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Economic Trades in Energy Communities and Optimal Allocation : A comprehensive literature review

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Abstract. The crucial issue on how to model an optimal economic trading model for Energy Communities (ECs) reveals the need for adapted trading mechanisms and pricing strategies in emerging decentralised market forms. Yet, the extent to which these trading models influence the allocation of costs and benefits to EC members remains unexplored. This article provides an overview of existing literature findings, lays down relevant models and derives essential principles for economic trades inside ECs. For this purpose, this article conducts a comprehensive review of relevant literature across economic and engineering domains, with a specific focus on ECs and Peer-to-Peer (P2P) markets. By examining these concepts, important obstacles and enablers of local energy trading are discussed and related to the framework of ECs. Among the assessed models, the community-based P2P model emerges as highly adaptable for ECs, primarily due to its potential to foster cooperation among prosumers. Furthermore, this article delves into vital insights concerning sharing mechanisms and their integration within trading models. Finally, essential conditions and key considerations are proposed to determine the optimal energy trading structure for ECs, including the need to find a balance between efficiency, fairness and scalability in the design of allocation methods.

Keywords: Local energy trading, Energy Communities, Prosumers, Peer-to-Peer trading, Cost allocation, Optimisation models.

1 Introduction

In the urgent need to create more decarbonised energy systems, Distributed Energy Resources (DERs) have been supported by emerging policy schemes and benefit from increased affordability (IEA, 2022). However, as renewable energies are characterised by intermittent and unpredictable energy production levels, their integration into the centralised energy system comes with major hurdles. Distribution grids, in particular, will be impacted as they connect small DERs with end-consumers (Wang et al., 2015). In this context, Local Energy Markets (LEMs) gain increasing interest and constitute a new

market approach enabling the real-time pricing and the local balancing of energy supply and demand with the inclusion of DERs and prosumers, i.e. users who both generate and consume electricity in the energy system (Mengelkamp et al., 2018; Parag and Sovacool, 2016). Among several market designs of LEMs, there has been a growing interest for Energy Communities (ECs), in which prosumers benefit from energy cost reductions due to joint-owned DER assets. These communities provide members with a platform to generate, store, and trade energy within their local area. The trading activities are generally operated on a small scale and within a collaborative structure, with the support of a non-profit centralised manager (Moret and Pinson, 2019). Hence, local ECs play a pivotal role in the energy transition by fostering local energy generation, particularly with the use of renewable energy resources. To enhance self-consumption incentives and ensure the viability of ECs, the development of efficient trading and allocation schemes is essential.

However, ECs constitute a rather recent market model for decentralised energy systems and their financial and technical viability are still questioned a lot. While the current literature on emerging trading concepts is particularly discussed in engineering studies, the underlying trading designs of local energy and allocation mechanisms between the members of the community have not been explored much in economic papers nor have these aspects been distinctly differentiated.

This paper aims to provide a comprehensive understanding of relevant energy trading

models in the context of ECs. This should clarify related economic questions concerning the organisation inside ECs, with a focus on the adaptability of cooperative systems in relation to the community market. This paper pays particular attention to the analysis of optimal energy trading designs, which incentivise community members to invest in joint renewable energy assets. Therefore, this literature review gives an overview and analysis of relevant optimisation approaches in the context of economic trades inside ECs and encompasses insights from industrial economics, game theory and regulation schemes, while discussing their outcomes.

The present paper is structured as follows. Section 2 introduces the current framework of ECs and presents key aspects of local energy trades. Section 3 reviews recent literature on Peer-to-Peer (P2P) trades by analysing their theoretical framework and their optimisation approaches with high relevance for the EC framework. Section 4 presents how trading designs are connected to sharing mechanisms and explains their crucial components. Section 5 discusses some major challenges for their implementation inside ECs and identifies essential research gaps. Finally, Section 6 states some concluding remarks and future research avenues.

2 Emerging framework of Energy Communities and the concept of energy trading

With the same aim as larger power systems to supply energy from the generation point to the consumption point, ECs provide a local market arrangement to closely located energy

prosumers who trade their energy surplus with each other (Li et al., 2021). This section presents in a first step the global framework of ECs (2.1) and explains in a second step the main concepts of local energy trading (2.2).

2.1 Framework of ECs

The concept of an EC is flexible and encompasses a range of configurations (Mantegazzini et al., 2023). Typically, the EC consists of the collective, participatory, and local grouping of several end-users, which can act as traditional consumers or prosumers (Mustika et al., 2022). These groups can include citizens, firms and organisations that are located in the same neighbourhood and invest collectively in renewable energy production units. In some cases, they represent a virtual platform that connects participants virtually without the need to be located close to each other (Rossetto et al., 2022).

As self-sufficiency is still hardly economically and physically feasible, ECs need to interact with the national grid to export excess energy or import power when the community production does not match the community supply. Therefore, the community is mostly equipped with energy storage systems (such as Li-ion batteries or electric vehicles) to increase their self-consumption rates. To facilitate the energy and economic trades between members and with the grid, a Community Manager (CM) aggregates the respective loads of the members and communicates with external parties, just like the Distribution System Operator (DSO) and managers of connected neighbouring communities (Rebenaque et al.,

2023). Figure 1 depicts a general framework of an EC.

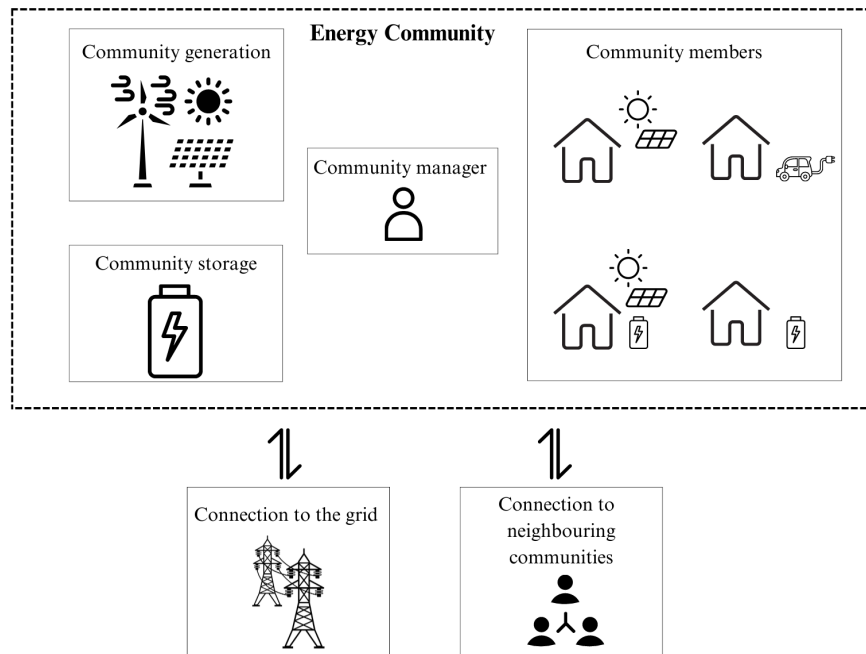


Fig 1 The general framework of an EC.

