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Consumer-centric electricity markets: A comprehensive review on user preferences and key performance indicators

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ABSTRACT

The power system is facing a transition from its traditional centralized model to a more decentralized one, through the emergence of proactive consumers on the network, known as prosumers. This paradigm shift favors the emergence of new electricity market designs. Peer-to-Peer (P2P) based structures have been gaining prominence worldwide. In the P2P market, the prosumer assumes a more active role in the system, being able to directly trade its energy without the need for intermediaries. This paper contributes with a comprehensive overview of consumer-centric electricity markets, providing background on different aspects of P2P sharing, in particular the inclusion of peer preferences in the electricity trading process through product differentiation. A performance assessment of the different modeled preferences was carried out using key performance indicators (KPIs). Different user preferences under the product differentiation mechanism were simulated. The results demonstrate that consumer-centric markets increase the penetration of renewable energy sources into the network and tend to affect loads flexibility according to the renewable generation.

1. Introduction

1.1. Motivation

The decentralization of power generation is increasingly becoming a reality, driven by supportive environmental policies that promote the use of renewable energy sources (RES). On a decentralized scale, individual consumers have been encouraged to invest in local renewable energy systems to move toward self-sustainability. At the same time, large traders also motivate consumers and prosumers to be more flexible, with the time-of-use tariffs implementation [1,2].

The way electricity is consumed and generated is directly impacted by the increasing deployment of distributed energy resources (DER). Rooftop solar photovoltaic (PV) production in homes and buildings is expected to account for 530 GW by 2024 globally, representing 60% of all renewable capacity expansion from 2018 [3]. This is mainly due to the investment costs in solar PVs and batteries that have been declining exponentially over the recent years, supporting the transition from consumerism to prosumerism [4]. In this way, electricity systems are being transformed by the increasing number of locally distributed energy systems and the deployment of smart grid mechanisms, like demand response, storage technologies, and smart meters. This change is enabling an increase in the end-users' self-sufficiency and lowering their dependence on the centralized energy system, whether through the acquisition of individual energy home-systems or participation in microgrids and/or energy communities. This new decentralized paradigm, inspired by the collaborative economy principle that changes the way consumers perceive energy, can promote growth in consumer-centric markets, especially peer-to-peer (P2P) energy markets. Traditional electricity markets are not prepared to handle the proactive behaviour of consumers/prosumers, as well as the desire for trading energy with who they wish [5]. Thus, P2P energy markets through decentralized energy trading platforms, enable consumers, producers and prosumers to negotiate directly with each other [2,6].

The wide integration of DER into the power network promotes opportunities to provide value streams for both the grid and users [7]. On the one hand, from the network operator perspective, DER can benefit by providing flexibility to improve local network performance issues such as voltage fluctuation [8] and network management capacity [9].

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Nomenclature

Acronyms

P2P	Peer-to-Peer;
RES	renewable energy sources;
KPI	key performance indicator;
PV	photovoltaic;
PD	product differentiation;
DER	distributed energy resources;
DSO	distribution system operator;
QoS	quality of service;
QoE	quality of experience;
TCRI	total cost reduction index;
PII	participation intention index;
EPARI	energy peak-to-average ratio index;
PRI	peak reduction index;
AEI	average efficiency index;
ERRI	emission reduction rate index;
CHP	combined heat and power;
SW	social welfare;
TC	total cost;
TR	total revenue;
Bk	benchmark;

Parameters

$\underline{P_n}$, $\overline{P_n}$	lower and upper bounds for agent n;
h	model of community manager;
C_n	extended cost function of agent n;
$\widetilde{C}_n$	bilateral trading cost function;
a_n, b_n, d_n	price offer by agent n;
c_n^g	relative price offer by agent n for a criteria g;
γ_{nm}^g	trade characteristic for criteria g between peer n and m;
SW	social welfare cost function;
c_{nm}	PD cost penalty applied to trades between peer n and m;
dist_{nm}	distance from peer n to m;
$CO2_{nm}$	CO_2 emissions from the energy trade between peer n and m;
c^{uniq}	unique unit fee;
c^{zone}	zonal unit fee;
N_{nm}^{zone}	number of crossed zones for the power trade between peer n and m;
τ	price spread between import and export price;
$c_{\text{imp},k}$	price of electricity import for community k;
$c_{\text{exp},k}$	price of electricity export for community k;
α_x	amount of gas emitted per unit of electricity;

Sets and Subscripts

Ω_n	set of agents n;
ω_n	set of neighboring agents m in agent n;
Ω_k	set of communities k;
Ω_c	set of consumers c;
Ω_p	set of producers p;
G	set of criteria for PD application;
K	set of nodes in the network;
T^+	set of values that peers sell energy to the grid;

Variables

P_n	power produced/consumed of agent n;
P_{nm}	bilateral trade between peer n and m;
$P_{k,n}$	power produced/consumer of agent n from community k;
$\alpha_{k,n}$	imported electricity by agent n from community k;
$\beta_{k,n}$	exported electricity by agent n from community k;
$q_{\text{imp},k}$	imported electricity by a community k;
$q_{\text{exp},k}$	exported electricity by a community k;
$P_{k,k'}$	bilateral trade between community k and k';
$q_{k,n}$	internal trade by agent n at the community k;

On the other hand, prosumers can reduce their energy costs by using on-site DER generation and earning revenues by selling the surplus energy [7,10]. The DER expansion in the power grid also allows the formation of new energy communities and encourages P2P tradings in local electricity markets through a new framework that can manage RES in low-voltage grids. In recent years, there has been a growth in real-life pilot projects demonstrating their feasibility and challenges [11–13]. The decentralized management and collaborative principles that characterize these structures allow for prosumers' preferences to be taken into account in a local market creation [5]. Studies suggest that P2P trading reduces total electricity costs, improves self-consumption, and promotes more effective utilization of local DER [4,10,14,15]. Moreover, the advance in controllable DER techniques [16] to control the power injection limit of prosumers has further motivated the evolution of P2P trading with the promise to not violate network constraints during energy trading [7].

In P2P sharing, a prosumer can independently decide on its energy sharing parameters and preferences, such as quantity, price, with whom, and when to share energy. It is important to note that in P2P negotiation, although a centralized controller or a third party may partially influence the prosumer's decision process, it cannot directly control how a prosumer chooses to trade with other peers. For example, a third party or centralized controller may impose a constraint on the maximum power injection limit for a prosumer in the P2P market [17–19]. Such limits will influence the prosumer's decision, but the amount of energy that will be traded is an independent decision of the prosumer, without any direct control by a third party (or centralized controller).

Prosumers and consumers, having this decision-making power, need a mechanism that allows them to express preferences for some types of generation and to reflect social aspects. In this context, product differentiation (PD), which is a concept that allows for attributing value to aspects of electricity other than just the energy content, has been used [20]. To directly assess the performance of the market or evaluate the fairness among users once the integration of the product differentiation is done, key performance indicators (KPIs) play a crucial role. KPIs are meant to assess the relationships between the different communities of agents or even different single agents and the impact that each of them can have on the market. These indicators can point out the agent satisfaction on the market, the equilibrium of the participants in the market, or even energy parameters related to peak load reduction or emission reduction [21,22].

1.2. Related works

A large number of interesting studies on the P2P-based energy market have been reported in the literature recently. Tushar et. al [23] provides a complete review of the state-of-the-art in research on P2P tradings, highlighting the main features of the negotiation and its benefits to the network and prosumers. Another panorama of this new market structure highlighting the challenges and suggestions for their proper implementation in power systems was done in [5,24] and also a review of different pilot projects on P2P worldwide [7,11]. This market design relies on bilateral contracts between individual peers, as proposed in [25]. Through the designed contract, [25] captures both upstream-downstream energy balance and forward market uncertainty within the model. In [5], the authors base their work on the emergence of consumer-centric markets that empower prosumers, reviewing what these markets rely on, their first appearance in the literature, real projects, and their potential strengths, weaknesses, opportunities and threats. The present work differs from [5] as it is based on reviewing the product differentiation mechanism and different indicators to assess the technical and economic performance and fairness of these consumer-centric markets.

The authors of [20], propose another fully decentralized market for multi-bilateral economic dispatch, where peers with energy demand can choose their preferences for the type of energy source, such as local or green energy. Other examples of full P2P markets can be found in [26] and [27]. In [26], the authors discuss several properties of decentralized markets by referring to a test case of the Brooklyn microgrid. In [27], alternatively, the authors propose a distributed methodology based on the consensus and innovations method to coordinate local generation, flexible load, and energy storage devices in the microgrid to derive a distributed economic dispatch algorithm.

Most works consider some other aspects along with P2P transactions. For example, aspects related to distribution networks [6,28,29], local DER uncertainties [30] and also other related issues such as electric vehicles [31,32], microgrids [15,33,34], blockchain technology [31,35, 36] and ancillary services [37,38].

As already mentioned, another important consideration about the P2P market is that it allows considering the market participants' preferences through PD. According to [39] applying PD can help end-users satisfy their energy demand more effectively and efficiently. Morstyn and McCulloch [6] propose a P2P platform based on multi-class management, where the generation source attributes influence the commercialized energy prices. Another proposal based on relaxed consensus + innovation method for multi-bilateral energy trading allowing PD is made by Sorin et. al. [20]. The authors in [19,40] use PD based on the electrical distance between peers to promote energy negotiation between neighbors and solve network congestion problems. Similarly, Guerrero et. al. [41] use preference lists to help the DSO determine the shortest path between peers, thus boosting P2P energy trading based on the electrical distance between the peers. Also, [41] complements their analysis with KPIs, namely Quality of Experience and Quality of Service. The study in [42], incorporates network constraints, user preferences such as distance and CO_2 emissions, and trade-independent network fees into the P2P market, ensuring requirements such as secure operation, market's consumer-centric nature, and benefits provided to the network. The authors of [28] propose different exogenous network charges, being uniform, by zones and based on the electrical distance between peers, as metrics for sharing the costs related to the use of common infrastructure and services. Moret and Pinson [43] demonstrate that when prosumers are allowed to share energy at the community level, the overall purchase of electricity for the community reflects prosumer preferences. They also analyze community energy trading fairness, which can be seen in 1 presenting the different PD and KPIs used in the literature.

