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Scaling-up Power Flexible Communities business models empowered by Blockchain and AI

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1 Executive Summary

A fundamental element to the EU energy transition lies in the renewed, empowered role of citizens. Once perceived as passive price-taker participants in the energy value chain, customers are now taking charge of their energy matters, becoming more and more active in electricity market activities. One way in which citizens can become more active in the energy system is by actively engaging in flexible energy communities.

Flexible energy communities are groups of citizens cooperating around the goal of capturing the collective value from optimal management of local energy flexibility. Flexible sources could be energy storage, demand response, and electric charging. If managed optimally, these *flexibility pools* can be made available to the energy markets.

In the context of FleXunity, flexible energy communities are focused around peer-to-peer energy sharing, a paradigm under which customers exchange energy within the boundaries of an energy sharing region (ESR). Furthermore, FleXunity envisions a scenario where flexible energy communities become active players in the energy system, by trading demand response flexibility in the balancing markets with support from aggregators.

The goal of this report is to survey and feed from relevant literature and projects where P2P trading (or competitive P2P) approaches have been employed, so to provide a generic market design for flexible energy communities that could be adopted in the FleXunity project, and to drive initial impressions as to the applicability of such design to the Corby and Iberia pilots.

Chapter 2 starts by offering an extensive account of the technical, market-related, socio-economic, and environmental benefits of P2P energy sharing, and describes the structural elements of P2P networks. Figure 4 offers a generic visual comparison between energy flows in the conventional energy supply paradigm and energy flows within P2P energy networks – P2P energy sharing paradigm.

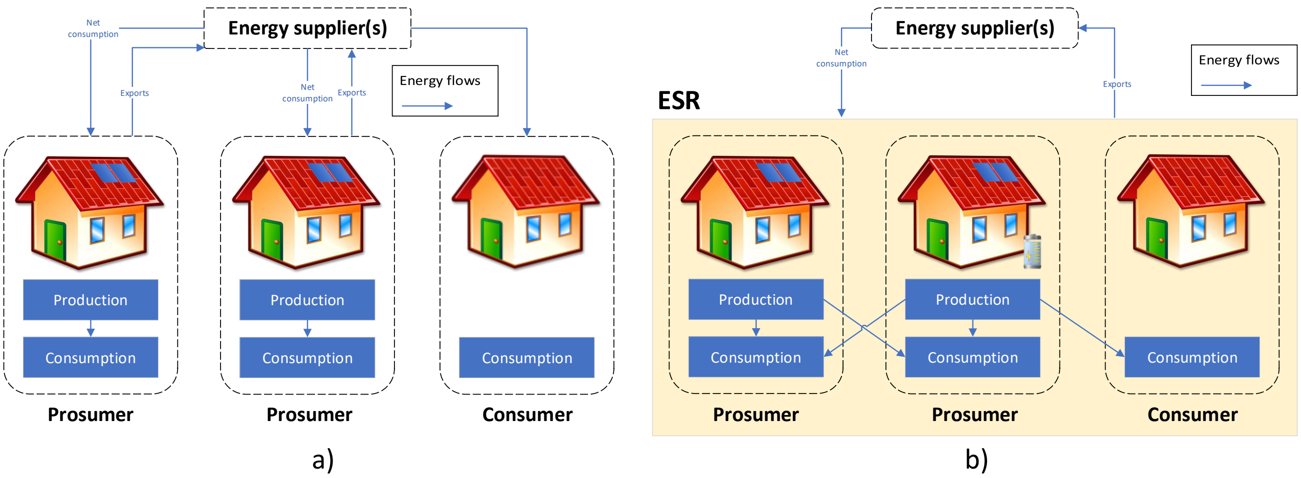

Figure 1 – Comparison between a) contemporary electricity supply paradigm and b) P2P energy sharing paradigm. Please note that depending on model, customers in the ESR can reach energy suppliers both directly and/or in a coordinated fashion (Adapted from [4]).

In Section 2.14, we have reviewed market designs for P2P markets. The relevant literature pinpoints three generic types of such designs based on their degree of decentralization: 1) Fully decentralized; 2) Community-based; and 3) Hybrid. Among these, **community-based structures, or "energy collectives" appear as the most suitable to the aggregator-facilitated supervisory control approach proposed by FleXunity**. These models release a substantial amount of technical burdens from peers and are particularly valued for their ability to maximize revenue opportunities. Besides, they can be applied to both localized and distributed systems, which is precisely the structure of FleXunity's Corby and Iberia pilots. Figure 2 provides a generic visualization of the potential energy and information flows under a community-based P2P market design.

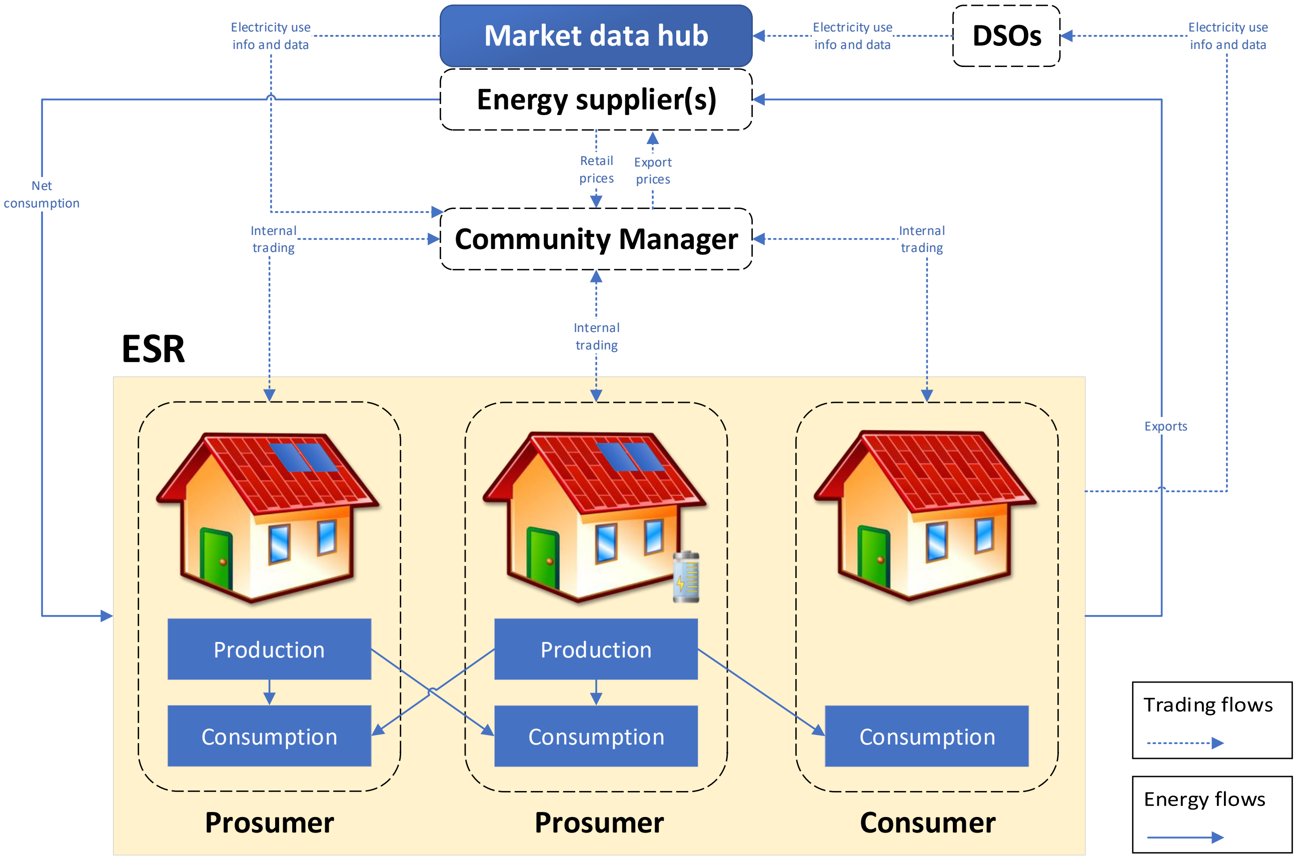

Figure 2 – Generic representation of energy and trading exchanges in a community-based P2P market design.

Section 2.1.6 explained that the key challenges of P2P trading reside in the virtual layer of P2P networks, where market trading and computational operations take place, rather than on its physical, structural and hardware-related layer. In one way or another, these key challenges fall into one of four categories: **1. Minimizing energy costs**; **2. Balancing local generation and demand**; **3. Developing pricing and engagement mechanisms**; or **4. Ensuring secure and transparent environments for transactions**.

Section 2.2 provides a reflection on the potential, open questions, and current status of flexible energy community interactions with external balancing markets. Although this is a highly promising concept, it is still at a nascent stage; our research indicates it has not yet been fully realized in a real-world environment.

Chapter 3 attempts to offer a concise overview of the current state-of-the-art in P2P trading both at the academic research and real-world project levels. It is first found that **most popular technical approaches to address market-related problems include game theory, auctions-theory, and optimization**. Scientific literature on these topics is extensive, but real-world – even experimental – applications of it are scarce. Secondly, our review has revealed a range of options in the Blockchain domain, including the Elecbay platform, which being specific to P2P trading applications deserve our further attention.

Our overview of P2P trading projects uncovered a rapidly growing body of knowledge and portfolio of solutions for enabling efficient, secure, and transparent P2P energy trading within local energy communities, as well as under a plethora of contexts and applications. It is noticeable, however, that projects focus on either one of the P2P network layers, which is an undesirable trend. It is crucial that future projects are able to efficiently capture and integrate the requirements of both the virtual and the physical layers, into a unified model of P2P trading, albeit such approach is yet to be developed.

Chapter 4 consolidates the main goal of this report by providing a generic market design for the concept of flexible energy communities in FleXunity. This design **combines intra-community P2P interactions with aggregated demand response flexibility provision to the external balancing markets**, under the supervision of an aggregator entity. Effectively, this creates the situation of a virtual power plant – VPP – formed by the released collective flexibility of the participant peers.

FleXunity's concept of market interactions includes a series of interdependent and sequential mechanisms (Figure 3). Firstly, **intra-community trading takes place under a constrained optimization routine.** Then, residual generation/demand could be balanced by the electric supplier under a residual balancing mechanism. Subsequently, the network operator assesses operational needs and issues incentive signals for ancillary services, to which the community may respond for obtaining added revenue streams.

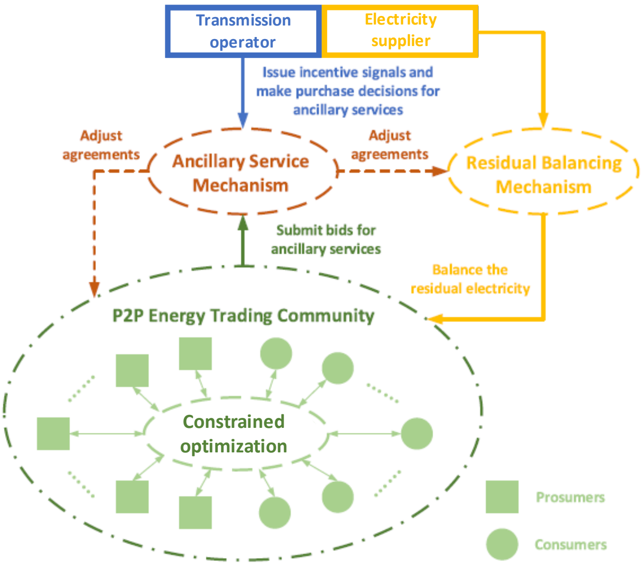

Figure 3 – Mechanisms of internal and external market interactions of flexible energy communities (adapted from [38]).

FleXunity will also produce **Blockchain-based technical approaches that establish smart contracts** to guarantee trusted and transparent energy trading, and enabling business models for subscribing participants, VPP players offering aggregation and CM services, and retailer entities involved for portfolio optimization

Lastly, we briefly analyse the compatibility and applicability of the above concepts to the ongoing FleXunity pilots in the UK and Spain/Portugal, even if these are still at an infancy stage. **Structurally, both pilots conform to the requirements of implementation for a community-based P2P market design**. Nonetheless, the Corby pilot is in an advantageous position for testing external balancing market interactions, given the highly progressive context of England's energy markets (balancing market managed by National Grid TSO). It is unlikely, on the hand, that real-world demand response participation in reserves takes place in the Iberia pilot, due to a combination of reasons that include FleXunity's timeframe and two non-supportive regulatory contexts (balancing markets managed in Spain by REE TSO and in Portugal by REN TSO). For this reason, we suggest that **it could be more beneficial to the Iberia pilot to use computational simulation approaches to assess the benefits of external market participation**.

2 Introduction

The European Union (EU) is undergoing a swift transition towards a carbon-neutral economy, which enables economic growth while addressing existential threats posed by climate change. **A fundamental element to the energy transition lies in the renewed, empowered role of EU citizens**. Once perceived as passive price-taker participants in the energy value chain, customers are now taking charge of their energy matters, becoming more and more active in electricity market activities. The European Commission (EC) has been fully supportive of this trend, strategically pursuing greater market efficiency and strengthening of consumer rights. The recently enacted Clean energy for all Europeans policy package [1] consolidates these intentions to a great extent. The package aims at ensuring a not only a clean but also fair energy transition across all Member States. It perceives EU citizens as equal participants in the broad energy markets, while recognizing and formalizing their sovereign rights to choose their own energy suppliers, to produce or co-produce their own energy, as well as to engage in any other energy services and/or market activities, either individually or collectively, if they so wish. It establishes a view of a user-centric, non-discriminatory, and yet competitive EU electricity market, which further enables the realization of energy communities. In energy communities (also formalized in the policy package), **citizens organize themselves around the goal of cooperating in energy activities, based upon open and democratic rules, as means to provide benefits for themselves and/or the areas where they operate** (adapted from [2]). In renewable energy communities, these activities are always, in one way or another, linked to the exploitation of local renewable energy resources.

Flexible energy communities are groups of citizens organized around the goal of cooperating for capturing the collective value that could be exploited from optimized management of local energy flexibility. Small-scale sources of flexibility could be energy storage, demand response, and electric vehicle charging, among other actions. If managed optimally, such communities could generate *flexibility pools*, to be made available to the energy markets.

The FlexUnity project aims to develop technical solutions and services that enable market interactions and trading between retailers, aggregators, and network operators with flexible, renewable energy communities. **FleXunity is rooted on the assumption that for maximum market value to be captured from these interactions, it is first necessary that the communities' flexibility pool is optimally managed and controlled**.

FleXunity's physical scope is of either distributed or localized mixed-used energy communities (commercial and residential) with a disparate distribution of individually owned distributed energy resources (DER), including PV systems, battery storage and EV charging stations. Each customer owns a share of flexible resources and is willing to shift their energy use as means to provide demand response (DR), which in practical terms works as an additional DER. The buildings are equipped with home or building energy management systems (HEMS or BEMS, respectively), allowing for external optimal flexibility control by a community manager. Flexible energy communities could form virtual power plants (VPPs) if customers are distributed.

In terms of energy activities and services, **FleXunity focuses on peer-to-peer (P2P) energy sharing, under which community participants actively exchange energy between themselves and in real time**. P2P facilitates the sustainable and reliable balance between DER generation and energy consumption within the community, which enhances both the local flexibility pool and the hosting capacity for renewables [3]. This creates value creation opportunities for the communities, which can be capitalized on via a portfolio of market participation alternatives. FleXunity looks especially into the potential contribution from demand-side flexibility in the balancing markets (see *D2.1 – Legal and technical requirements of balancing markets*).