2.2 Energy trading concepts

To understand how the trading system inside an EC works, it is essential to get a general comprehension of different concepts and trends in local energy systems. Local energy trading consists in selling the energy surplus to other energy consumers or entities within or outside the local market, contributing to the local economy and enabling revenue generation for the community. When prosumers are producing more energy than they consume, they have typically three main options to avoid energy surplus being wasted (Shrestha

et al., 2019). Community members can either exchange their energy surplus with the members of the community, store it in their individual or joint-owned storage systems, or sell it to either other communities (if existing) or the grid at grid tariffs.

These trading tariffs may depend on various factors, including the specific energy market rules and national regulations. However, trading tariffs need to fulfill some important conditions. Firstly, it is essential that the price to buy energy from the grid $p^b(G)$ is higher than its proposed selling price $p^s(G)$. Otherwise, prosumers would be incited to sell their energy for a higher price and buy it again from the grid at a smaller price to gain an additional profit. This would result in a cost-inefficient outcome and in a significant revenue loss for the DSO (Limmer, 2023; Long et al., 2019). For similar reasons, we can assume the same relationship between the buying and selling prices inside the community ($p^b(C) > p^s(C)$). Additionally, members need to be incentivised to stay and to trade within the community, so that the local price for selling surplus energy to the community at $p^s(C)$ (or buying deficit energy from the community at $p^b(C)$) needs to be higher (or smaller) than the price when selling excess energy to the grid $p^s(G)$ (or buying from the grid $p^b(G)$). These economic relations can be summarised under condition 1.

$$p^b(G) > p^b(C) > p^s(C) > p^s(G) \quad (1)$$

After having identified the main conditions of local energy trading, this paper relates to

three relevant concepts in order to adopt a comprehensive overview of economic trades inside ECs. As these concepts serve different purposes and involve different considerations, it is important to consider how they are related to each other. Local energy markets can be considered as the overarching concept, in which a business model and the framework conditions for different trading and sharing models are defined. However, it is important to distinguish between energy trading mechanisms and energy sharing models. Energy trading mechanisms, on the one hand, refer to systems and processes through which energy can be bought and sold. These mechanisms aim to facilitate efficient trading processes of energy and are often associated to market structures and trading arrangements such as the frequently analysed P2P trading approach. On the other hand, energy sharing models determine the implementation of these trading rules, such as guidelines for defining the allocation of costs and benefits among the involved stakeholders in energy transactions. These sharing models should aim to establish fair and equal allocation conditions inside the trading mechanisms for the actors participating in the local energy market. In this context, it is essential to analyse trading models, which seem appropriate for ECs (see [3](#)), before relating these models to appropriate sharing mechanisms (see [4](#)). These three interrelated concepts are visualised by [Figure 2](#).

To derive some relevant trading models that seem suitable for ECs, especially markets that present a variable demand profile (e.g. very diverse participants) and which are unable

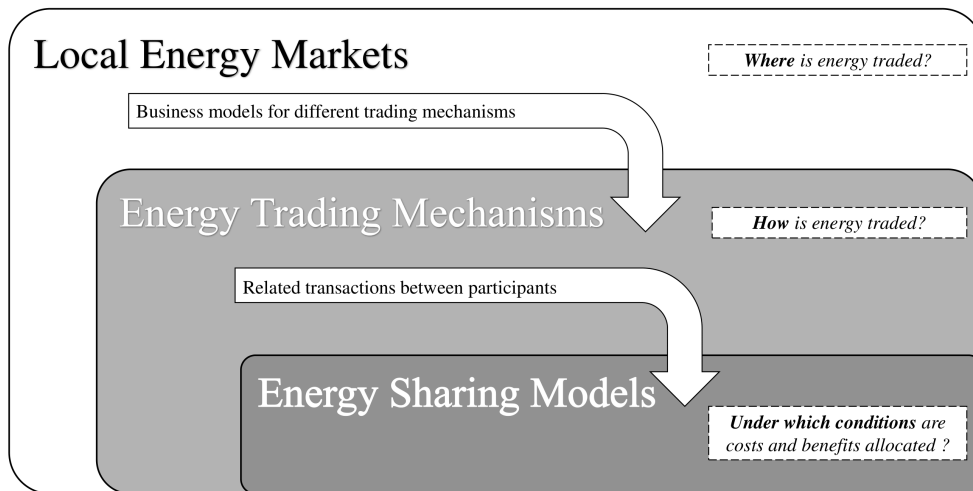


Fig 2 Key findings from three integrated energy trading concepts.

to reach large economies of scale in production, are of interest in this analysis (Shrestha et al., 2019). Capper et al. (2022) observed a lack of substantial research contributions in the field of collaborative local market forms and a significant under-representation in literature compared to P2P markets and transactive energy markets. While transactive energy models do not constitute a marketplace, but offer a set of supporting tools focusing on optimal control systems and the price parameter (The Grid-Wise Architecture Council, 2015), a P2P market entails a service platform that aims to facilitate exchanges and communication between unequal sellers and buyers in a direct way (Steinmetz and Wehrle, 2005). Given these characteristics and many available studies on P2P trading markets, it is imperative to focus on this market niche and to derive some major implications for ECs.