The complex nature of the P2P energy market optimization problem, as well as the wide range of techniques used to solve it, justify the need for a comprehensive review of the P2P state of the art, in particular the mechanisms that allow consumers to express their preferences in energy trading. Thus, this review can help researchers develop more efficient energy trading mechanisms for market users.

1.3. Main contribution

This work intends to compile and evaluate the different PD applications proposed in the literature of consumer-centric electricity markets, as well as the main KPIs that are applied in the assessment of such markets. A realistic test case of the different PD criteria is carried out using a 37-bus radial distribution system. Specifically, this work fills the gap in the literature by compiling, modeling and comparing different consumer preferences through the PD application to a local energy community, ensuring consumers the opportunity to choose between different generation sources. Additionally, a performance evaluation of the different PDs is carried out, through several KPIs. Seven different KPIs are put forward to quantitatively assess the performance of P2P energy sharing in the energy community.

1.4. Paper structure

After this introductory section, this paper is organized as follows: Section 2 describes the different consumer-centric market designs available in the literature and implemented in this work. Section 3 introduces the product differentiation mechanism and mathematically reviews user preferences. Section 4 provides the KPIs to assess the impact of user preferences on the market. Fairness indicators are included. Section 5 assesses the different market approaches through a test case, considering a 37-bus distribution network grid based on real data. Finally, Section 6 gathers the main conclusions of this work and provides insights for future work.

2. Consumer-centric electricity market

The consumer-centric market, also known as P2P market, can be divided into three types of markets [5,7,23,44,45]: (i) full P2P market, also known as decentralized market, which enables all his participants to directly trade with each other without any need of an central facilitator; (ii) community-based market, where a central entity supervises energy exchanges within the community participants; and (iii) hybrid P2P market, also known as coordinated or composite market. The present work focuses on the first two.

2.1. Full P2P market

In a decentralized market, peers can negotiate directly with each other and decide on their energy trading parameters without the need to

Table 1
PD and KPIs used in the literature.

Reference		[19,20,40]	[21]	[22]	[28]	[41]	[42]	[43]
Product differentiation	Geographical preference	✓			✓	✓	✓	✓
	CO2 emissions preference		✓				✓	
	Unique unit fee policy				✓			
	Uniform zonal fee policy				✓			
	Market-base interface							✓
	Community autonomy preference							✓
	Maximum importer policy							✓
	Peak-shaving preference							✓
Key Performance indicators	Quality of service		✓			✓		✓
	Quality of experience		✓			✓		✓
	Min-Max indicator		✓					✓
	Economic indicator			✓				
	Energy indicator			✓				
	Average efficiency index			✓				
	Emission reduction rate index			✓				

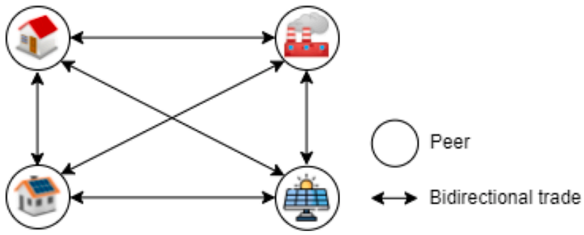

Fig. 1. Full P2P market design.

involve any centralized coordinator [46]. Therefore, both the communication and trading processes are done in a decentralized way, giving peers full decision control, as depicted in Fig. 1. Peers can easily decide, at any time, whether to participate (or not) in the process of energy sharing without compromising their data privacy [23]. Furthermore, the decentralized market scalability is also exceptional [47] due to prosumer-centric properties. Thus, full P2P markets serve his participants better than other markets structures.

To better illustrate the full P2P market model, we consider a system with a set Ω_n of N agents that are defined as producers or consumers. The presented objective function for the optimization model shown in Eq. (1), constrained by Eqs. (3)–(5), minimizes the overall cost C_n for every peer n, which is the same as maximizing social welfare.

$$\min_{D} \sum_{n \in \Omega_n} \left(C_n(P_n) + \widetilde{C}_n(P_{nm}) \right) \tag{1}$$

where $D = (P_n \in \mathbb{R})$ with P_n being the net power injection of peer n. Following [20,27], the cost function C_n is composed of a production cost (or willingness to pay) and it is assigned as a quadratic cost/demand function for each peer n, as defined by (2a). $\widetilde{C}_n$ is a linear function related to the preferences of peer n to each trading partner m, presented in (2b). It is common to model cost functions for this type of problem in a quadratic form [5,20,27,28,38,43]. Also, according to [20] it is common to use such cost function, which is seen as realistic for most conventional generators, small consumers and producers. Still, note that in the case of RES, parameters a_n and d_n can be equal 0 (as set for the test case in Table 2, section 5.1.2), so that the quadratic function becomes a linear cost function. The PD preferences applicable to this specific P2P market design are presented in Eqs. (16), (18), (20), and (22).

$$C_n = \frac{1}{2} a_n P_n^2 + b_n P_n + d_n \tag{2a}$$

$$\widetilde{C}_n = \sum_{m \in \omega_n} \sum_{g \in G} c_n^g \cdot \gamma_{nm}^g \cdot P_{nm} \tag{2b}$$

with $a_n, b_n, d_n \geq 0$ and $P_n > 0$ if the power is generated or injected into the market and $P_n < 0$ if it is consumed from the market. c_n^g is a relative cost by peer n toward a preference used for PD to a given criteria $g \in G$, this relative cost is a parameter called *criterion value*. The relative value of a trade between peers n and m from the perspective of c_n^g is expressed through γ_{nm}^g, which is a positive parameter and is called P2P trade characteristic under criterion $g \in G$. γ_{nm}^g represents the objective valuation of a trade between peers n and m from the perspective of peer n, e.g., γ_{nm}^g can be the physical distance between peers n and m or the CO_2 emissions for that same trade. P_{nm} corresponds to the power exchange between peers n and m.

The problem is subjected to constraints (3)–(5), in which the net power injection P_n of each agent $n \in \Omega_n$ is split into a sum of bilaterally traded quantities with a set of neighboring agents $m \in \omega_n$, i.e,

$$P_n = \sum_{m \in \omega_n} P_{nm} \tag{3}$$

The power set-points of an agent n are constrained by the power boundaries $\underline{P_n}$ and $\overline{P_n}$,

$$\underline{P_n} \leq P_n \leq \overline{P_n}, \quad \forall\, n \in \Omega_n \tag{4}$$

Each agent n is able to optimize its volume traded P_n within the range given by (4), with $\underline{P_n}$ as a lower bound and $\overline{P_n}$ an upper bound.

Considering the bilateral trades between the agents, as in [20], every possible bilateral power trade within the community can be condensed in a matrix P_{nm} as defined in (5).

$$P_{nm} + P_{nm}^{\top} = 0 \tag{5}$$

where P_{nm} is necessarily equal to zero if agent m is not in agent n's trading partnership set ω_n. $P_{nm}^{\top}$ represents the transposed matrix of P_{nm} so symmetry between agents n and m trades is achieved.

For the case study presented in Section 5, a benchmark model is also carried out where there is no PD application. This means that in Eq. (1) the PD preferences component expressed in Eq. (2b) is discarded. To solve the optimization model with PD, the objective function must account for the penalty function $\widetilde{C}_n$, in (2b), thus, PD incorporates any user-related penalties or preferences for the purchased energy. Different definitions of PD will be shown in section 3 for the markets presented.

Another approach to model the full P2P market is through the maximization of the community agent's social welfare (SW), which can be seen in (6), according to [27,48],

$$\max_{D} \sum_{n \in \Omega_n} SW(P_n, P_{nm}) \tag{6a}$$

$$\text{s.t.} \quad (3)-(5) \tag{6b}$$

where $SW(P_n, P_{nm}) = C_n(P_n) - \widetilde{C}_n(P_{nm})$.

All the constraints subjected to the objective function (1) are applied to the objective function in (6a). PD is also applicable in this model, as in (1). Each agent n has a positive price $c_n^g > 0$ to buy energy from an agent m. The total trading cost function of the peer n is given by 2b.

2.2. Community-based market

A community-based P2P market can be readily applied to community microgrids [49,50], and groups of neighboring peers [51], in which the community members share common interests and goals, even though they are not at the same location. In this market design, a community manager acts as a coordinator of P2P energy sharing among the peers, as can be seen in Fig. 2 [23]. However, unlike the centralized market, the community manager cannot directly control the export and import of energy by different peers within the market. Rather, the community manager indirectly influences peers to share via suitable pricing signals [51]. Thus, in a community market, peers need to share limited information with the community manager to maintain a higher privacy level [5,7].

One core focus of the energy community-based market literature is to design suitable pricing schemes that can facilitate P2P sharing and, at the same time, provide energy services to different entities within the network. Pricing schemes also focus on engaging many prosumers in energy sharing. Different energy sharing mechanisms within community markets have been discussed in [43,49,50].

Table 2
Coefficients a_n, b_n and d_n of the agents in the market.

