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A review

Ponnaganti, Pavani; Sinha, Rakesh; Pillai, Jayakrishnan Radhakrishna; Bak-Jensen, Birgitte

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Review article

Flexibility provisions through local energy communities: A review

Pavani Ponnaganti[a,*,1], Rakesh Sinha[a], Jayakrishnan R. Pillai[a,2], Birgitte Bak-Jensen[a,3]

[a] *Aalborg university, PON 111, Aalborg 9000, Denmark*

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ABSTRACT

The energy communities have the potential to accelerate energy transition and empower consumers, thereby, promoting collaborative social transformation. The local energy communities can support the power grid by offering a variety of flexibility services through demand response, load shifting and energy storage. However, existing electricity markets, tariffs and regulations often hindering effective and sustainable solutions. This paper provides a comprehensive review about designing flexibility provisions for local energy communities in the context of existing and emerging flexible electricity markets. Further, it also discusses the need for social arrangements, technical designs, and their impact on energy communities. Based on reviewed literature findings and from the research projects at Department of Energy, Aalborg University as a part of the SERENE and SUSTENANCE EU Horizon 2020 projects involving sustainable energy communities, future directions will be highlighted.

1. Introduction

According to the EU energy directives [1], citizen energy communities are defined as legal entities that can engage citizens directly in energy consumption, generation, storage, and trading activities with right to access to suitable market as self-representing entity or can hire a third-party energy service provider such as an aggregator. Energy communities are often cooperatives or municipal corporations and may transform into various legal forms. Community energy initiatives primarily focus on dispensing affordable energy for their members or shareholders and facilitate the uptake of new technologies [2]. Increasingly, citizens become 'prosumers' and eventually pool their resources through these energy initiatives and thereby, allowing the community to participate in the electricity markets [3]. The vision for these initiatives is to enable consumers Behind The Meter (BTM) to determine their own energy mix, while lowering costs and also providing flexibility to enhance the overall security of the grid. Nonetheless, the mobilization of Local Energy Communities (LECs) poses not only technical challenges but also requires new social, economic, and regulatory arrangements [4]. In order to examine the existing literature about the provisions of flexibility services through energy communities, this paper aims to address the following research questions: .

- How to design flexibility provisions in energy communities?
- How to make the activities of energy communities in electricity markets noticeable?
- What are the social and economic barriers that hinder these energy initiatives?

These research questions are tackled here based on the detailed review of the state-of-the-art literature on energy communities. The general overview of LECs, roles and interaction of various stakeholders is given in Section 2 together with identified relevant mechanisms for designing flexibility provisions for LECs. Section 3 recognises the importance of appropriate market design to ensure efficient allocation of goods and services according to the community needs. The integrated community energy systems are not without technical and operational challenges, where Section 4 describes the techno-economic perspectives to ensure reliability. Further, the regulatory barriers associated with the implementation of the energy initiatives are elaborated and Section 5 highlights the findings from the EU horizon projects on local energy communities that the authors are currently working upon. Finally, Section 6 provides the conclusions and practicable future directions.

2. Designing flexibility provisions for energy communities

Energy communities promote local sustainable energy production, create new business opportunities, and form new kind of energy providers while interacting with local, regional and national power systems, thereby bringing social innovations in a decentralized energy system i.e., a decoupled energy system that can be operated

* Corresponding author.
E-mail address: pap@energy.aau.dk (P. Ponnaganti).
[1] 0000–0003-3679–1003
[2] 0000–0002-9354–1580
[3] 0000–0001-8271–1356

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independently [5]. Besides, energy communities encourage the participation of end-users owning various energy technologies to take advantage of these devices for optimizing their energy costs and also supports local economic growth by trading the flexibility services in the emerging electricity markets [6]. The typical generation technologies in the LECs consists of photovoltaic (PV), wind turbines, Combined Heat and Power (CHP) plants. In addition, thermal energy systems based on CHPs, solar heating and Thermostatically Controllable Loads (TCLs) such as Heat Pumps (HPs), electric boilers etc. are employed for meeting the heat demand. Further, the storage technologies including both in electrical (Battery Energy Storage System (BESS)) and thermal forms are realised for the effective utilization of local production from Renewable Energy Sources (RES). Moreover, the flexibility offered by the storages, HPs, Electric Vehicles (EVs), water boilers etc., that are present either at the household level or as shared assets of the LECs is crucial for increasing the energy efficiency and minimizing the energy costs for end-users [7].

The demand side flexibility is defined as the modification of expected consumption or generation by the end-users in response to financial or non-financial incentives and/or to dynamic electricity price signals either to reduce energy costs or to provide services to the grid [8]. The emergence of LECs created competent economic and sustainable opportunities for DSO to deploy their flexibility potential towards various grid services [9]. Fig. 1 shows the flexibility value chain presented in the Universal Smart Energy Framework (USEF) [10] for the BTM customers. For diversifying the range of flexibility services, aggregation of lower capacity assets within the LECs is required that can further reduce the risk for the service providers. The aggregator plays a major role in procuring the flexibility from LEC and trading it to balance responsible party (BRP), to the distribution system operator (DSO), or to the transmission system operator (TSO). This flexibility chain involves the interaction of many actors/stakeholders in the energy landscape, where their participation will depend on the different factors including economic benefits. The traditional power systems is well established with developed groups of institutional and industry actors, such as system operators, utilities, policy makers covering various functions of generation, transmission and distribution forming efficient socio-economic alliances [11]. The technological and social innovations incorporated by the LECs in their energy behaviour requires some level of cooperation from the key actors to achieve their objectives. Likewise, technology actors should endeavour to collaborate with the LECs and other key actors [12].