3 P2P trading models

P2P trading systems allow prosumers to trade their energy within the neighbourhood through local buying and selling activities without involving any intermediary entity (Long et al., 2019). Many recent contributions from engineering-related studies refer to microgrids and transactive energy markets to analyse related trading models. Parag and Sovacool (2016) studied market structures for prosumers and identified four distinct trading models, suitable for either P2P markets, connected microgrids, standalone microgrids or virtual power plants. Based on this categorisation, Sousa et al. (2019), Zahraoui et al. (2023) and Garcia et al. (2023) highlighted three relevant types of P2P energy trading mechanisms for local energy markets, which are described further in the following. In these papers, the authors compared the typical P2P model, allowing bilateral negotiations and direct trades without any third party, to the community-based model and the hybrid model. In the community-based model, prosumers are not directly negotiating about energy trades, as an intermediary entity or aggregator controls and coordinates those activities. The hybrid model instead allows prosumers to trade directly with each other while being supervised by centralised coordinator. Table 1 summarises the main characteristics of the presented trading models.

While the community-based model presents beneficial opportunities for the local organisation inside neighbourhoods and communities, the hybrid model presents a more or-

Table 1 P2P trading models and their characteristics.

Trading model	Level of trading	Communication of information	Level of cooperation
Fully P2P	decentralised	decentralised	low
Community-based	centralised	centralised	very high
Hybrid P2P	decentralised	centralised	high

ganised model (Parag and Sovacool, 2016). However, with the community-based model, the level of cooperation between members is expected to increase, as they transfer their trading activities to a centralised entity, which aims to increase the community's benefit. Inversely, the decentralised forms of trading mechanisms show a lower level of cooperation between the participating actors compared to the community-based model. In this sense, the full P2P trading model seems hardly applicable for trading within small community platforms due to the decentralisation of trading and communication processes, which implicate high transaction costs. In addition, as the competition level will increase with the decentralised form of local trading, the security of P2P transactions is threatened and needs to be ensured (Shrestha et al., 2019). This can be challenging while complex methods could discourage the participation of those members (Abada et al., 2020). In contrast, it appears much more efficient to centralise trades with the help of a CM, as implemented in a hybrid or community-based trading model. Hence, it will be of further interest to investigate and compare the economic effects of the different P2P trading models on community members. Additionally, to define adequate platforms for small-scale communities, the direct and indirect impacts of these models on the allocation of costs and benefits should be

further evaluated .

3.1 Theoretical approaches of P2P trading models

As P2P trading models seem to be of high relevance for the operation and the viability of ECs, it is essential to analyse theoretical approaches that have been highlighted in current literature in the context of P2P energy trading modelling and community operations. There exist already some relevant studies that summarise existing trading methods and approaches for P2P energy trading. Zahraoui et al. (2023) and Tushar et al. (2019) limited their evaluation to four methods and referred them to important literature contributions. In addition, Shrestha et al. (2019) developed an overview of the features, advantages and disadvantages of the six methods used in P2P energy trading. Mengelkamp et al. (2019) reviewed methodologies related to local energy markets, microgrids and P2P trading and found that optimisation programs were mostly modelled by P2P trading markets, whereas simulation and game theoretical approaches were mostly conducted with other market forms than ECs. Gržanić et al. (2022) listed P2P trading mechanisms according to their theoretical framework and optimisation approaches, where most of them could be related to distributed methods, game theoretical- and auction theoretical-based models. These three approaches are further described as they were highly presented in the analysed literature.

(a) *Distributed optimisation methods* were often mentioned in the context of P2P trad-

ing (Gautier et al., 2023; Mengelkamp et al., 2018). P2P trading models are often formulated as general optimisation problems, which can be decomposed into sub-problems (Zahraoui et al., 2023). These optimisation techniques are most commonly used to study the scalability of energy markets within a centralised energy management, the power limits and optimal characteristics of installed DERs. For instance, the works of Paudel and Beng (2018) and Gokcek et al. (2022) developed a hierarchical optimisation model to improve P2P trades for ECs. The former modelled the EC as a middle level between the residential level and the utility grid level, while the latter proposed a two-level problem to model an optimal bidding strategy with community storage and generation assets. A two-level optimisation program was also implemented by Perger and Auer (2022) to model the dynamic participation of community members with P2P trades and to determine the optimal number of accepted new members inside the EC.

- (b) *Game theoretical models* proved to be significant in the development of incentive business models for decentralised energy systems as well as the sharing management for energy assets and associated costs. By using cooperative or non-cooperative games, strategic and complex interactions can be analysed and modelled among multiple decision-makers inside the community, given some set rules (e.g., rationality assumptions) and outcomes. To avoid manipulated results in the energy trad-

ing process, only relevant parameters should be integrated into the model (Shrestha et al., 2019; Zahraoui et al., 2023). The most common solution concepts for these games are the Nash and the Stackelberg equilibrium (Tushar et al., 2020). In particular, coalition games and cooperative games seem to be adapted to represent the collective energy system, which is formed by EC members. Chau et al. (2019, p.5) modelled different possible subgroups formed by the users of the community, derived from hedonic coalition formation games and claimed that “*a coalition structure represents a feasible state of coalition formation*”.

(c) *Auction-based models* were found to be less represented in literature, compared to other methodologies. Some papers studied the exchange of energy as a bidding process, by comparing different bidding strategies suitable for P2P trading or by modelling double-sided auctions. Although these strategies enable members to bid on the energy (either the consumer or both prosumer and consumer are sending bids), such that they can control the energy costs, their economic viability for ECs is questionable and their price prediction in a non-cooperative game framework needs to be further investigated (Shrestha et al., 2019). In this context, Lin et al. (2019) studied the impacts of different bidding strategies from a game-theoretical perspective to derive some economic implications for the P2P trading market.

After having laid down the most common methodologies and associated properties,

Table 2 Overview of methodologies and methods in P2P and EC markets.

