading [55].

Recent studies examine the stakeholder group of prosumers in more detail and examine which aspects or preferences are decisive for prosumers and to what extent these have to be considered in the design of local energy trading schemes.

As such, the authors of [54] explore to what extent and under which circumstances private actors are willing to participate in local peer-to-peer energy trading with self-generated electricity. They classified three groups of prosumers. Prosumers who react sensitively to price changes, prosumers that strive for self-sufficiency and individual independence and prosumers who sell electricity depending on a certain level of the individual energy storage charging state. The latter two groups react less sensitive to price changes. On this basis, the authors gave recommendations to politics, to industry and especially to energy suppliers to create products tailored towards corresponding target groups. For instance, they suggest to emphasize the financial benefits of local communities for the first group, to communicate the value of autarky on the community level instead of focusing just on individual independence as well as the chance of independence from external stakeholders for the second group and to create technical conditions like a deterministic electricity buffer to allow energy trading just in case if the level of charging exceeds a defined threshold for the third group.

Reinforcing latter, another study also revealed that implementation of local energy trading shows to be successful if at least 50 percent of the participants' energy needs can be satisfied [56].

Although these different preferences should be separately considered, studies also show the complexity and overlapping of classifications. Moreover, the heterogeneity of prosumers' preferences may also lead to common goals at the local energy exchange [53].

Besides the complexity dealing with different preferences, further aspects related to prosumers as well as to consumers need to be considered. For both the factor of cost and the energy price play a major role. Payment procedures need to be secure and easily manageable. Additionally, consumers are by definition less engaged than prosumers as their interaction is unidirectional instead of bidirectional. For prosumers, autonomy, personal and business image do not play an insignificant role. Participating in local energy trading bears the opportunity of individual self-sufficient energy production. It also can determine participants' external perception: They may be seen as advocates of environmental protection and as actors in an innovative market [52].

Further findings show that people are more likely to participate in localized trading schemes that operate at the region/city level and that involves their local council. Project framing needs to emphasize anonymity of consumer data and prepare for negative PR regarding blockchain's association with Bitcoin [56].

Overall, the main challenge is to develop schemes and business models that encourage participants to trade energy with one another. An approach may be via gamification. In such a 'gamified' system, people are more prone to participate if they assume it will benefit the environment, lower their energy costs or if they get informed about a specific existing grid problem and its possible solutions. As discussed previously, local energy trading necessitates the prosumers to rely on each other for trading electricity. The authors of [48–50] examined the aspect of social cooperation among prosumers utilizing a game setting. According to them the 'canonical coalition game' model is the most promising approach as all participating prosumers (aka players) benefit equally. The outcome would be a group of households working together to achieve both global (e.g., reducing CO2 emission) and local (e.g., reducing the cost of electricity) objectives [50].

Virtual local energy networks need to avoid discrimination, enabling equal access for all users. Further, and as discussed above, users' security and privacy need to be guaranteed. Similarly, if the number of users increases, it has to get guaranteed that network congestions get stabilized. Without a centralized authority the trust between users and their trust into the technology needs to be constantly maintained [48].

4 Implementations of local markets

There have been numerous R&D projects deployed across Europe in recent years implemented local energy market. One of the key metrics of the R&D projects is the product offerings of the local energy market. Energy or flexibility or both have been considered as product offering in those R&D projects. In terms of types of flexibility services for the LV distribution network from the end-users' resources, they range from congestion management, voltage management, reduction of line loss etc. Local flexibility markets are used as platform to acquire end-users' resources to offer flexibility to the flexibility buyers, e.g. distribution system operator (DSO), transmission system operator (TSO) balance responsible party (BRP). This section focuses on the R&D projects which has flexibility as product offering to meet the challenges primarily to distribution grid with DSO as flexibility buyer. Some of the other R&D projects with energy as product offering also incorporates grid services in an implicit way where transacted energy is validated by DSO to be grid compliant. This section enumerates few key representative R&D projects implemented local flexibility market with a technology readiness level (TRL) from 5 to 7 (validate and demonstrate in real-life environment) and even above (market ready product).

- **iPower:** This project explores the potential of utilizing domestic and industrial demand side response to create flexibility services for DSOs and TSOs. The project has a specific focus on challenges in distribution grid due to intermittent generation units, new consumption pattern and even possible problems instigated by demand response. It has investigated control scheme, ICT, and market mechanism to mobilise the flexibility from end-user to DSO/TSO. A significant contribution of the project, a market-based framework, with a market clearing platform, has been formed for flexibility trading where DSO, TSO submit their flexibility requirement and aggregators offer to sell flexibility from end-users. This project initiated back in 2011 and supported by Danish government and other industrial partners [69] [70].

- **InterFlex:** This is an EU project with a six demonstration sites in five partner countries. The project was launched to examine the capacity of local flexibilities to solve the existing and future grid constraints. It laid out five business cases out of which one of the cases experimented local trading of flexibilities to provide distribution grid services. Two of the demonstration sites in Netherland and

France implemented the business case. To demonstrate, a consolidated IT platform, which includes forecasting tool, market platform and stakeholder interfaces, has been developed. Whenever a constraint is expected in a distribution grid, through forecasting tool, in a particular location for a particular period, DSO requests for flexibility and aggregators sent bids to DSO based of customer availability and portfolio. DSO selects the most suitable one [71]. The assets in the demonstration sites range from residential appliances, public EV charging facilities, industrial process, stationary batteries and controllable PV system [72].

- **EMPOWER:** This project worked with the development and validation of cloud based ICT and control platform and user app. The cloud-based ICT and control platform is designed to accommodate a local market managing local renewable energy resources, active participation of prosumer. A new, central role has been created for local market named "Smart Energy Service Provider (SESP)" which manages necessary operation, within the community and outside as well, through developed cloud-based ICT platform. Three business models, based on three different value streams: energy trading, flexibility trading and other services, have been investigated as use cases. Use case related with flexibility trading tested SESP market platform to operate hour-ahead local flexibility market for DSO as flexibility buyer. End-users acting as flexibility providers send bids to the SESP market platform. SESP selects the flexibility providers based on solving of optimization problem formulated to serve DSOs' request at minimum cost. Market clearing approach of the local flexibility market, organized by SESP, takes pay-as-bid approach instead of pay-as-clear [73].