Despite its potential, P2P is an emerging area and most research or industry-oriented P2P projects are or have been experimental. There are no clear and/or standard guidelines that dictate how to establish such a local market model, especially when involving the high number of structural elements considered in the FleXunity project. There is, however, a background of research advances and industry pilots, offering valuable insights.

Taking the above into consideration, this report surveys relevant literature and projects where P2P has been employed. It aims to overview, describe, and assess high-level market design options and corresponding approaches that flexible energy communities inclusive of P2P flows and balancing market interactions can adopt, thus providing a reference pathway for FleXunity's pilot implementations. Based on the above steps, the report delivers insights on that design's applicability to each of the pilots, specifically in the context of the UK/England and Spain/Portugal (Iberia pilot).

The next subchapters provide an overview of P2P energy sharing operations – the core topic for this deliverable – and of the potential P2P community interactions (explicit demand response) with external balancing markets. Please refer to FleXunity's deliverable *D2.1 – Legal and technical requirements of balancing markets* for overviews on balancing market operations, demand response mechanisms, and independent aggregation models in the European context.

2.1 Peer-to-Peer energy sharing

The increased adoption of distributed energy resources (DER), especially renewable-based, and the continuous evolution of information and communication technologies (ICT) brought about opportunities for prosumers and consumers to engage in peer-to-peer (P2P) energy sharing i.e. the sharing of energy at the demand side of the power system. In this new energy paradigm, prosumers (and consumers) exchange energy with each other directly, within the boundaries of an energy sharing region (ESR). The internal energy sharing results in a smaller amount of collective energy purchased from the retailers within the ESR, which generates lower overall electricity costs [4]. Sometimes, the direct economic benefit of P2P for customers can be marginal, as energy exports also reduce. However, export prices are generally lower that retail prices, which still plays in favour of P2P participants.

2.1.1 Benefits and barriers brought by P2P energy sharing

The drivers for P2P are truly multifaceted and multi-stakeholder, extending well beyond economic interests. A review of recent literature suggests P2P energy sharing benefits belong to at least four main families, namely **Technical**, **Market-related**, **Socio-economic**, and **Environmental** benefits. Technical benefits are to a great extent linked to better local RES resource utilization and added local flexibility. Network operators, for example, can use this flexibility to tackle local grid reliability and congestion challenges. Communities see energy security reinforced, at a time where the traditional power system may not offer the reliably levels of the past, as a result from increasingly frequent extreme weather events driven by climate change. In terms of economics and market, the opportunities from optimized liquid flexibility pools can be tapped not only by communities but also at least by aggregator entities and energy retailers.

Socio-economic aspects also play an important role; for one, many customers are motivated to seek smart and sustainable alternatives as means to break away from their dependency from the institutional, dominant incumbent actors linked to the centralized energy grid [3]. P2P offers a more communal, autonomous, and democratic[1] approach to energy delivery, symbolizing customer empowerment at its core. At the same time, environmental improvements are inherent to DER and RES, as fossil emissions continue to be generally offset.

[1] Energy democracy could be defined as a growing social movement prioritizing the potential for redistributing power to the people through renewable transformation and towards local sustainability. For more details, consult for example [6].

Table 1 summarizes potential benefits enabled by P2P energy sharing for various stakeholders. More detailed overviews of advantages and opportunities brought by P2P can be found in [3][7][8][9].

Table 1 – Summary of benefits enabled by P2P energy sharing (Adapted from multiple sources, including [3][7][8][9]).

	Description	**Recipient stakeholder(s)**
Technical benefits	• Higher resource use efficiency and avoidance of energy surplus waste, given that consumption of locally produced energy is fully optimized; • Enhanced demand-supply matching within the ESR, particularly in the presence of RES assets; • Increased grid reliability and energy security, as a result from localized energy production and optimized energy balancing.	Energy communities and their participant customers/citizens
	• Local source for technical support with potential peak demand, grid congestion, and grid reliability issues;	Distribution network operators
Market-related benefits	• Lower customer bills, when compared to traditional market mechanisms, given the use of cheaper, locally produced energy and avoidance of added distribution grid fees and taxes; • Untapped revenue opportunities due to higher amount of tradable energy flexibility, when compared to traditional market mechanisms;	Energy communities and their participant customers/citizens
	• Deferral of grid expansion and other power grid infrastructural investment and operational costs.	Distribution network operators
	• Access to potentially lower-cost energy for portfolio optimization, when compared to traditional access to wholesale markets;	Retailers
	• Enhanced market opportunities for DER flexibility aggregation and placement in the markets; • Enhanced market opportunities for community trading assistance.	Aggregator entities
	• Access to potentially lower-cost energy, when compared to locally produced or retail energy (exchanges between multiple communities);	(Other) energy community entities
Socio-economic benefits	• Customer empowerment and institutional independence from incumbent players – can lead to further prosumer emergence; • More transparent and open market mechanisms, characterized by enhanced customer choice, which facilitates competition; • Market, technology, and energy service innovation, enabling greater energy literacy and awareness, as well as potentially local growth; • Improved community resilience to possible grid faults, especially as a result from increasingly frequent extreme weather events.	Energy communities and their participant customers/citizens
Environmental benefits	• More extensive use of DER and specifically RES, with potential energy efficiency improvements, emissions' reduction, and power transmission and distribution losses offset.	All stakeholders (Societal benefits)

Despite its many advantages, P2P sharing also entails challenges. Perhaps its main barrier lies in the lack of supporting regulatory frameworks that facilitate transition to this type of mechanisms, particularly influencing the trading relations between peers [7][9]. P2P networks also involve a potentially very high number of transactions, which imposes difficulties of different types. For example, information on these transactions needs to remain private and secure, which becomes difficult when no ledger entities are involved. Additionally, enough processing capacity needs to be ensured, while operational costs need to remain low. To tackle this, it is important that technologies that guarantee smart and secure data handling and trading mechanisms could be implemented, a popular example of which is blockchain technology. On a related note, it seems evident that the success of P2P markets is dependent on technology advancements. While blockchain is an example, other energy technologies apply; if in the near future, regular customers (either engaged or not with P2P networks) do not become prosumers themselves, by adopting local energy generation and/or storage, as well as other smart grid technologies, such as advanced metering and energy management systems, it will be difficult to avoid situations of exclusion. In such cases, consumers or communities with less economic power and thus not in a financial position to directly engage, could even face energy poverty, which would defeat the key purpose of P2P energy sharing. Similarly, the highly open nature of P2P networks can pose challenges. The willingness of consumers and prosumers to engage and their retention in the P2P market cannot be planned ahead and it is well known that generally citizens have little interest in electricity market aspects [7]. Moreover, customers will continue to have full control over their retail options; going back to traditional energy supply contracts, if customers so wish, needs to be allowed and cannot be discarded. Lastly, it must be noted that in P2P arrangements, not always decisions are taken under a strict economic principle, since they reflect the multifaceted preferences of many citizens (e.g. proximity between peers, environmental aspects, social aspects…) [9][10]. This human factor may lead to price sub-optimality and thus potential market inefficiencies [7]. It is known that product differentiation affects power exchanges in a meaningful way [11]. However, decision making and computation under these circumstances are complex [10][11] and still poorly understood [7]. This gap has been pointed out by various authors and is a prominent area of ongoing and future work, particularly in the context of real-world market settings [12].

2.1.2 Energy flows in P2P networks

P2P energy sharing takes physical shape in P2P energy networks, which could be defined as networks where its members "*can share a part of their resources and information to attain certain energy-related objectives. Example of such objectives includes renewable energy usage maximization, electricity cost reduction, peak load shaving, and network operation and investment cost minimization. Each member can be a provider, a receiver, or both, of the network resources, and can directly communicate with the rest of the peers of the network without any intervention from a third-party controller. Further, a new peer can be added to or an old peer can be removed from the network without altering the operational structure of the system*" [5].

Figure 4 offers a generic visual comparison between energy flows in the conventional energy supply paradigm and energy flows within P2P energy networks – P2P energy sharing paradigm (Adapted from [4]).

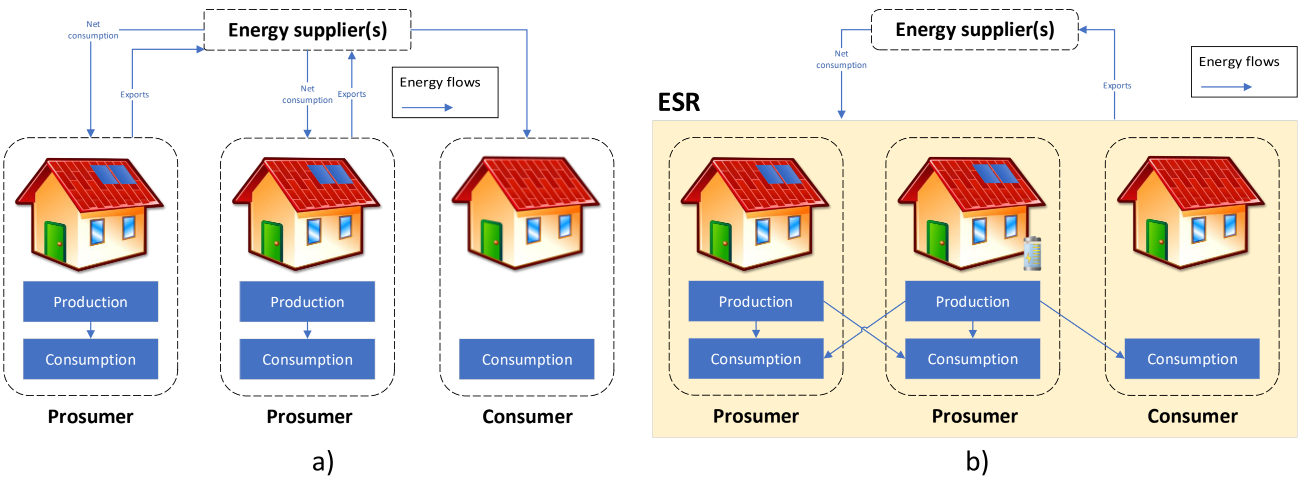

Figure 4 – Comparison between a) contemporary electricity supply paradigm and b) P2P energy sharing paradigm. Please note that depending on model, customers in the ESR can reach energy suppliers both directly and/or in a coordinated fashion (Adapted from [4]).

As Figure 4 shows, in the contemporary paradigm, retail energy flows exclusively and separately between suppliers and customers ("siloed" structure). Customers could be prosumers, in which case retail purchases correspond to net consumption and energy flows may be bilateral (if any exports take place). In the case of consuming-only customers, energy flows are unilateral. In the P2P energy sharing paradigm, regardless of any trading arrangements, energy always flows between customers and/or peers within the ESR and in a multidirectional manner. The existence of the ESR is the fundamental distinction between the two paradigms. As to the interactions between customers and supplier entities, there are different ways in which this can happen, and that is dependent upon the P2P model in place. These models will be discussed further in the report (see 2.1.4). In any case, it is generally applicable that energy that is purchased from suppliers corresponds to the net consumption of either individual customers or of the whole of the ESR, while exports take place only in case local production creates individual or aggregated energy surpluses.

2.1.3 Cooperative vs. Competitive P2P

There are two major trends in the P2P energy sharing space, which dictate the nature of the interactions between the peers, and the existence, or not, of related energy markets:

- The first one is based on **free cooperation** (cooperative P2P), with roots in philosophical and social theory and linked to concepts such as participation fairness and equitability (Narayanan, 2019). Cooperative P2P emerged as a critical and alternative approach to centralized social structures, focusing less on individual value creation and more on joint communal performance, towards the creation of a common good. In cooperative P2P networks, energy assets are often jointly shared, and resource allocation is based on satisfying overall demand/supply matching requirements at the minimal possible collective cost. These processes are thus less aligned with established energy market rationales and more consistent with autonomous cooperative governance movements;
- The second one, while still involving decentralized forms of decision-making, is driven by price mechanism dynamics, being commonly known as **P2P energy trading** (non-cooperative, or competitive P2P). P2P trading is the buying and selling of energy between two (or more) customers in real time, which effectively forms **P2P energy markets**. In P2P markets, participants are usually (but now always) prosumers, both producing and consuming energy. The energy shared within the peers is typically solar, due to the specific load profiles of solar production (although it can be any type of energy). In most cases, surplus solar production can be stored (if storage is needed), transferred, and then sold to other participants, at rates that are mutually advantageous.

The FleXunity project focuses on the market integration of P2P community networks. Thus, **this report will exclusively address P2P energy trading**.

2.1.4 Types of P2P markets

The relevant literature is consistent in considering three generic types of P2P market designs [7][8][10][13]. Based on their degree of decentralization and/or hierarchical structure, these designs can be categorized as: 1) **Fully decentralized**; 2) **Community-based**; and 3) **Hybrid**. The present section provides a brief overview of each of these potential designs and a critical comparison between them.

2.1.4.1 Fully decentralized P2P markets

Fully decentralized P2P markets represent the epitome of energy democracy in the prosumer era, in that they're completely distributed, without any specific structure or centralized control [13]. In addition, all participants have equal rights, which is the same as saying all P2P nodes have equal functionality. Other terms used in the literature for naming this market structure are “**Full P2P**” and “**Purely decentralized**.”

This type of market allows peers to directly and independently interact for energy trading purposes (Figure 5). Peers can negotiate, buy, and sell energy among themselves, without any centralized (or even decentralized) supervision. Furthermore, peers can set preferences on which type of products they want to consume, such as local green energy, or choose to buy from peers with specific attributes of virtually any type (social attributes, physical attributes, etc.), which enhances the emergence of product differentiation phenomena. The uncertain nature of these marketplaces creates conditions for their logical P2P topology to be often random and unstructured [13].

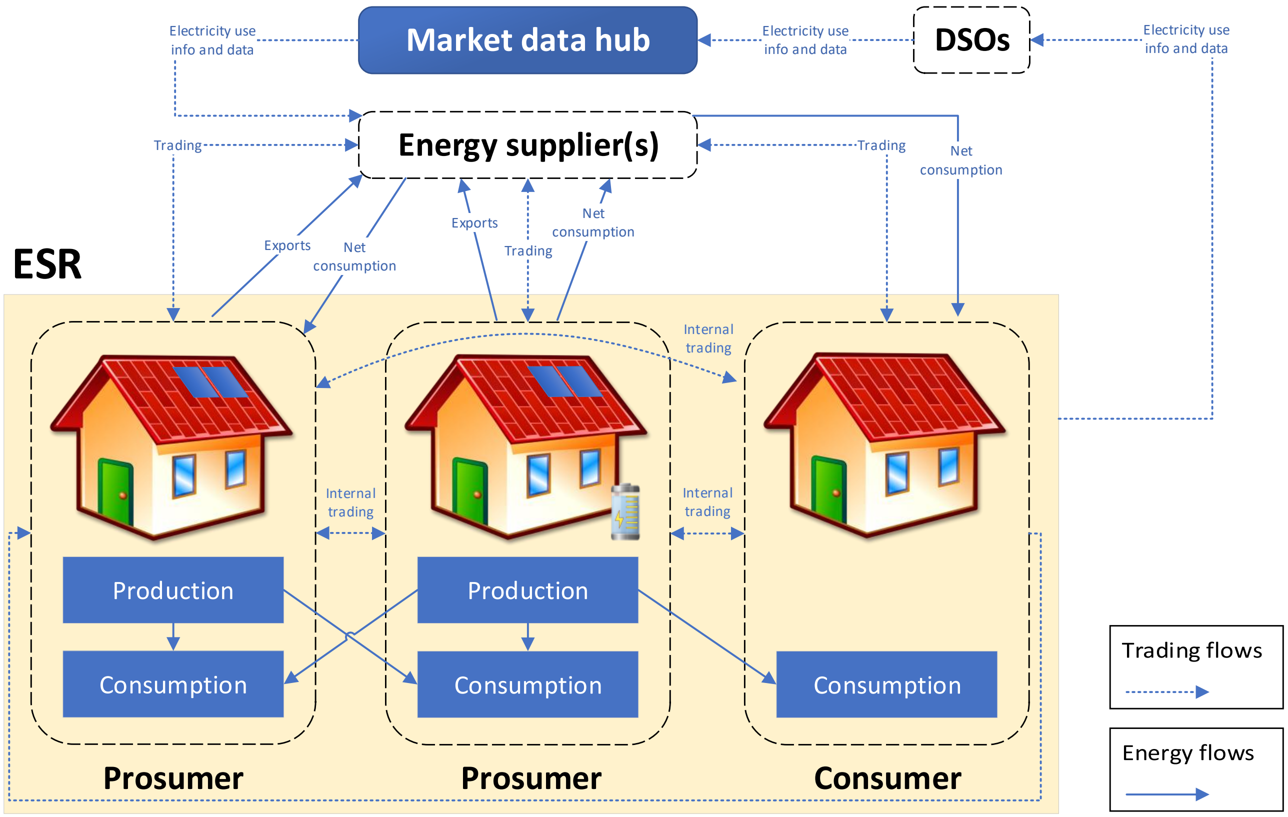

Figure 5 – Generic representation of energy and trading exchanges in a fully decentralized P2P market design (Adapter from [4][7]).