Agents	a_n	b_n	d_n
Ext. Grid	0	58	0
CHP 14	10	30	6
CHP 16	1.5	20	10
CHP 24	5	10	5
RES	0	4	0

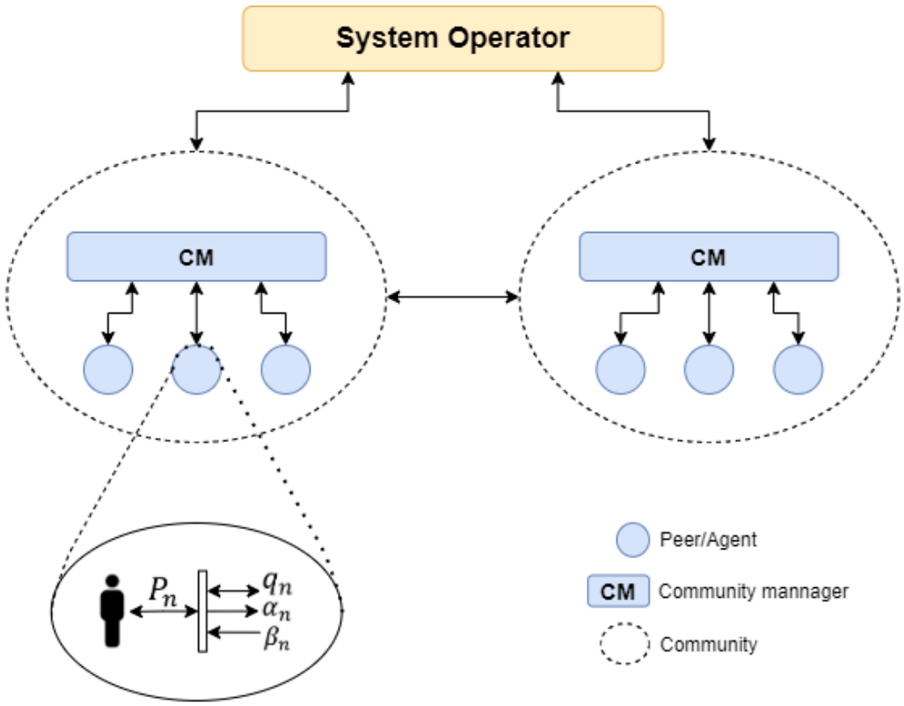

Fig. 2. Community-based market design, inspired in [43].

The general objective function of the community-based market design is presented in (7), subject to constraints (8)–(15), according to [21,43],

$$\min_{\Gamma} \sum_{k \in \Omega_k} \sum_{n \in \Omega_n} \left(C_{k,n} \left(P_{k,n}, q_{k,n}, \alpha_{k,n}, \beta_{k,n} \right) \right) + h\left(q_{imp,k}, q_{exp,k}, \vartheta \right) \tag{7}$$

where $\Gamma = (P_{k,n}, q_{k,n}, \alpha_{k,n}, \beta_{k,n}, q_{\mathrm{imp},k}, q_{\mathrm{exp},k} \in \mathbb{R})$, $(k,n) \in (\Omega_k, \Omega_n)$ is the set of the decision variables of the problem. $q_{\mathrm{imp},k}$ and $q_{\mathrm{exp},k}$ are continuous variables relative to the community energy imports and exports, respectively. ϑ is used to introduce a set of relevant parameters or additional variables to the function h, where PD preferences can be applied, specifically for these community-based market Eqs. (23)–(25). For the benchmark model, as in the full P2P market, this model does not support preferences for its participants. Therefore ϑ is removed from function h in Eq. (7). For each peer n within its community k, power balance $P_{k,n}$ must be considered between all energy imported $\alpha_{k,n}$, all energy exported $\beta_{k,n}$ and all energy traded within the community $q_{k,n}$, as presented in constraint (8).

$$P_{k,n} + q_{k,n} + \alpha_{k,n} - \beta_{k,n} = 0, \ \forall (k,n) \in (\Omega_k, \Omega_n) \tag{8}$$

As in every market, each peer n within his community k has boundaries defined by (4). The sum of the internal trades made in a community k evolving all his agents must be equal to zero (9). The sum of the external trades for each agent with other communities is centrally handled by the community manager through the constraints (10) and (11).

$$\sum_{n \in \Omega_n} q_{k,n} = 0, \ \forall k \in \Omega_k \tag{9}$$

$$\sum_{n \in \Omega_n} \alpha_{k,n} = q_{\mathrm{imp},k}, \ \forall k \in \Omega_k \tag{10}$$

$$\sum_{n \in \Omega_n} \beta_{k,n} = q_{\mathrm{exp},k}, \ \forall k \in \Omega_k \tag{11}$$

The essence of this market lies in the way that agreements between communities are made and managed. The role of this management is the responsibility of the community manager, represented by the $h(q_{\mathrm{imp},k}, q_{\mathrm{exp},k}, \vartheta)$ function modeled in Eq. (7).

Considering bilateral trades between communities, (12) represents the symmetry of electricity traded between all the communities. Eqs. (13) and (14) balance the exported and imported electricity by a community k with other communities k', respectively. Also, the sum of all the community bilateral trades must equal the difference between the electricity exported and imported by community k, presented in constraint (15).

$$P_{k,k'} + P_{k',k} = 0, \ \forall (k,k') \in \Omega_k \tag{12}$$

$$q_{\mathrm{exp},k} = \sum_{k' \in \Omega_k} P_{k,k'}, \ \forall k \in \Omega_k \tag{13}$$

$$q_{\mathrm{imp},k} = \sum_{k' \in \Omega_k} P_{k,k'}, \ \forall k \in \Omega_k \tag{14}$$

$$\sum_{k' \in \Omega_k} P_{k,k'} = q_{\mathrm{exp},k} - q_{\mathrm{imp},k}, \ \forall k \in \Omega_k \tag{15}$$

Note that $P_{k,k'}$ is the traded electricity from a community k to another community k'.

3. Product differentiation mechanism

As mentioned earlier, PD allows to set a dynamic value on aspects of electricity other than energy content only. In the PD framework, bilateral trading costs depend on the consumer's choices. For instance, PD can be used to better describe consumers' utility through the expression of their trade preferences. These trades can be beneficial or harmful to system management. In this way, the PD framework is eager to benefit or penalize the trades that leads to such consideration [20,21]. Currently, large energy consumers or producers already use PD through bilateral contracts or Energy Purchase Agreements. Additionally, it can be used to implement tariffs for grid usage, build a dynamic tax system and for consumers to express their preferences regarding the energy they purchase. Some retailers are beginning to offer this possibility to domestic

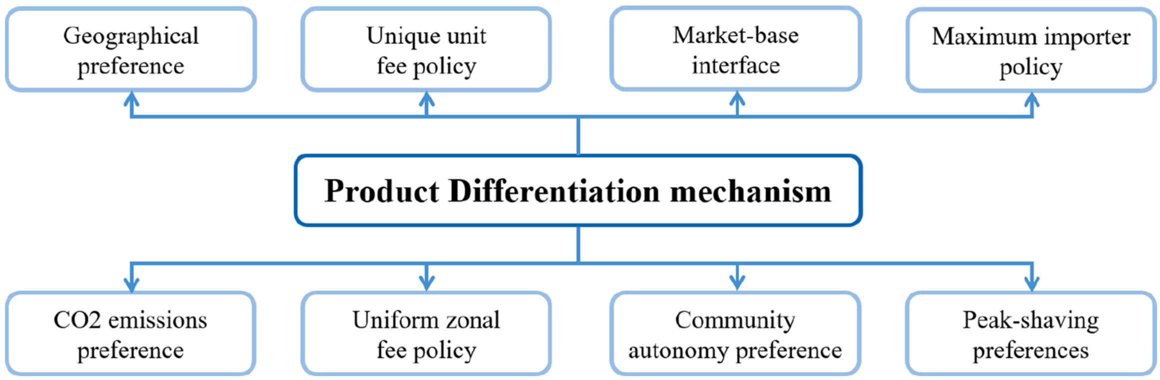

Fig. 3. Summary of product differentiation preferences.

consumers, by collecting data related to their preferences, which are generally the demand for renewable energy, and celebrating bilateral contracts [20].

A summary of the different PDs preferences identified in the literature is highlighted in this work and shown in Fig. 3.

Note that the present work does not address the impact of product differentiation mechanism in the network operation, therefore, it is not verified whether the application of any of the enumerated preferences can create network operating problems. However, it is worth mentioning that recent studies [19,20,28,40–42] have proposed that the PD mechanism can be used to solve potential congestion and voltage issues in the distribution network caused by P2P trades. These works use PD preferences to solve, in an iterative way, congestion and voltage problems that P2P trades may create in the network operation.

3.1. Distance preference

Several researches have been investigating different approaches to calculate the electrical distance between nodes in the electricity network [6,20,28,43], including the power transfer distance and the *Thevenin* impedance distance [28].

Sorin et al. [20], uses the Euclidean distance as a penalty criterion to encourage self-production or local production. In this case, given the Euclidean distances between market agents n and m, Eq. (2b) can be adapted, replacing γ^{g}_{nm} by a matrix $dist_{nm}$, as given in Eq. (16),

$$\widetilde{C}_n = \sum_{m\in\omega_n} c_n \cdot dist_{nm} \cdot P_{nm} \tag{16}$$

where c_n is a distance unit fee expressed in € /km/KWh and $dist_{nm}$ is the distance between peer n and m.