Methodologies	Reference	Methods
Constrained optimisation	Morstyn and McCulloch (2019)	Distributed price-directed optimisation mechanism for multi-objective problem, using Alternating Direction Method of Multipliers (ADMM).
	Moret and Pinson (2019)	Distributed optimisation approach, using iterative local optimisation and dual price adjustments with ADMM and the Karush-Kuhn-Tucker (KKT) conditions.
	Cortade and Poudou (2022)	Welfare maximisation within a dealing platform
	Perger and Auer (2022)	Bi-level optimisation with an upper-level problem and a lower-level problem (using KKT conditions). The resulting conditions are then transformed into a Mixed-Integer Linear Programming (MILP) condition using the Big M approach.
Game theory	Paudel et al. (2019)	The interaction between the sellers and buyers is modelled as a non-cooperative Stackelberg game, where sellers are leaders and buyers are followers. The seller selection competition among buyers is modelled as an evolutionary game and a distributed iterative algorithm is proposed to reach the stable state in a game. Also, the price competition among sellers is modelled as a non-cooperative game.
	Malik et al. (2022)	Cooperative game theory with a coalition formation model
Auction theory	Zhou et al. (2020)	Double-sided auctions

Table 2 identifies the theoretical framework of the seven investigated papers. These papers revealed to be of high relevance, focusing on either P2P trading mechanisms, the EC framework or a combination of both. In addition, Table 3 classifies these papers based on their field of study and applied market approach. It is worth noting that the majority of these papers originate from engineering studies, revealing a notable gap in economic studies that simultaneously explore P2P trades and EC markets. Furthermore, there exist no pertinent research that employs an interdisciplinary approach to examine the concepts

under investigation.

Table 3 Focus of the investigated papers in the EC and P2P framework.

Reference	Field of study		Market Approach	
	Economics	Engineering	ECs	P2P
Morstyn and McCulloch (2019)		X		X
Paudel et al. (2019)		X	X	X
Moret and Pinson (2019)		X	X	
Zhou et al. (2020)		X	X	X
Malik et al. (2022)		X	X	X
Perger and Auer (2022)	X		X	X
Cortade and Poudou (2022)	X			X

3.2 Optimisation approaches of P2P models

After having laid down the theoretical approaches and methods used in P2P energy trading, this paper will review more deeply the optimisation techniques of the investigated studies, with special respect to the implemented objective functions as well as the variables and parameters that were included in the paper. Whereas theoretical backgrounds for P2P energy trading are largely investigated in current literature, objective functions of different optimisation models are less compared according to their equations and variables in question. Zahraoui et al. (2023) conducted a review of 29 different objective functions used in energy trading and categorised them according to their service operator. Only eight of the analysed papers belong to the EC framework, whereas not all of them focus on P2P trading but for instance also on the uncertainty of Photovoltaic (PV) generation.

Therefore, the distinct methods on how P2P trading was modelled are analysed more concretely in order to derive some major lessons for future works from it. For this, the conducted review focused on the following questions:

- (1) How were trades managed inside the given context, e.g. who are the main trading actors?
- (2) How was the trading scheme modelled, e.g. what are the objective functions?
- (3) Who is implicated in the trading process, e.g. what are the variables and parameters that need to be optimised?
- (4) To which investigated P2P model can this context be approached, e.g. to the full, hybrid or community-based P2P model?

The last question entails an important research contribution as none of the investigated papers links or relates their optimisation approaches to the highlighted P2P trading models. This review however derives the most suitable trading model to the optimisation model in question by looking at the framework conditions and variables of the model. A special focus was given to community-based trades inside ECs that are connected to the grid and supported by a CM. In Table 4, the most essential information about the optimisation approaches is described and categorised accordingly.

Table 4 Optimisation approaches in a P2P and EC context.

Ref	P2P market	Context	Objective function	Variables and parameters
Cortade and Poudou (2022)	hybrid	A P2P platform in a non-cooperative framework with heterogeneous agents and an aggregator (dealer) which resells excess energy from prosumers to consumers or to the grid.	For each state of nature, the platform chooses the prices that maximises the total welfare of all participants inside the platform. $W(x) = \int_{\underline{\phi}}^{\phi} U(\phi, x, q)dG + \pi(x)$	x: state of nature (weather conditions or the occurrence of failures) U: prosumer's surpluses ϕ : load factor q: production capacity G(ϕ): cumulative distribution function π : dealer's profit
Paudel et al. (2019)	hybrid	Prosumers in a smart community microgrid are either P2P trading as a seller or as a buyer with optional battery systems. The aggregator sends and receives trading information within the grid-connected EC	The prices of the sellers are updated towards reaching the Stackelberg equilibrium state inside the game between buyers and sellers. $\pi_j^t(l+1) = \pi_j^t(l) + \eta_2(S_j^t(l) - P_{ex,j}^t)$	j: seller η_2 : the rate at which the prices of the sellers are updated during each iteration $S_j^t(l)$: total demand that comes to seller j at time t and iteration l $P_{ex,j}^t$: seller's available power that can be exported to the buyers at time t
Morstyn and McCulloch (2019)	community-based	Centralised energy management for an EC with a P2P model aiming at maximising energy transactions between prosumers. Different energy classes are introduced to treat energy as a heterogeneous product and to coordinate P2P trading to minimise the costs with network losses. The preferences of different classes of prosumers are reflected in their choice of energy parameters to trade within the community.	Every prosumer updates his local decision variables by minimising an augmented Lagrangian L_i (including cost function, price of each energy class and penalty terms). $\min_{y_i(\kappa), z_i(\kappa), b_i(\kappa)} L_i = f_i + \sum_{t \in \mathcal{T}} \left[\nu_g^{(t)}(\kappa - 1)(z_{ig}^{(t)}(\kappa) - x_{ig}^{(t)}(\kappa - 1) - y_{ig}^{(t)}(\kappa) - b_{ig}^{(t)}(\kappa)) + \frac{\rho}{2}(z_{ig}^{(t)}(\kappa) - x_{ig}^{(t)}(\kappa - 1) - y_{ig}^{(t)}(\kappa) - b_{ig}^{(t)}(\kappa))^2 + \sum_{k \in \mathcal{K}} (\nu_k^{(t)}(\kappa - 1)(z_{ik}^{(t)}(\kappa) - x_{ik}^{(t)}(\kappa - 1) - y_{ik}^{(t)}(\kappa) - b_{ik}^{(t)}(\kappa)) + \frac{\rho}{2}(z_{ik}^{(t)}(\kappa) - x_{ik}^{(t)}(\kappa - 1) - y_{ik}^{(t)}(\kappa) - b_{ik}^{(t)}(\kappa))^2 \right]$	Cost function f_i of prosumer i : $f_i = \sum_{t \in \mathcal{T}} T_s^{(t)} [C_{dep}(B_{ci}^{(t)} + B_{di}^{(t)}) - \sum_{k \in \mathcal{K}} (u_{ik}^d z_{ik}^{(t)} + u_{ik}^s y_{ik}^{(t)})]$ C_{dep} : cost of battery depreciation B_{ci}, B_{di} : total battery charging/discharging power u_{ik} : utility coefficient z_{ik} : average allocated load power at current iteration k y_{ik} : generation capacity at interval t p : penalty terms for violations of the coupling constraints $x(t)$: energy class assigned to prosumer over time horizon