Fully decentralized P2P markets rely generally on the establishment of multiple bilateral trade agreements and subsequent energy transactions between peers [10]. There are a few contributions in the literature where such systems have been devised and modelled, as comprehensively described in [7][8]. Specific points of interest include the complex inclusion of expression of individual preferences in the trading [10][11], and cases of P2P energy trading between electric vehicles, as an alternative to “traditional” charging [14][15].

Figure 5 also includes the figure of a “Market data hub”, which is a centralized data storage and exchange platform for energy market information and data, most notably energy customer load profile information. These data hubs provide electricity market parties with equal and simultaneous access to information, speeding up, simplifying and improving electricity market information exchange processes [16]. Data exchange hubs are perceived as a key component in context of new EU smart grid operations and are being developed by many EU countries, including Finland, The Netherlands, Poland, and others [17].

One key role of the data hub is to take care of all information exchange in electricity retail markets, as means to facilitate electricity supplier changes or specific changes in customer electricity contracts (address, personal details, etc.) [16]. After electricity use data is collected by the DSOs, it should be sent to and stored in the data hub. Electric suppliers can then directly access the data hub to obtain load data, rather than exchange information with other competing suppliers. Currently, the data hub is mostly serving electric suppliers. In a full P2P scenario, prosumers are more likely to adopt ways in which they exchange electricity data within themselves. However, it is possible that in a near future this information is also extracted from the data hub.

2.1.4.2 Community-based P2P markets

In community-based P2P markets trading activities between peers take place through a supervisory community manager (CM) entity, which operates as a trading facilitator (see Figure 6). This gives these markets an internal structure that fully decentralized P2P markets lack [7]. The CM can also act as an intermediator of the interactions that occur between the community and the outside markets, which could include trading with other P2P communities [8]. Decisions by the CM affect directly the energy dispatch, as well as peer revenues and payments. However, these activities are collectively optimized, rather than individually optimized. Appropriately, the CM has been termed a "supervisor of convergence to system optimality" [18]. In their interactions with the CM, participants can include strategic criteria and parameters to their participation i.e. they have a partial say in the general outcome of the market. While energy dispatch will reflect these individual preferences and strategic schemes, they are assured by the CM to remain private [18]. Alternative terms used in the literature for naming this type of P2P design include "**Centralized P2P**", "**Purely structured decentralized**", or simply "**Energy collectives**". The latter are comprehensively addressed in [18].

Community-based P2P markets can be applied to both localized systems, such as community microgrids, and distributed prosumer systems. In both cases, the CM's role can be appropriately taken by an aggregator entity. This is line with earlier mentioned European regulation, which broadly defines energy communities as groups of like-minded citizens cooperating in energy activities, even though they may not share a same location [1][2].

Recent reviews to a limited number of technical approaches to community-based P2P can be found in [7] and [8]. Some highlights are a study where the CM assumes the role of an auctioneer managing internal bids for shared/communal use of energy storage assets [19], and a reference study where the CM not only supervises internal trade but also mediates energy imports and exports with the external market [7]. In [20], the authors tested a two-stage battery control algorithm for energy sharing within a low voltage community network, concluding that a community-based P2P approach reduced overall energy costs for the community in about 30%, when compared to a fully decentralized P2G market design. Yet, most experts appear to agree that less localized and more widespread results supporting the superiority of these approaches, perhaps via adoption of systematic evaluation methodologies, are still necessary before conclusive academic insights are produced.

Lastly, as Figure 6 shows, in a community-based P2P approach, the market's data hub is expected to coordinate with the CM entities the exchange of individual and aggregated electricity consumption data. This data is essential for supporting the trading activities on behalf of the community the CM is tasked with. It is important to recollect that the existence of a CM, handling P2P trading for the community does not preclude traditional customer interactions with energy suppliers. In this type of market design, that trading is as well intermediated by the CM, as long as participant customers do not opt out from the "community arrangement" in place (according to new EU regulation, the customers are at all times entitled to go back to a situation of trading directly with the energy suppliers, as well as to change suppliers whenever thy so wish – this should be fully enabled by other market players, including the CM, network operators, and other suppliers).

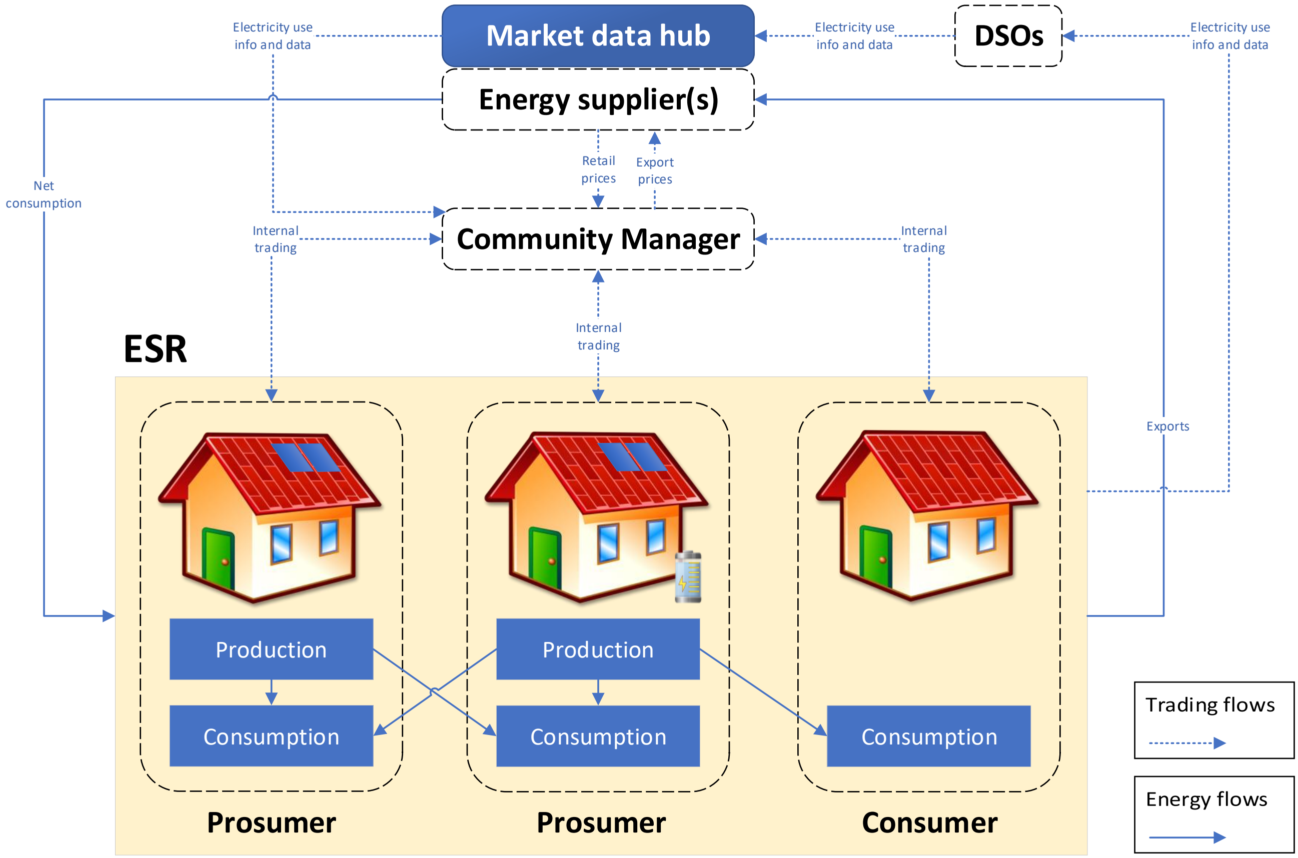

Figure 6 – Generic representation of energy and trading exchanges in a community-based P2P market design.

2.1.4.3 Hybrid P2P markets

Hybrid P2P markets are constructs that reflect the combination of attributes from both the fully decentralized and community-based P2P market designs. This type of market is also termed in the literature as "**Composite P2P**". There are no restrictions to the trading possibilities in hybrid P2P markets, which results in a sort of "organized chaos". Peers can either exchange energy directly with each other or allow a CM to mediate trading for them. Likewise, they can, if they so wish, access the services of an energy supplier to purchase energy. They could also access external markets directly, or alternatively seek for collective opportunities through the assistance of the CM. These markets can establish a type of "layered trading" structure, where energy collectives, with own community and external trading dynamics, and single peers interact reciprocally. There is also the chance that energy collectives are nested into each other. This has been named in [7] a "Russian doll" type of approach. In [13], a distinction is done between "hybrid centralized" and "hybrid decentralized", depending on the number of "central nodes" or managing entities in the market.

The authors have refrained from introducing here a detailed stakeholder flow representation for hybrid P2P markets, such as the ones in Figure 5 and Figure 6. Alternatively, Figure 7 reproduces the schematic approach adopted in [7] (note that in the figure community-based P2P markets are termed "energy collectives").

Example approaches in the literature of these clustered market designs are even more scarce than for fully decentralized and community-based P2P. However, in [8] two specific cases are listed. In [21], an online energy sharing method is proposed that used Lyapunov optimization for improving the self-sufficiency of DC microgrid clusters equipped with photovoltaics and energy storage. In [22], the authors provide a power trading system for energy transactions between prosumers and consumers of smart homes, using a decentralized, transparent and secure blockchain-based P2P platform.

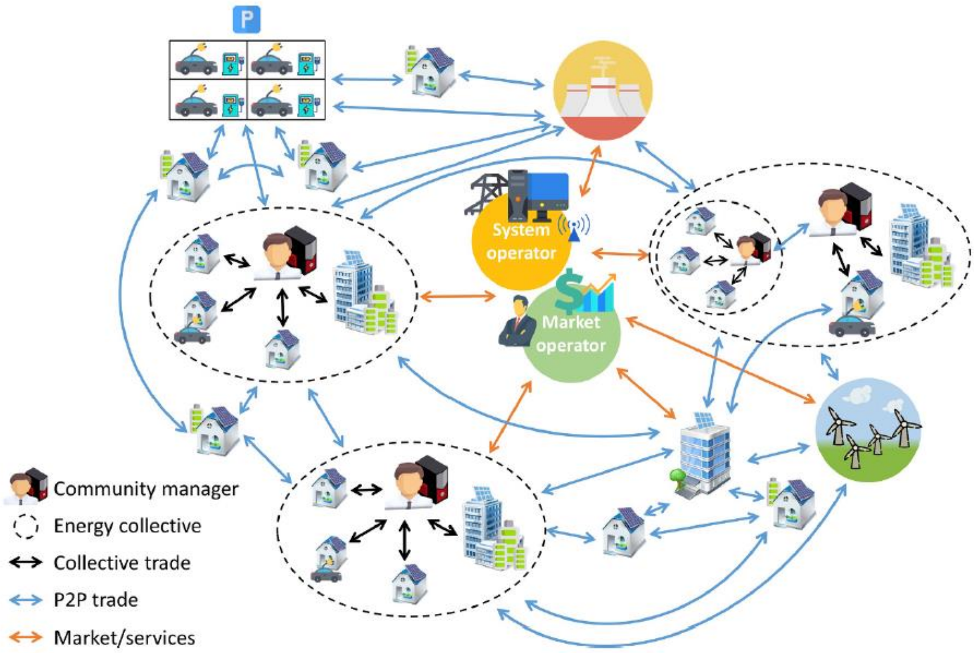

Figure 7 – Generic representation of energy and trading exchanges in a hybrid P2P market design ("Russian doll approach") [7].

2.1.4.4 Comparison between P2P market designs

As explained earlier, the literature converges on three dominant market designs for P2P trading, which have been overviewed in the above subsections. To conclude this analysis, Table 2 summarizes the main defining characteristics of these designs and highlights its key strengths and weaknesses.

Table 2 – Key characteristics, strengths, and challenges faced by the three dominant P2P market designs ([7][8][10][13]).

	Fully decentralized P2P	Community-based P2P	Hybrid P2P
Defining characteristics	• Direct trading between peers and between peers and external markets, with no central supervision • Individual optimization	• Supervisory community manager entity intermediates internal and external trading activities • Collective optimization	• A combination of fully decentralized and centralized P2P approaches • Concurrent, potentially conflicting, optimizations
Key strengths	• The most "democratic", autonomous choice, where energy use fully reflects peer preferences • Because there is no central entity managing information flows, these systems are inherently more flexible and resilient	• Optimal trading options are computed by manager entity and not peers • Many technical burdens off the shoulders of peers, which dictate quality of service and privacy of data • Improved peer access to external market revenue opportunities • "Communal value", enhancing mutual cooperation of peers towards a common good	• In theory, more revenue opportunities are available • The distributed, intelligent nature and the combination of optimal centralized and decentralized controls may make of these systems less prone to collective failure, as well as more flexible and resilient to potential malicious attacks

	Fully decentralized P2P	Community-based P2P	Hybrid P2P
Key weaknesses	• Trading optimality, forecasting, etc. are a responsibility of customers • Potential investment and O&M/technical burdens, which can compromise the management, security, and quality of service • May result in reduced peer access to external market revenue opportunities • Unstructured, random arrangements, with no central entity to resolve potential conflicts • Scalability challenges or limited to own community	• While decisions are meant to be collective, it may be challenging to initially reach or maintain shared preferences of energy use for all peers at all times • Technical challenges for community managers with data collection from market hubs, peers and subsequent aggregation • Assuring fair, unbiased energy sharing among community participants • A central point of command/failure makes these systems more vulnerable to attacks	• Processing, coordination, and optimization logic of multiple direct and collective trading layers may reveal unfeasible and/or financially prohibitive for all parties

2.1.5 Structural elements of P2P networks

From a structural and functional perspective, the key elements of P2P networks have been categorized differently by different literature. In [23], a framework inspired in the Smart Grids Architecture Model (SGAM) is adopted, which considers four key interoperable layers:

1. **A Power grid layer**, composed of the physical electricity distribution components of the P2P network, including the DER, transformers, feeders, as well as the electrical wiring itself, etc. This is a sort of “base layer” or “backbone” over which other layers are implemented;
2. **An ICT layer**, entailing the devices, the communication protocols and applications together ensuring the information flows across the P2P network, including routers, sensors, switching, and connections, servers, computer workstations, information and data exchange processes, etc.;
3. **A Control layer**, consisting of control functions and strategies implemented in the power system (which could be owned by network operators), including algorithms for power quality and reliability management, resource allocation, and other;
4. **A Business layer**, which dictates market and trading aspects of the network, including externally, and involving all actors in the power system.