- **DOMINOES:** The project investigated a scalable local energy market platform that allows energy trading among prosumers in the community and also facilitates trading of energy and flexibility with other market players: DSO, TSO, retailer and aggregator. A central entity named "Energy Community Service provider (ECSP)" acts as an intermediary to trade energy/flexibility outside of the community and enables LEM solutions. Out of five use cases, one use case [74] presents the use of local market platform to acquire flexibility from end-users' flexible loads to provide service to DSO to solve forecasted grid congestion. Other use cases are based on different local flexibility market solutions serving different stakeholders e.g. energy community to maximize its economic benefit, retailer to self-optimize its portfolio. In latter use cases, DSO plays the role of technical validator ensuring the market dispatches are not violating network constraints. The project plans to validate the use cases in three types of sites: microgrid environment in university laboratory, distribution grid environment in pilot site and VPP demonstration in commercial sites [75] [76].

- **PEBBLE:** PEBBLE project is a R&D project supported by Federal Ministry of Economic Affairs and Energy in Germany started from March, 2018. The project aims to design, develop and validate a prototypical, blockchain based digital platform which will establish a LEM for decentralized energy trading within market participants in the community without violating grid constraints. The energy trading is performed with an objective of utilizing expected flexibility to support local balancing in a grid-compliant manner. Provision of energy trading is present for both Day-Ahead market and intra-day market to reduce the effect of forecasting error to possible extent. Market matching algorithm in the project is auctioned based and blockchain based P2P strategy will be implemented in settling contractual agreements. This project does not plan to implement flexibility market. Rather, a minimum dataset of grid topology is incorporated in the matching algorithm as additional constraints. This results in the LEM participants to utilize their asset's flexibility to avoid violating of grid boundaries. The project plans to demonstrate for validation in simulation and in a village of Wildpoldsried in Southern Germany [77].

- **SmartNet:** This is an EU project which explored different co-ordination schemes between TSO and DSO to obtain ancillary services from distribute resources in LV and MV level. Two out of five co-ordination schemes deployed local flexibility market with DSO as operator to solve local congestion management and to achieve balancing in local level [78]. It runs in parallel with central ancillary service market. DSO calls for bid from flexible resources connected to local grid and clears the market to resolve local needs. Remaining bids are aggregated and sent to central ancillary market run by TSO. Pilot in Spain demonstrated the above mentioned co-ordination schemes.

- **ENERA:** This project is experiment novel design of market-based congestion management through establishing regional flexibility market covering regional distribution area. These flexibility markets will be on-demand and operating in parallel with central market but in intraday time horizon. TSO and DSO in coordinated way, initiates the local flexibility market based on forecasted grid congestion at certain node/s. Both flexibility providers and system operators (as flexibility buyers) send bids and eventually system operator activates the suitable flexibility resources in real-time through direct control. The initiation of flexibility market and activation of flexibility is determined by the status of the grid proposed in terms of Traffic Light Concept (TLC) presented in [79].This project is led by EPEX SPOT and Siemens along with TSO and several DSOs and it is demonstrated in West Germany [80].

- **NODES:** This project aims to create a marketplace for flexibility providers to offer flexibility both locally to DSO for local congestion management and centrally to TSO and BRP for balancing services. Several live test sites in Germany, Norway and Sweden are being used to validate NODE platform for different use cases [81]. The decision of using flexibility resource locally or globally depends on the highest value being offered by DSO or TSO/BRP. Since, the flexibility procurement need locally is limited to few hundred hours in a year, the provision to alternative global markets reduces the risk for flexibility provider which may arise due to lower liquidity and less competition in local market place [82].
- **GOPACS:** This project is initiated by Dutch TSO and four DSOs to develop market-based mechanism to alleviate grid congestion. The market mechanism is designed to collaborate with existing Dutch intra-day market platform where flexibility provider can place flexibility offers for same resources to both wholesale intra-day market and locational market with additional location information. GOPACS provides the intermediary platform with TSO-DSO co-ordination functionalities to avoid double activation of same resource. Still market clearing is not incorporated in GOPACS rather resource is chosen by grid operator based on several factors: difference between buy/sell bids, effectiveness of the resource activation in congestion management and impact on other part of the grid [83].
- **Piclo Flex:** Piclo Flex provides single market platform to multiple DSOs to procure flexibility. It provides market participants with wider scope of choices where flexibility reservation can be arranged with a lead-time ranging from intraday-time frame to six months or more and flexibility payment includes both for dispatch and availability [84].

Mostly the projects were involved in congestion management (CM) with few projects are also planned to focus on other grid services such as, voltage management (VM) and line loss reduction (LLR). Congestion management comes as priority as it enables the grid operator to defer network reinforcement and supports in grid operation. The market model for the projects covers both centralized structure with central entity maximizing welfare/minimizing cost for the entire system deciding market position for all participants and decentralized structure with market participants engaging in trading with an aim to maximize individual profit. There are several market designs based on clearing mechanism ranging from optimization-based, auction-based clearing and continuous trading existing in European intra-day market etc.. Projects can be categorized into following categories based on the degree which flexibility being used as grid services: **category 1:** projects with market platform to trade flexibility explicitly for grid services; **category 2:** projects with provision for energy trading taking into account grid congestion in traded energy. This implies the market participants use their flexibility to avoid grid congestion and to maximize energy trading potential. DOMINOES and PEBBLE projects are example of category 2 while other projects fall under category 1. PEBBLE is the only project among all implementing blockchain technology with others are pursuing Information and communication technology (ICT) based trading platform. Most of the flexibility-only market platform (category 1) facilitates trading in intraday timeframe with exception Piclo Flex providing trading opportunity with lead time ranging from intraday time frame to months. SmartNet project among all project focuses on TSO-DSO coordination scheme and its implication while procuring flexibility through market mechanism. Some of the projects, e.g. NODES, Piclo Flex, EMPOWER and SmartNet, extends the possibility for balancing services in addition to the locational grid services.Table 3 summarizes the R&D projects mentioned above with few more additional projects.