2.1. Stakeholders

The major stakeholders are prosumers, aggregator, energy supplier, DSO, and policy makers those who shape the goals of energy communities while pursuing their own goals [13]. .

- *Prosumers*: A prosumer is a type of consumer having the capabilities of on-site generation and can act as a service provider. Although not all the consumers own production and storage units, they can reap benefits by joining the energy community. Therefore, the collective union of prosumers and consumers as energy communities have the potential to increase the energy efficiency and thereby, generating a new economic activity in the form of energy aggregators [14].
- *Aggregator*: Aggregators serve as intermediaries between LECs and network operators. The existing actors in the power systems, such as, energy supplier or BRP can take the role of an aggregator or there can be an independent actor not associated with either supplier or BRP [15]. When a supplier chooses to be an aggregator, they become eligible to trade the flexibility in addition to their existing responsibility of purchasing and selling electricity for the customers. At present, the BRPs are responsible for aggregation and a third-party can become an independent aggregator after having an agreement with BRPs/retailers [16]. Aggregators procure flexibility from the energy communities and sell it to both TSO/DSO, thereby, playing the role of both the retailer and service provider [17].
- *Other stakeholders*: The potential additional stakeholders include energy supplier, regulator, asset owner, housing associations, local authorities etc. The public actors (local authorities) and government policies are important for developing sustainable local energy communities. Energy communities are considered as economic opportunities for profit-driven stakeholders such as energy suppliers and aggregators. Further, devising regulatory mechanisms for decarbonising, decentralizing and democratising energy constitutes the major interests of the policy makers [18]. Since the aim of DSO/TSO is to operate the distribution/transmission networks in a secure and reliable manner, the energy communities can support them through flexibility services.

The interaction among stakeholders changes over time in order to adapt to the uncertainty levied by many actors. On the other hand, the co-ordination of multi-stakeholders supports in efficiently allocating the resources within LECs, thereby assists for opening the possibilities of multi-energy markets [19].

2.2. Flexibility provisions using DR

The main concept of local community energy systems is to include diverse multi-carrier energy systems for enhancing the flexibility of the entire network. In addition, the emergence of active residential consumers with higher demand response potential created better opportunities to DSOs by providing flexibility services. In this context, the application of Demand Response (DR) and control of Distributed Energy Resources (DER) provide different degrees of flexibility that enables active participation of LECs in the electricity markets. In addition, the sector coupling of power to - heating, cooling or transportation can also be used to obtain flexibility [20]. The alternative/efficient way is to motivate the end-users to change their energy consumption through DR programs avoiding the need of additional generation/storage infrastructure [21]. Flexibility provisioning using DR has surfaced as an

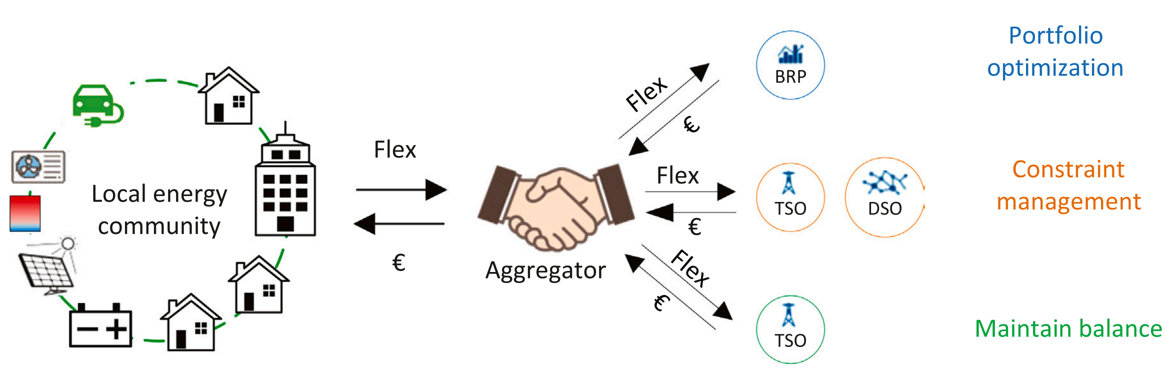

Fig. 1. USEF: Flexibility value chain [10].

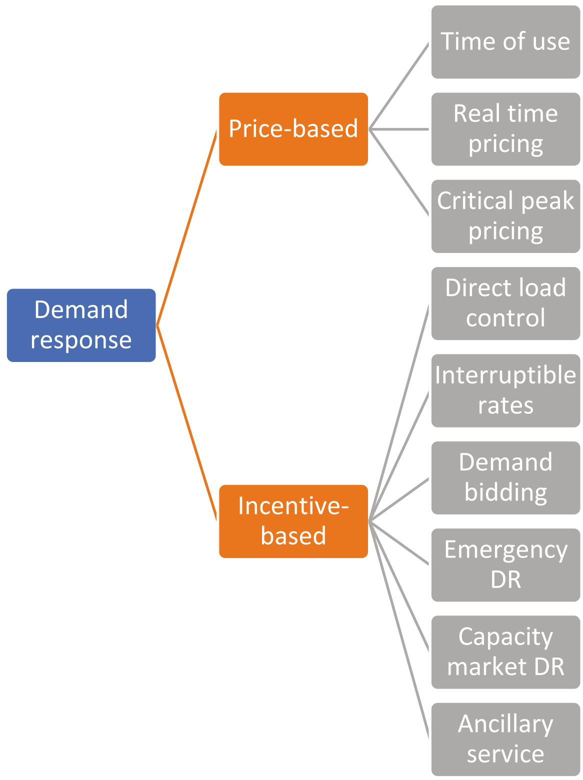

Fig. 2. DR programs.