A more commonplace approach has been used in [3][7][8], which reorganizes the above elements into two distinguishable physical and virtual layers (Figure 8). As the name suggests, the **Physical layer** is composed of the distribution network that facilitates electricity transfer between selling and buying peers and/or other participants in the P2P market, regardless from its length, range, or ownership (this network could be the main distribution network managed by a network operator, for example in the case peers are widely distributed, or a local network, in the case the peers are part of an autonomous system such as a community microgrid) [3][8]. The physical layer includes all the necessary hardware and equipment for enabling efficient communication between consumers, prosumers, grid operators any other actors involved in the good operation of the market. The **Virtual layer** provides for the information flows that enable the interlinked market, trading, and business activities that take place over the physical layer. It is the platform where all the communications of buy and sell bids and financial transactions take place in a safe, secure, and equal manner. Control strategies and functions, such as those used for handling network power quality, as well as energy management and allocation algorithms are as well implemented under the umbrella of the virtual layer, even though they may reside physically in grid or customer equipment. To a degree, all of these are market enablers.

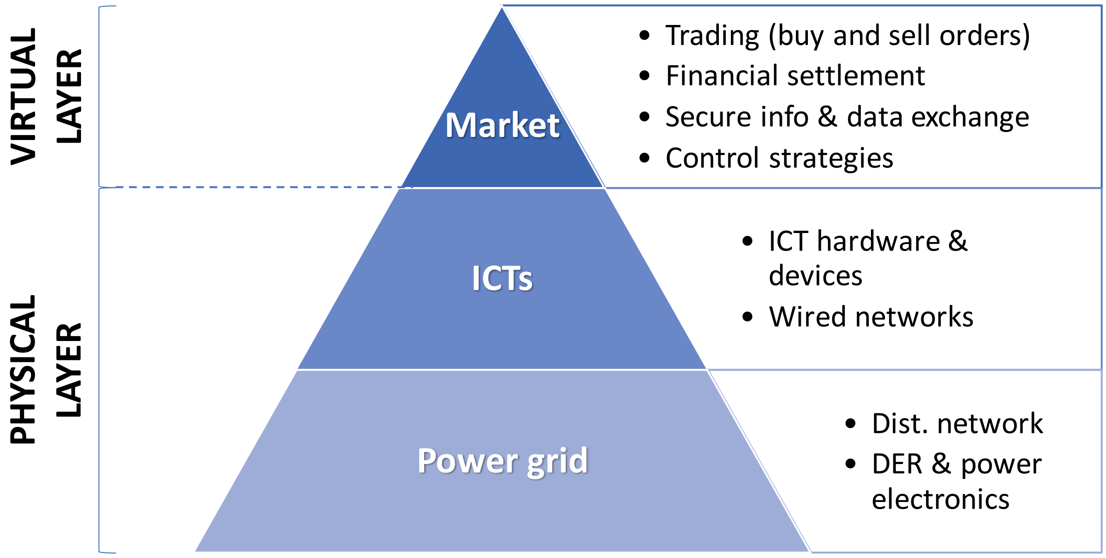

Figure 8 – The two pillar layers and example constituting elements in P2P energy networks.

2.1.6 Overview of key challenges in P2P trading

Different types of technical and market-related challenges can emerge in each of the abovementioned P2P network layers. These challenges are succinctly listed and described in the next subsections.

2.1.6.1 Challenges residing in the virtual layer

The most daunting challenges brought by P2P trading lie in its market-related components, which is the possible reason why this area has been the focus of most P2P work in recent years (as Section 3 will further elaborate on). There is a complexity of interweaved elements that justifies this, such as the need for efficient and transparent trading mechanisms in own marketplace, cost-effective interactions with additional marketplaces, compliance with energy balancing and matching requirements, and private and secure information and transactions. These challenges could be potentially split into the following categories:

1. **Minimizing energy costs**

For customers to adopt and participate in P2P trading, it is essential that it becomes economically feasible and worth for them. In principle, prosumers should be better off if given the chance of selling excess energy otherwise wasted or consumed only after considerable losses. Consumers should be able to access this energy at more accessible rates. This trading mechanism should be enabled, tested, and validated in the virtual layer under different technology scenarios and market designs. In addition, peers may have access to revenue streams from external market participation, especially under community-based arrangements.

2. **Balancing local generation and demand**

One key assertion in P2P networks is that energy trading between peers needs first and foremost to be in line with the balance between energy production and consumption within the energy community. For this to happen, it is necessary that all transactions, as well as each peer's energy availability and demand, are monitored and tracked at all times, and that these data are incorporated in the buying and selling processes into some type of enabling platform. Additionally, it needs to be considered that if imbalances remain at a post-trading stage, the community could seek to solve it by accessing the grid.

3. Developing pricing and engagement mechanisms

In order to assure effective buyer and seller trading, it is crucial that specific, suitable, and innovative pricing schemes are designed, so that each party receives the appropriate signals that makes them feel engaged. In addition, to successfully reap P2P benefits, prosumers need to be actively involved in the trading mechanisms, which is only possible if these outcomes are fully understood and perceived by them. This field of work deals with devising customer-centric mechanisms that incentivize prosumers to trade energy within P2P networks.

On a related note, the lesser use of grid infrastructure suggests a change in the way electricity customers have been charged network fees through their bills. One point of incentive for P2P could be revised billing methods that take this aspect into consideration.

4. Ensuring secure and transparent environments for transactions

To enable prosumers to seamlessly engage in P2P trading it is necessary to guarantee that contractual information remains private and that financial transactions, as well as buy and sell orders, are kept secure. Currently, the dominant technology for assuring secure P2P transactions over the virtual layer is blockchain.

2.1.6.2 Challenges residing in the physical layer

Once energy trading decisions are established in the virtual layer, the agreed amount of energy is transferred over the infrastructure provided in the physical layer. This could potentially disrupt the existing power system in myriad ways, since its infrastructure has not been originally designed for supporting P2P flows. Challenges in the physical layer could be tentatively divided as:

1. Violating network power quality and reliability, and capacity constraints

P2P trading needs to be able to accommodate the demanding parameters of power distribution across energy networks, so to minimize negative, potentially debilitating, technical impacts. For example, energy production activities in low voltage distribution networks are known to cause node voltage imbalance issues. In addition, there are challenges related to bidirectionality and reverse power flows, as well as potential complications linked to the coexistence of multiple voltage levels in case of larger communities. Furthermore, the increasing prominence of RES technologies in local electric distribution systems is challenging greatly the maintenance of system strength (the ability of a power system to manage fluctuations in supply or demand while maintaining stable voltage levels) and system inertia (the ability of a power system to manage fluctuations in supply or demand while maintaining stable system frequency). This is especially true when there is need to recover from power quality disturbances, which would be traditionally well handled by synchronous generators. Not properly handling these problems can lead to power system failure and outages. These issues need further investigation, specifically on ways in which the impact in system strength from production of multiple renewables can be minimized. In addition, alternative means to regulate power quality, such as energy storage, need to be considered.

Another problem that could emerge from extensive transaction of energy is reaching the original operational capacity limits of the network. When power quality requirements are not followed, there is a risk of that the grid may default, which puts whole system reliability at risk. To avoid these detrimental impacts, it is necessary to adopt grid intelligence support approaches that efficiency regulate the aforesaid criteria. A related issue is the power cap on injection for each prosumer, which limits their ability to install larger DER capacities and capture corresponding value streams. In a P2P trading reality, these limits should be more flexible, by adjusting to local demand and supply, thus allowing customers to freely negotiate.

2. Losing power in energy distribution

The power exchange between peers necessarily includes losses. These losses should be accounted for above the consumption requirements in the energy trading activities, and they have energy cost recovery implications. In addition, resource allocation and power flow algorithms should be designed in ways that minimize the power loss ratio in the network.

The above provides no more than a brief outline of the many established and emerging research challenges and/or directions in the area of P2P energy sharing and trading. For a more detailed overview of these, consult at least the excellent work provided in [8].

2.2 Balancing market participation of demand response in P2P communities

As discussed earlier, P2P energy trading, particularly when under a community-based design, offers opportunities for communities to engage in trading with external energy markets in addition to the trading already taking place within the community. Such opportunities can reside in existing wholesale, balancing, and ancillary service markets, as well as in other future market designs. In a community-based design, the supervisory node (CM entity) facilitates not only the local energy trading, but also the interface with these markets. This approach maximizes value for participating peers, working as an incentive mechanism for P2P.

One product that communities will be able to collectively trade is aggregated demand-side energy flexibility, whose generation is maximized in P2P networks, due to a more efficient utilization of local energy resources. Flexibility is highly valued in the energy markets; network operators can use it to tackle local congestion challenges and players such as energy retailers can tap into it as means to optimize their customer portfolio. Under the umbrella of a multi-energy community paradigm, different CMs can also trade with each other the net energy production that is made available in their flexibility pools, at different times of the day. Lastly, demand response could be traded in the balancing energy and reserve markets, whose structure depends on the dominant regulatory context, but that includes at least ancillary services to the transmission system operators. For a comprehensive view on the potential contribution from demand-side flexibility in the balancing markets and on the specific regulatory contexts that prevent it or enable it in selected countries, please consult *D2.1 – Legal and technical requirements of balancing markets*.

An approach similar to the one described above has been envisioned in [18], where it is considered that multiple “energy collectives” interact with a system operator for providing ancillary services and peak-shaving support, each under the supervision of a CM entity (Figure 9). The presence of a supervisory node greatly simplifies market regulation and the interactions between the various players. It also allows the distribution of computational efforts and grants the privacy protection of preferences or strategies for each participant. Moreover, while there is a centralized aggregated control, prosumers also have the possibility of optimizing their assets individually. The combination of these advantageous aspects makes it likely that community-based P2P structures will become dominant in the near future [18].

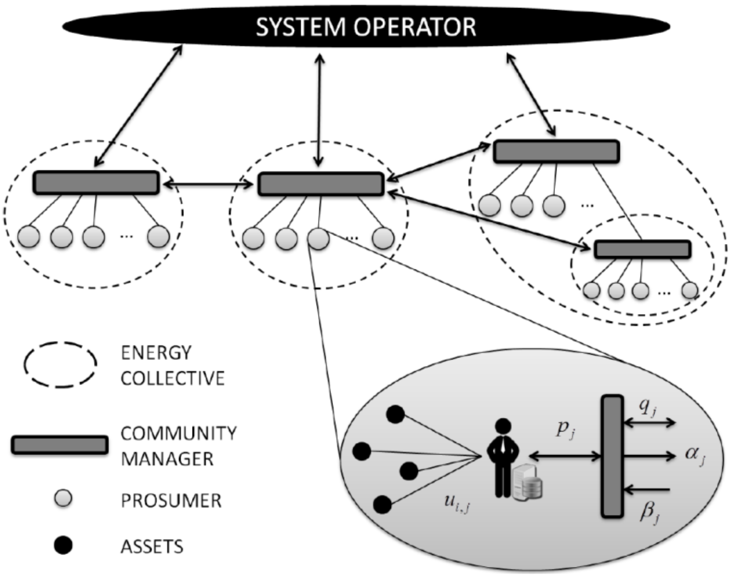

Figure 9 – Interactions between energy collectives and with a system operator, and focus on a prosumer j with individual optimization of net production (p_j), imports (α_j), exports (β_j), and inner exchange (q_j) of energy under specific power setpoints for asset i ($u_{i,j}$) [18].

The following subsections describe some of the key questions that remain open in terms of participation of P2P communities in external (and specifically balancing) markets opportunities.

2.2.1 Main open questions

However, there are always challenges in such a type of market structure related to reaching agreements to satisfy energy use preferences and having fair energy sharing among community members. Besides, for the CM, managing community members' data and fulfilling their expectations can be challenging. In particular, there are several key questions that need to be tackled before such a "local market within an external market" mechanism is implemented. The most important of these key questions and their sub-questions are as follows.

2.2.1.1 Where and when should the available flexibility be allocated?

While the external market opportunity is available, the revenues it may offer must be continuously compared against opportunities linked to the internal market. Whatever mechanism implemented, it must address the issue of whether the flexibility is to be sold to the external market or whether it is to be made available for local consumers via the local market. Additionally, there is the question of local market prioritization: *Should local consumers be prioritized over the external market, based on the philosophy of keeping the consumption close to the production?* There is a trade-off between the external market requirements and local market requirements, based on factors such as price, electrical infrastructure, social issues and requirements, or needs of local population. These trade-offs need to be considered and resolved [9]. In [8], it is additionally suggested that future P2P trading mechanisms should incorporate policies and technologies ready to accommodate this type of decision-making.

Furthermore, there is the aspect of flexibility allocation timing. Flexibility timing allocation should be optimized towards maximizing benefits for all stakeholders. This could be a simple optimization task if the local market time resolution matches the time resolution of the external market, but not being that the case, this becomes a considerably more difficult problem to solve. Moreover, there are physical network elements than can create flexibility timing issues, such as various performance parameters of ICTs that interconnect network elements, and on which the flexibility allocation depends on. Examples are latency, data speed, and reading accuracy.

2.2.1.2 How should accrued benefits be distributed among peers?

When market revenues from external interactions are realized, it becomes a sensitive issue to distribute them between the participant peers. This is an often either disregarded or misunderstood topic. There are several strategies under which profit allocation could be achieved [9]:

1. The profits are equally distributed among all participant peers. This strategy follows **Economics** and/or **Social**-based profit allocation principles. Strong community bonds (as opposed to individualistic approaches) have considerable influence in profit allocation. A local community with a strong tradition of cooperation may desire, for example, to forward their market profits to community development;
2. The profits are distributed based on the relative contribution of each of the peers (for example, using marginal contributions). Such strategy would likely be based on **Economics** profit allocation principles;
3. The profits are distributed based on the background of the peers and its social and economic means (for example, disadvantaged community members may receive a greater share). This approach follows a **Stakeholders**-based profit allocation principle, but it corresponds to a mere example. The outcome would be different if, for example, the community had been put together by for-profit enterprises;
4. The profits are distributed based on the intentional proliferation of RES (for example, prosumers are allocated higher profits as means to encourage RES investments and production). This strategy follows **Environmental** and/or **Legislation and Regulation**-based profit allocation principles.

In the real-world, profit allocation relies on hybrid strategies that follow combinations of the above principles. In fact, energy communities tend to organize from the onset around the same strategies and corresponding value systems. These could be multifold, albeit according to emerging definitions inspired in the new EU policy package, these should be geared towards providing environmental, economic, and social good for their members or the local areas where they operate, as well as based upon open and democratic rules [1][2].

2.2.2 Current status

The participation of P2P communities in external market services is still at a nascent stage, being currently more a theoretical concept than a real, demonstrated one. It has been an aim of various projects, but one that has not yet been fully realized. For example, start-up LO3 Energy intends to have the much-renowned Brooklyn Microgrid offering ancillary services to the grid in the near future [24], but this idea has not yet come to life. The technical and policy challenges that come with implementing P2P markets are so many and so varied (as the previous subsection shown), that most efforts in this area are currently dedicated to internal trading-related challenges. In addition, the wide variety of local and external requirements, of applicable optimization problems, and possible market opportunities, makes it difficult to develop "catch-all" solutions, which calls for adopting more systematic analyses.