Table 3: Key local market R&D projects focused on distribution grid

Project Name	Grid services	Market model	Participants	Market Design	Technology	Objective/ Outcomes
iPower (Denmark)	CM,VM	Centralized & Decentralized	Buyer:DSO, Seller:Aggregator	Optimization-based & auction-based	ICT platform	Control scheme and market mechanism to mobilise flexibility from end-user to DSO/TSO by utilizing demand response
InterFlex (Europe)	CM	Decentralized	Buyer:DSO, Seller: Aggregator, Large prosumers	Auction-based	ICT platform	Tools and process for local flexibility market to solve the existing and future grid constraints
EMPOWER (Europe)	CM	Centralized	Buyer:DSO, Seller:Aggregator, Prosumers	Optimization-based	ICT platform	Cloud based ICT platform and user app to facilitate local energy/flexibility market
DOMINOES (Europe)	CM	Decentralized	Buyer:DSO, Seller:Aggregator	Auction-based	ICT platform	Market platform that enables prosumer to engage with other prosumer and also with different market players: retailer, DSO, TSO, aggregator
PEBBLE (Germany)	CM	Decentralized	Buyer:DSO, Seller:Prosumer	Auction-based	Blockchain	Blockchain based energy trading platform with congestion management functionalities embedded in matching algorithm
SmartNet (Europe)	CM,VM, LLR	Decentralized	Buyer:TSO,DSO, Seller: Aggregator	Auction-based, pay-as-clear	ICT platform	Different DSO-TSO co-ordination schemes to procure ancillary services from distributed resources in LV/MV network
ENERA (Germany)	CM	Decentralized	Buyer:DSO, TSO(in future), Seller: Aggregator,	Continuous trading, pay-as-bid	ICT platform	Market-based congestion management through establishing regional, "on-demand" flexibility market covering regional distribution area
NODES (Europe)	CM	Decentralized	Buyer:DSO, TSO (in future), Seller:Aggregator	Continuous trading, pay-as-bid	ICT platform	Create a marketplace to improve grid operation, tap additional flexibility potential and enhance congestion management options for grid operators
GOPACS (Netherland)	CM	Decentralized	Buyer:TSO, DSO, Seller: Aggregator	Continuous trading, pay-as-bid	ICT platform	Development of integrated TSO-DSO coordination platform to procure flexibility in intra-day timeframe to avoid congestion
Piclo Flex (UK)	CM	Decentralized	Buyer:DSO, Seller: Aggregator, Large prosumers	Continuous trading, pay-as-bid	ICT platform	Development of marketplace for mutiple DSOs to procure flexibity with lead-time ranging from intra-day timeframe to six months or more. Provison of availabilty payment and dispatch
Cornwall (UK)	CM	Decentralized	Buyer:DSO, Seller:Aggregator, Large prosumers	Auction-based	ICT platform	A virtual marketplace to procure flexibility services from homes and busniesses to serve the need of DSO and TSO in co-ordiantion
StoreNet (Ireland)	CM,VM	Centralized	Buyer:DSO, Seller:Aggregator, Prosumers	Optimization-based	ICT platform	Market plaform to procure flexibilty from end-users storage facilities through aggregator to serve DSO's need

5 Modelling approaches

The vast majority of studies on local and P2P markets addresses not only problem formulation of the market clearing, but also aspects related to different challenges as discussed in Section 3. Existing studies encompass multiple aspects, such as technical, regulatory, social, and economic challenges. In this section, we categorize the focal points, assumptions and implications in recent works with respect to grid-related challenges, model approaches and market designs.

5.1 Grid-related challenges

5.1.1 Direct grid modeling

Consumer-centric markets empower investments in renewable generation and flexibility in the distribution grid, but also poses new challenges to the DSO with respect to quality of supply. Peer-to-peer trading and local markets have received high attention in state-of-the-art research, using mathematical models to ensure fairness, market efficiency and incentives for DER. After a market is cleared and transactions and 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 new problems as presented in Section 3.

This has been covered more adequately in recent research where power flow is taken into consideration as part of the market clearing problem [85], where the problem of trades violating grid constraints is highlighted. To deal with this challenge, a coordination methodology between the DSO and P2P markets which allocates grid tariffs to prosumers causing grid problems. Using euclidean distance, grid tariffs are allocated to trading prosumers if there are congestions. AC-PF is considered in [75], where the DSO analyses each market clearing and informs the aggregator if congestions or voltage problems arise. Trade-off between free P2P trade and grid operation is also considered in [86] where AC-PF is not considered directly, but losses and voltage levels are simulated to highlight the need for coordination between grid state and P2P trading. Community based and decentralized P2P approaches are compared in [87], where the authors highlight that the different market schemes impact voltage levels significantly. This is done using distributed optimal power flow, extracting DLMPs as a result of the grid constraints. Congestion management and power loss reduction can also be achieved using a network constraint penalization terms in the objective function of each agent [88]. Distributed optimal power flow (DOPF) also shows high synergy with the distributed nature of P2P markets, and have therefore been investigated in [89, 90]. DOPF is also reviewed as a promising method of ensuring proper voltage control with decentralized control in [91]. However, the implementation of DOPF requires radical changes in market design [92], mostly due to technical and market design barriers.

The mentioned studies cover losses and voltage levels which requires either AC-PF models or similar approaches based on the AC-PF formulation. These formulations are per definition non-convex and non-linear, increasing the computational efforts when solving the problem. DC-PF approaches are therefore investigated e.g. based on the Newton method [64] to address challenges related to congestions and distribution grid expansion. A DSO pricing approach based on DLMP is presented in [93], where linearized power flow constraints are considered.

5.1.2 Indirect grid modeling

An alternative to modeling grid constraints is implicitly modeling the grid or the potential grid impact. This is typically simulated by assuming maximum import or export levels from a specific geographical area in the grid. Many of the studies which incorporate power flow equations face scalability issues due to the complexity of power flow problems. Further, assuming that prosumer utility functions and grid data can be accessed by the same operator is unlikely in most liberalized markets. Therefore it is of interest to investigate the impact of price signal and grid tariff based end-user response. Studies on grid tariffs design and their impact on peak loads in neighborhoods are also considered in [94, 95] where capacity based tariffs were found to be efficient when aggregated on neighborhood level in order to reduce peak loads. In these two studies, grid tariffs were analyzed based on proposals from the regulator in the relevant country. A more fundamental analysis was performed in [96] where the optimal grid tariff is designed using a Stackelberg game where the leader (DSO) scales and chooses between three grid tariff structures to minimize peak loads in the distribution grid. Similarly, [97] designed an optimal cost-recovery based grid tariff with the goal of minimizing peak imports from an energy community.

Grid tariffs represent an efficient way of incentivizing demand response and grid friendly demand patterns as the DSO alone can control the price signals. However, a perfect grid tariff is hard to design and is often challenged in terms of fairness and comprehensive for the customer [98]. More direct approaches are considered for example in [89], where network charges are allocated based on electrical distance to reduce stress on the grid in a P2P market. A blockchain-based smart contract trading mechanism was demonstrated in [99], where an evaluation of congestions in a distribution network was performed to ensure feasibility in trading.