Table 4 (Continued)

Ref	P2P market	Context	Objective function	Variables and parameters
Zhou et al. (2020)	full P2P	Agreements between end-customers inside a P2P trading EC are made with continuous double auctions in order to submit bids for ancillary service provision, who then adjust agreements for the residual balancing of electricity inside the EC. Inside the community, prosumers and consumers are directly trading with each other without any CM.	Each customer will face this optimisation problem for his bidding strategy on whether and how much to bid in the ancillary service mechanism. $\min \sum_{t \in \mathbf{T} \setminus \mathbf{T}'} p_t \cdot NL_t - NL_t^* \cdot \Delta t + \sum_{t \in \mathbf{T}'} (-\Delta B_{b_t^{AS}} + C_{b_t^{AS}})$	Objective function of each customer i , as he wants to minimise his electricity costs and thus optimises its operational schedule of flexible loads and storage capacities: $\min \sum_{t=1}^T p_t NL_{i,t} \Delta t$ T: Target Time Period \mathbf{T}' : set of time slots for which the power utility calls for ancillary service provision p_t : electricity price NL_t : new net load of the customer to be decided at the time step t NL_t^* : net load of the customer before providing any ancillary service $\delta B_{b_t^{AS}}$ and $\delta C_{b_t^{AS}}$ are the benefit and cost of ancillary service provision regarding the submitted bid to the power utility for ancillary service provision.
Moret and Pinson (2019)	community-based	Community-based P2P model with a CM that interfaces with retailers. Market organisation including agreements on the collective trading inside and outside the community. Equilibrium problem in which each agent individually minimises its costs.	Exchange problem that gives the optimal trading model by minimising the sum of the total costs of the prosumers (f_j) and the model of the CM (g) $\min_{\Gamma} \sum_{j=1}^n f_j(p_j, q_j, \alpha_j, \beta_j) + g(q_{imp}, q_{exp}, \vartheta)$	Objective function $\Gamma = \{p_j, q_j, \alpha_j, \beta_j\}$ n: prosumers indexed by j p_j : net energy production q_j : sum of energy exchanges inside the EC x_j and β_j : imported and exported energy by prosumer j from outside the EC q_{imp}, q_{exp} : continuous variables describing import and export exchanges with the system operator (perspective of CM) ϑ : set of relevant additional variables

Table 4 (Continued)

Ref	P2P market	Context	Objective function	Variables and parameters
Perger and Auer (2022)	full P2P	Direct P2P trading (without a CM) between prosumers in a local EC, connected to the public distribution grid.	<p>Optimisation problem for the dynamic participation of prosumers in an EC, giving a leader at the upper level who minimises the cost-emission function (with optimal electricity demand and PV capacity of new prosumers) and a follower at the lower level who maximises community welfare (maximising exchanges of each member in the EC).</p> $\min_{\{load_i, PV_i, b_i, Q_{i,t}\}} \sum_{i \in \mathcal{P}_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i$ $\max_{Q_{i,t}} \sum_{t \in \mathcal{T}, i \in \mathcal{P}} p_t^{Gout} q_{i,t}^{Gout} - \sum_{t \in \mathcal{T}, i \in \mathcal{P}} p_t^{Gin} q_{i,t}^{Gin} + \sum_{t \in \mathcal{T}, i \in \mathcal{P}} wtp_{i,j,t} q_{i,j,t}^{share}$	<p>α_i : upper-level preference factor of prosumer i minimisation regarding the following decision variables: $load_i$ - annual demand of prosumer i, PV_i - installed PV capacity of prosumer i, b_i - binary decision variable of prosumer i, $Q_{i,t}$ - lower level primal decision variables including $Q_{i,t} = \{q_{i,t}^{Gin}, q_{i,t}^{Gout}, q_{j,i,t}^{share}, q_{i,t}^{Bin}, q_{i,t}^{Bout}, SoC_{i,t}\}$ p_t^{Gout}: average spot market electricity price $q_{i,t}^{Gout}$: sales from prosumer i to the grid p_t^{Gin}: retailer's electricity price $q_{i,t}^{Gin}$: purchase of prosumer i from the grid $q_{i,j,t}^{share}$: purchase of prosumer j from prosumer i $SoC_{i,t}$: Capacity of prosumer i's battery $wtp_{i,j,t}$: willingness-to-pay of prosumer j at time t to buy from prosumer i</p>
Malik et al. (2022)	community-based	An EC with peers, an aggregator, solar PV, electric vehicle charging points and smart meters is presented as a cooperative game-theoretical model.	<p>the power balance between generated energy and P2P energy traded is minimised relative to v</p> $\min_V \sum_{N \in} P_N(E_d, E_S, W_c, W_p) + B(Chg, Dhg)$	<p>E_d: energy demand of the consumer at time interval t E_s: energy surplus of the prosumer W_p, W_c: Willingness factors of consumer and prosumer to trade $B(Chg, Dhg)$: parameter for charging and discharging the community storage</p>

A repeating key assumption from the investigating papers is that agents inside a platform have heterogeneous profiles, which comes from variations in their load factors. Without this assumption, the community would have a high energy deficit in peak hours, respectively a high energy surplus in off-peak hours. This would make P2P trading less attractive as there would be no more incentives to develop a collective platform. Another common assumption is that the size of the local production unit cannot vary with the load profile of each consumer (Cortade and Poudou, 2022). In a community-based P2P market, there exist connections between the prosumers and together they are coupled to the grid via one single point (Paudel et al., 2019). Often, imperfect information exists between the EC members, as only the CM possesses knowledge of the trading partners of each agent (Moret and Pinson, 2019). Since the constraints examined in the research papers were largely similar, they were not specifically emphasised in this elaborated Table. An important recurring constraint is the energy balance constraint inside the EC since all non-served demands and supplies through the platform are provided by the grid (Cortade and Poudou, 2022). Moreover, technical constraints for capacity limits of installed DERs or charging and discharging limits for associated batteries are often taken into consideration in the proposed models (Chau et al., 2019).