efficient tool for the economic and reliable operation of LECs [22]. For the system operator, devising appropriate pricing schemes through DR has been the focus to match supply and demand [23]. The end-users are interested in reducing their energy costs while meeting the requirements from both the individual's and LEC as a decentralised energy system. Though aggregators are the business oriented entities, it is important to consider the interests of the community members (mainly consumers) while defining business models. Further, it is the installation of smart metering devices and responsive loads that provides greater opportunity for the residential consumers to participate in DR programs individually or as a community. The DR programs are of two types [24]: (1) price-based and (2) incentive-based and are shown in Fig. 2. The DR programs can form different groups according to time-scales (day-ahead or real time), objectives (reducing energy costs, minimizing user discomfort, maximizing the local renewable generation etc.) and optimization methods (deterministic and stochastic).

2.2.1. *Price-based DR program*

Price-based DR (PDR) programs are subdivided into three main groups, where the electricity price is varied to influence the consumer's consumption especially to reduce it during period of peak demand. The tariff in Time of Use (ToU) varies for different blocks of time during the day that is known in advance and duration of one price remains constant for several hours [25]. The Real Time Pricing (RTP) represents the hourly fluctuation of electricity price directly reflecting the wholesale electricity price, which are notified on a day-ahead or hourly basis. The Critical Peak Pricing (CPP) tariff is a superimposition of some pre-specified high electricity price over ToU/flat rate during peak demand hours on critical days (either lack of production or unexpected large demand), which should enforce the users to shift the energy usage to off-peak hours. Table 1 presents the selected literature on PDR towards the interests of the end-users while adhering to the operational requirements of the distribution grid. Formulating appropriate fair pricing mechanisms affects the consumers participation, which can transform PDR a dispatchable DR, thereby, encouraging the consumers

Table 1
Selected works presenting price-based DR.

Price-based DR	Objective	Optimization/tool	Load dimension	Assets	Reference
ToU	Minimizing the energy cost by increasing the share of local production	Heuristic	Commercial buildings	Solar-PV, TCLs, lighting	[28]
	Cost minimization and peak shaving using storage facility	Deterministic	200 000 users	Solar-PV, battery	[29]
	Distribution grid impact studies	Deterministic	Distribution network with 118 nodes	Solar-PV, battery	[30]
RTP	Price responsive EVs	Machine learning	Typical household	Water heating systems, dish washer, EVs	[31]
	Peak load shaving	Game theory	Aggregated residential households	Residential consumption	[32]
	Maximizing financial benefits to community members	Stochastic bi-level program	Energy community	Distributed generation, battery	[33]
	Peak load reduction	Heuristic	Community BESS	Solar-PV, energy storage systems (electrical and thermal), home appliances	[34]
CPP	Optimal sizing of PV and BESS	Bi-level heuristic	Single household	Solar-PV, BESS	[35]
	Distribution network impact studies	Deterministic	Single household	Wet appliances, TCLs	[36]
	Optimal scheduling of residential loads	Deterministic	Single household	Residential appliances	[37]
	Energy cost reduction	Game theory	Energy cooperatives	Aggregated load	[38]
	Peak load reduction	Heuristic	176 households	Household consumption	[39]
	Optimal scheduling of flexible loads	Deterministic	LEC	Solar-PV, EVs, BESS, HVAC loads	[40]

to shift their demand from peak hours [26]. In this DR program, the aggregator offers time-varying tariffs by providing access to day-ahead market and notable has no direct control over consumers assets, where it is consumer's decision to respond to the tariffs and minimize their energy costs. The studies have showed that the end-users prefer simple pricing mechanisms despite economic disadvantage [27].

2.2.2. Incentive-based DR program

The incentive-based DR (IDR) is inherently called as dispatchable DR, where the load flexibility is actually delivered upon requests or contractual agreements. While the consumer participation is voluntary in PDR and will highly be dependent on the attractiveness of the pricing mechanisms. There are different forms of IDR including Direct Load Control (DLC), Interruptible load (INL), Demand Bidding (DB), Emergency DR (EDR), Capacity market (CM) and Ancillary service (ANS). The similarity in all the IDR types is that that end-users receive incentives by allowing to modify their energy profiles through direct or indirect measures. If the consumer disobeys the contractual agreement in any one of these IDR, then they will face penalty costs. The monetary incentives associated with IDR forms the primary motivation for the consumer to participate in this DR program. The literature dealing with IDR towards various grid services and consumer benefits is given in Table 2.

In the DLC or INL DR, the consumer agrees to directly control their electrical equipment in a short notice [41]. The communication can be two-way between control unit and the controller or time of day controllers in order to achieve the control the desired load remotely [42,43]. The ANS DR is a part of instantaneous reserve, where the load should be shed within seconds to maintain frequency of the main grid [44]. Large energy users can earn regular income through the participation in ANS DR. The end-user directly submit their bids in DB DR to wholesale or retail market for load reduction in a day-ahead basis and receives incentives for the same [45]. As the name suggests, EDR is called upon pre-planned grid emergencies [46]. Likewise, the consumer agrees for load reductions whenever system contingencies takes place in CM DR [47]. The regulation service or ANS DR performs the increase/decrease of the load demand during the contractual period for maintaining system balance. Communication play a key role in sending load modification signals to the end-users through aggregator in the IDR [48]. In addition, the aggregators serve as significant participants by supporting consumers/LECs to participate in the energy markets for trading their flexibility. The uncertainties associated with IDR are the consumer responsiveness and local renewable generation deviation, which can bring under/over- target responses that can gives rise to financial risks. The important factors that are specified in the IDR contractual agreement are as following. .