5.2 Planning approaches

A local market has underlying assumptions about how the market is designed and how the peer utility function is considered. We mainly separate between centralized vs decentralized solution methods, but also consider whether or not the market clearing is performed centrally or in a decentralized fashion. In addition we consider other aspects such as scalability, uncertainty and optimality.

5.2.1 Centralized planning

In a centralized approach, a single optimization problem is solved in order to clear the local market as well as dispatching assets of each agent in the market. This is often done using an optimization model with one master objective function. Typically the objective function tries to either 1) maximize the social welfare or 2) minimize the costs of all agents incorporated in the system. This approach often leads to what is typically called the system optimal solution which is the solution which causes the lowest overall costs for the system as a whole. However, the objective of each agent in the system is considered, implicitly meaning that one agent might be worse off than he/she could be because the benefit of the system is higher than the cost of that specific agent.

Because agent interests are not considered in the centralized approach, this approach is often used for benchmarking: how good of a solution can theoretically be found? This is widely used in the literature because of the efficiency when solving specific problems. For example, [100] analyzed the impact of risk-neutral and risk-averse agents in local markets. An optimal matching of stochastic load and local generation is presented in [64]. In [101], it was found that decentralized batteries leads to almost 20 % savings compared to one centralized battery in a neighborhood P2P market. Similarly, [94,95] found that a best-case coordination of flexible assets in a neighborhood could reduce peak loads. As described in Section 4, aggregators are a promising market player to deal with centralized control, as it can coordinate end-users in markets as well as interacting with the DSO. In [75], 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 reiterate to avoid congestions.

5.2.2 Decentralized planning

Unlike centralized planning, a decentralized planning approach considers multiple objectives in a non-cooperative game theoretic framework. In game theory, a number of competitive agents make decisions which maximize their own profits or social welfare, and the decision of one agent often influences the decisions of other agents in the system. Therefore, the problem must be solved so that a Nash Equilibrium (NE) is found. In a NE, no agent is better off by changing his decision, meaning that there is a stable state in the non-cooperative game. Although there are versions of cooperative games, the number of studies using non-cooperative games outnumber the former.

Alternating direction method of multipliers (ADMM) algorithms have been widely described in the literature due to its capacbility of solving convex problems by splitting them into smaller problems and solve them in a distributed fashion. For solving distributed problems, iterations are performed where dual variables of each agent is updated until a convergence is achieved from all agents in the system. This was proposed by [102] where scalability and privacy issues were highlighted as advantages. A consensus version of the method is showcased in [89] where a competetive equilibrium can be achieved. A unified formulation for consensus ADMM under different market designs are presented in [103], where the market design can be changed purely by changing the communication links. The authors also claim faster convergence and better resilience to asynchronous behaviours [104]. A similiar approach is investigated in [105], where a relaxed consensus + innovation (RCI) approach to solve the P2P market clearing is used. Compared to ADMM, RCI was found to converge faster for coordination distributed P2P coordination in a microgrid, contesting the previous claim.

An alternative to ADMM are complementarity models which are commonly used in energy market modeling [106]. The complementarity problem can be used to model the Karush-Kuhn-Tucker (KKT) optimality conditions for convex programs. These types of problems can be solved by solvers like PATH [107]. In [108], local generation and consumption was coordinating using a game-theoretic approach, and as a consequence found that sparsity in peer behaviour resulted in higher savings and lower peak loads. Complementarity models can be extended to Stackelberg games where a master level problem with equilibrium constraints based on the KKT conditions are formulated. In [109], a Stackelberg game formulation (also known as math program with equilibrium constraints (MPEC)) is used to optimally design peak load grid tariffs in order to avoid high peak loads from the prosumers in the market. A more comprehensive cost recovery approach is used in [96] where the leader (DSO) scales and chooses between three grid tariff structures to minimize peak loads from end-users in a non-cooperative game. A similar approach is used [97], where an optimal cost-recovery based grid tariff is designed to minimize peak imports from an energy community. An equilibrium model is also used in [110], where a Nikaido-Isoda function and Relaxation algorithm is applied to a local market with a high share of DER.

5.3 Market design

A variety of structural peer-to-peer and local markets are described in [3], spanning from full P2P markets to organized prosumer group models also referred to as energy communities or neighborhoods. Hybrids versions with community-connected versions were discussed, and further described in [10]. Although the literature covers a variety of versions, the two main concepts are local community markets and local P2P markets. As described in Section 3, there are a number of challenges related to stable operation of the power system. The question therefore rises: which local market design has the best underlying structure to address these challenges in an efficient matter?

5.3.1 Centralized market clearing

Centralized market clearing is the common approach in social welfare maximization models due to the ensured global optimum which can be guaranteed in optimization models with a central entity. However, centralized market clearings are not only limited to centralized planning problems where a single entity possesses all information about all aspects of the market. Centralized market clearings are useful also in energy communities as sensitive information about utility functions of each agent only has to be shared with a market operator. In [111], authors prove that energy communities can achieve similar market clearings as a fully decentralized P2P market under the assumption of a supervisory node with access to utility functions of all agents. Both were found to be viable approaches in [87], but that result can be different as the community-approach ensures DSO interests to a greater extent. Other advantages of the 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 [111]. 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. [112] defined the need for less information flow between the market operator and the peers, but still highlights the need of coordination from a supervisory node to lower costs and increase self-consumption inside the community. Another aspect often ignored in local market research is the necessity for coordination in intraday markets due to uncertainty in load and distributed generation in the local market. In [113], a local intraday market is suggested to handle deviations from the scheduled demand and production, coordinated by a central market clearing entity. Further approaches considering community managers are shown in [114, 115].

5.3.2 Decentralized market clearing

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 there is no way to influence the flexibility and transactions in the market clearing to facilitate healthy operation of the grid[1]. A full P2P market design with complete MBED was designed in [116], where agreements are made in a complete bilateral fashion without a supervisory node. Lagrangian relaxation, ADMM, RCI (or CI) are recommended in [10] due to their ability to define the individual objective of each end-user while still considering privacy issues. With this context, end-users share only their volume and willingness to pay for electricity, keeping asset information or other aspects private.