Regardless of the implemented trading model, the first objective of prosumers is to maximise their economic benefits. In other words, they seek to minimise their net costs,

which include the operational cost of electricity by optimising the Feed-in Tariffs of PV systems, battery charging and discharging rates as well as their grid consumption rates (Chau et al., 2019). The objective functions in Perger and Auer (2022) and Zhou et al. (2020) minimised overall electricity costs of the prosumers in a full P2P framework. Moret and Pinson (2019) proposed a community-based problem in which the function of the CM is added to the minimisation problem, whereas in Malik et al. (2022) the objective function includes the community storage parameters. The hybrid P2P model in Cortade and Poudou (2022) presents a welfare maximisation objective function, which is calculated from the sum of prosumer's surpluses and the platform's profit in the case it has a non-profit objective. In contrast to this, the objective function in Paudel et al. (2019) excludes the CM function and uses an iterative pricing mechanism to converge the game of sellers and buyers to a stable solution. In addition, the costs of P2P trades with and without battery storage are compared to the cost of conventional trading and result in significant cost reductions. The same benchmark approach was used by Zhou et al. (2020) and Cortade and Poudou (2022). The former study proposed a mechanism that achieves Pareto improvements compared to the conventional grid system without ancillary services. The ancillary service provision creates positive value for both the power systems and EC members, who benefit from higher social welfare. The study of Cortade and Poudou (2022) suggested that P2P energy trading platforms can be economically attractive for both buyers and sellers of en-

ergy surplus, as prosumers can generally expect to gain more from the platform than from the central grid by installing DERs.

Concerning CMS, its role was highlighted in the study of Moret and Pinson (2019), who claimed that the CM directly influences and facilitates the collective agreements and negotiation process with the DSO, which will also directly affect the energy dispatches, revenues and payments of the participants. Compared to the benchmark model in which prosumers trade individually in the wholesale market, the community-based model decreases yearly costs for all prosumers and the community as a whole, according to common agreements and preferences. This study is of high relevance for ECs and should be further verified with associated approaches. The prosumer's preferences have been analysed by Perger and Auer (2022), who evaluated the inclusion of new members according to the collective community's preference. They suggested that a community with environment-oriented preferences would opt for a new member with high PV capacities while a profit-oriented community prefers new members with no production units, but a high energy demand. To find a beneficial solution for all members, Malik et al. (2022) integrated an algorithm with prosumers' individual priorities. To guarantee a stable coalition that ensures the participation in P2P trading and high energy savings, members should prioritise a low trading price (during daytime), the closest geographical distance between two prosumers as well as the maximum energy demand and generation (at night).

4 Economic Sharing Methods inside Energy Communities

After having analysed different P2P energy trading models in the context of ECs, energy sharing methods constitute a second major concept within local energy trades. These sharing models determine the implementation of the trading rules and their related transactions. In a first step, energy sharing models will define how energy will be shared among the community, where different strategies of energy allocation lead to different bill reductions for the members (Mustika et al., 2022). While energy allocation methods are investigated by engineering studies, this review will focus on current literature studying the allocation and distribution of the related costs and benefits between the members of an EC. These three stages are depicted by Figure 3 and include various methods, of which the economic ones are further described in the following subsections.

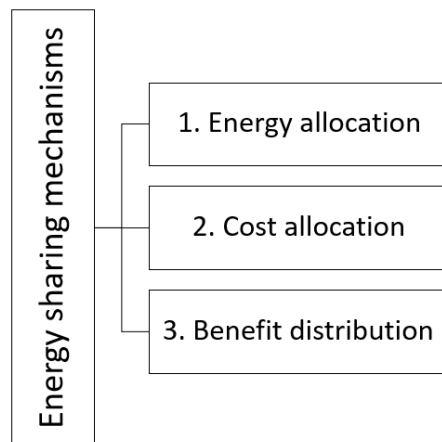


Fig 3 Three stages of energy sharing methods.

First of all, it is essential to define how to share investment costs as well as to distribute

the benefits from joint-owned energy projects among participants (Norbu et al., 2021). Li et al. (2022, p.2) suggested that “*costs should be allocated to those who cause them and benefits should accrue to those who make the investments*”. Therefore, effective methods that calculate the costs and benefits that have to be allocated and distributed among the participants should be identified to ensure the success and sustainable development of ECs.

While there are limited sources addressing energy trading models, there is a significant amount of research dedicated to energy sharing models, particularly in the context of ECs. As most of them only focus on either cost sharing mechanisms or benefit distribution models, they can be categorised accordingly. In Table 5, the most important methods are identified and related to the references and their associated models.

Table 5 Categorisation of investigated references concerning cost and benefit sharing mechanisms.

Cost and benefit sharing mechanisms for ECs	References	
	Related to cost allocation	Related to benefit distribution
Equal Split scheme	Chau et al. (2019); Li et al. (2022)	Norbu et al. (2021); Limmer (2023)
Mid-Market Rate scheme	Long et al. (2017); Zhou et al. (2018); Long et al. (2019); Gržanić et al. (2021)	Limmer (2023)
Bill Sharing method	Long et al. (2017); Zhou et al. (2018); Long et al. (2019); Gržanić et al. (2021)	/
Supply demand ratio	Zhou et al. (2018); Long et al. (2019); Gržanić et al. (2021)	/
Marginal contribution	/	Ma et al. (2019); Norbu et al. (2021); Casalicchio et al. (2021)
Shapley value	Long et al. (2019)	Abada et al. (2020); Fioriti et al. (2021); Limmer (2023)
Nucleolus approach	/	Fioriti et al. (2021); Limmer (2023)
Shapley core	/	Fioriti et al. (2021); Limmer (2023)

Recent contributions analysed diverse methods to identify sharing models that are both cost-effective and socially efficient (Chau et al., 2019). The investigated methods vary in terms of both their time horizon and their implemented distribution schemes. Works such as Abada et al. (2020) and Gržanić et al. (2021) modelled up to eight schemes for a time period of one day, while Gjorgievski et al. (2022) considered one month and Long et al. (2019) even one year. The models can also be distinguished between more simple schemes such as the equal split scheme and the Mid-Market Rate (MMR) scheme, and more complex methods such as the Shapley value, the nucleolus, and the Shapley core. As this literature review is interested in current methodologies and their relation to energy trading models, the identified sharing models are classified according to their allocation rules and described in the next two subsections.