Only a small number of publications was identified that studied the external market interactions with P2P communities. Some of the earliest work found explored the concept of "federated power plants" or VPPs shaped from P2P transactions between self-organizing prosumers that unlock additional value from ancillary service participation [36]. In [18], the authors proposed and tested a novel market structure based on the concept of energy collectives interacting with a system operator under a CM's supervision, which is expected to be adapted in subsequent studies. In pioneering work presented in [38], a mechanism was designed for ancillary service provision from P2P energy trading based on continuous double auctions, originating additional value for both the community peers and the power system. In this study, the optimal bidding strategy was designed to maximize customer benefits, which leaves questions as to grid support optimality unanswered. Indeed, a very limited body of work has investigated the potential for P2P trading coalitions to support the grid via ancillary services' provision to network operators [8].

The provision of demand flexibility from P2P networks to the balancing markets could follow similar approaches to those that sometimes rule internal P2P energy trading, namely auction-based mechanisms. Under those mechanisms, participants could bid for providing flexible demand response together with other flexibility providers. Within the community, peers receive payments based on their share of traded demand response. This is similar to the bill sharing pricing method, where each peer pays their individual share of electricity usage from the overall electricity trade recorded in the utility meter at the grid point of common coupling. The work in [37] explored the benefits of P2P sharing on the centralized grid's operations, using an auction-based framework for energy and capacity markets. Specifically, the authors proposed an energy sharing scheme under which an aggregator takes advantage of users' shared DERs for providing peak shaving and load balancing. As described above, the authors designed an asymmetric Nash bargaining incentive mechanism, which achieves a fair allocation of benefits according to the users' service contributions.

The relations of P2P communities with external markets have been preliminary examined in the above literature. Most of this work is still conceptual, focused on investigating implications, benefits, challenges, and on developing modeling frameworks for future analyses. Surprisingly, no studies focused policy or regulation have been identified, which could aim at smoothening the integration of these new mechanisms into already strongly disrupted marketplaces – this will be crucial for bridging research outcomes with real world implementations. There is also a strong need for more research on non-consumer-centric approaches (such as the one provided in [37]), which could inform on the beneficial or detrimental impacts that P2P trading may have in the distribution grid and in the broader operations of the external energy markets [8].

On the other hand, there is no doubt that the involvement of P2P communities with external markets offers considerable prospects in terms of additional revenue streams and access to a more diverse portfolio of market products. Depending on how these interactions will evolve, they can also reveal crucial for further engaging and incentivizing customers to join P2P networks. As a result, this area is commonly featured as one of the main future research directions in P2P trading [8].

3 Survey of P2P trading literature and projects

This section has the goal of providing a concise overview of the current state-of-the-art in P2P trading both at the academic research and real-world project levels. It does not provide a comprehensive analysis, rather pinpointing dominant approaches and key developments of interest to the FleXunity project.

3.1 Technical Approaches in the literature

As already widely discussed, implementing P2P trading in power system networks entails numerous challenges. Here, we introduce the most dominant technical approaches identified in the range of available literature for tackling those challenges in both the virtual and physical layer platforms. Two main families of approaches have been adopted in the literature; one is related to modeling P2P interactions and the other is related to assuring the private and secure communications within in the P2P networks (Figure 10). The following subsections develop further each of the technical approaches used to tackle those two types of challenges (Constrained optimization, Auctions, Game theory, and Blockchain).

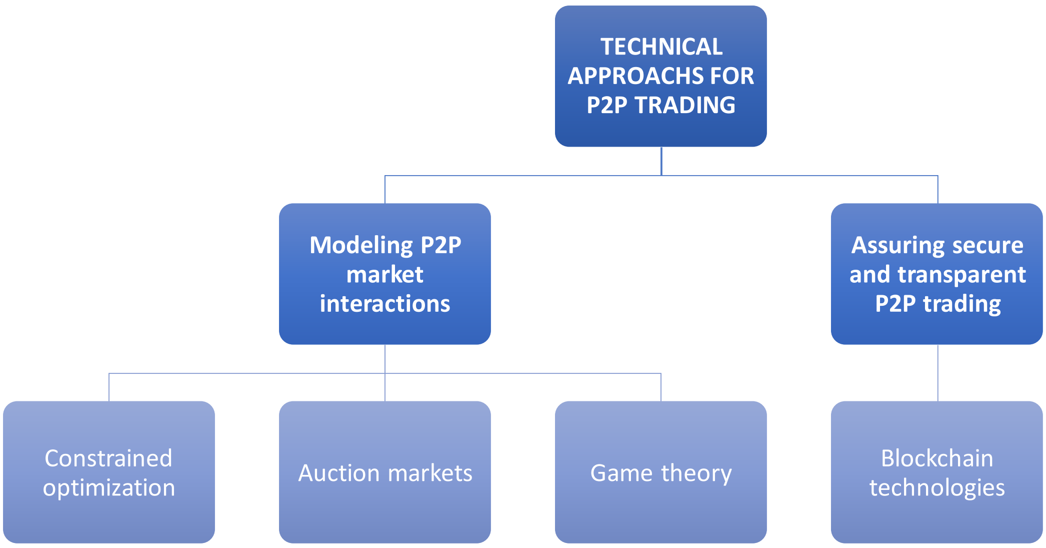

Figure 10 – Technical approaches identified in the literature to handle P2P trading research challenges.

As discussed in 2.2, the literature is limited in terms of external market interactions, reason why the approaches introduced here have been mostly tested and demonstrated in the context of intra-community P2P trading.

3.1.1 Modeling P2P market interactions

Researchers have employed three general types of technical approaches to enable P2P trading, namely optimization-based, auctions market-based, and game-theory-based approaches (Figure 10). These are only briefly described below. Please note that these methods are not new, and its merits have been widely discussed in both related and unrelated literature – this is not the objective of this report. For more comprehensive reviews please consult, at least, the work presented in [3][4][8][9][10] and corresponding source materials.

3.1.1.1 Optimization-based approaches

These approaches use mathematical programming techniques for optimizing P2P trading goal functions under various hard and soft constraints imposed by the market and the power system itself (constrained optimization) [8]. Several optimization-based methods have been proposed in the literature, including convex optimization, stochastic optimization, particle swarm optimization (PSA), linear programming (LP), mixed-integer linear programming (MILP), non-linear programming (NLP), and agent-based methods [9].

In P2P energy trading problems, **the general optimization formulation consists in an objective function to be minimized and constrained by some type of "fairness function".** This constraint function handles peer remunerations and should do so in some sort of "fair" manner [9]. Therefore, if that of approach is followed, fairness functions need to be defined before optimization techniques are applied to solve the problem. In addition, it has been discussed that peers can set preferences on their electricity use and consumption. This type of product differentiation affects the trading and is also perceived mathematically as a constraint that adds complexity to the optimization problem.

The type of mathematical programming techniques used depend on how the problem is formulated mathematically, which then is contingent on the complexity of the phenomena modelled. LP is a very popular approach and perhaps the simplest. A standard LP optimization can be expressed in its canonical form as:

$$\min\{C^T x \mid Ax \leq b, L \leq x \leq U\} \tag{1}$$

where C is the cost coefficient vector and C^T the matrix transpose, x is the decision variable vector, A is the constraint coefficient matrix, b is the constraint coefficient vector, L is the decision variable lower boundary vector, and U is the decision variable lower boundary vector.

As the name implies, in LP optimization, all decision and constraint functions are described linearly. MILP is mathematically similar, but unlike LP, it allows a mix of non-integer and integer variables. MILP optimization is a powerful and popular technique, which adapts well to the structure of many resource allocation problems.

In P2P trading, convex optimization consists usually of adopting alternating direction method of multiplier algorithms (ADMM), which break problems into smaller pieces and make them easier to handle [8]. This augmented Lagrangian variant could be approximately be described as:

$$\max_{x,z} f(x) + g(z) \tag{2a}$$

$$s.t.$$

$$Ax + Bz = c \tag{2b}$$

where is z is a vector of second variables (ADMM supports two objectives with two separate sets of variables).

NLP are complex mathematical techniques that can be formulated using non-linear objective functions and constraints. The above canonical representation used for LP is also applicable to NLP, as long as nonlinear functions are considered.

Constrained optimization has been used to tackle challenges both at the virtual and the physical layers of P2P networks. There are numerous problems related to the former, which usually fall under DER resource allocation or scheduling and energy management strategies for trading purposes. In this sense, it is important that optimization algorithms properly identify the energy availability for trading and match it with demand at all times, while respecting local requirements. These problems become increasingly more complex the bigger the variability of DER resources. For example, there is a lack of innovative scheduling optimization techniques able to perform multi-level storage management (applicable to networks with different types of storage systems and deployed at different levels of the network) [8]. Some example applications of constrained optimization to P2P trading include [14][15][20][21].

3.1.1.2 Auctions market-based approaches

Many researchers have adapted market trading-based methods to accomplish local electricity exchanges, based on well-established economic theory (P2P markets were first examined in economics literature over three decades ago). Market platforms are advantageous because they allow for efficiently and flexibly co-ordinating self-interested consumers, prosumers, energy suppliers, and any other intervenient stakeholders.

The most common local energy market approach is use auctions, especially continuous double auctions (CDAs). A double auction involves a number of buyers and sellers interact so as to trade electricity as a commodity. Under this approach, an auctioneer entity or moderator manages bids – buy and sell orders – from the participants, via a public order book. In [3][8], the sequential CDA process is described as in Figure 11.

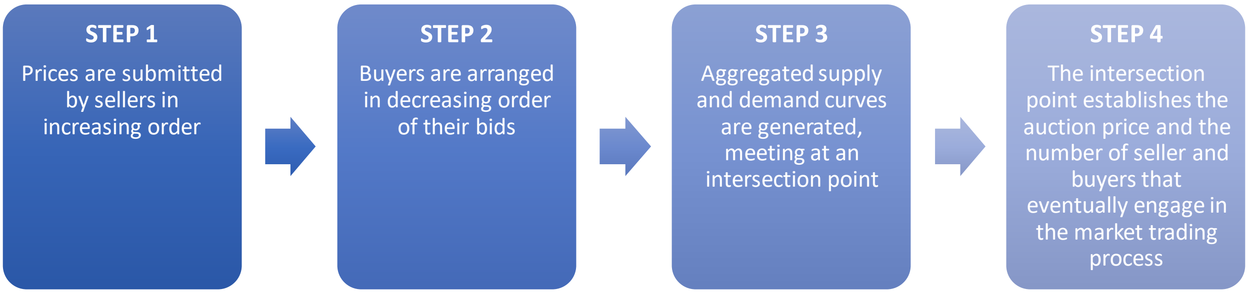

Figure 11 – Step-by-step process of a continuous double auction.

CDA markets only operate efficiently if sellers and buyers truthfully and rationally report their reservation prices and bids. Thus, it is strictly necessary that the utility that a prosumer receives for participating in the auction mechanism cannot be improved otherwise [8]. Furthermore, a CDA mechanism is called incentive-compatible if every participant of the auction mechanism can achieve the best outcome to themselves by acting upon their true preferences [3]. Electricity pricing strategies and how they affect market rationality is an important branch of CDA research [9].

On the downside, with market-based methods, the profits for peers are strongly dependent on the “cleverness” of bidding strategies. In addition, auction bidding may not efficiently capture the value of local DER resources if under-bidding happens. Low market prices can thus generate unfair conditions to prosumers.

CDA has been extensively applied to tackle research challenges located in the P2P networks’ virtual layer. The most popular approaches correspond to the use of optimal bidding strategies to efficiency handle local demand and RES supply balancing, reducing and/or managing customer demand during peak hours, and improving prosumers' engagement in P2P trading [9]. CDA-inspired applications to P2P include [19][38].

3.1.1.3 Game theory-based approaches

Game theory models strategic interactions between rational decision-makers in competitive settings. According to game theory, the action taken by one player depends on and affects the actions of other players. It has attracted extensive attention as a key analytical tool in power systems design, including in the analysis of its evolution towards decentralized energy systems, such as microgrids [3][9]. The excellent work in [3] provides a comprehensive analysis of the advantages and limitations of using game theory for designing energy-management schemes both considering and not considering P2P trading. In a nutshell, its ability to model user behaviour and interactive trading, while easily integrating pricing and incentive designs, and to potentially establish trust between peers and motivate them to cooperate all are arguments that play in favour of its use in P2P context.

Game theory can generally be divided into two categories:

- **Non-cooperative games** model the strategic decision-making process of a number of independent players that have partially or totally conflicting interests in the outcome of a decision-making process. Such processes allow players to take optimal decisions without any coordination or communication.
- **Cooperative (or coalition) games** analyse processes where one can provide incentives to independent decision makers to act together as one entity, as means to improve their position in the game.

Local P2P trading can be realized by applying concepts from both non-co-operative game theory, in which either there is no communication or coordination of strategic choices among the players, and cooperative game theory, in which the players exchange information and cooperate actively.

3.1.1.3.1 Non-cooperative gaming approaches

In general, two types of non-cooperative games have been used for designing energy trading schemes: **Static games** and **dynamic games**. In a static game, the players take decisive action only once, either simultaneously or at different times. In contrast, players in a dynamic game act more than once and have some input regarding the choices of other players. In dynamic games, time plays a central role in the decision-making process of each player [3].

The Stackelberg game has been a particularly popular non-cooperative dynamic game used in P2P trading [8]. This is a type of game in which at least one player is defined as first-deciding leader and commits a strategy before the other players. The other players act as followers, optimizing their strategies in response to the action taken by the leader. The solution concept of a Stackelberg game is called the Stackelberg equilibrium.

3.1.1.3.2 Cooperative gaming approaches

Cooperative games or coalition games can fit into three categories: Canonical coalition games, coalition formation games, and coalitional graph games.

The key goals of **canonical coalition games** are to determine whether or not a "grand coalition" involving all players can be formed, to investigate if the grand coalition is stable, and to formulate a fair distribution method for the coalition gains between all the players. In this type of games, forming grand coalitions is not detrimental to any participant in the game [3]. Popular revenue distribution methods used in canonical coalition games include the Shapley value, the Kernel, the nucleolus, and the strong epsilon-core [8].

Coalition formation games study processes leading to coalitions and their structure through the players' interactions, in environments where formation of coalitions has associated costs (unlike in grand coalitions), thus delivering also limited gains [3][8].

Coalitional graph games deal with the connectivity of communications between players, which in some scenarios, can have a major impact on various characteristics of the game. The main goals of coalitional graph games are to derive distributed algorithms for players who wish to build a network graph and to study properties of this network graph [3].

Along the years, a plethora of research has applied game-theoretic approaches to challenges located in the P2P networks' virtual layer. The Stackelberg game has been used to reduce the energy costs and to design pricing mechanisms for P2P transactions. Other non-cooperative games have been applied to local energy balancing and peak shaving problems, incentivizing prosumer participation, and improving security of transactions [8]. Finally, the effectiveness of canonical coalition games has been demonstrated in a series of P2P trading applications, which include local energy demand-supply balancing, fair trading price designs, and prosumer engagement in energy sharing. Example work on game theory applications to P2P trading can be found in [5][9][37].

3.1.2 Assuring secure and transparent P2P trading

The reference approach to ensure that transactions and general information flows in P2P trading remain private, secure, and are transparently communicated is through distributed Blockchain data structures. Blockchain has profound applications to energy systems and shares principles with the P2P philosophy. In [7], the authors argue that Blockchain may be the most important asset in enabling the successful deployment of P2P markets. Blockchain structures are distributed in that they're replicated and shared among the members of a network, eliminating the need for a trusted mediator and/or ledger entity, while achieving same results.