Auction based approaches are also viable options for clearing in local markets, and often deals very well with respect to scalability compared to optimal power flow or DLMP methods. An auction based approach benefits 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 (CDA) have been demonstrated in [117], where trading with a shared electric energy storage in an energy community is proposed. In [92], zero intelligence plus (ZIP) algorithms were investigated to match buyer and seller bids in P2P markets, also allowing for no market supervisor. Iterative CDA have also been applied for energy trading in microgrids [118]. The use of P2P trading with CDA together with blockchain was suggested for charging of plug-in hybrid electric vehicles (PHEV) in [119], where sensitive information about the

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[1] Of course, the system operator could be one of the agents in the market clearing, but is forbidden in most countries from participating

PHEV would remain private. Integration of flexible resources into electricity markets using CDA in a prediction-integration strategy optimization model was suggested by [120]. Common for the mentioned studies is that grid concerns are not included specifically, indicating that research is still to be done on integration of DSO requests in decentrally cleared markets.

6 ICT: Distributed Ledger Technologies and Blockchain

Local energy markets are the result of the combination of layers, each of them focused on different dimensions [39, 109, 121]. We can identify 4 layers in distributed energy systems: the physical layer, the control layer, the market layer and the ICT layer.

- *Physical layer:* It is formed by different physical components installed in the distribution grid. Among them we can find the small-scale flexible assets from private owners (e.g. PV solar panels, residential batteries) or other grid-side flexible sources (e.g. remotely controllable switches, static var compensators). It also comprise more common components like transformers or grid lines.
- *Control layer:* This layer refers to the combination of control functions managed primarily by the system operators and DSOs. Voltage control, congestion management and loss reduction are main priority for DSOs to avoid blackouts and keep the energy balance of local areas within certain grid limits. Also activation processes to activate flexibility services are part of the control layer.
- *Market layer:* The market layer comprise the rules and approaches to implement local markets. Therefore, incentive mechanisms, price setting rules, market clearing approaches, grid tariffs or the roles of participants are subjects to consider when designing this layer.
- *ICT layer:* The last one consists of communication devices, information flows, protocols and applications, conforming the virtual dimension [108]. This layer provides tools that allows automatizing processes, the communication between agents, data protection, machine-to-machine (M2M) information flow or external transactions like financial settlements.

We find in the literature several studies that also consider the layer architecture in local flexibility or energy markets. [50] understand that peer-to-peer networks can be split into a virtual and a physical layer. In their approach, the authors incorporate to the virtual layer all communication flows and processes except those involving electricity transactions. [39] and [121] also present 4-layer architectures in which the ICT or virtual layer is considered as an horizontal layer of the energy system. The main pitfall of this horizontal perspective is that it may not efficiently show the application communication technologies.

In Figure 2 we present an alternative approach in which the ICT layer is presented, not as an horizontal layer, but as an integrated vertical layer. This alternative perspective aims to highlight that: i) ICT are bridge technologies to allow the interoperability within and between layers, ii) it may incorporate some processes from other layers, overlapping their functionalities and iii) it may interact with external environments to the local market (e.g. financial system, other energy system dimension). Consequently, the virtual layer is usually formed by tech that have the characteristic of being suitable and adopted for a wide range of purposes. This opens new paradigms and opportunities for finding new interactions with other sectors or the design of new disruptive business models [5, , 122].

Distributed Ledger Technologies and specially blockchains, alone or in combination with other Industry 4.0 applications (e.g. machine-to-machine, IoT), can aid the incorporation of smart grids [123]. The goal of the following chapter is to frame the recent status of blockchain and distributed ledger technologies (DLT) in the energy sector. In Section 6.1 we define the purpose and basic technical features of this tech. Then we give a brief overview of the general application domains. Section 6.2 digs into their synergies with the energy sector. Here, we present different areas of study within the sector as well as ongoing projects in the energy sector domain. To conclude, in Section 6.3 we present a literature review of the applications of blockchain in local flexibility markets. Most reviews have focused on the general idea or the potential for utilities and companies of ongoing projects (see the reviews by [124], [125] and [126]). However, we aim to distinguish ourselves by providing a more detailed explanation on how blockchains are integrated in different market designs. To do so, we review the existing literature regarding blockchain

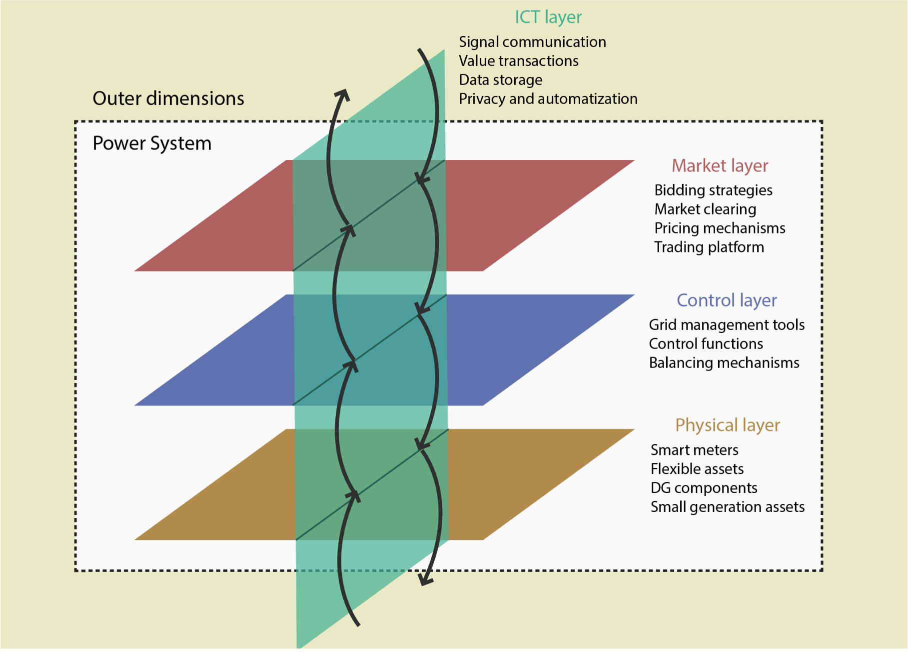

Figure 2: Layer architecture of distributed energy systems. The ICT layer acts as the connectivity layer within the power system. Note that it may also connect it with outer dimensions (e.g. financial sector, governance tools, etc)

in local flexibility or energy markets.