- **Notification of DR**: The notification of the DR action can take place in the day-ahead market (Nord Pool spot market) with the physical demand response action on the following day, and likewise for notifications within hours in hour-ahead market, etc. In general, the shorter the notification time is, the more costly the demand response activity will be.
- **Frequency of DR**: The frequency of the activities refers to the number of times a demand response activity is called upon. A consumer may be more dedicated to supply a DR activity that might be called upon 10 times per year at a price of € 10/time, compared to supplying a DR activity that might be called upon 1 time in five years at a price of € 500/time - even though, for both activities, the expected revenue is € 500 per five years.
- **Duration of DR**: The duration of the activity refers to the period of time the activity must be active. For example, a short interruption of the electric heating in a household might cause less comfort than a longer interruption.

The duration and amount of flexibility are the major deciding factors for the aggregators to determine the type of DR that can be applicable. The duration is known by the consumer preferences and flexible assets' operating cycle, while the amount of flexibility has to be estimated depending upon the LECs energy priorities.

2.3. Demand flexibility forecasting

For the active participation of aggregators in the existing/flexibility markets to facilitate timely DR actions, the information about aggregated energy flexibility in their portfolio is needed for determining the amount of flexibility that can be traded. The quantification of flexibility on the demand side requires the knowledge of 1) flexible assets 2) end-user willingness to participate and 3) consumption patterns. In general, the identification of community energy patterns and consumer behaviour helps the aggregator to determine the market applicability and the appropriate incentives. Since the flexibility contracts takes place before the day of delivery date, the available energy flexibility within LECs needs to be forecasted, which is highly influenced by the end-user behaviour, weather conditions and other variables that challenges the model accuracy.

The flexibility prediction methods can be divided into two categories: first category requires measurements directly from devices and the other category collects household's total consumption. The former approach provides accurate knowledge about each device and allows better estimation of flexibility; however, this approach needs installation of many smart sub-metering devices, and this may lead to consumer privacy infringement [70]. Whereas the latter one, also called as non-intrusive load monitoring (NILM) approach, which uses household's aggregated consumption through high frequency meters, thereby extracting individual signatures and consumption patterns of each device [71]. The flexibility profile of aggregated consumers is more predictive than that of the individual consumer due to highly random nature of the latter ones [72]. In both the approaches, there is a notable amount of data that is required to be processed, where it increases significant storage requirements, algorithms' complexity, and computational cost. These limitations urge data-driven methods like machine learning (ML) techniques that are scalable to handle big data time series [73,74]. In addition, the ML techniques can be prescribed when the data generation process cannot be described through a set of equations. The forecasting has been carried out with respect to flexible assets including shiftable loads (dishwashers, washing machines [75], hair dryers etc.) and interruptible loads (TCLs such as electric boiler, space heating, heating, ventilation and air cooling (HVAC) [76] etc.) and storable loads (battery storage [77], residential EVs [78,79] etc.).

3. Flexible energy markets for local energy communities

The concept of flexibility has been existing in the central power systems through redispatch and reserves for maintaining grid frequency and to avoid grid congestions that are attributed in the form of ancillary services offered by the TSO. Further, the increased integration of DERs in the distribution network introduces grid variations and congestions, which needs better coordination among DSO and TSO for the stable operation of the power grid. Developing Local Flexible Markets (LFMs) for trading the energy flexibility from the LECs can be a viable solution apart from other technological options. The aggregator emerged as a new market participant representing LECs by aggregating the pool of flexible resources enabling their participation in the electricity market. The diversity of technologies within the aggregator's portfolio and their responsiveness to engage in various markets drives the profit volumes with optimal and sub-optimal solutions. Currently, the flexibility offered by LECs are being traded by aggregators in the markets that were designed for conventional central power plants. The existing electricity markets are the day-ahead, intra-day and balancing markets, where flexibility can be traded [80].

Table 2
Selected works presenting incentive-based DR.

Incentive-based DR	Objective	Optimization/tool	Load dimension	Assets	Reference
DLC	Reduce electricity cost and enhance market operation of LECs	Heuristic	Energy communities (114 single family houses)	Household appliances	[49]
	Reduce consumer's energy cost	Stochastic	Group of DER and prosumers	DER and household appliances	[50]
	Optimizing thermal demand	Machine learning	Three major cities in Southern China	Air conditioner loads	[51]
	Minimizing power outages and peak demand	Machine learning	100 consumers	Household appliances	[52]
	Increase RES integration	Machine learning	Distribution system with 20 controllable loads	BESS, controllable loads	[53]
INL	Optimize the operational cost	Deterministic	Island microgrid	Refrigeration load	[54]
	Peak load reduction and minimize total interruption cost	Machine learning	24 devices	Household, commercial and industrial devices	[55]
	Optimizing electricity import	Non-cooperative game theory	Energy community	Residential consumption	[56]
	Optimal coordination between DSO, EV aggregator and EV owners	Game theory	9 EV types	EVs	[57]
	Reduce peak load	Machine learning	Energy community	Household interruptible loads	[58]
ANSDR	Maximizing profit	Game theory	DERs	150 TCLs, 50 EVs	[59]
	Minimize the import from grid	Deterministic	LEC (100 households)	Solar-PV, Wind turbine, EV charging station	[60]
	EVs profit maximization through regulation services	Deterministic	EV aggregator	EVs	[61]
	Optimal aggregation of DER for minimizing line congestions	Machine learning	Distribution network	DERs	[62]
	Maximize the economic potential of storage systems	OpenDSS,Python	Distribution network	BESS, Solar-PVs	[63]
	Primary voltage control using demand flexibility	Deterministic	IEEE 13 node distribution network	Solar-PVs, household controllable loads	[64]
EDR	Improve short-term voltage stability	Heuristic	High voltage transmission grid	Motor loads	[65]
	Maintain system reliability	Stochastic	IEEE 24-bus system	Commercial, residential and industrial loads	[66]
	Minimize shedding costs and maximize rewards	Game theory	Mixed use buildings	DC servers, HVAC systems, diesel generator	[67]
DBDR	Peak load shaving	Stochastic	Large consumers and utilities	Time shiftable loads	[68]
	Optimal bidding strategy for aggregator	Deterministic	IEEE 123-node system, centralized BESS	Residential loads	[69]