Baroche et al. [28] considered *Thevenin* impedance distance and Power Transfer distance for the electrical distance between two agents. These two electrical distances were initially developed to allow a better approximation to the electrical network typology concerning the conventional topological visualization of the electrical network [28]. *Thevenin* electrical distance Z^{th}_{ij} between nodes i and j is given by (17a), and Power Transfer distance d^{PT}_{ij} between nodes i and j by (17b). According to [28] the *Thevenin* impedance distance is more suited for radial networks, such as distribution grids, while Power Transfer distance is more suitable for meshed networks like transmissions grids.

$$Z^{th}_{ij} = \left|Z_{ii} + Z_{jj} - Z_{ij} - Z_{ji}\right| \tag{17a}$$

$$d^{PT}_{ij} = \sum_{(s,e)\in K} \left|P^{B}_{ij,se}\right| \tag{17b}$$

Note that $P^{B}_{ij,se}$ is the power transfer distribution factor of the branch, where s is the start node and e is the end node, considering an injection at node i and a withdrawal at node j. K is the set of all nodes in the network.

3.2. CO_2 emissions preference

The CO_2 emissions penalization for product differentiation consists of penalizing peer transactions that emit higher emissions. In other words, P2P trades in which the power generating sources have high levels of CO_2 production are penalized. This preference can be formulated in the same way as a geographical preference [42]. Being the CO_2 applicable in the energy trade between peer n and m, $CO2_{nm}$, then we have the PD reformulated according to Eq. (18).

$$\widetilde{C}_n = \sum_{m\in\omega_n} c_n \cdot CO2_{nm} \cdot P_{nm} \tag{18}$$

3.3. Unique unit fee policy preference

Equal sharing of network usage costs among market members is another way of assigning preferences. In this way, everyone is equally responsible for network congestion. If the network fees are such that both exchange shares in the trade are also responsible, they can be described as (19), according to [28].

$$c_n\gamma_{nm} = \pm\frac{c^{\text{uniq}}}{2} \tag{19}$$

Replacing this unique fee policy into the PD function (2b), we have (20).

$$\widetilde{C}_n = \sum_{m\in\omega_n} \pm\frac{c^{\text{uniq}} \cdot P_{nm}}{2} \tag{20}$$

where the sign of c^{uniq} is such that $c^{\text{uniq}} \cdot P_{nm} \geq 0$, so ≥ 0 for producers and ≤ 0 for consumers. Unique unit fee c^{uniq} is expressed in € /KWh in the case of an hourly time unit.

3.4. Uniform zonal fee policy preference

In contrast to geographical PD, the single cost allocation policy does not evidence the individualism of each peer. To find a good compromise between both policies, the network can be divided into several zones, each of which has different zone rates. In this way, each zone would be politically independent, however, this scheme is heavily dependent on the network topology [28].

A way to simulate the charges on the network can be obtained by the sum of the zones covered by each exchange between agents n and m at the corresponding rate of the zones. To know which and the number of zones crossed in the market exchange, the criterion of the shorter electrical trajectory can be applied, as in (17a). If the costs are also shared by both exchange participants, the uniform zonal network rate is described by (21), according to [28].

$$c_n\gamma_{nm} = \pm\frac{c^{\text{zone}}\cdot N_{nm}^{\text{zone}}}{2} \tag{21}$$

where N_{nm}^{zone} corresponds to the number of crossed zones for trade P_{nm}. The zonal unit fee c^{zone} is expressed in € /kWh. Replacing this uniform zonal fee policy into the PD function (2b), we have (22).

$$\widetilde{C}_n = \sum_{m\in\omega_n} \pm\frac{c^{\text{zone}}\cdot N_{nm}^{\text{zone}}\cdot P_{nm}}{2} . \tag{22}$$

As any exogenous approach, this policy may not guarantee P2P market efficiency, as pointed out in [52] in the case of transmission rights. While local marginal prices seem effective, they can be largely rejected for their lack of transparency by P2P market participants [28].

3.5. Market-base interface preference

This preference tries to minimize the costs of importing and maximize the revenues from exporting in the community [43]. This interface can be modelled through Eq. (23)

$$h(q_{\text{imp},k}, q_{\text{exp},k}) = (\lambda_{\text{DA}} + \tau)\cdot q_{\text{imp},k} - \lambda_{\text{DA}}\cdot q_{\text{exp},k} \tag{23}$$

where λ_{DA} is the day-ahead market price and τ is a parameter to describe the spread between the import and export price.

3.6. Community autonomy preference

The community autonomy preference naturally wants autonomy from other communities and the power system [43]. To this end, it is important to reduce the energy income from external sources to the community. This can be done through (24).

$$h(q_{\text{imp},k}, q_{\text{exp},k}) = c_{\text{imp},k}\cdot q_{\text{imp},k} + c_{\text{exp},k}\cdot q_{\text{exp},k} \tag{24}$$

Note that for $c_{\text{imp},k} = \lambda_{\text{DA}} + \tau$ and $c_{\text{exp},k} = -\lambda_{\text{DA}}$, Eq. (24) generalizes Eq. (23), with $c_{\text{imp},k}$ and $c_{\text{exp},k}$ representing the price the community is willing to pay or to receive as compensation for exchanging energy, respectively.

3.7. Maximum importer policy preference

Due to their commercial nature, P2P markets are prone to strategic behavior stemming from the size of the participants, which can make the market an unfair market for the community. In this way, it is important to penalize users who import more energy than they need just to control the market. Thus, agents attempting to obtain higher yields from unnecessary energy imports will be penalized to reduce imports using a factor c_{max} that penalizes the maximum imports determined for prosumers [43], as one can see in Eq. (25)

$$\begin{gathered} h(q_{\text{imp},k}, q_{\text{exp},k}, \vartheta) = c_{\text{imp},k}\cdot q_{\text{imp},k} + c_{\text{exp},k}\cdot q_{\text{exp},k} + c_{\max}\cdot\alpha_{k,n} \\ \text{with} \\ \alpha_{k,n} \le \alpha_{k,n}^{\max}, \quad (k,n)\in(\Omega_k,\Omega_c) , \end{gathered} \tag{25}$$

where $\alpha_{k,n}^{\max}$ is the upper bound for the maximum import shares for each agent.

In [43], the authors consider arbitrariness, that way the situations aforementioned can happen and neglect the fairness among peers. In the present work, arbitrariness is disregarded in the formulation of consumer-centric markets. Therefore, the community-based market formulation (7)–(15) ensures that producers can not import electricity and prosumers cannot import and export at the same time.

3.8. Peak-shaving preference

In a multi-temporal optimization of the community-based market, the community manager can implement peak shaving services for peers' energy imports over the considered timestamps, $t = 1, \cdots, \tau$, as in [53]. To model this, function $h(q_{imp}, q_{exp}, \vartheta)$ becomes (26) [43]

$$\begin{gathered} h(q_{\text{imp},k}, q_{\text{exp},k}, \vartheta) = c_{\text{imp},k}^{\top}\cdot q_{\text{imp},k} + c_{\text{exp},k}^{\top}\cdot q_{\text{exp},k} + c_{\text{peak}}\cdot P_{k,n} \\ \text{with} \\ q_{\text{imp},t} \le P_{k,n}^{\max}, \quad \forall t , \end{gathered} \tag{26}$$

where c_{peak} is the penalization coefficient for the energy import.

4. Key performance indicators

Generally, trading markets aim to eliminate unfairness and balance the average revenue of each seller and the average cost of each buyer [54,55]. There are different notions in the literature about fairness for P2P markets, and we intend to expose them in this work. A summary of the different KPIs highlighted in this work is shown in Fig. 4.

4.1. Quality of Service

According to [43], the Quality of Service (QoS) indicator is normally used to evaluate allocation fairness by employing Jain's index and defined as (27).

$$\text{QoS} = \frac{\left(\sum_{n\in\Omega_n} |q_n|\right)^2}{\sum_{n\in\Omega_n} q_n^2} \tag{27}$$

This index is calculated to indicate how fair the energy exchange within the energy community is, through q_n. The system is 100% fair when the amount of energy traded per agent in the community is equal. Low QoS values indicate the presence of players who trade large

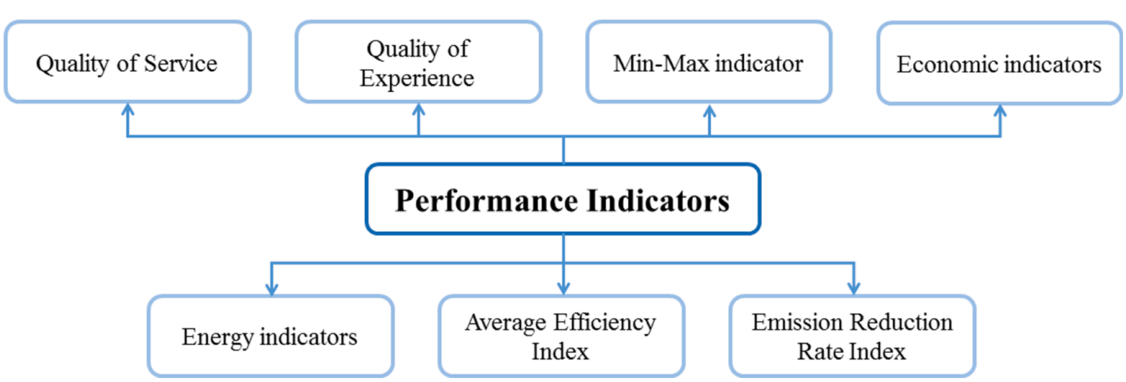

Fig. 4. Key performance indicators summary.

amounts of energy with other members within the community.