4.1 Energy consumption-based allocation

To derive some implications to local energy sharing inside ECs, Li et al. (2022) derived pricing strategies from tariff designs in regulated and centralised large energy systems. These allocation methods either charge the community based on its consumed energy, generated capacity or the number of users inside the community. To assess how well costs are being allocated, the authors measured the performance of the various allocation schemes by considering their ability to accurately reflect and predict costs. They found that methods based on energy as the single charging component reflect and predict costs

in a better and more desirable way for the community. This is also confirmed by Li and Okur (2023), who highlight that the energy exchange cost with the grid is also energy component-based. Three cost allocation methods are presented, all of which rely on the total energy consumption volume (in kWh) :

- The flat energy pricing method, which does not differentiate between peak and off-peak periods and obligates the members to pay the same rate during a predetermined period.
- The Time-of-Use (TOU) energy pricing method, which does differentiate between peak and off-peak consumption periods and incentivises consumers to reduce or shift their peak demand to peak generation hours.
- And the segmented energy pricing method, which differentiates between consumption levels above and under an average energy consumption threshold to avoid peak demand.

Li et al. (2021) stated that whatever pricing structure is chosen, it should be clearly communicated to the members of the community and that an *ex-ante* communication would increase the acceptance of the scheme and the overall social acceptance of the EC. Given these three allocation methods, it is difficult to evaluate which of the presented allocation methods is most suitable for ECs, as there exist many different contexts and aspects

that need to be taken into account, such as consumption levels and time differences. Li and Okur (2023) claimed that the ToU and segmented energy pricing model are specifically designed for a community energy system that relies on almost full renewable energy generation. However, self-sufficiency is rather hard to achieve, as it is still not economically feasible (high costs of DERs) nor supported by well-developed storage systems to face the intermittent nature of renewable energy sources. Hence, it is challenging to find an appropriate pricing method, which satisfies all the stated requirements at the same time and new methods will be required to provide more suitable options in the different contexts (Li et al., 2022).

4.2 Game theory-based allocation

Various contributions employed game theoretical methodologies to model cost allocations within ECs (Tveita et al., 2018; Yang et al., 2021). These models often included a cooperative setting and primarily focused on assessing fairness, particularly in scenarios where an EC has implemented a community-based P2P trading model. In some studied community-based models as the one in Li et al. (2021), the CM trades energy from and to the supplier in the name of the community, but does not assign the costs to the community members. In this scenario, the members need to cooperate and design their own sustainable and fair cost allocation model. Thus, there is a need for a community committee as well as the long-term commitment of the EC members to design cost allocation methods that are socially

accepted by the members.

Some of the most investigated models are the MMR as well as the Shapley value, both based on game theoretical principles. The MMR method sets the trading prices between prosumers at the average of the retailer's selling and buying prices and adjusts it when the total energy generation is not equal to the total demand of the community. The Shapley value, however, calculates the average marginal contribution of a member considering all possible combinations of cooperation between the members in the community (Limmer, 2023). By using a cooperative game theoretical model, Abada et al. (2020) investigated how the allocation of energy can lead to a stable community and found that simple allocation rules create unstable ECs and that it is essential to integrate the individual's contribution to the value of the community (known as the Shapley distribution method).

By considering different methods on how to set pricing and economic allocation rules inside ECs, the present paper identifies some important links between the identified sharing methods and trading models. Figure 4 illustrates that energy consumption-based methods are derived from frameworks based on competition. As the full P2P model promotes competition between the members of the community, as explained in Section 3, allocation methods based on energy consumption seem more suited than methods based on game-theoretical aspects. Allocation methods based on game theory, however, derive important cooperative settings for ECs, increasing the fair outcome of the sharing model. Hence,

these methods should primarily be used to implement allocation rules inside community-based P2P and hybrid P2P trading models. In other words, the energy trading model will influence the cooperation level between the agents and may influence the choice of the implemented cost allocation and underlying rules inside the EC. In addition, the economic sharing methods are impacted by the pre-defined trading models and the implemented market structure of the EC.

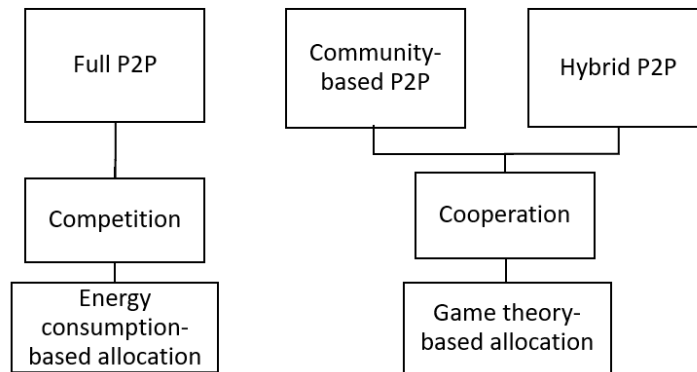


Fig 4 Cost allocation methods according to P2P trading models.

5 Challenges and future research directions

As ECs can be perceived as collaborative multi-agent systems, this paper proposes to opt for trading and allocation models that are designed in a way to strengthen the cooperation and engagement between community members. The previous analysis showed that cooperative theory is essential to ensure the collaboration between prosumers while exchanging

energy in a community framework. Nevertheless, a major hurdle remains to allocate costs and benefits among the engaged members. The implementation of economic allocation in local energy markets encounters significant obstacles distinct from those faced in larger energy systems. Hence, economic allocation methods for ECs need to be further assessed.