3.1. Day-ahead market

The bidding for selling and buying actions takes place for the hourly energy production of the next day in the Day-ahead Market (DAM), where this process gets closed at noon of the day before the delivery. This mandates the participant in DAM including aggregators to forecast the flexibility within LECs at least a day-ahead with a reasonable uncertainty [81]. There is a substantial amount of research that investigated the ways for maximizing the profit using various optimization methods under different operating conditions and flexible assets. The two different features are observed while studying the interaction between the LEC flexibility aggregator and the electricity market, one being the aggregator acting as a price-taking agent [82,83] while aversing the financial risk. The other feature is price-making aggregator by strategically developing bidding strategies for the LECs' flexibility competing with a group of generation companies [84,85]. Alternatively, the research includes optimal bidding strategies for DER aggregator [86,87], load aggregator [88] and EV aggregator [89,90] in the DAM. Moreover, these services possibly cause discomfort to the end-users, where the aggregators compensate them for their flexibility provisions through incentives [91] or dynamic pricing schemes [92].

3.2. Intra-day market

In the Intra-Day Market (IDM), the bidding is done on the day of actual delivery and the trading closes 5 min before the contract starts [93]. The inaccuracies in the day-ahead flexibility forecast can be dealt in the IDM [94]. The certainty in the flexibility forecast can be improved by devising appropriate DR programs by the aggregator, where the participation in both DAM and IDM can be made possible [95,96]. The intra-day scheduling requires collaborative nature of the LEC through fair participation providing economic advantage to all the community members with and without flexibility capabilities.

3.3. Balancing market

Balancing market procures the reserves to deal with the frequency deviations due to power imbalance or generation loss. Participation in balancing market requires the deployment of flexible power at faster rate, since the activation times are 5 mins, 12.5 mins and 30 mins for automatic frequency restoration reserve (FRR), manual FRR and replacement reserve, respectively [97]. More importantly, the local constraints of DERs that are dynamic in nature creates difficulties for aggregators to compute the flexibility costs. These computations must be run in real-time so that the aggregator can actively adjust its bid in the balancing market [98]. The aggregated flexibility offered by the heat pumps [99], energy storage technologies including battery [100] and EVs [101] are attractive to participate in the balancing market.

3.4. Local flexibility markets

A LFM can be seen as a form of sub-market creating independent trading platform for local flexible resources [102]. The key players can be system-oriented (TSO), grid-oriented (DSO) and market-oriented (BRP, retailers), while the aggregator has to implement the economically feasible business models for trading the LECs' flexibility in the LFM. Either aggregator or DSO can take the role of LFM operator, thereby, acting as an interface to procure flexibility from LEC and offer it to corresponding services to maximize the profit. The flexible nature of the LECs support the DSO by decreasing the distribution network dependency on upstream grid. This builds a competitive environment for energy communities to trade their energy flexibility to distribution networks through LFM [103]. Several studies investigated the flexibility trading opportunities assisting system operator in [104–106]. The common practice is to directly append LECs flexibility in the distribution power flow studies to resolve any voltage and congestion issues [107]. A decentralised local market based flexibility trading at distribution level is described in [108], where DSO procures flexibility from aggregators in DAM for demand balance and also reserves a specific amount towards ancillary services. Further, with the better coordination between DSO-TSO [109], the TSO can procure the flexibility from LFM for grid balancing mechanisms [110]. Nonetheless, a proper energy trading model is necessary to manage the LEC's energy trading. The peer-to peer (P2P) network as applied in computer science for resource sharing is befitting for energy communities and the following section illustrates the application of P2P approach for LECs.

3.4.1. Peer-peer trading

The P2P trading enables LECs to directly trade energy among their peers forming a virtual power grid. The main areas of interest in the P2P research is comprehensively reviewed in [111], where the topics include data-driven, deterministic and stochastic methods to maximize profits to peers, block-chain technology to devise trading mechanisms and game-theory-based modeling of the participant. The development of community-based P2P trading [112] reduces the end-user reliance on the main electricity grid benefiting the utility by reducing the peak demand and improving grid reliability [113]. The P2P electricity markets fully rely on the initiatives from citizens and community members becoming an integral part of renewable energy decisions about how much and when it should be shared [114]. The prosumers will have the highest flexibility in the P2P trading as they can determine whether to sell to other community members or to increase their distinctive autarky [115]. Three different market designs (bill sharing, mid-market rate and auction-based pricing mechanisms) were proposed for P2P trading in [116], where it resulted in the energy savings. Howbeit, the P2P trading faces the challenge of scalability that was said to be handled using dynamic allocation of P2P clusters creating optimal match between demand and local RES profiles [117].