4.2. Quality of Experience

To evaluate consumer's satisfaction the Quality of Experience (QoE) indicator, given by Eq. (28a), is used. This KPI is based on the energy perceived price, λ_n, (28b) for each peer $n \in \Omega_n$ as the sum of costs or revenues from trading within the energy community and with the system operator divided by the net power consumed or produced [43].

$$\mathrm{QoE} = 1 - \frac{\sigma}{\sigma_{\max}} \tag{28a}$$

$$\lambda_n = \frac{\lambda_{\mathrm{DA}}\beta_n - (\lambda_{\mathrm{DA}} + \tau)\alpha_n - \lambda_{\mathrm{com}} q_n}{P_n + l_n} \tag{28b}$$

Note that σ is the standard deviation of prices λ_n and $\sigma_{\max}$ is the maximum price deviation, *i.e.*, $\lambda_{\mathrm{imp},k} - \lambda_{\mathrm{exp},k}$. Hence, the energy collective fairness is higher as the price variation among the consumers is smaller, with maximum $\mathrm{QoE} = 1$ whenever all consumers prices λ_n are the same.

4.3. Min-Max indicator

The Min-Max indicator assesses the fairness of the import shares among all the consumers in the energy community, and is given by Eq. (29).

$$\mathrm{MiM} = \frac{\min\ \alpha_n}{\max\ \alpha_n} \tag{29}$$

According to [43], when this index reaches values close to 1, it means that all prosumers participate almost equally in the community energy imports. This leads to a greater diffusion of prices perceived individually, indicating less system justice. Prosumers who do not need to import energy for their supply are forced to buy a share from the system operator and then sell it to other community members. This indicator is particularly interesting in cases where arbitrariness is allowed in the market.

4.4. Economic indicators

Economic indicators represent the economic benefit for a community or individual peers. The Total Cost Reduction Index (TCRI) is presented in (30), indicating the reduction rate of the implemented P2P market with product differentiation compared to the benchmark model, following [22]. In the benchmark model, users have no preferences or penalties on the energy traded with other market users, *i.e.*, it is a P2P market without any product differentiation application.

$$\mathrm{TCRI} = \frac{TC_{\mathrm{ref}} - TC_{\mathrm{P2P}}}{TC_{\mathrm{ref}}} \tag{30}$$

where TC_{ref} is the total cost of all consumers in the benchmark model, and TC_{P2P} is the total cost for the P2P market with PD. TC is calculated from the internal price of the market, *i.e.*, the price of energy at the time that the consumer is buying energy, multiplied by the electricity consumed.

Another economic indicator can be denoted by profit measurement before and after the participation in the market of each peer. This is called Participation Intention Index (PII) and can be formulated as (31), according to [22].

$$\mathrm{PII} = \frac{N_p}{N} \tag{31}$$

where N_p represents the number of peers that have more profit between the P2P market with PD and the benchmark market model, while N is the number of participants in the market.

4.5. Energy indicators

Energy indicators are meant to evaluate the overall energy fluctuation in different P2P markets. The authors in [22] propose two indexes to assess the reduction of power fluctuation for different markets, which are given by equations (32a) and (32b). The Peak Reduction Index (PRI) compares the reduction in the maximum absolute power value between the P2P market with PD and the benchmark market model, through an Energy Peak-to-Average Ratio Index (EPARI), indicating the prominence[1] of the peak or valley of power [22].

$$\mathrm{PRI} = \frac{\mathrm{EPARI}_{\mathrm{ref}} - \mathrm{EPARI}_{\mathrm{P2P}}}{\mathrm{EPARI}_{\mathrm{ref}}} \tag{32a}$$

$$\mathrm{EPARI} = \frac{\max\limits_{t \in T}\left(\sum\limits_{n=1}^{N} P_n(n)\right)}{\frac{1}{T}\sum\limits_{t=1}^{T}\sum\limits_{n=1}^{N} P_n(n,t)}, \forall n \in \Omega_c \tag{32b}$$

where $P_n(n,t)$ is the power of agent n at the time $t \in T$, and Ω_c is the subset of consumers that belongs to the set Ω_n of N agents.

4.6. Average efficiency index

The Average Efficiency Index (AEI) refers to the efficiency in the market exchanges, through the proportion of traded and tradable energy [22], presented in (33). Tradable energy ($\overline{P_n}(t)$) stands for the maximum energy that could have been exchanged by the agent.

$$\mathrm{AEI} = \frac{\sum\limits_{t=1}^{T} P_n(t)}{\sum\limits_{t=1}^{T} \overline{P_n}(t)}, \forall n \in \Omega_n \tag{33}$$

4.7. Emission reduction rate index

The Emission Reduction Rate Index (ERRI) is used to evaluate the reduction rate of waste emission for different markets and is given by (34a) and (34b). When electricity is generated via RES instead of fossil fuels, the ERRI is reduced otherwise it increases. Hence, this indicator is used to measure the environmental impact upon the proposed markets.

$$\mathrm{ERRI} = \frac{\sum\left(\mathrm{EM}_{\mathrm{x-ref}} - \mathrm{EM}_{\mathrm{x-P2P}}\right)}{\sum \mathrm{EM}_{\mathrm{x-ref}}} \tag{34a}$$

where the index X represents the emission gas to be considered, $\mathrm{EM}_{\mathrm{X-P2P}}$ is the amount of emissions in the P2P market with PD and $\mathrm{EM}_{\mathrm{X-ref}}$ is that of the benchmark model. Hence, EM_{X} is determined through

$$\mathrm{EM}_{\mathrm{x}} = \alpha_{\mathrm{x}} \sum_{t=1}^{T^{+}} \left(\sum_{n_p=1}^{N} P_n(n_p, t) + \sum_{n_c=1}^{N} P_n(n_c, t) \right), \ \forall n_p, n_c \in \Omega_p, \Omega_c \tag{34b}$$

where α_{x} is the amount of gas emitted per unit of electricity, T^{+} is the set of values that the peer n sells energy to the grid, and Ω_p and Ω_c are the subsets for producers and consumers/prosumers, respectively in Ω_n.

5. Case study

A case study illustrating the applicability and performance of the reviewed models, accounting for a variety of KPIs, is presented in this section.

[1] See Prominence for more details.

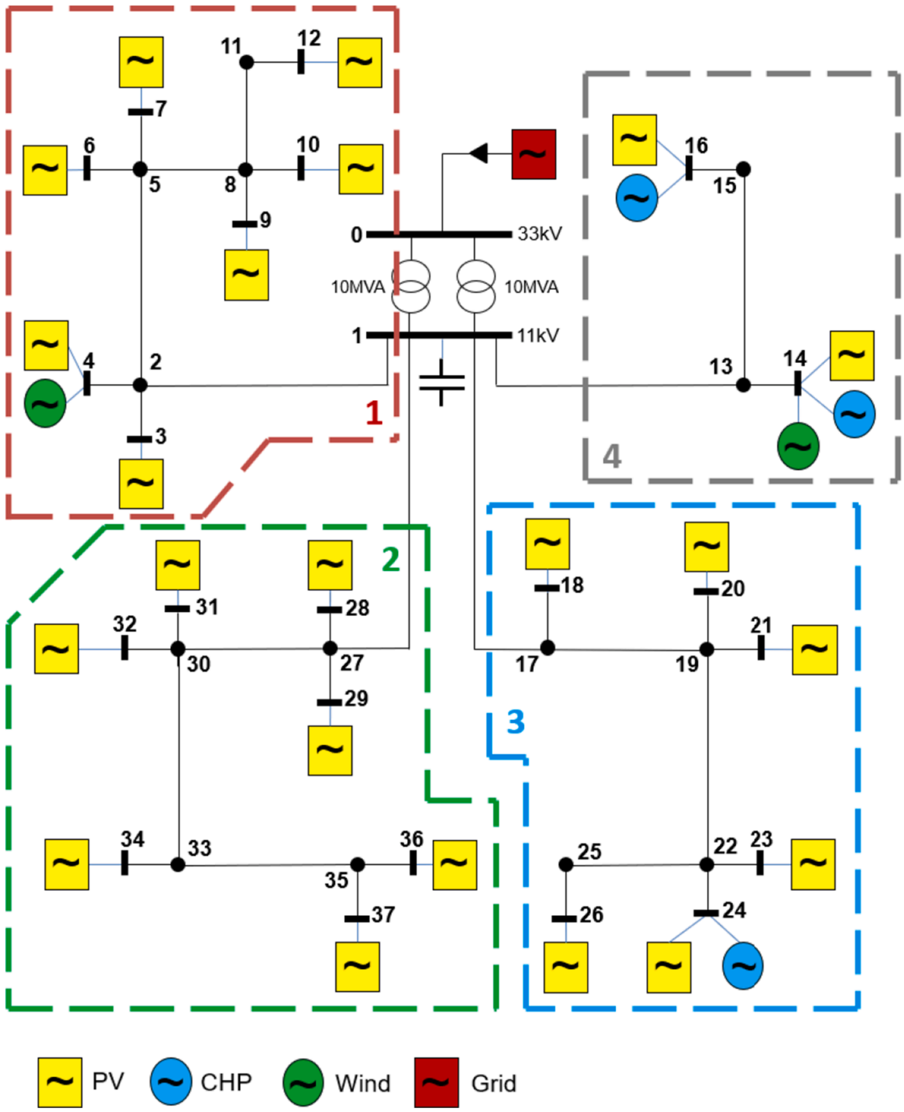

Fig. 5. 37 bus radial distribution network.

5.1. Case characterization

5.1.1. Network description

The case study is based on the 37-bus radial distribution system [56], adapted from [57]. The system voltage level is 11 kV for all buses. The network is composed of:

- 1 external supplier (representing the energy from the upstream connection).
- 3 combined heat and power plants (CHP).
- 24 RES consisting of 2 wind farms and 22 PV systems.
- 22 flexible loads.

In addition, the 22 flexible loads distributed in the network, are composed of 1908 single consumers divided into 1850 households, 2 industries, 50 commercial stores, and 6 service buildings. These 22 loads are considered for the proposed market as 22 agents, with a flexibility of 30% of their base load, for maximum and minimum loads, as presented in (35).

$$P_{con} - 0.3P_{con} \leq P_{con} \leq P_{con} + 0.3P_{con} \quad (35)$$

where P_{con} is the base power for the consumer. The electricity demand is presented in Fig. 6, together with the flexibility considered over 24 h.