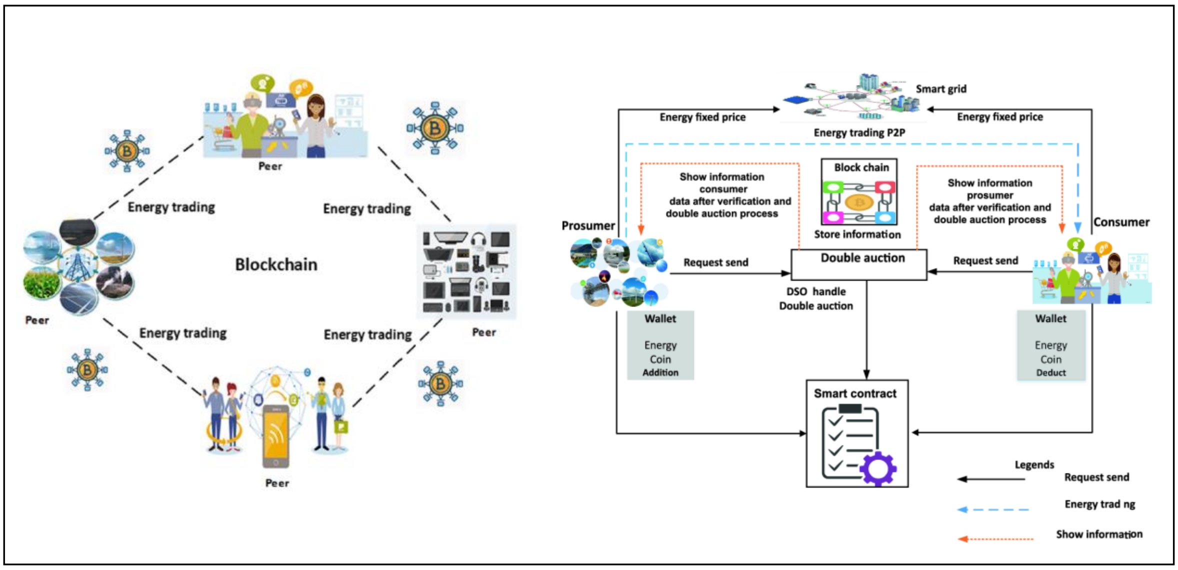

Figure 12 – Conceptual application of smart contracts in CDA-based P2P trading community [39].

Given the interest of this technology to P2P trading, a number of blockchain-based platforms and protocols have emerged specifically in this area, from which the keystone is **Smart contracts**. These are computerized protocols executed under the form of a "contract", which are very safe due to their encrypted language and complementary embedding procedures. This greatly minimizes data and information exposure to malicious threats. Smart contracts are scripts stored on the blockchain with a unique identifier, and once they are "triggered", they're executed in every node of a network [8]. Figure 12 shows an example diagram of how smart contract protocols can integrate into the operations of an auctions-based P2P trading market [39].

Other blockchain platforms include initiatives such as **Hyperledger** and **Ethereum**. The former is an open source collaborative effort launched by the Linux Foundation, with the goal of advancing widely blockchain technology. It uses a consensus mechanism to create a transparent and non-tampering distributed ledger [8]. The latter is a programmable public blockchain using a native cryptocurrency called *Ether*, whose nodes carry more information than a standard blockchain node.

Elecbay is a software platform dedicated to the development of P2P trading specifically within microgrids, which was designed in the work presented in [23]. Under this platform, each P2P order contains information on the time period of the energy exchange, the amount of energy to be exchanged, the price of the energy to be exchanged and the details about the seller and buyer [23]. Orders placed by peers are either rejected or accepted by the platform based on local network requirements and conditions [8]. After this process takes place, energy could then be or not delivered according to the instructions across the microgrid network.

In its essence, Blockchain lives in the virtual layer of the P2P network, hence its extensive application in this domain. Many adoptions and adaptations of this technology can be found in the literature, about which [8] provides extensive account. Some specific P2P trading applications include securing settlement and transactions in decentralized markets and developing trusted trading platforms for electric vehicle sharing networks [8]. Smart contracts have been applied in multiple contexts, being one ambitions application the secure trading between energy storage systems and a heterogeneous portfolio of end-users, specifically from the residential, commercial, and industry sectors [39][40]. The Hyperledger platform has been used to create an operational model of crowdsourced energy systems in distribution networks considering various types of energy trading transactions and crowdsources [41]. The Elecbay software platform has been advanced in [23]. Further example work where blockchain has been applied to P2P trading include [22][24].

3.2 Real-world P2P trading projects

P2P is at an early stage of development. Yet, the last decade – especially the last five years – has seen a plethora of P2P initiatives taking shape in various countries. Much of these are research and technology-based and still exploratory, with little application to current regulatory reality, mainly as a result from the persistent lack of supporting regulatory and market frameworks. Literature is consistent in that it places ongoing project efforts in two main and distinct categories [7][25]: 1) projects targeted at the development, implementation, and testing of **control and ICT solutions** (greater focus on the P2P trading's physical layer) and 2) projects focused on devising **market designs and business models** (greater focus on the P2P trading's virtual layer).

In addition, the literature suggests that projects linked to fully decentralized P2P designs have been majorly popular, perhaps due to its disruptive nature. The most iconic one may well be the **Brooklyn Microgrid**, a blockchain-based energy marketplace set up in 2016 by US start-up company LO3 Energy. The microgrid allows locally generated solar energy from prosumers to trade their excess energy with secure blockchain technology. Participants in the energy trade are from three distribution grid networks that were already vulnerable before the project, facing frequent congestion issues, which justified the experiment [24][26].

In the Brooklyn microgrid, the virtual layer consists of implemented Ethereum blockchain protocols for securely verifying data and handle smart contracts, as well as of the market and pricing mechanisms that realize energy exchanges (Figure 13). The trading is based on measured supply and demand, using real-time market prices. Trading operations are mostly automatic, while still accounting for participant preferences. The physical layer consists of the solar panels, installed on buildings' rooftops, as well as of and the existing distribution grid and required power electronics. The Brooklyn microgrid can operate in an islanded mode, in which case those customers defined as critical facilities (medical, public services) receive energy at fixed rates and residences and businesses have to compete for obtaining the remaining microgrid energy.

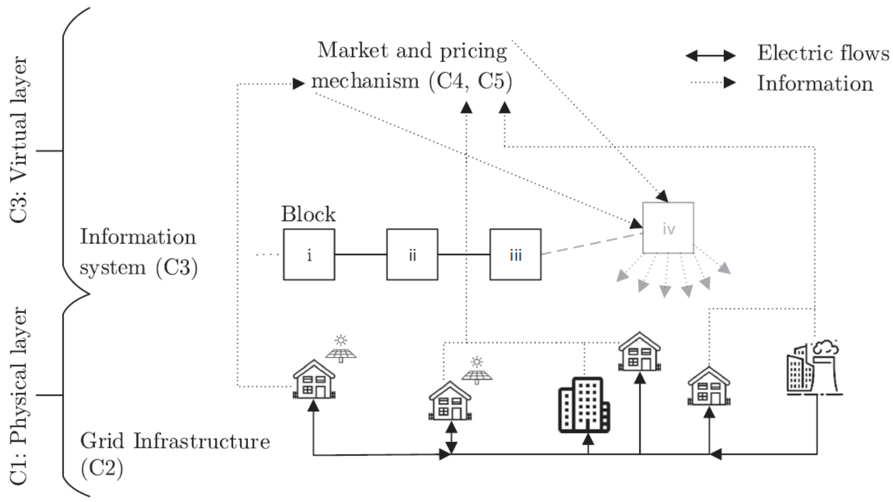

Figure 13 – Structural elements of the virtual and physical layers of the Brooklyn Microgrid as described by Mengelkamp et al., being C1 the microgrid setup, C2 the grid connection, C3 the information system, C4 the market mechanism, and C5 the pricing mechanism [24].

The Brooklyn Microgrid still faces many regulatory challenges. For one, the expansion of participating customers requires strong cooperation from the monopolistic utility and energy regulators. This has led LO3 Energy to seek partnerships around the world to further develop their innovative concepts in less constrained environments [26]. In South Australia, for example, LO3 partnered with Yates Electrical Services to develop transactive energy technologies for grid infrastructure. The initial stage of a project in Riverland offers commercial customers with renewable source options and pricing schemes in a secure blockchain-based marketplace and is expected to be further expanded to larger areas that also include residential customers [27]. In Texas, LO3 joined Direct Energy, also an energy services company, for devising a project that enables commercial and industrial customers equipped with smart metering to participate in the energy markets by using LO3's "Exergy" ledger platform [27]. The same transactive energy platform has been implemented by LO3 in an ongoing 200-customer local energy market trial in Cornwall, UK, under the umbrella of a technology partnership with Centrica, an energy solutions provider. Through the virtual marketplace, the participants can sell their flexible energy capacity to both the grid and the wholesale energy market [28][29]. An unrelated but similarly focused, still shaping up initiative, is being led by UK-based technology company Electron. The company is gathering a multifaceted consortium to develop a large-scale, single-access multi-product flexibility exchange market for DER, based on blockchain technology and to be named **TraDER**. In this marketplace, end users of electricity, such as households, could reduce their instantaneous energy consumption—for example, by reducing the usage of their smart appliances for a price [26].

Trading and ICT platforms have been recently deployed and tested in various European countries. In Germany, **Lumenaza**'s utility-in-a-box energy solution enables P2P energy sharing at local, regional, and national level. The platform matches producers' demand with consumers' needs, and manages balance and supply, aggregation, and billing. The platform further allows communities in participating in the electricity market design [29]. In UK, the **Piclo** trading platform uses location and user preferences to match prosumers and consumers in 30-minute intervals (48 times per day) [25]. The project is targeted at commercial electricity consumers equipped with renewable energy, rather than individuals [29][30]. In the Netherlands, the **Vandebron** online platform allows direct and independent trade between consumers and independent producers, such as farmers owning renewable energy [30]. The platform also provides generation forecasts for energy suppliers. The goal is to reach mutually beneficial arrangements by removing the role of the utility. Producers get better sale deals per unit power, and consumers save money by not paying for electricity bill charges [30]. Yet, both sides are charged a monthly subscription fee to participate.

These developments are not exclusive to the most industrialized economies; in Medellín, Colombia, the **Transactive Energy Initiative** pilot was established for allowing prosumers and consumers with different socio-economic backgrounds to trade surplus energy through a blockchain-based network [29]. In Shariatpur, Bangladesh, **SOLshare** successfully piloted surplus energy trading among rural households with and without solar home systems, enabling a valuable additional revenue stream for the involved communities. The trading networks use a low-voltage DC grid to connect households and bi-directional metering with an ICT backend to control the power flow. Transactions between peers are processed through a mobile application [29][31].

All of the above projects have similar general orientation in that they focus on virtual layer developments of P2P markets. The Brooklyn microgrid, along with its Australian and UK counterpart projects, and the traDER initiative are centred on the development of independent, secure, blockchain-based distributed ledger platforms, which facilitate and circumvent the requirements for involving large incumbent traditional players in customer energy market operations. Lumenaza, Piclo, Vanderbron, and the Transactive Energy projects are all fundamentally geared towards developing platforms that enable or improve elements of the P2P trading process, as well as towards seeking new service and business models that facilitate the incorporation of P2P into current market frameworks. In [25], it is mentioned that at least Piclo and Vanderbron pay exclusive attention to business model aspects, while ignoring the possibility of introducing those models to smaller-scale local energy markets. The SOLshare project is slightly different, since it has a broader focus; while it is effectively implementing local electricity marketplaces in rural areas, it does so by deploying an enabling whole range of both ICT and DER technologies.

More decidedly focused on the design of ICT and control systems was for example the European H2020 project **EMPOWER**, geared at developing and testing a cloud-based, real-time monitoring and management platform for securely executing the metering and trading within local energy communities. The project's main innovation lies in the new technologies it delivered, which create foundations for the sale of products and services related to both IT and energy [7][32]. The **PeerEnergyCloud** was a German project that looked into developing cloud-based technologies for local P2P markets, but was more inclined to studying problems related to short-term load forecasting of local RES production and consumption [25][33]. **Smart Watts**, also proposed in Germany, introduced and tested new advanced optimization components for maximizing and comprehensively integrating the market portfolio of VPPs, as means to support new business models in energy trading and sales, and achieve greater cost-effectiveness and security of supply in the overall energy system [25][34]. Figure 14 shows the main virtual marketplace components that have been addressed in the Smart Watts project.

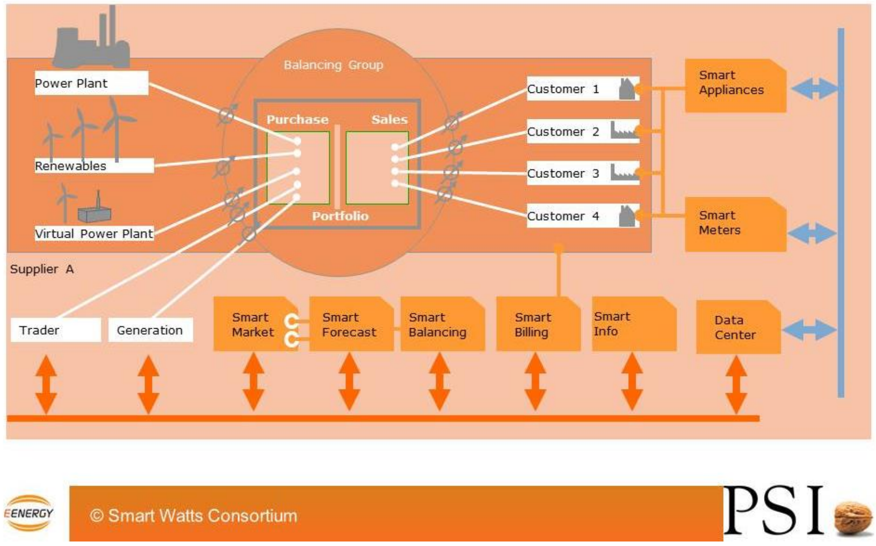

Figure 14 – Key technical components of the Smart Watts project [34]

The **P2P-SmartTest** project is inherently distinct from all of the above in that it pays a greater deal of attention to technical power grid challenges currently hampering the development of P2P markets. Its key focus is on ensuring "the integration of demand side flexibility and the optimum operation of DER and other resources within the network while maintaining second-to-second power balance and the quality and security of the supply" [35]. The project also looks into automatic meter reading (AMR) data and real-time network control, developing solutions to solve low inertia, uncertainty and stability issues in distribution grids.

EMPOWER, PeerEnergyCloud, Smart Watts, and P2P-SmartTest all have a clear technology focus i.e. they focus on developments in the physical layer of P2P markets. Yet, these projects also look into market and business-related aspects (some more than others). In most cases, this is necessary for testing technologies in piloting environment (EMPOWER, P2P-SmartTest…). For example, EMPOWER has a work package on market design, and Smart Watts, as a commercially oriented project was interested in exploring novel services for the VPP segment. Even P2P-SmartTest, with its highly technical orientation, has a work package on developing "suitable business models for P2P-based distributed smart energy grids" and subsequently quantify captured value by these models [35]. This is due to the highly integrated nature of smart grids, where information and systems are deeply enmeshed. Furthermore, these projects are distinguishable based on their technology focus. EMPOWER and PeerEnergyCloud target cloud-based technical solutions for empowering the P2P market. Smart Watts offers new functionalities to a commercial ICT platform targeting VPP services. P2P-SmartTest looks into asset control and electrical distribution network power quality and reliably challenges.

The adopted paradigm for market design varies from project to project. Among the discussed initiatives, the Brooklyn microgrid and its parent projects, the Transactive Energy Initiative, and SOLshare follow a decentralized approach in its core. The work undertaken by Electron disregards to a certain degree the type of market design that P2P participants may be involved in (for example, it is possible that a CM entity participates in Electron's flexibility exchange on behalf of the P2P community). Projects such as Lumenaza, Piclo, and Vanderbron consubstantiate platforms that supervise trading for customers, hence their community-based inspired design. Community-based as well are the four physical layer-focused projects discussed above, namely EMPOWER, PeerEnergyCloud, Smart Watts, and P2P-Smart Test.