3.5. LFM design principles

For efficiently trading the flexibility in a consumer-centric market, there needs appropriate incentives for valuing the flexibility [118]. A flexibility product has four dimensions including, .

- Time (how long the flexibility is available and specify timely valuation). This impacts the resource utilization, thereby, influence the cost efficiencies in various electricity markets.
- Spatial (the location of flexibility resource connected to the power grid).
- Flexibility resource including supply-side, demand-side, grid-side and storage-side.
- The last dimension is the risk associated with the uncertainty of flexibility resources that impacts the characterisation of flexible assets and the market design.

Long-term and short-term solutions can be provided by flexibility assets towards various markets and grid services. The flexibility product is energy for short-term market mechanisms (intra-day and DA), whereas for long-term market mechanisms (Forward market, capacity markets etc.), the flexibility product can be power, energy or capacity towards grid expansion services. While in real-time flexibility trading, power based products are considered as a flexibility resource. Further, the flexibility provision is affected by the investment and regulation risks in long-term mechanisms.

4. Key barriers for energy community implementation

The existence of conflict of interests among various actors such as competitive (aggregators, BRP, technology providers etc.) and regulated (DSO, TSO, policy makers etc.) evolves over time. Due to which there are several barriers including external (technological, environmental, market access etc.) and internal (socio-economic, organizational etc.) that the actors of LEC aggregators have to overcome while preserving affordable energy prices.

4.1. Technical barriers

These barriers refer to the obstacles faced by LEC aggregators while attempting to pool the flexible resources within the LECs. The DER technologies that depend on weather conditions (wind and solar irradiation) gives rise to intermittency of local generation leading to balancing issue on a local community level. This can be handled by the use of energy storage technologies with appropriate control mechanisms. Even though the research is well-established for implementing BESS, the practical implementation faces regulatory barriers [119]. Besides, this variability gives rise to uncertainty in the forecasting of flexibility demanding better tools. Extensive smart metering and data acquisition are crucial to determine the aggregated flexibility. Lacking adequate Information and Communication Technology (ICT) infrastructure can become a major technological barrier [120]. The interconnection of renewable-based LECs poses a number of risks to existing distribution networks including grid congestions and power quality issues [121]. Furthermore, the network operators face challenges in new connections with DERs due to interoperability issues [122].

4.2. Market barriers

Financial cost acts as a strong barrier to adopt to the environmental goals [123]. In most of the EU countries, the role of aggregator is still not defined and the aggregation service is not fully functional in short-term electricity markets [124]. Further, appropriate market mechanisms are required for the aggregators to enable flexibility offered by LECs. Market power and imperfect information leads to market failure discouraging the participation [125]. The minimum bid size in most of the markets are set too high that prevents aggregators' engagement [126]. The unidirectional flexibility feature in the aggregators' portfolio makes it difficult to enter into certain reserve markets that requires symmetric bidding. In addition, the factor that affect the reliable forecast of available flexible resources is the low frequency of bidding and clearing activities reducing the aggregator's confidence to participate especially in balance markets [127].

4.3. Socio-economic and regulatory barriers

Energy security, road map towards autarkic energy system, reduction in CO_2 emission through use of sustainable energy, and affordable energy prices are the main reasons for the development of LEC system. In recent concept, the local energy is not limited to electricity, but includes other form of energy such as heat and transportation as well [128,129]. This initiative facilitates several advantages such as lower dependencies on centralized energy system, which further enhance low carbon energy system to build consumer engagement through flexibility in market and initiatives. Further, LECs along with end user initiative support in reducing escalating grid congestion and voltage problems in the local electricity grid. These problems arise due to decarbonization of transport and heating/cooling sector supported by electricity [6,128]. However, contribution from end users in energy community can significantly help in the efficient use of available energy, through participation in flexibility services. Promotion of local energy communities to enable decision making for modifying their consumption pattern, energy balancing and active participation in energy market, can be supported through price and incentive based scheme, with proper regulation.

Some of the major social challenges in energy community would be initial cost and financing, and resistance from some local community members. The resistance can be due to conflict in their interest as a consequence of unfair cost benefit allocation, during low energy price [6]. Energy security and equal share of cost benefit is straightforward in community-based HP station with thermal storage facility, in comparison to that in case with heating facility at individual house [130]. Single large thermal system in community enhances control flexibility and reduces equipment cost (as there is single unit and the size of generation and storage in the central system is smaller than the sum of individual unit in the houses), but there is a need to develop appropriate infrastructure [130]. However, similar solution of single aggregation of energy system is not appropriate for EV charging. During low energy prices, all the EV owners crave to charge their vehicle, where this unregulated charging would cause adverse effect towards the objective of LEC for low voltage distribution grid (e.g, grid congestion, peak electricity demand, voltage dip, line and transformer loading) [131].

Proper methodology is necessary to be investigated for sharing of electricity within the electric vehicles to participate in demand response effectively. The lack of initiative from the LECs members to participate in the DR programs is one of the major potential barrier. E.g, the battery cycle life and the cost of degradation, due number of charge-discharge cycle of EV, may discourage EV owners to participate in DR programs without proper compensation. The monetary benefits are highly important for citizens for engagement of residential consumers in DR programs [132,133]. Another potential barrier can be cost benefit analysis against the effort, time and loss of comfort [134]. Thus, energy security and transparent information on shared objectives of DR is necessary to be provided for the community members. Despite several barriers, the path towards integration of LECs in the energy market is welcomed in Denmark through amendment in legislation of Danish Energy Agency.