6.1 DLT and Blockchain: The technology

Distributed Ledger Technologies has gain popularity after the adoption of blockchain by Nakamoto to disrupt the financial sector [127]. Nonetheless, different DLTs have appeared in order to provide different strengths to the technology. Being its main purpose to get rid of the need of trusted third parties, they are conceived as a technical revolution for digital trust [5, 124]. [128] identifies four types of DLT: blockchain, tangle, hashgraph and sidechain. All of them sharing common concepts such as its application on distributed peer-to-peer networks and the incorporation of public key cryptography and consensus mechanisms. Nonetheless, their level of implementation differ from each other, being blockchain the most common type of DLT implemented and studied in the energy sector. As such, hereinafter we analyze primarily the latter technology.

Blockchain is a digital immutable ledger that can securely store transactions in a distributed and decentralized network without trusted intermediaries. The security and the trust among participants is ensured using cryptography. Each block is identified by the output of a hash algorithm that employs the transaction information and the hash of the previous block as input information. Cryptographic hash functions are one-way algorithms. This means that the input cannot be extracted from the output. Additionally, they are deterministic, computationally fast and generates avalanche effect[2]. The sum of these properties brings the opportunity to ensure the ledger to be tamper-proof and offer trust about the validity of its content [129].

As a distributed technology, any modification in the chain has to be accepted by participants. The way these changes are accepted by the community is outlined in the *consensus protocol* adopted. Consensus protocols are of key importance in the security and functioning of blockchains as they set the necessary strategies to defend the chain from attackers and the rules to accept the inclusion of new blocks. Depending on the blockchain architecture, we may find different protocols. Each of them will possess different features such as scalability, transaction speeds, security or spending of resources [124]. Proof-of-work (PoW) mechanism is the most common consensus algorithm as it easily solve the "Byzantine Generals

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[2] This refers to the ability of the algorithm to withstand artificial collisions that can cause the data to be forged

problem". Under its rules, miners compete with each other to validate new blocks. The competition consists in solving a cryptographical problem. The goal of this mathematical puzzle is to find the correct hash for the block under determined limits. As the hash function is a one-way algorithm, the only way for miners for finding the solution is by trial and error. This brute-force approach supposes expending quite a lot of computational effort which help to prevent the participation of bad-intentionally nodes. Other types of consensus algorithm have also proved to be efficient or even less energy demanding than PoW strategies. This is the case of proof-of-stake (PoS) which instead of relying on the computational effort, it deploys a random selection process for validators. We refer to [124] and [123] for a more detailed explanation of the existing mechanisms.

Blockchain consists of two types of network participants: users and validators, also known as miners. Consensus protocols define how these validators should operate and establish security measures in the validation phase. However, the security functionality regarding *who* is allowed to participate in the network depends on the access rights and the privacy considerations. When the access rights are granted to all the Internet users, the blockchain is classified as a *public* or *permissionless.* On the contrary, if some restrictions are established and only certain nodes can be part of the ledger, we are facing a *private* or *permissioned* blockchain. An hybrid version is known as *consortium* blockchains. Closer to private blockchains, they differ from the latter in the generation of the data blocks as it can be decentralized. Basically this means that there are more than just one block validator. Depending on the application purpose, the security needs or the technical requirements (e.g scalability or transaction speeds) the adoption of one or the other will be more or less appropriate. Table 4 shows the differences between these three types of blockchains.

The main driver for the development and expansion of blockchain was to allow monetary transactions without third parties and with the goal of democratizing the financial system [127]. For this reason, it is common to consider blockchain as a technology for merely cryptocurrency transactions. However, since the second generation blockchains, we are able to transact any type of digital asset in the network (e.g. property rights, cryptocurrencies, commodities). Examples of these second generation of blockchain platforms include for example Ethereum. A second distinct characteristic of these blockchains is that they are built-in to support smart contracts, allowing the adaptation of blockchain to other functionalities beyond the financial sector. [130] refer to smart contract as digital protocols which by cryptography we can secure and automate their formalization and compliance. As an innovative feature, it has opened the possibility of new applications in transport, healthcare, supply chains, education or the energy sector. It is such its versatility that the relevance and opportunities of blockchain and DLT is even highlighted by the political arena as stated, for instance, in the European Parliament resolution of October 2018 [131]. This text recognizes these technologies as "tools that promotes the empowerment of citizens and can significantly improve key sectors of the economy".

Table 4: Classification of blockchains and their characteristics depending on access rights. Based on [108, 125, 132]

Property	**Public**	**Private**	**Consortium**
Access	Permissionless	Permissioned	Permissioned
Consensus nodes	All nodes	One organization	Selected set of nodes
Blocks generation	Decentralized with resource expenditure	Centralized	Decentralized or centralized
Consensus protocols*	PoW, PoS	PoS, PoA	PoW, PoS and PoA
Rule versatility	Low. Required 50% of acceptance	High. One organization decides	Medium. The consortium needs agreement
Transaction times	Slow (PoW)	Fast	Faster than public
Energy expenditure	High (PoW)	Low	Low
Digital token	Required (incentives)	Optional	Optional
Example	Bitcoin, Ethereum, etc	MultiChain, HyperLedger, Tendermint, etc.	MultiChain, HyperLedger, Tendermint, etc

6.2 Blockchain in the energy sector

Blockchain and distributed ledger technologies (DLT) were specifically designed to allow the proper functioning of decentralized systems. Not surprisingly, it is common to state the natural fit of blockchain with the new decentralized local energy system [124]. The match between electricity and blockchain reside in the instantaneous transfer of the commodity what hinders possible discrepancies between the recorded data and the real transfer [123]. The rapid increase in the system complexity requires a more intelligent and efficient use of power grids in which blockchain can be a determinant tool for the paradigm-shift of the sector [125]. The possibility of integrating large networks of devices connected in real-time promises to shape the future system and improve the allocation of flexibility [, 122]. The data or financial transactions occurring in these networks can be managed by DLT which offers better control of data usage (data sovereignty) and the direct interaction of agents (desintermediation) [, 125, 133]. The availability, traceability of the energy data and the personalization of the product will suppose a very high democratization of the energy chain [5].

During the last decade, the number of energy-related projects implementing DLT or blockchain has increased considerably worldwide [134]. Although the major application is within local markets [124, 134], the projects extends to all stages of the value chain. Aware of the potential, authorities have argued the importance of paying serious attention to other applications beyond P2P trading for the realisation of smart grids [135]. The German Energy Agency [126] found five big areas of applications: trading, financing, asset management, market communications and data management. These can be implemented in different processes or involve different actors of the system. [133] provides an alternative hybrid segmentation of the deployment of blockchain by naming the applications throughout the supply chain, the actors involved and the precise functionality of the blockchain (energy transaction, financial transactions and data recording). The value of this approach is that we can identify areas of applications that applies to different stages. For instance, the application domain of trading may apply to wholesale trading and local energy markets. Despite the different approaches when identifying the applications, most experts emphasize the versatility of blockchain for being adopted in the energy sector [,122,124–126,133].