Table 3 summarizes the projects discussed in this section, while highlighting some of its key characteristics. LO3 Energy (Brooklyn Microgrid), Lumenaza, Piclo, Venderbron, and SOLshare are not merely projects but full-fledged start-up companies operating in the P2P space. Their solutions have been or are being piloted, improved, and continue being implemented today, reason why these projects are considered "ongoing". Electron is also a company, but the TraDER marketplace has not been implemented yet. The Transactive Energy Initiative, EMPOWER, PeerEnergyCloud, Smart Watts, and P2P-Smart Test are research and/or innovation projects limited in time, either ongoing or already finished.

Table 3 – Selection of relevant P2P trading projects and key characteristics ([24][25][26][27][28][29][30][31][32][33][34][35]).

	Countries involved	Scope of market	Type of P2P design	Key focus
Brooklyn Microgrid and parent projects (2016 - present)	Unite States, Australia, United Kingdom	Local (microgrids)	Fully decentralized	Virtual layer: Blockchain-based solutions for enabling direct, secure P2P trading
TraDER (has not started yet)	United Kingdom	Regional/National	Hybrid (irrelevant)	
Lumenaza (2013 - present)	Germany	Local/Regional/ National	Community-based	Virtual layer: Trading platforms for optimal P2P matching between prosumers and consumers
Piclo (2015 - present)	United Kingdom	National		
Vanderbron (2014 - present)	The Netherlands	National		
Transactive Energy Initiative (2019 - present)	Colombia	Regional	Fully decentralized	Virtual layer: Blockchain-based P2P trading app
SOLshare (2015 - present)	Bangladesh	Local (microgrids)		Virtual/Physical layer: Marketplace enabled by ICT and solar home systems
EMPOWER (2015 - 2017)	Norway, Switzerland, Spain, Malta, Germany	Local (microgrids)/ Regional	Community-based	Physical layer: Cloud-based management solutions for local and external energy trading optimization
PeerEnergyCloud (2012 - 2014)	Germany	Local (microgrids)		
Smart Watts (2008 - 2012)	Germany	Regional/National		Physical layer: VPP market platform enhancement
P2P-Smart Test (2015 - 2017)	Finland, United Kingdom, Spain, Belgium	Regional		Physical layer: New control strategies and ICTs for P2P energy networks

While not a very comprehensive one, the above assessment reveals a growing body of knowledge and portfolio of solutions for enabling efficient, secure, and transparent P2P energy trading in the medium-term. Nevertheless, the projects seem to focus on either one of the P2P network layers. This issue has been recently highlighted in [8]; it is noted that for a successful deployment of P2P trading, it is most important that requirements of both layers are efficiently captured in a "unified model" approach, yet to be developed. In the above survey, far more projects address virtual layer challenges, specifically those related to connecting of participant peers and to enabling the sharing of surplus energy. Interactions with external market opportunities and the trading of not only surplus energy but energy flexibility driven by behavioural change, for example, have been rarely addressed in these projects, and possibly not at all in an explicit manner. Furthermore, while there are exceptions, it appears that less interest exists currently in tackling physical layer challenges. These problems, particularly related to distribution grid power quality and reliability maintenance, are also pressing, and P2P trading will not be fully enabled until they are tackled. In addition, very few projects focus exclusively on the local scope and specifically on local energy communities, energy cooperatives, or community microgrids. This has renewed interest in light of recently enacted EU legislation, which is fully geared towards community energy and collective customer empowerment [1]. On a related note, another unexplored area is business models that empower communities and allow for local growth. Most analysed initiatives have been energy company-driven and the business models tested have been those that generate value for trading platform service providers. While these are incredibly valuable developments, it remains open the question on how much monetary worth can individual participants extract from community-based participation in flexibility markets, for example if supervised by an aggregator entity.

The lack of specific regulatory frameworks and support policies for establishing P2P markets remains a challenge to address in the near future. No projects seem to put much emphasis on these aspects at this point.

This report offers only a selection of P2P projects. There are many other described in recent literature. For a reading on those please consult [24][25][26][27][28][29][30][31][32][33][34][35].

4 Discussion on generic market designs for FleXunity

FleXunity is an industry-geared project under H2020's Fast Track to Innovation (FTI) programme, whose overarching goal is to support close-to-market innovation activities, as means to help co-create and test breakthrough products, services and business processes.

In the specific context of electricity markets, **FleXunity intends to develop technical solutions and services that enable P2P trading within energy communities and its market interactions with retailers, energy aggregators, and network operators**. The project consortium expects FleXunity solutions to become available in selected EU energy markets in the short-term after project completion.

FleXunity operates in the realm of the virtual layer of P2P networks. Accordingly, the project will develop:

1. A market design that combines intra-community P2P interactions with aggregated demand response flexibility provision to the external balancing markets under a VPP model;
2. Business models for subscribing flexible participants and/or communities, for VPP players offering aggregation and CM services, and for retailer entities involved for portfolio optimization;
3. Real-time optimization-based P2P platforms for DER resource allocation, demand/supply matching and energy balancing within energy communities;
4. Blockchain-based technical approaches that establish smart contracts to guarantee trusted and transparent energy trading within FleXunity's concept of flexible energy communities.

FleXunity's concept of market interactions includes a series of interdependent and sequential mechanisms. Firstly, intra-community trading takes place under a constrained optimization routine. Then, residual generation/demand could be balanced by the electric supplier under a residual balancing mechanism [38]. Subsequently, the network operator assesses operational needs and issues incentive signals for ancillary services, to which the community may respond for obtaining added revenue streams. We adapt to FleXunity's context an excellent representation advanced in [38] to highlight these system mechanisms (Figure 15).

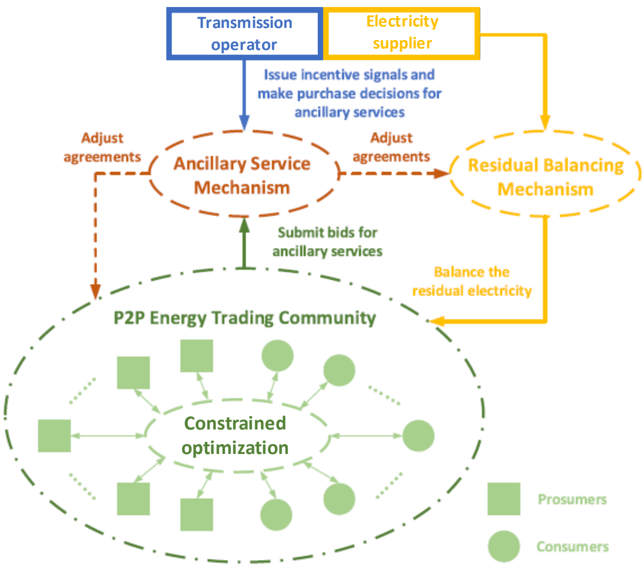

Figure 15 – Mechanisms of internal and external market interactions of flexible energy communities (adapted from [38]).

This section elaborates on a tentative market design for FleXunity's generic model of flexible energy communities and for each of its two pilots in the UK and Spain/Portugal (Iberia pilot).

4.1 A generic market design for FleXunity

The FleXunity project is rooted in the concept of remote aggregated control of small flexible resources under a VPP model. The project consortium strongly believes that this approach is beneficial for both markets and communities, allowing for the optimal exploitation of local flexibility opportunities by energy citizens and of new market services by the aggregator entity. **This is compatible with literature envisioning a supervisory control entity that optimizes internal energy trading activities and also capitalizes on revenue opportunities on behalf of participant prosumers and consumers** (advantages and compatibility of these structures have been argued comprehensively in subsections 2.1.4 and in 2.4). Therefore, the starting point to FleXunity is to adopt a community-based P2P market design, as explained in 2.1.4.2. Here we follow the simplified approach presented by [7] of the mathematical formulation introduced in [18]:

$$\min_{D} \sum_{n \in \Omega} C_n(p_n, q_n, \alpha_n, \beta_n) + G(q_{imp}, q_{exp}) \tag{3a}$$

$$s.t.$$

$$p_n + q_n + \alpha_n + \beta_n = 0, \qquad \forall\, n \,\epsilon\, \Omega, \tag{3b}$$

$$\sum_{n \in \Omega} q_n = 0, \tag{3c}$$

$$\sum_{n \in \Omega} \alpha_n = q_{imp}, \tag{3d}$$

$$\text{and} \sum_{n \in \Omega} \beta_n = q_{exp}, \tag{3e}$$

where

$$\underline{p_n} \le p_n \le \overline{p_n}, \qquad \forall\, n \in \Omega, \tag{3f}$$

$$and\ D = (p_n, q_n, \alpha_n, \beta_n \in \mathbb{R}) \tag{3g}$$

where p_n corresponds to the energy production or consumption of peer n, whether it is a prosumer or consumer, respectively, Ω is the set of all peers in the community, q_n is the traded flexibility within the community, α_n and β_n are the energy imports and exports from and to outside of the community, respectively. The sum of individual peer imports and exports is given by community-traded volumes q_{imp} and $q_{exp.}$

The above model minimizes costs for a P2P community's energy economics by combining the intra-trading and external trading functions C and G, respectively, in objective function $(3a)$. Please note that p_n and q_n are bidirectional values. For p_n, a positive value means energy production, while a negative value means energy consumption. The reasoning is the same for q_n, but in terms of trade within the community. Also, p_n

is capped by $\underline{p_n}$ and $\overline{p_n}$ (which add to the constraints to the optimization). The above model is also subject to a series of energy balancing constraints, expressed via equations $(3b)$ and $(3c)$. These balances are centrally handled by the CM, which means that peers are unaware of the recipients of their trading volumes q_n – these activities take place securely and privately. Furthermore, the sum of outside trading is managed through equations $(3d)$ and $(3e)$. The cost structure for the community is then affected by specific transaction costs for inner P2P (φ_{com}), which are applicable to the modulus of traded volume. Peer preferences as to external market trading can be expressed via scalar weighting coefficients (δ_{imp}) and (δ_{exp}), applicable to α_n and β_n. It remains open how will external energy exchanges be modelled by a function γ, which is dependent upon the specific nature of the applicable energy markets, but [7][18] could be consulted for further details.

Figure 16 provides a generic and representation of the above mathematical model. This is the simplest configuration possible for a P2P community following the specific criteria of FleXunity project, i.e. composed of two customers – one prosumer and one consumer.

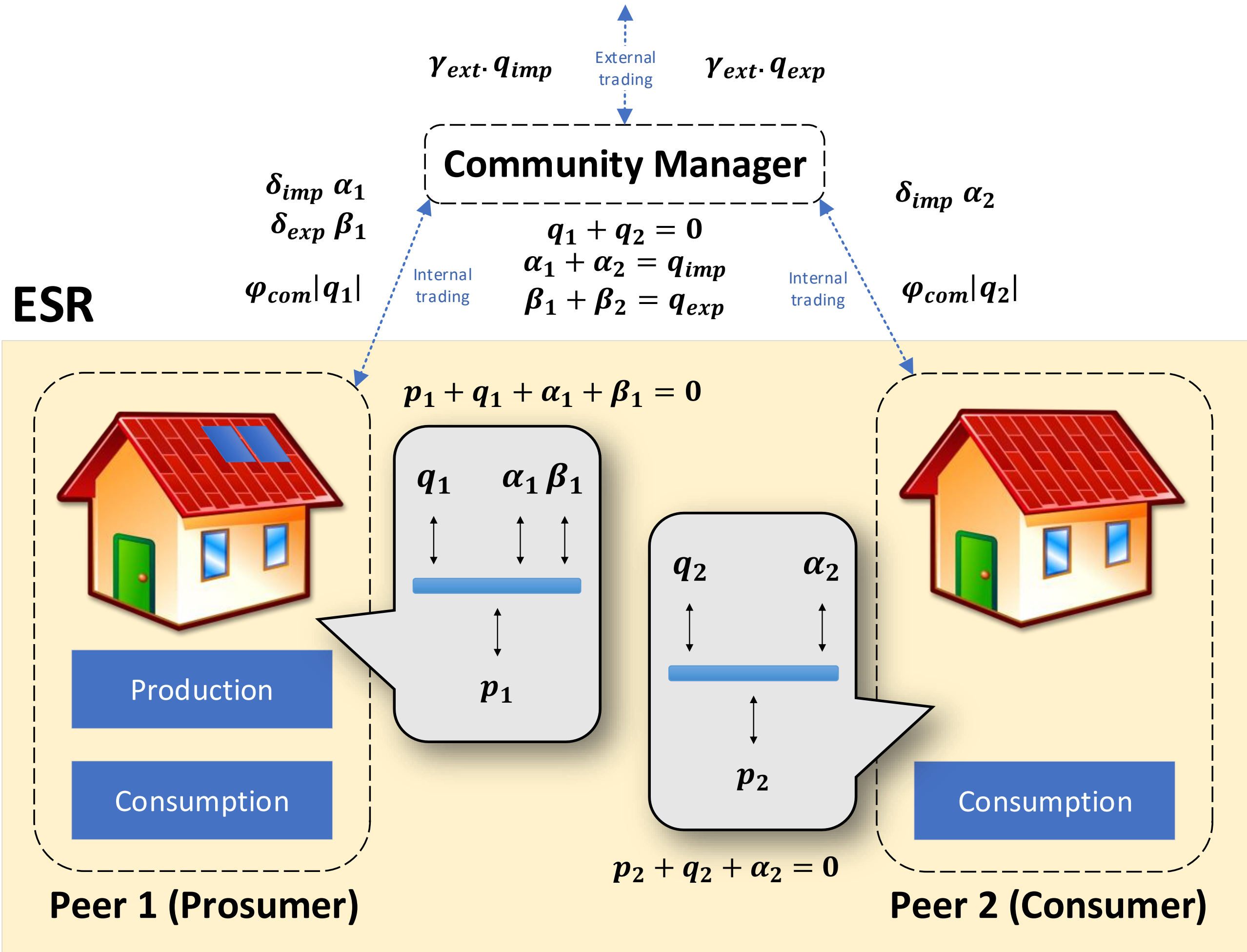

Figure 16 – Illustrative representation of a tentative P2P community model for FleXunity.

The next subsection will provide more details on the planned FleXunity pilots, as well as to the specific potential for application of this market design in each pilot's context.

4.2 Application and feasibility in the FleXunity pilots

In this subsection, a brief overview will be provided of plans for ongoing flexible community pilots in the FleXunity project and of specifically applicable regulatory conditions in terms of external markets. This will be then analysed in light of the tentative market model and respective interactions described in 4.1.

4.2.1 The Corby community pilot (England/UK)

Corby is a town and borough in Northamptonshire County, England, with a population of 72 218 people, approximately. Estimates for domestic electricity consumption in Corby point to about 100 GWh per year. The town has a high proportion of industrial electricity consumers, with around 393 GWh electricity consumed per year. Corby is an energy-progressive community, with over 1 000 homes with installed solar PV systems, including 100 council homes. Figure 17 offers an aerial view of the urban fabric in Corby town.