Among the presented emerging trading and sharing models, it remains largely challenging to find the right scheme for local energy trades inside ECs, as there exists no uniform acceptable consensus on how to allocate costs and benefits within a community. Koirala and Hakvoort (2017) stated that the success of ECs relies essentially on the business model and its flexibility to adapt to changing circumstances. The EC's environment is largely dependent on factors such as local regulations, governance structures, and stakeholder preferences. Due to the complexity of the members' coalitions, the national context and the aim of ECs, it is preferable to design different sharing methods that should align with the goals, values and local context of the EC, e.g. the specific needs and characteristics of the local community. According to Li et al. (2021), it is recommended to first identify the amount of costs and benefits to be allocated and distributed before proceeding with their allocation design. During this process, it is essential to provide information transparency by explaining pricing and allocation methods in a simplified and comprehensive manner to the members and by eventually including them in the decision-making process.

In view of achieving optimal trades inside a collective economy, Daly (1992, p.185) identified “*the efficient allocation, the equitable distribution and sustainable scale*” as three important and distinct economic goals. This paper refers to these three allocation goals and identifies an important trade-off between them, illustrated by Figure 5.

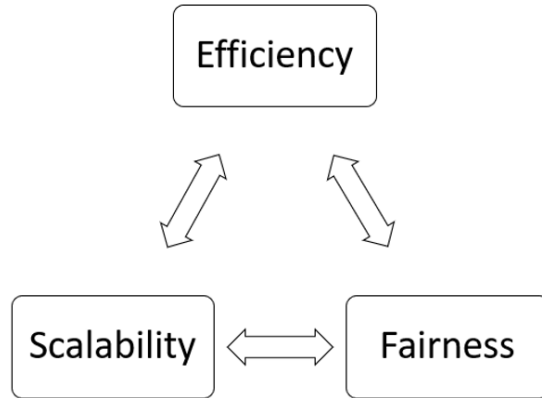


Fig 5 Trade-off between the three economic allocation goals.

The main goal of an allocation is to be cost-efficient to ensure minimum overall energy bills and benefits to members in contrast to trading only with the grid. In addition, an efficient allocation method should reflect different time periods to incite consumers to shift their consumption to off-peak hours and to reduce overall peak demand Li et al. (2021). However, designing a sharing method that addresses at the same time cost-efficient and fair exchange prices remains challenging. Fairness and stability constitute vital conditions for well-functioning trades inside an EC (Abada et al., 2020; Limmer, 2023) and highly impact the social acceptance and thus the success of the allocation method put in place (Li et al., 2021). To further support the community acceptance while ensuring the participation

of low-income households, inclusive prices need to be part of an enabling and supportive framework of energy trades inside ECs (Gautier et al., 2023). However, methods that guarantee fair outcomes (such as the Shapley value) and are robust to strategic behaviours are computationally complex and thus are not easy to scale up for larger ECs (Gjorgievski et al., 2022). This will additionally limit the scalability of the allocation designs for ECs, especially when there is a high number of players inside the coalition (Norbu et al., 2021).

Each of these economic goals constitutes an economic problem in itself and needs to be analysed distinctively to identify important issues with their implementation and finally to find an adopted framework with regard to the limit of each goal. This work emphasises the need to respect the three principles of efficiency, fairness and scalability when modelling optimal allocations within ECs. In order to mitigate the negative effects between the identified allocation goals, more investigation on their impacts on community members must be done. Scalability issues of ECs have been highlighted to be major concerns (Moret and Pinson, 2019; Shrestha et al., 2019), as goods and services can only be efficiently shared within a market if this latter has been “*firmly and collectively fixed within scale and distributive limits*” (Daly, 1992, p.189). However, both economic theories and policy schemes about scale issues have been neglected for a longer time. In addition, the community’s scale should be perfectly adapted to its members and capacities, such that it is sustainable and does not result in an energy over- or underproduction.

6 Conclusion

ECs refer to a connected and collective system of prosumers and consumers who aim at maximising ecological, societal and monetary advantages, with a focus on community benefits. According to several literature findings, ECs seem to be a promising way to decarbonise and decentralise our current energy system. In order to be economically viable and sustainable in the long term, trading and sharing models inside ECs need to be well-defined. Therefore, this paper reviewed current literature findings and laid down foundational principles and common theories for optimising economic trades within local community markets. One remarkable market and trading system that was highlighted is the P2P model. In the context of ECs, community-based P2P trading includes a CM, who provides essential services to community members and helps organising energy trading processes. By comparing different methods and trading mechanisms, cooperative game theory emerged as highly relevant for ECs, ensuring prosumers to collaborate when exchanging local energy while preventing free-riding behaviours. The choice of the trading design and the implemented market structure of the EC will influence the design and the rules of the economic sharing methods between members.

However, the choice of a trading model and their allocation rules remain challenging, as the adaptability of the schemes largely depends on the characteristics and circumstances of the EC. The self-governance of these communities should be characterised by lower

transaction costs and a fair cost-benefit allocation, while being framed by simplified legal requirements. Different methods may be suitable for different scenarios, and the decision may involve trade-offs between simplicity, fairness, and efficiency. The allocation of costs and benefits should provide fair outcomes for the users to ensure social acceptability, but also be computationally efficient and comprehensive to provide methods that are easily scalable for larger ECs. Moreover, energy trading needs to be cost-effective in order to incentivise members to join and stay inside the coalition of the EC. In addition, the scheme must be tailored to the participant's characteristics as well as to the size of the community. Implementing effective cost and benefit allocation schemes not only contributes to the long-term sustainability of ECs but also fosters widespread social acceptance, thereby facilitating a smooth transition to sustainable energy practices.

Therefore, future research avenues include potential allocation methods about the community's scale to identify the optimal size to avoid inefficient and inequitable allocation results. Moreover, technological advancements and strategic considerations are crucial aspects that should be carefully considered. The impact on the grid was neglected in this article but needs further investigation. With the further integration of ECs into the electricity grid, more research must be carried out on how trading mechanisms of community-based energy systems affect the network system, as well as their associated changes for the revenues and tariffs of the participating actors. Given a trade-off scenario between

the conflicting goals of optimal economic trades, complementary research should evaluate direct and indirect effects on the members and the grid while achieving a balance between the economic goals. This could for instance be done by decision-making tools like cost-benefit analyses, multi-criteria decision-making methods, or optimisation techniques to assess the trade-offs and to evaluate the potential solutions objectively. These implications should be studied by appropriate models, involving various stakeholders and considering a long-term horizon.

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