For zonal fee PD, different zones must be considered. Therefore, four zones are created according to the numbered dashed areas in (Fig. 5).

Regarding the CO_2 emissions, the RES are considered carbon-free, the CHP emits 703 grams of CO_2 per kilowatt hour (gCO_2/KWh), and the external supplier, that relies on the electricity mix, emits 255 gCO_2/KWh. The CO_2 signals for the CHP were calculated from [58], where some parameters have to be inserted. For instance, the CHP technology can be a boiler/steam turbine, fueled by natural gas, with a unit capacity of 500 kW, operating 2080 h. per year. The remaining parameters were chosen as defaults from the calculator. The external grid greenhouse gas emission intensity is calculated as the ratio of CO_2 emissions from public electricity production and gross electricity production at a country level by [59]. The CO_2 emission level in Portugal (2019) was used as a reference for external grid emissions.

5.1.2. Cost curves in the day-ahead market

Since the day-ahead market is formulated with a quadratic cost function, with the coefficients a_n, b_n and d_n, this section intends to illustrate the cost curve for both producers and consumers, presented in Table 2. Typically, the conventional generator cost curve is determined

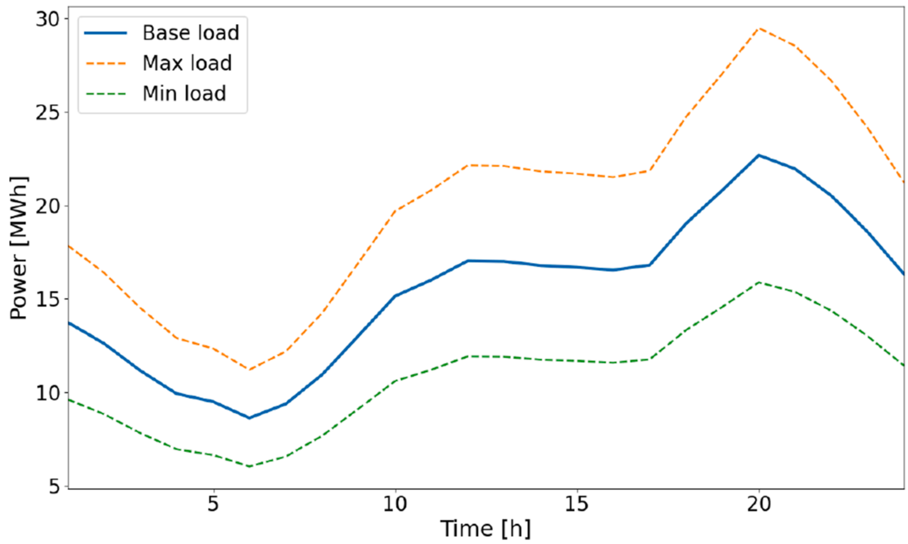

Fig. 6. Electricity demand with considered flexibility.

by his cost curve derivative, *i.e.* the marginal cost[2].

In this case, the cost curve for producers is modeled differently. The price for the energy imported from the grid, *i.e.*, the external supplier, is constant, regardless of the quantity of energy injected in the network. Therefore, the coefficient a_n is set to zero. In cases where the network purchases energy from the upstream grid, in the day-ahead market, a price of energy import is considered equal to the average price of the Iberian electricity market (MIBEL) [60]. This means that for the external supplier, the coefficient b_n is set to 58 € /MWh. For the CHP, the cost curve is not obtained considering the marginal cost, it is set lower than the wholesale market price of 58 € /MWh. Lastly, the RES, have a marginal cost equal to zero, so they are modeled with a nearly zero cost curve, to be the cheapest units in the market.

Note that coefficient d_n is set to zero except for CHP sources, which represent the start-up costs. For the RES, the coefficient b_n is set to 4 € /MWh, which is set arbitrarily to avoid hours when the price of electricity is equal to zero, that can happen in day-light time, more precisely between 11h and 15h, that matches with the time of maximum production rate from the PV systems. Since all the RES have the same cost curve, when no PD is applied, the consumers can choose the type of RES they want to purchase electricity from.

To properly model the load's cost curve considering flexible agents, the loads' marginal curves need to be designed in a way that they intersect with the producers' marginal curves. This means that, in case the loads' marginal curves are lower than producers' ones, the consumers would always consume $\underline{P}$. Otherwise, in case loads' marginal curves are higher than producers', they will consume their maximum demand $\overline{P}$. The coefficients a_n and b_n for the consumer n at time t are defined by (36).

$$a_n(n,t) = \frac{\text{Up} - \text{Down}}{P_{\text{con-min}}(n,t) - P_{\text{con-max}}(n,t)} \tag{36a}$$

$$b_n(n,t) = \text{Down} + \frac{\mathrm{P}_{\text{con-max}}(\mathrm{n},\mathrm{t})(\text{Up} - \text{Down})}{\mathrm{P}_{\text{con-min}}(\mathrm{n},\mathrm{t}) - \mathrm{P}_{\text{con-max}}(\mathrm{n},\mathrm{t})} \tag{36b}$$

where Up $= 58$ € /MWh, Down $= 5$ € /MWh, $P_{\text{con-min}}(n,t)$ is the minimum power, and $P_{\text{con-max}}$ is the maximum power for the peer $n \in \Omega_c$ and $t \in T$.

[2] See marginal cost for more details.

5.2. Results

This section presents the results for the consumer-centric markets proposed with and without user preferences. More precisely, it compares the impact of each user's preference on each consumer-centric market, separately. Note that a comparison between the full P2P market and community-based market designs is disregarded as it was already provided by [5] and user preferences for each market design are considerably different. Nevertheless, future work may include the comparison of both market designs in a more detailed way.

All modeling was performed in the Python language and computations were carried out with Gurobi [61] as a QCP solver on an AMD Ryzen 5 PRO 4650U 2.10 GHz processor with 16GB RAM. Also, all simulations were performed hourly for an entire day of market operation, *i.e.*, $t = \{1, 2, \cdots, T\}, \quad T = 24$ h.

5.2.1. Full P2P markets results

Fig. 7 shows the load diagram for the different P2P market scenarios together with the electricity demand. The market scenarios presented for this market design are the benchmark market model, the dist PD, the CO_2 PD, the unique fee PD, and the zonal fee PD. Note that in the benchmark model, market participants have no preferences or penalties on the energy traded with other market users, this means there is no PD application. It can be seen that for most of the market conditions, consumers tend to reduce their cost, buying the minimum electricity possible from 01:00h to 04:00h and from 19:00h to 24:00h, and buying the maximum possible from 09:00h to 16:00h. This is due to the electricity production from RES, since most of the RES systems are PV systems. Thus, there is only significant electricity production from 09:00h to 16:00h. Wind resources are also available in the other hours but can be neglected due to their low production values.

The scenario in which the peak-shaving PD is applied has exactly the same result as the benchmark model and therefore is not presented in Fig. 7. In the benchmark market model, consumers already consume as minimum electricity as possible at times when prices are high and maximum as possible at times of low prices. Thus, in peak hours where consumption is higher, *i.e.*, between 18:00h and 21:00h (where peak-shaving PD would act) consumers are already consuming as minimum possible within the assumed flexibility.

Two scenarios that are easily distinguished from the others, are the distance PD and the CO_2 PD. For the distance PD, consumers never reach their maximum load, due to their distance for the wind and PV plants. Even though the price is low to purchase electricity from RES sources,

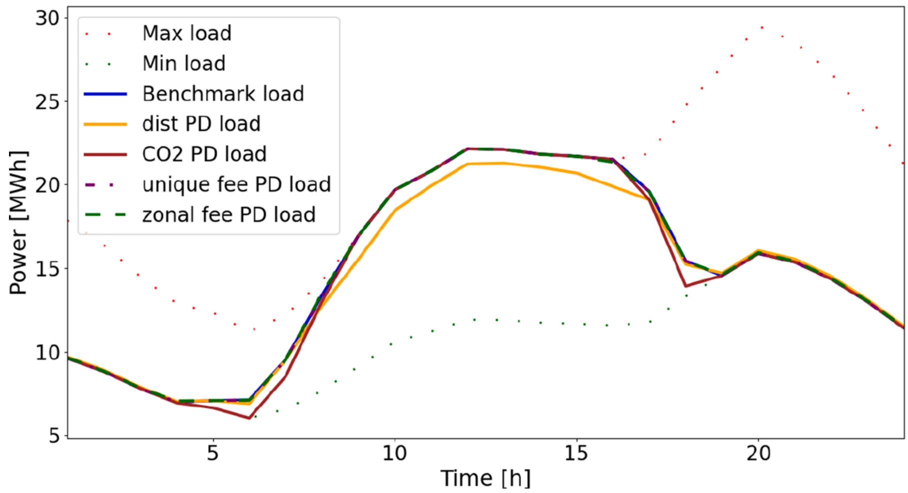

Fig. 7. Load diagram for the different P2P market scenarios.

the penalization restrains them to cover their maximum loads. For the CO_2 PD market scenario, the slight difference can only be seen when RES sources are unavailable, and only the external supplier and CHP sources are the possibilities for the consumers to cover their minimum load. This happens from 04:00h to 06:00h and from 18:00h to 19:00h, when the consumers decide to cover minimum load from the external grid instead of CHP sources, since the CO_2 levels are lower for the external supplier.