According to executive order 4 mentioned in the amendment of Danish Energy Agency [135] for order on renewable energy communities and citizen energy communities, the participants in local area are provided with environmental, economic or social community benefits rather than financial gain. The details of these benefit needs to be investigated. Without appropriate financial incentive from the government, it is challenging for the individual participants from society to be motivated for development and implementation of energy components due to the huge investment. Financial support in the form of incentives, low-interest loans, compensations, grants and subsidies are provided in Germany [136] and community energy grants are available in Ireland [137]. Executive order 6 subsection 4 discusses on the opportunity to establish electricity trading for the vehicle to grid. Similarly, executive order 8 focuses on engagement of energy community in production, supply, consumption, aggregation, energy storage, energy efficiency services or services for charging electric vehicles or provide other energy services to its participants. Financial responsibility for the imbalances created by energy community in the electricity system is mentioned in executive order 9. To participate as the balance responsible party, storage of electricity is required which may be victim of double taxation during storing and release of energy [138]. However, the legislation in Denmark is open to the participation of LEC assets in the energy markets.

Summing up, regulations sometimes restricts the development of new mechanisms and design of LFMs. The consumers to become flexibility providers should be incentives financially and socially to ensure their active participation. The existing regulatory framework should be modified that can support DSOs to facilitate trade through LFMs.

5. EU Horizon projects on sustainable communities at AAU

Sustainable and Integrated Energy Systems in Local Communities (SERENE) [139] and Sustainable Energy System for Achieving Novel Carbon Neutral Energy Communities (SUSTENANCE) [140] are the two of the major EU Horizon 2020 projects on sustainable communities which are ongoing at AAU Energy. One of the aims is to recognize socio-economic, governance and regulatory aspects in more autarkic LEC with the support of demonstrators including Denmark, The Netherlands, Poland and India. The implementation of energy autarky reclines on decentralizing the energy systems and increasing the energy efficiency. The pilot studies are based on EVs, heat pumps and storage with provision of local demand response and demand side management in the local integrated energy system. Investigation on the factors such as community motivation and user-engagement will be performed along with feasibility to participate in the local energy markets, ownership and business models. The work through these projects will help to develop a comprehensive analytic framework of business models in the local community based energy systems.

The projects demonstrate several use cases including power-to-heat and power-to-transport solutions while increasing local RES generation, which includes.

- Community-based heating in SERENE,
- Individual house heating and optimal EV charging with roof-top solar-PV installations in SUSTENANCE.

The flexible asset installations are funded through the project as an initiative for the LECs. Data sharing and anonymization has been challenging as it requires consent from the participants respecting general data protection policy in EU. The main aim is to engage local prosumers, local aggregator and DSO as key stakeholders. The DR interventions that are being designed for the Danish pilot focus on the smart control of heat assets and EV charging, while concurrently maximising the utilisation of the community's own solar energy that is produced on-site by solar-PV panels. On the behavioural side, the intervention focuses on consumer preferences such as room temperature limits and EV charging preferences, as well as monetary savings. On the technical side, the intervention focuses on electricity and heat storage limits, and on voltage and grid capacity limits. One set of physical-technical obstacles that have been identified are the insufficient local capacity to produce renewable energy, as well as the limited management capacity to optimise demand and increase efficiency. A second set of social-regulatory obstacles has been identified in the form of regulations that reduce the cost-effectiveness of energy sharing, as well as the potential difficulty of realigning underlying motivations and values away from economic aspects, towards ecological ones.

5.1. Expected outcomes

The specific focus of these projects is to utilize the aggregated flexibility from heating devices and EVs of an energy community towards various grid services. Both Denmark and the Netherlands have seen an adoption of dynamic prices within the energy sector as stimuli for consumers to change their behaviour on an individual level. This necessitates the inclusion of smart control electricity-to-heat devices such as heat pumps as their electricity consumption forms a major part of the energy bill. Not only do these devices utilize significant amounts of energy, but they also provide a sheer amount of flexibility through thermal storage, both in buffer vessels as well as by utilizing the thermal mass found in buildings. Value can be created through offering flexibility to the energy markets, in which a shift is observed to more dynamic tariffs and flexibility services by aggregators. Moreover, in Denmark, the residential consumers with on-site smart meter installations have got the possibility of witnessing variable electricity and/or grid tariffs that encourages them to shift their consumption to periods of low-electricity prices. The suitable demand-side response strategies for the demonstration sites for utilising energy flexibility for enhanced energy efficiency and increased self-consumption from renewable energy are as following. .

- **Peak shaving**: BESS will be able to store energy produced by PV and discharge during peak demands. The aim is to perform energy flow forecasting to provide optimal charging and discharging scheduling and to reduce time of deep discharge and full charge of the BESS. The algorithm therefore takes battery degradation into account.
- **Peak shifting**: The heat pump working schedule can be fitted into forecasted PV peak production to maximize self-consumption in the microgrid.
- **Minimization of energy costs**: Utilizing energy management system (EMS) feature, the EMS can store energy during the energy price valleys to minimize energy consumption when energy is expensive.
- **Taking part in global DSM**: The whole system can be part of DSO's Demand-Side Management (DSM) and deliver services such as energy demand reduction.
- **Island mode**: The system will be a self-sustainable microgrid "ready" to enable off-grid mode functionality in case of additional energy storage installation in the microgrid. An existing BESS planned to be installed during the project has limited power and capacity to make this mode applicable in practice. Major limitation is related to the size of community and loads out of the controlled grid. However, the capabilities of the EMS are expected to be able to reduce energy usage (especially the demand stemming from heat pumps and EV chargers). Moreover, EVs could also take part in energy balancing using V2G possibilities.