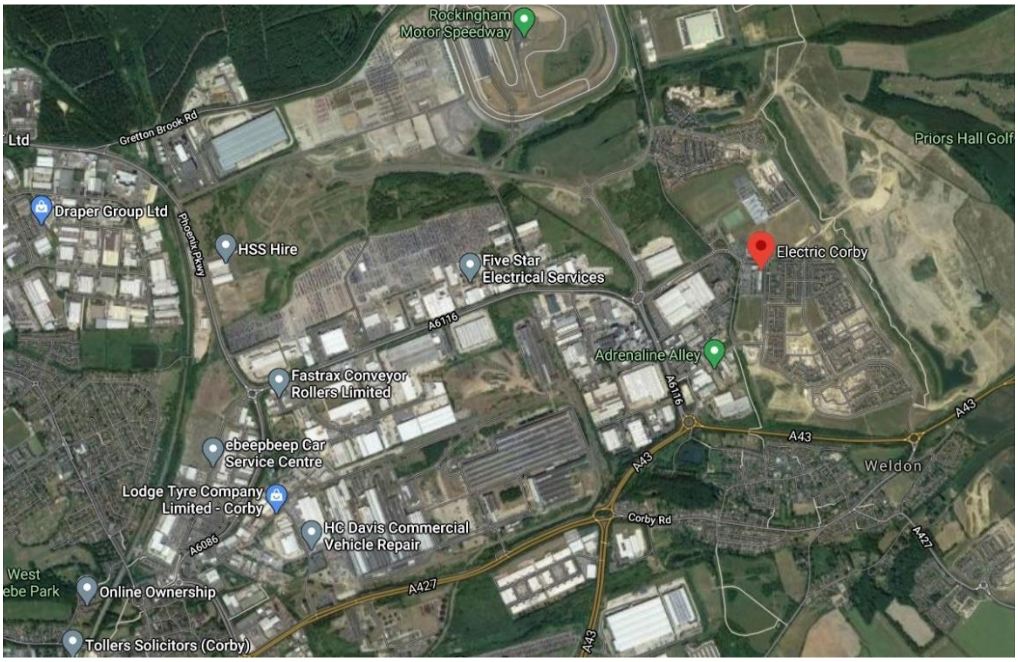

Figure 17 – Google Maps view of the urban topology in Corby town, in Northamptonshire County, England.

Recruitment efforts for joining the flexible community pilot are ongoing. However, a substantial number of customers, particularly the business ones, have communicated already intentions to get involved. Electric Corby has interacted extensively with these prospective participants. In total, Electric Corby aims to recruit:

- 4 businesses at least with solar PV generation (commercial prosumer customers);
- 20 homes at least with solar PV generation (residential prosumer customers);
- 10 homes without any DER (consumer-only customers, working as a control group).

Furthermore, Electric Corby has been carefully selecting the customers it works with, **as means to ensure some form of flexible loads are included in the facility**. The businesses, for example, are equipped with centralized HVAC systems, while the homes have electric heating. As explained earlier, the pilot will use this demand response flexibility as a capital asset in the energy management of the community.

The business customer participants have been well studied. Some key characteristics of these four facilities have been highlighted in Table 4.

Table 4 – Key characteristics of prospective business customers to be recruited for FleXunity's Corby pilot.

Business customers	Relevant characteristics
#1 Industrial food plant	• Annual electricity consumption of approximately 4,000 000 kWh; • PV generation of about 40-45 MWh per year; • Flexible load at least from a 600kW chiller unit.
#2 Industrial manufacturer	• Annual electricity use of around 45,000 kWh; • Installed PV generation capacity of 8 kWp; • Flexible load at least from centralized HVAC, deployed across the facility.
#3 Business centre	• Annual electricity consumption of 300 000 kWh; PV generation capacity of 50 kWp; • Flexible load at least from electric heaters throughout office areas.
#4 Council depot	• Annual electricity consumption of approximately 65 000 kWh; • Installed PV generation capacity of 30 kWp; • Flexible load at least from air Conditioning units throughout office areas

In terms of residential customers, six council homes, owned by Corby Borough Council, have been surveyed so far. There are big disparities in this sample in terms of annual electricity consumption, which may range from about 1,100 kWh to over 8,000 kWh per year (average of about 2500 kWh per year). All these houses are equipped with solar PV systems (12x 250Wp PV panel installations). The discussion on load flexibility is ongoing and requires further work. Few UK homes have flexible loads such as HVAC/electric heating. As such, the project will consider the use of flexibility from appliances such as large freezers or electric water heaters. There is also an EV charging network in the area, and specifically four charging points within the community. Thus, the possibility of incorporating EV charging in the flexibility share of some customers will also considered.

The FleXunity project will deploy ICT devices and cloud-based platforms for flexibility management linked to recruited customer facilities. **The Corby pilot reflects well the setup envisioned in Figure 16, as it includes both consumers and prosumers**. This will enable the flexibility needs for establishing a P2P community.

The community manager role in FleXunity is played by an aggregator entity, even though Corby is a localized energy community. **This is in line with the ability of the supervisory control model introduced in 2.1.4.2 and with the capabilities of the generic market design developed in 4.1**. The aggregator will thus manage the energy balance for the community and mediate revenue opportunities with the external markets. **In terms of balancing market participation, the Corby pilot will benefit from one of the most progressive energy markets in Europe for decentralized energy**, as comprehensively described in *D2.1 – Legal and technical requirements of balancing markets*.

Balancing markets in England, specifically Reserves and Frequency Response markets, are extensively developed and increasingly open to the participation of small-scale resources – especially demand response. In addition, the role of independent aggregation is not only regulated and recognized as of great value in securing the system's balancing, but also facilitated in various market streams. For example, demand turn-up requires a minimum bid of 1MW, but aggregators can participate if the minimum site aggregation is of at least

0,1MW. In the case of the Corby pilot, because it involves some large clients, even a higher minimum bid could possibly not block the ability to provide demand response flexibility. National Grid (England's TSO) has consistently encouraged the participation of small customers in the balancing markets. Thus, it is likely that this operator would be open to explore the unique flexibility exploitation opportunities brought by the FleXunity project. While in England there has been a growing interest in demand response, with several pilots and commercial projects having been or being launched, FleXunity has novel characteristics that may drive renewed interest. Nevertheless, this aspect of the Corby pilot has not yet been comprehensively addressed and requires further study (for example of which balancing services would be more beneficial to tackle) at a point when more structural elements of the community have been established.

4.2.2 The Iberia virtual energy community pilot (Portugal and Spain)

FleXunity's Iberia pilot is considerably different from the Corby one. It configures a **virtual energy community, which is distributed across the territory of two countries** – Portugal and Spain. The participants are residential and commercial customers of SIMPLES, which operates as a retailer in both countries. Figure 18 highlights the geographical distribution of these customers across the Iberian Peninsula. While the majority of the Spanish customers are located in the Northern Galicia region, three more prospective customers are located in the Castilla-La Mancha and Castille and León regions.

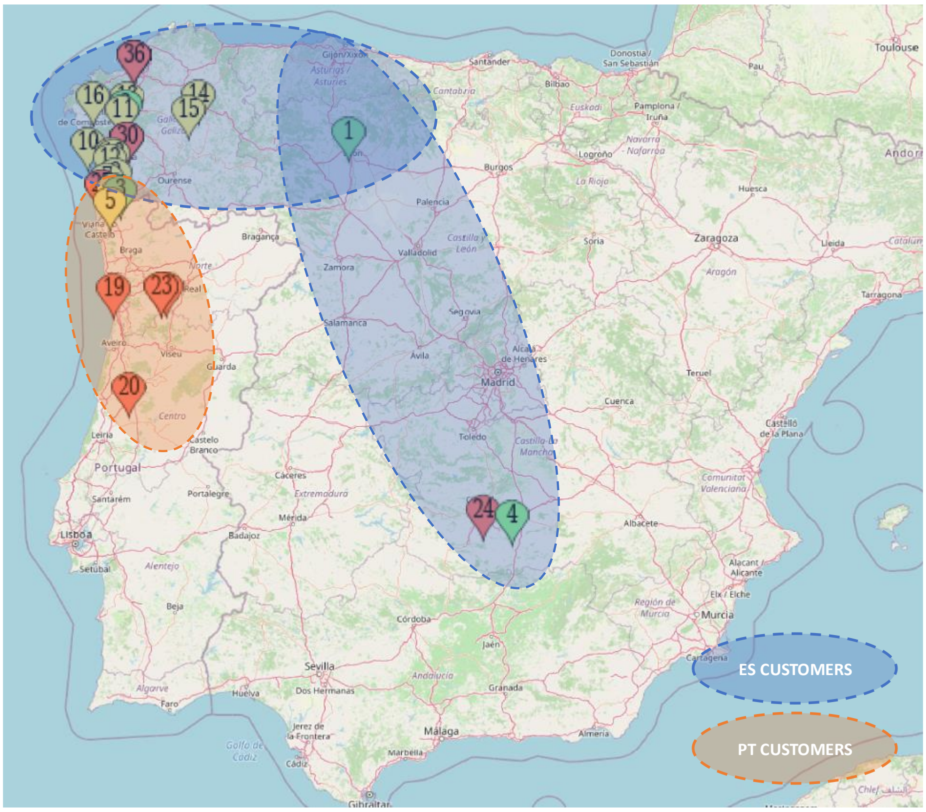

Figure 18 – Zoomed out geographical distribution of customers under recruitment for FleXunity's Iberian flexible community pilot.

The level of decentralization imposed by the Iberia pilot could pose some technical and regulatory challenges but is nonetheless of great interest for the FleXunity consortium. In addition, the type of customer groupings it establishes is in line with the new formal EU definition for "citizen energy communities" [1], which establishes that **customer co-location is not a requirement *per se* for citizens to organize around common**

energy service goals. FleXunity is pioneering the testing of these community setups, as well as of enabling community ownership and business models under this new regulatory setting.

Developments with FleXunity's Iberia pilot are still in its infancy. However, SIMPLES has already reached out to a substantial number of customers for recruitment. The overall goals of the pilot are to involve:

- In Spain
    - 20 homes equipped at least with solar PV and electric storage (residential prosumers);
    - 1 municipal building, 1 small industry facility, and 2 office buildings, all of these equipped at least with PV and storage (commercial prosumers);
    - 10 homes (residential consumers – control group).
- In Portugal
    - 3 homes, whose DER equipment is not known yet;
    - 2 office building customers (commercial consumers).

As criteria for participation in the pilot, **all the above customer facilities will entail some level of load flexibility**. In addition, there are tentative plans to include four EV charging stations in commercial building premises, which could potentiate the flexibility pool available to the community. Since this pilot involves a high number and widespread distribution of customers, the collection of client data is bearing exceptional efforts and further surveys have not been performed yet, nor have customers been inquired as to their energy profiles. Table 5 summarizes the available information at this point.

Table 5 – Key characteristics of prospective business customers to be recruited for FleXunity's Iberia pilot.

Country location	Customers	Relevant characteristics
Spain	20 residential prosumers	• Solar PV systems; • Electric storage; • Smaller load flexibility to further determine.
	10 residential consumers	• Smaller load flexibility to further determine.
	Municipality Building (commercial prosumer)	• Annual electricity consumption of approximately 25 000 kWh; • Flexible load from HVAC; • Solar PV system; • Electric storage.
	Company dealing with construction of Hydraulic Works (commercial prosumer)	• Annual electric consumption of 230 000 kWh; • Flexible load from HVAC; • Solar PV system; • Electric storage.
	Office Building #1 (commercial prosumer)	• Annual electric use of approximately 10 000 kWh; • Flexible load from HVAC; • Solar PV system; • Electric storage.
	Office Building #2 (commercial prosumer)	• Annual electric use of approximately 10 000 kWh; • Flexible load from HVAC; • Solar PV system; • Electric storage.

Country location	Customers	Relevant characteristics
Portugal	3 residential customers	• Flexible load from HVAC; • No further information yet.
	2 office buildings (commercial consumers)	• Flexible load from HVAC; • No further information yet.

During the pilot, the community members will be equipped with flexibility management devices for partial remote control of their loads. Through novel ICT interfaces, members of the energy communities will be able to sell their energy and share their flexibility by subscribing to new pricing schemes, setting up their member profile and monitoring their monthly revenues/rebates in their energy bill. In this setup, members will be able to provide other user preferences for participation in the energy community. FleXunity's cloud-based optimization will then enable the resource allocation and manage internal energy trading. **Due to the geographical distribution of the peers, in this pilot, the aggregator is the only market player in the position to offer community management services, which is fully in line with the market design introduced in 4.1.**

Theoretically and according to the models developed, the aggregator entity can facilitate external participation in the balancing markets. However, **in the Iberia pilot, customers are spread across two transmission system operator territories** – Red Eléctrica de España (REE), in Spain, and Redes Energéticas Nacionais (REN) in Portugal. This is yet another remarkable characteristic of this pilot; indeed, the new EU energy policy package [1] contemplates the possibility of energy communities that extend beyond country borders. Nonetheless, **the regulatory burden of such option may be too great for effective market participation to take place during FleXunity's timeframe**.

In addition, as *D2.1 – Legal and technical requirements of balancing markets* has revealed, both the Spanish and Portuguese TSOs are among the least conducive to the participation of demand response in balancing markets, particularly via independent aggregation. In reality, both countries have been piloting such frameworks; in Spain, this has been done already through aggregation mechanisms, and the role of aggregator parties is expected to be recognized in the near future. In Portugal, the tested participation has been for large, industrial customers, with minimum 1MW bids. The results of this pilot have been published only in July 2020, and among the policy recommendations there's also the recognition for aggregator entities, which is a significant step ahead. Nevertheless, while regulatory reform is either planned or under way in both countries, it seems improbable that the FleXunity project could leverage any real-world opportunities from it in the short timeframe it has left. Therefore, **it could be more beneficial to the Iberia pilot to use computational simulation approaches to assess the benefits of external market participation**. For maximum approximation to reality, these simulations could run over models entailing expected regulatory contexts for the short-medium term applicable to both countries. This topic, of course, has not been addressed in detail yet in relation to either of the pilots, reason why more substantiated discussion will be required during the next steps of the FleXunity project.

5 Conclusions

This report has investigated the inner workings of flexible energy communities for the FleXunity project. These entail groups of citizens organized around the goal of capturing the collective value from optimized management of local energy resources. In the context of FleXunity, flexible energy communities are focused around peer-to-peer energy sharing. Furthermore, FleXunity envisions a scenario where flexible energy communities become active players in the energy system, by trading demand response flexibility in the balancing markets with support from aggregators.

A review of market designs for P2P energy sharing revealed that **community-based structures, or "energy collectives" are suitable to the centralized supervisory control of flexible communities** introduced above. According to recent literature, these models gather many advantages, but are particularly valued for their ability to maximize revenue opportunities for P2P participants. Besides, they can be applied to both localized and distributed systems, which is precisely the structure of FleXunity's Corby and Iberia pilots, respectively.

Technical approaches to address market-related problems in P2P trading include game theory, auctions-theory, and optimization. Scientific literature on these topics is extensive, but real-world – even experimental – applications of it are scarce. **FleXunity will adopt a type of constrained optimization to tackle supervisory energy management decisions and market allocation problems**. The project will additionally use blockchain mechanisms to secure financial flows. This report has revealed a range of options in that domain; Blockchain is currently the "golden standard" for assuring trusted transactions in multitude of applications, but platforms such as Elecbay are specific to P2P trading and deserve further consideration.

A generic market design **combining intra-community P2P interactions with aggregated demand response flexibility provision to the external balancing markets** under a VPP model has been proposed for FleXunity.

While both the Corby and the Iberia flexible community pilots are at an infancy stage, the applicability of the proposed market design to their context was briefly discussed. **Both pilots reflect well the structural requirements for an implementation of the community-based model**. However, the Corby pilot is in an advantageous position for testing external balancing market interactions, given the highly progressive context of England's energy markets. It is unlikely, on the hand, that real-world demand response participation in reserves takes place in the Iberia pilot, due to a combination of reasons that include FleXunity's timeframe and two non-supportive regulatory contexts. Therefore, **it could be more beneficial to the Iberia pilot to use computational simulation approaches to assess the benefits of external market participation**.

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