It is worth mentioning that when there is no PV generation and insufficient wind generation to cover the electricity demand, the network needs to import electricity from the external grid or be supplied by CHP, in particular, this happens between 19:00h-04:00h. In those hours, load consumption is equal to the lowest possible load, *i.e.*, $P_n = \underline{P_n}, \forall n \in \Omega_c$. This behaviour results from the loads' cost curve definition, and that is a reflection of what happens in the load diagram: when there are imports from the grid, the electricity price is equal to the wholesale market price, 58 € /MWh as shown in Fig. 8. Hence, consumers are willing to pay that price only to cover their minimum load. The opposite happens when there are RES available, at that moment they are willing to cover their maximum load for 4 € /MWh. The electricity prices shown in Fig. 8 are the maximum prices charged to consumers.

Table 3 shows the social welfare (SW), the total cost (TC), total revenues (TR) and AEI indicators for each scenario achieved over the simulated period. Looking specifically for the SW, CO_2 PD is the scenario that stands out with a smaller SW. As already mentioned before, CO_2 PD is a scenario based on reducing the levels of CO_2 produced by the system. Hence, since the purchases from the grid are more expensive than from CHP sources, the total revenues rise by approximately 12%.

Regarding the AEI, formulated in subsection 4.6, through the load diagram, it would be expected that the AEI for the scenarios would be practically the same. The distance PD market has a lower value, due to the hours it does not cover the maximum load while the other scenarios of PD preferences do. That is, the power that could be traded versus tradable is slightly less when applied to the distance PD market in this case study.

Table 3
Results for the different P2P market scenarios.

Scenarios	SW (€)	TC (€)	TR (€)	AEI
Benchmark	21963.48	26309.79	4346.31	0.54
distance PD	21855.73	26225.99	4370.26	0.53
CO_2 PD	21242.12	26098.62	4856.49	0.54
Unique fee PD	21963.43	26308.25	4344.82	0.54
Zonal fee PD	21961.68	26330.96	4369.28	0.54

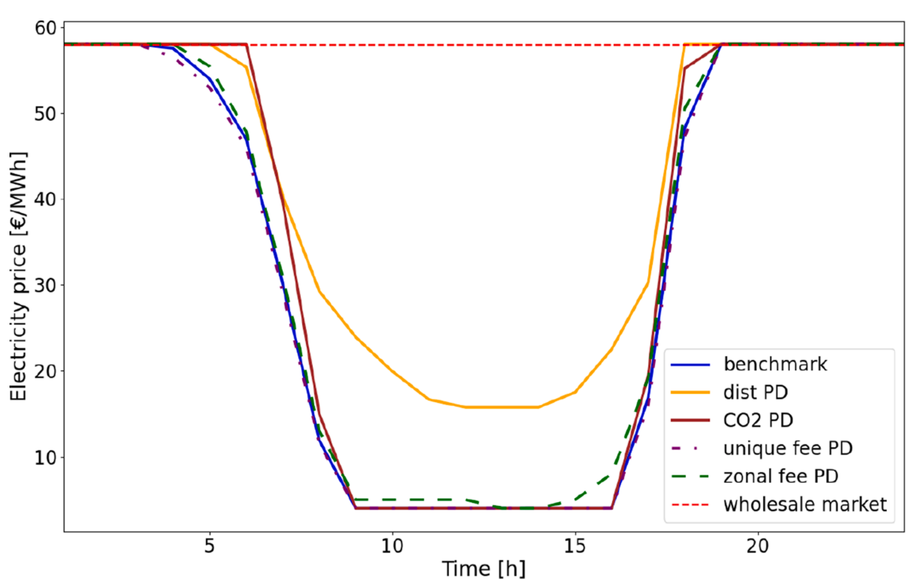

Fig. 8. Electricity price for the different P2P market scenarios.

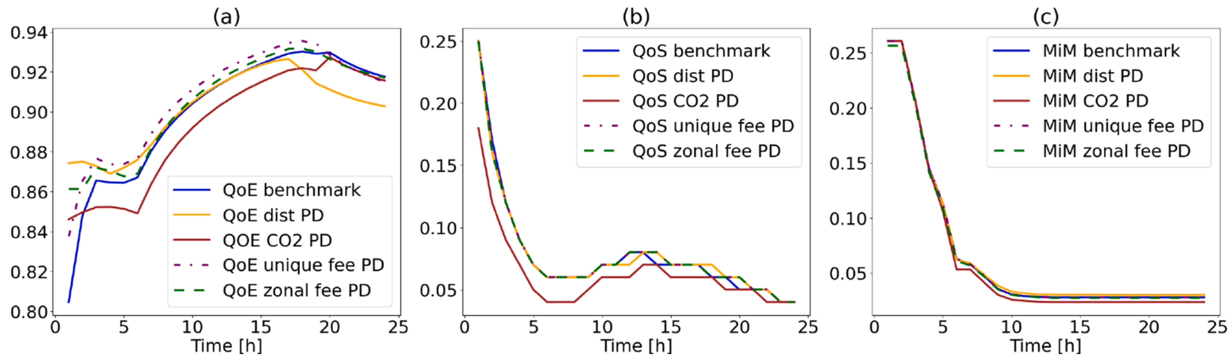

Fig. 9. (a) QoE, (b) QoS and (c) MiM for the different scenarios presented.

Table 4
Fairness between the benchmark and the different P2P market scenarios.

Scenarios	TCRI	PII	PRI	ERRI
Bk - dist PD	0%	43%	-1%	+4%
Bk - CO_2 PD	-1%	34%	+1%	-40%
Bk - Unique fee PD	0%	42%	0%	0%
Bk - Zonal fee PD	0%	24%	0%	+1%

Bk = Benchmark.

Concerning fairness among peers, Fig. 9 presents the QoE, QoS and MiM indicators for the different market scenarios. There are no significant fluctuations in the indicators shown. For almost all the different market conditions presented, the average QoE, QoS and MiM are 90%, 8% and 7%, respectively. Except for the CO_2 PD market, which is slightly different showing a QoE of 89%, and a QoS and MiM of 6%. Lower QoS values means that there are agents in the market with larger capacities when compared to others. This leads to discrepancies in the network, which can be seen in initial hours for the CO_2 PD due to the preference of imports from the external grid rather than from CHPs. The QoE, related to the user viewpoint, presents similar values for all P2P market preferences, which points out a relatively large satisfaction of the agents involved in the trades with other agents. In general, the low values of MiM presented in 9 (c) point to the significant difference between the electricity that is exchanged among the consumer agents.

Table 4 presents the TCRI, PII, PRI, and ERRI results, which are the indicators that compare the benchmark market condition with the other P2P markets considering PD preferences. Looking specifically to TCRI and PRI, there is no significant total cost reduction or peak reduction across the simulated markets. Regarding the PII indicator, it can be seen that all markets compared to the benchmark have more agents with profits. This KPI is directly related to the reduction in consumer costs and increase in producer incomes, as shown in (3). For instance, the CO_2 PD preference market has 34% of its agents with more profits compared with the benchmark market model. This is due to the reduction in the total costs, most of the 22 consumers have more profits in this market. Nonetheless, the number of the 29 producers present in the market do not havemore profits, since consumers have preference to consume from the external grid rather than from CHP sources. Consequently, the PII lowers since the external grid counts as one agent and CHP sources as three agents. The significant difference between the benchmark market model and the other P2P market models with PD preferences can be seen in the ERRI indicator, with a 40% reduction of CO_2 emissions from benchmark to CO_2 PD (Bk - CO_2 PD).

5.2.2. Community-based markets results

In the case of the community-based market, the network is divided into four energy communities according to the dashed areas in Fig. 5.

Fig. 10 shows the load diagram for each community for each scenario, *i.e.*, benchmark market condition, market-base PD and autonomy PD. It can be seen that for communities 1, 2 and 4, *i.e.*, Fig. 10 (a), (b) and (d), the load variation between the different scenarios is practically nil. However in community 3, one can see some load shifting to the

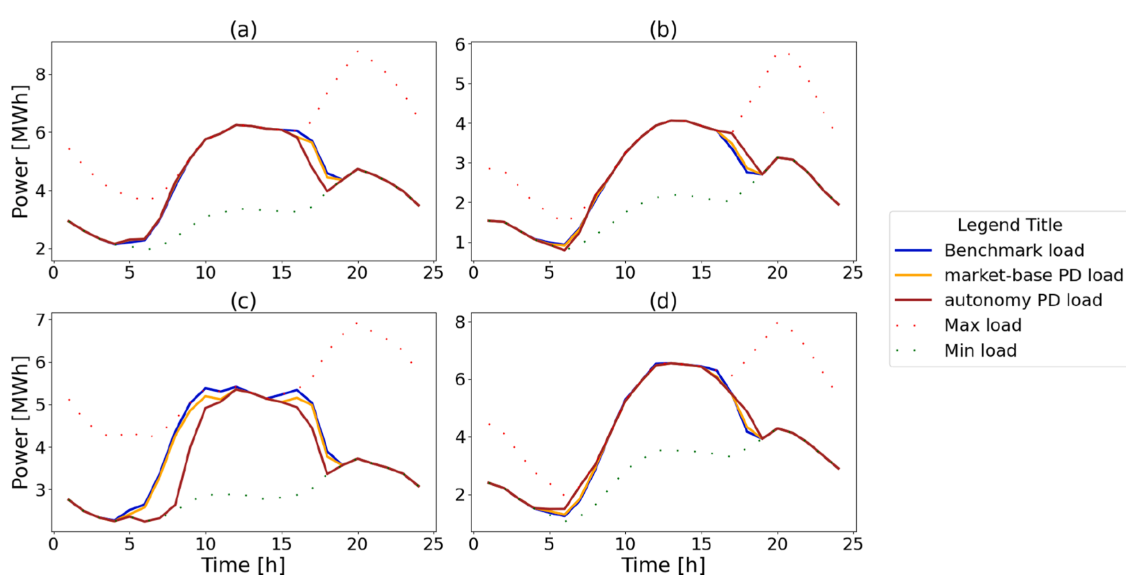

Fig. 10. Load diagram by community, (a) community 1, (b) community 2, (c) community 3 and (d) community 4, for the different community-based market scenarios.