The holistic approach of blockchain applications has given raise to new projects and start-ups beyond local energy markets. In Germany, the IT service provider PONTON developed the GridChain project [136]. Its goal is to create an integrated process to coordinate all actors and allow them to request balancing power as well as manage congestion situations. Another European entech company that work towards the digitalisation of the grid services is Electron [137]. In collaboration with British system operators Electron is leading RecorDER, a project that will build a shared asset register of energy and flexibility assets that are connected to the transmission and distribution grids [138]. Also big and well established companies as the Pacific Gas and Electric Company (PG&E) are looking with interests to the possible advantage blockchain can offer them, specially in access to asset origin and traceability [139]. With the objective of stabilising the distribution grid, the transmission system operator TenneT and the storage tech enterprise sonnen, developed a project to demonstrate how residential storage can be manage using blockchain to offer balancing services to operators [140]. Although in the present paper our focus is in the application of blockchain and DLT in LEM, it is relevant to keep in mind other types of implementations. This is not merely for expanding knowledge but also because the potential inter-operability of ICT. Despite their different goals, various blockchains may require to share common data to exploit all their potential.

6.3 Blockchain and local flexibility markets

Knowledge regarding the application of blockchains and DLT in the energy sector is getting more clear for utilities and the sector. Most experts are positive towards the benefits and importance of the ICT layer for innovative applications and business models [5, , 122, 125]. Still, experts and utilities raise the importance of more academic research as well as implementation cases to understand the viability and real potential of the technology [122,141]. The following section will analyze how the academic community in local markets: i) analyzes the ICT features in local markets, ii) establishes its role in the system and iii) connects local flexibility markets with the virtual layer.

The literature covering the topic of blockchain in local markets vary in the goal and approach of the study. We can find authors that are mainly focused on the ICT layer configuration needed to offer a secure and transparent system while other studies may look closely to the role of blockchain within the local market dynamics. Other touch upon the possible interactions between some layers of the system as well as with outer sectors or other dimensions of the power sector (see Figure 2).

When addressing blockchain in local markets, some authors are more concern with the enabling mechanisms and key technical features of the ICT layer. Special focus is put into the security of transactions what suppose to explore different consensus mechanisms or the cryptography for identity management. A clear example of this approach is [142]. The study is focused on determining the cryptography mechanism to allow for a secure trading system as well as investigating the adoption of Proof-of-Stake as a substitute to Proof-of-Work. The paper propose the utilization of asymmetric encryption to resist security attacks. Regarding the market model, the authors define a simple bi-lateral market where the role of blockchain is merely to settle monetary transactions. There is no deep explanation of the market model. In other cases, the scalability of the technology or the configuration of smart contracts play a central role. This is the case of [143]. In order to reduce the number of transactions, they explore the *Merkle Trees* feature. By deploying it we can manage to decrease the length of the chain. [143] in the process of establishing a demand response market they give detailed explanations of smart contracts that allow balancing the energy demand, implement incentives and penalty rates as well as establish the flexibility levels required. Although in less degree than the above mentioned studies, most of the literature consider and reflect upon the technical characteristics of blockchain [99,144–147]. This considerations are vital to really understand the viability and realisation of the propose implementations.

A second type of studies are more oriented towards the direct application of blockchain in the market structure. These tend to present the steps and rules of the market and how blockchain is taking part in each of them. The level of details in this concern promotes deep definitions of the market structure. Therefore, even though blockchain and ICT are crucial components, the design of the market approaches are explored thoroughly in this type of articles.

[99] suggest an optimization model algorithm with the objective of maximizing the revenues of the power trading market. By determining the importance of deleting barriers of entrance, privacy of bids and the automation of the process, [99] develop a trading mechanism that relies on a smart contract and consists of six phases. An interesting contribution is the incorporation of sealed quotes and real quotes mechanism to ensure the privacy of bids before the clearing of the market. This approach consist on combining the real quotation with an aleatory string in order to elaborate a hash impossible to decipher without the input information. Before the deadline of the public quotation, each participant send the real quotation and the string so that the smart contract can verify that the quotation is the same submitted in the sealed quotation. Confidentiality and trust is ensure by adopting this mechanism. In a more recent study, [144] also employs sealed quotations for an EV trading platform. In this case, they propose an auction-based trading platform were the aggregator acts as the auctioneer. One drawback of to adopting this method is that it does not explore the complete decentralization of the system as it still relies on a central entity to clear the market. The blockchain in this case is the enabler for direct monetary transaction between charging and discharging EVs.

Another approach of blockchain integration was given by [145]. They present a community integrating PV assets that are able to trade energy between each other while the energy provider is just present to balance the system. The blockchain in this case provides a system for bidding, contracting and settle economic transactions. The author reaches the conclusion that decentralized markets lead to lower prices in the community but also argues that blockchain need to be analyze carefully due to its financial risks, computational resources and transaction costs that may counteract the benefits found at the first glance. Several studies, for example [141], [108] and [143] extend the application of blockchain to send signals for automatic activation of the electric devices (e.g. appliances, HVAC) according to the needs of the market. By the integration of smart controllers, [141] propose connecting them to the blockchain. In this way, the smart controllers may automatically programmed to operate the device when the smart contract send a determined instruction. Another innovative proposal suggested by [141] is the developmet of DApps as the platform where market participants, power retailers and the driver of hardware can get access to detailed information of the P2P market.

Another path of study is the implementation of monetary and non-monetary incentives. [147] demonstrated the capability of tokens to increase the participation in the market as well as promote the sustainable use of renewables. In his study, Zhang et al. implemented a market platform in a university campus where participants were rewarded when they charge their EV during peak generation of renewable energy.

The last orientation of research is to establish the combination of the different layers by implementing digital ledgers. An increase attention is found in the combination of the control layer and the market. This type of connection usually imply the connection between copper plate models and the market model. Foti and Vavalis [146] developed a new method for extending transactive controller objects to incorporate blockchain. In this way, the blockchain send signals for control within their GridLab-D architecture to perform the powerflow analysis at the distribution level. In the study of Liu et al. [144] they also consider AC power flows in order to check the viability of the trading system, however, it is not connected with the blockchain layer as it is run centrally by the operator. Others such as Noor et al. [141] they just simply introduce some grid constraints in the market model in order to determine the energy transactions. Unfortunately, it does not provide a closer look in important considerations such as voltage levels or congestions. Definitely, there is a gap in research on how the control layer may be integrated in a decentralized manner by using the potential of ICT technologies.