Direct load control-based local DR programs are suggested according to the needs of all the four demonstration sites in SUSTENANCE. These programs can provide various grid services such as distribution system congestion management, demand side management, ancillary services provisions etc. The flexible assets include among others battery storage, thermal storage, electric mobility, under an integrated cross-sector energy framework that is controlled by the local aggregator towards increasing the self-consumption of local RES production and better economic and energy efficiency. Citizen driven integrated local energy systems are the result of the transition from a centralized energy system into a more decentralized and a democratized energy system. However, the socio-technical regimes (e.g., normative, formal, and regulative rules) have complex structures and mechanisms that possess a high degree of rigidness to change. Therefore, a multi-level perspective will be used for the analysis of socio-technical transition for sustainability.

6. Conclusions and future directions

This paper aimed at reviewing the methods for designing flexibility provisions for LECs and trading it in appropriate flexibility markets while discussing the potential barriers for their implementation. Additionally, illustrated the EU projects about demand response applications to empower sustainable energy communities that the authors currently working on. Initially, the flexibility value chain for energy communities and the major stakeholders of the LECs along with their roles has been introduced. The integration of sector coupling (power-heat, power to transport) has positive impacts on increased utilization of the energy flexibility enabling the active participation of LECs. Considering DR as a key enabler for designing flexibility provisions in LECs, the literature dealing with the application of both implicit (PDR) and explicit (IDR) -based DR mechanisms has been evaluated. Here, the end-user engagement in implicit DR depends on the market price plans that allow them to choose the hourly or short-interval pricing for shifting their demand. The explicit DR is also called as dispatchable DR mostly opted by consumers who prefer a stable retail price avoiding the price volatility associated with direct market interaction. It is important for the aggregators representing LECs, to forecast the flexibility in order to participate in the electricity markets. In addition, one of the strong requirements for the independent aggregators is their contractual agreement with a BRP to gain the market access.

The market rules should be designed in a way that new entities such as independent aggregators/LECs can fairly compete with the existing market players in the day-ahead, intra-day and balancing markets. However, there is a need for establishing local flexibility markets to enable trading of flexibility offered by DERs in LECs to support DSO, TSO and BRP towards grid/market services. The LFMs should be scalable and adaptable to best suit the diverse operations and regulations. Also, they require investments in the ICT infrastructure to authorize energy transactions among the participants. Furthermore, P2P concept has been emerging as a promising solution for real time trading within LECs for better coordination of local generation and demand. Besides, the regulatory challenges are being faced by aggregators because of not so clearly defined responsibilities that involves flexibility aggregation in the existing and emerging electricity markets. The cooperation between aggregators, DSO and TSO is essential for avoiding grid-related issues. Moreover, the aggregation of flexible assets in the LECs require adequate ICT infrastructure and controllable smart devices, which is still not fully implemented in many EU nations. Co-ownership and community financing are promising solutions to deal with economic barriers depending upon the financial interests of LECs. Currently, there are no practical examples illustrating the concept of LFM in Europe, but many are in a pilot stage.

The balance between the goals and impacts can achieve the successful implementation of LECs. The following aspects needs to be further explored to bring the theoretical concepts into reality. .

- **Interaction of different actors**: The work that has been carried out in the literature recognizes that the LECs provide cost savings to its members. However, the interactions of LECs with outside actors needs to be explored enabling co-existence of all actors providing added value. Further, the interests of competitive actors and regulated actors are different, therefore, future research should include a holistic analysis considering technical, market, governance structure and billing preferences.
- **Aggregator business model**: Majority of the literature dealt with the objective of maximising the benefit for either aggregator or consumer through flexibility trading. It is equally important to consider the financial interests of both the aggregator and the consumer for assessing the economic feasibility of the business model in various electricity markets.
- **Regulatory frameworks**: There is a great need to design appropriate regulatory framework and pricing mechanisms to handle the revenue losses caused by LECs (grid congestions, tariff imbalances etc.) despite the benefits offered by them, while the community members are not burdened with extra costs. A multi-dimensional trade-off analysis examining the impacts of LECs respecting the policy makers, community members and investors has to be explored.

The following recommendations are made for increasing the likelihood of the LFMs: .

- Making the tools accessible that helps potential market participants to assess the technical and economic feasibility of their participation in LFMs.
- Flexibility procurement and delivery needs better automation, which requires innovation in digital platforms and standards that ensure integration and interoperability.
- The market regulations should have right balance between the required complexity for its successful operation and simple enough to understand by the prospective participants. Further, they do not restrict entry of inexperienced participants.
- Intermediaries and aggregators are likely to play an important role for engaging the participants with LFMs. They have the ability to manage the risk of asset uncertainty and build diverse portfolios, hence making legal agreements between flexibility providers and local network operators.

This study reveals the importance of understanding the flexibility dynamics and devising appropriate frameworks for LFM. Nevertheless, this paper highlights the importance of flexibility provisions through LECs and need for local flexible markets promoting energy democracy and community ownership. In this way, the local communities plays a significant role in energy production, consumption and distribution as well. With these new developments, there arises the need for new roles and responsibilities, evaluating behaviour of actors and realising business models for energy services. Barring the barriers, the LFMs should be considered as a promising instrument to promote the DERs at the sustainable LECs to create value for their flexibility service provisions.

Declaration of Competing Interest

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

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