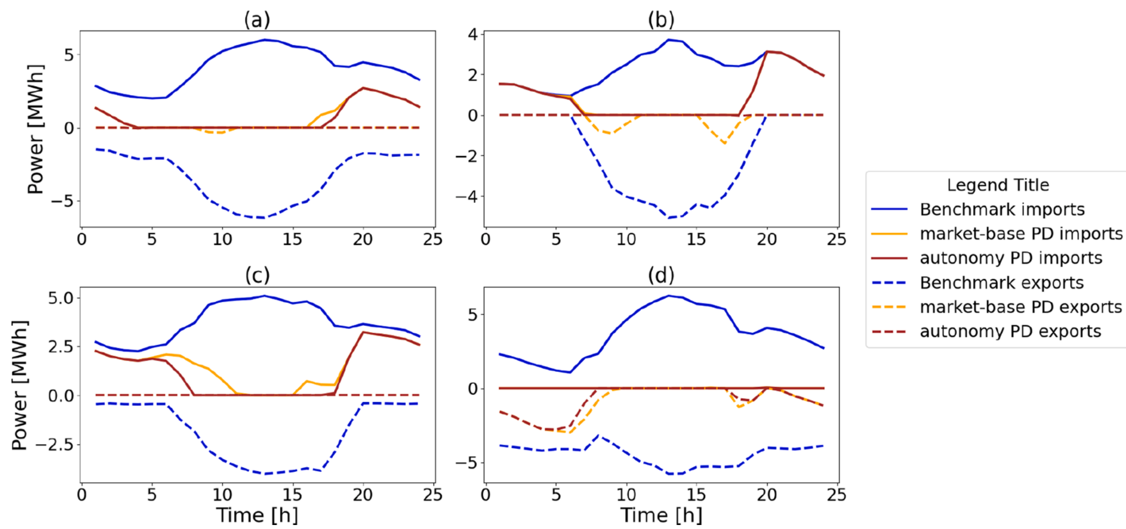

Fig. 11. Imports and exports by community, (a) community 1, (b) community 2, (c) community 3 and (d) community 4,for the different community-based market scenarios.

Table 5
Results for the different community-based market scenarios.

Scenarios	SW (€)	TC (€)	TR (€)	AEI
Benchmark	21963.48	26309.79	4346.31	0.54
market-base PD	21957.01	26298.24	4341.24	0.53
autonomy PD	21802.84	26119.99	4317.14	0.54

Table 6
Fairness between benchmark and the different community-based market scenarios.

Scenarios	TCRI	PII	PRI	ERRI
Bk - market-base PD	-1%	29%	0%	0%
Bk - autonomy PD	-2%	29%	+2%	+2%

Bk = Benchmark.

minimum possible within the flexibility. This is due to the type of producers in this community, which are mainly PV with only one CHP, and to the minimum load of consumers, which is the second largest among the four communities; consequently, this community cannot be autonomous. In Fig. 11 in (c), it can be seen that this community is the one that exports the least and imports the most in the network. This means that internal trades are insufficient to satisfy the request for electricity from the consumers of this community. Note that community 3, is the only community that does not export electricity in the market scenarios with PD (namely, market-base and autonomy) due to the lack of production from his producers to satisfy the needs of its consumers.

One can note a power imbalance between the communities through the needs of external supply from the grid and by other communities analysing the graphs in (11). More precisely, community 4 has no need for external supply when forced by the application of PD in the market. This is due to the low load of consumers and a variety of the different sources of energy available. In contrast, community 2 in (11) (b), cannot support consumer loads at hours when there is no PV production, requiring electricity from the grid or other communities. This is because the internal production of community 2 is exclusively from PV sources. At the same time, community 2 can export energy from 6:00h to 11:00h and from 15:00h to 18:00h, which is the time that consumers are in the transition from the minimum/maximum load according to their flexibility.

Analysing Table 5, we note that in the scenario where the autonomy PD is applied, both the total cost and the total revenues are lower compared to the other scenarios. Autonomy reduces the imports and exports of the communities to maximize the internal exchanges between the agents for each community. Therefore, communities that have alternative sources, *e.g.* CHP plants, and insufficient renewable energy to supply their consumers have to resort to these alternative sources, avoiding the import from the grid. This is due to the import penalty applied to each community that makes the grid a much more expensive alternative.

Comparing the results and the analyses made from Fig. 11 and Table 5, the results gathered in Table 6 prove their veracity. The PII values presented, together with TC and TR in 5, show the impact of the penalization on exports. Producers have their profit reduced with the PD preference in market-based PD and autonomy PD. The emission

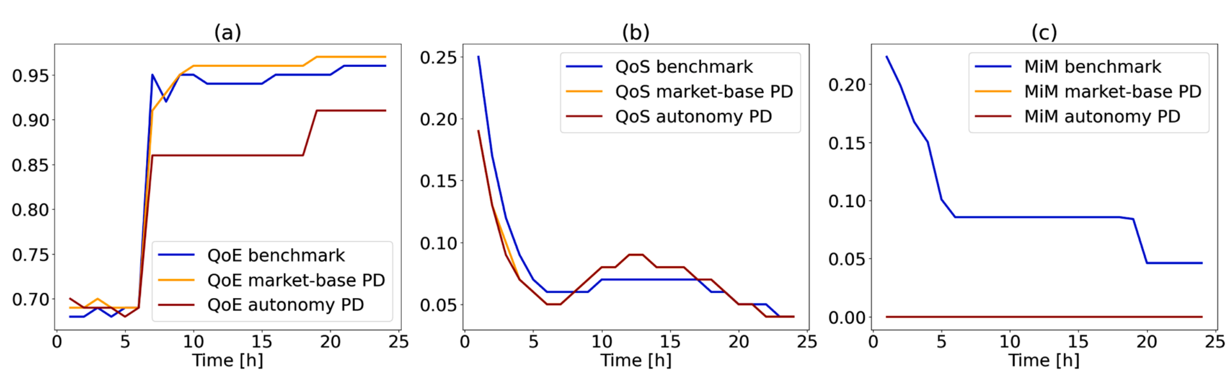

Fig. 12. (a) QoE, (b) QoS and (c) MiM for the different community-based market scenarios presented.

reduction rate observed on ERRI between the benchmark market model and autonomy PD of 2% is due to the penalty on imports and exports to the communities. Under this condition, consumers choose to trade with producers exclusively from the same community, consequently buying electricity from CHP sources whose CO_2 emissions levels are higher compared to the external grid.

The KPIs presented in Fig. 12 show the performance of each market scenario for the aggregate of the four communities. The average QoE for benchmark market model and market-base PD condition is 0.88, while for autonomy PD is 0.83. These small differences between the scenarios are due to the fewer competitiveness existing in each community. Therefore, agents are compelled to exchange with players who do not offer prices as favorable as their competitors at certain times. The average QoS for the different scenarios is 0.07, however we can see a slight increase between 9:00 and 16:00 for the scenarios with PD application due to the maximum increase in internal trades for each community. The effect on MiM for the market scenarios with PD is a consequence of the penalty on imports for communities. The average MiM for the benchmark market model is 0.09 and for the remaining scenarios is 0.

In the case study carried out, it was observed that social welfare is always reduced when any consumer preference is integrated through the product differentiation mechanism. However, this does not mean that the total costs for consumers have increased. As there is a flexibility consideration of 30% for the base load of consumers, the trend is to observe a load shifting according to the offer of the cheapest generators, in this case, renewable generation. In some cases, there may even be less consumption due to the impossibility of shifting the load. If there is no consideration of flexibility for the loads of the consumers, the consumers' costs will increase significantly and the social welfare will decrease due to the generator revenues.

6. Conclusions

The advantages and challenges that consumer-centric markets can bring to users are assessed in this paper through the simulation of full P2P and community-based market structures. This type of market gives consumers or prosumers a certain freedom regarding energy trading. However, the impact and effects of such markets in the network have yet to be completely assessed.

This work provides a detailed review of the PD mechanism and user preferences applied to these markets. The results of decentralized implementation based on consumer preferences are promising, as they allow for more proactive consumer behavior, for example, favoring local generation, clean energy generation, or community autonomy. In addition, it reviews the most commonly used KPIs for assessing technical, economic and environmental performance of these markets. To provide a fair comparison between the different models and user preferences, an illustrative case study is used. All market model variations are modeled, and the results are compared based on the different KPIs.

It was observed that P2P markets, in general, increase the RES penetration on the network, and tend to affect loads flexibility accordingly to the renewable generation. In the set of modeled preferences for the full P2P and community-based markets, the ones that stand out are the CO_2 PD, distance PD and autonomy PD preferences, with CO_2 emissions reduction rate index of -40%, +4% and +2% compared to benchmark model, respectively. In addition, the community-based market design reveals a disequilibrium between agent participation in the market when the communities have an imbalance between load and production. MiM highlights a imbalanced system with low values that points to a considerable difference between the maximum and minimum electricity traded amongst the consumer agents. Regarding the other KPIs, all the markets with PD preferences have similar behaviors, with averages QoE of 83-90%, QoS of 6-8% and MiM of 0-9%. These results show the effectiveness of the proposed approach according to the purposes of each preference.

An important conclusion is that even though PD mechanism is used to attend different preferences of the energy community, it always results in worse social welfare compared to the benchmark model. This means that despite individual satisfaction and increased profits, the well-being of the community or communities can be compromised.

Declaration of Competing Interest

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

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