The combination of layers is not limited to the control-market harmonization but also to the rest of layers and even external dimensions. There is a considerable amount of literature that consider the consider the physical layer as a crucial factor for ensuring the reliability of the market. Most of them refer to the necessity of smart meters to guarantee the real delivery and obtaining of energy [99, 142, 145]. Others go a bit further and incorporate smart devices capable of directly controlling the assets [141, 143, 146].

External considerations with the financial sector are also mentioned as in the case of Mengelkamp et al. [145] where the volatility of cryptocurrency prices is considered as a financial risk for their integration in the local market. In this respect, tokens which are connected to exchange markets are proposed as transacting assets within the market [141, 147]. Still, very little is known about the consequences of how the design of cryptocurrencies may impact the functioning of local markets. Foti and Valavis [146] explore the impact of gas prices in Ethereum to evaluate the cost of blockchain operation in local markets. The researchers propose different market approaches which will lead to different costs. Based on assumptions regarding the price of Ether and the average gas price they concluded that the operation of Ethereum for a participant sending transactions every 15' will result in approximately \$4 and \$12.5 if the auction period is reduced to 5'.

Summarizing, some studies aim to elaborate more on the technical features of blockchain, others on its performance in the local market or on its role as connection layer. However, these dimensions do not exclude each other and despite the central goal, most studies dive into all of these aspects. Section 6.3 presents the different blockchain properties analyzed or proposed in the literature. Technical features (e.g. blockchain platform, consortium algorithm), layers that interact with the chain, or the type of flexibility considered in their markets.

7 Conclusion

In this article we have focused on how grid challenges are addressed in state-of-the-art reserach and projects on local and P2P markets. Firstly, a description of local and P2P markets as well as incentives to incentivize grid friendly operation of flexible assets and local market trading was provided. Further, a series of challenges related to distribution grids was presented. Many pilot projects with actual implementation are currently trying to address the importance of grid considerations in local markets. An overview of model approaches for local market clearing considering the distribution grid was presented, as well as the organization of the market in terms of market clearing and information flow. In addition, an overview of ICT and blockchain technologies for coordinating trading in local markets specifically related to grid friendly purposes has been provided.

Integrating a rising number of decentralized agents in local and P2P markets while properly addressing distribution grid challenges boils down to well organized, modular systems in which all stakeholders can influence the outcome. Thus, in recent years, there have been growing attention on R&D real-life projects implementing local flexibility market to solve local distribution grid challenges. Since local market are mostly event-triggered and flexibility need is for limited hours in the year, it is necessary to bridge local flexibility market to central ancillary service markets to maximize the potential value of flexibility assets. Several projects are investigating such possibility with flexibility providers offering flexibility locally and also in central market. Proper market design has to be in place to avoid conflict of interests among different stakeholders, e.g. DSO, BRP and TSO, while procuring flexibility. Grid-influenced local and P2P trading is of rising interest from a modeling point of view, and is considered both with centralized and decentralized planning approaches. The use of ICT, Blockchain and DLT is fundamental for a correct synchronization between the market and grid requirements. We have identified a wide variety of methodologies to implement them in the market and the grid control layers. While some authors

Paper	**Technical features**	**Asset**	**Layers**	**Token**	**Purpose**	**Nodes**	**Flexibility type**	**Back-up**
[99]	-	-	Market, Control grid, Physical	-	Contracting & Bidding, Settlement	Prosumers/ Consumers, Operator	Supply-response	✓
[144]	Ethereum, PoA, private	EV	Market, Control grid*, Physical	-	Settlement	Prosumers/ Consumers	Supply-response	✓
[142]	PoS, consortium	-	Market, Physical	-	Contracting & Bidding, Settlement	Prosumers/ Consumers, Operator	Supply-response	✓
[148]	Ethereum, PoS, private	PV	Market, Physical	-	Contracting & Bidding, Settlement	Prosumers/ Consumers, Operator	Supply-response	✓
[146]	Ethereum, PoA, consortium	-	Market, Control grid, Physical	-	Contracting & Bidding, Settlement	Prosumers/ Consumers	Supply-response	✓
[108]	-	PV & EV	Market, Control grid, Physical	✓	Contracting & Bidding, Activation , Settlement	Prosumers/ Consumers, DSO, Aggregator	Demand-response	-
[141]	Zig-Ledger, consortium	Storage & appliances	Market, Control grid, Physical	✓	Contracting & Bidding, Activation , Settlement	Prosumers/ Consumers, DSO, Operator	Demand-response, Supply-response	✓
[143]	Ethereum, PoW	-	Market, Physical	-	Contracting & Bidding, Activation , Settlement	Prosumers/ Consumers, Operator	Demand-response, Supply-response	-
[123]	Multi-chain, Round robin, private	Natural gas burner	Market, Physical	-	Contracting & Bidding, Settlement	Prosumers/ Consumers	Supply-response	-

Table 5: Local flexibility or energy market studies that study the implementation of blockchain as ICT Layer

consider blockchain as a mere technology for financial transactions, others aim to take advantage of all its potential and adapt it as a cross-practice tech. Still there are concerns about their deployment, specially in terms of scalability, security and political and social acceptance.

We expect future research to continue towards more and more physical considerations made in local and P2P market research. Especially inclusion of the system operator in decentralized planning and market clearing cases has yet to receive substantial focus. Further, the nature of local markets with few participants, high uncertainty in demand, variable production and availability of flexible assets requires consideration of the stochastic aspects in the planning and operation phase. Research has been more focused on the integration of blockchain in the market layer. Recently, the potential of DLT has been extended to the physical and control layer allowing the ICT to interlink all the dimensions of the system. Still, there is a lack of common understanding of all the requirements of the technology (e.g. transaction costs, consensus mechanisms, platform, smart contract designs) in order to optimize and automatize the system. Finally, there is a necessity to have real-life projects exploring local market design which facilitates co-ordinated trading of energy and flexibility from same end-users resources in more detailed way. It is paramount important from the consumer point of view to find out the best route to participate in the future central EU wholesale market. Participation from local market to regional/central market and its mechanism are not yet focused in detail in the existing projects. TSO-DSO co-ordination is crucial and requires more attention to enable such participation.

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