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Highlights

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P2P flexibility markets models to support the coordination between the transmission system operators and distribution system operators

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- Design of congestion management services contracted by the DSO, in a P2P market.
- Design of voltage control services contracted by the DSO, in a P2P market.
- Design of frequency regulation services contracted by the TSO, in a P2P market.
- Coordination of TSO/DSO services through a P2P market.

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P2P flexibility markets models to support the coordination between the transmission system operators and distribution system operators

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ABSTRACT

The increasing integration of Distributed Energy Resources (DER) in the distribution network has brought more importance to Peer-to-Peer (P2P) markets. However, energy traded in P2P markets can lead to voltage and congestion constraints in distribution networks operated by Distribution System Operators (DSOs). At the same time, Transmission System Operators (TSOs) may need to solve system problems, requesting the participation of DERs in frequency regulation services. To ensure competitive participation in P2P markets, as well as to ensure a correct operation of distribution networks and to contribute to mitigate problems at the system level, coordination mechanisms between the P2P market and the System Operators (SOs) are required. This paper introduces a set of mathematical models considering P2P flexibility trading at the distribution system, while assisting the DSO and TSO in solving the congestion, voltage and frequency problems, respectively. The models are assessed on an IEEE 37-bus distribution network with high DER penetration. The first and second models are based on product differentiation to avoid violating the lines' thermal limits and the nodes' voltage limits, respectively. The second model also considers reactive power control in order to impact voltage constraints. The third model uses a virtual load, connected to the TSO network (before the power transformer), to model frequency regulation services. The last model proposes the integration of all methods. Results showed that each model was effective in solving its constraint. However, they do not dismiss the use of the peers' flexibility assets to assure an overall feasible techno-economic solution. The use of the methodology proposed in the present paper can significantly facilitate the adoption of full P2P markets as well as the confidence of the system operators in the integration of these markets.

1. Introduction

1.1. Context and motivation

Prosumers are consumers with generation technology (mainly PV) that can self-consume and, to a certain extent, generate surplus power to inject into the distribution network. They are often categorized as flexible resources due to their ability to control their consumption and generation and therefore enable flexibility [1]. However, current electricity markets are not ready to accommodate small prosumers due to their capacity and behaviour. A way to have consumer-centric electricity markets is by adopting a P2P structure, which can exist with different degrees of decentralization or topology, as shown in [2,3]. In a P2P market architecture, prosumers (also called peers) can choose their economic or environmental preferences over the electricity they are buying.

A P2P model based on multi bilateral trades was proposed in works such as [4,5] to replace the current pool market. In this model, different prosumers could trade with each other, deciding both the amount of power exchanged and the corresponding trading price. However, this structure did not take into account the impact of the bilateral settlements on the operation and management of the distribution and transmission systems, operated by DSO and TSO, respectively. This can lead to line and transformer congestion and/or voltage constraints, increasing the complexity of operation of both distribution and transmission system operators. At the same time, prosumers can contribute for solving congestion and voltage issues by providing flexibility (in the form of services), but this requires proper coordination between the TSO and DSO. The coordination implies that both the TSO and DSO need to be aware of the available peers' flexibility

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Nomenclature

Sets and Indices

Ω	Set of peers
Ω_c	Set of consumers
Ω_p	Set of producers
$\Omega_{p_{RES}}$	Set of producers with renewable generation
ω_n	Set of trading peers of peer n
k	Index for iteration
l	Index for lines
t	Index for time periods
n, m	Indices for peers
i, j	Indices for nodes

Parameters

$\overline{P_n}, \underline{P_n}$	Upper and lower active power limits of agent n
P_n^{max}	Maximum active power of agent n
a_n, b_n, d_n	Coefficients of agent n in cost function C_n
α	Penalization factor for the activation extra flexibility

Functions

C_n	Cost function of agent n
C_n	Product differentiation cost function of agent n
C_{nT}	Product differentiation cost function of agent n including congestion and voltages factors

Decision variables

P_n	Net active power of peer n
$P_{n,m}$	Bilateral active power between peers n and m
$\lambda_{n,m}$	Dual variable, shadow prices
c_n^g	Trade coefficient, preference coefficient of agent n for criterion g
$\gamma_{n,m}^g$	Trade characteristic, value of criterion g of agent m from perspective of agent n
$P_{n,t}^{Flex_{Ext}}$	Activated extra flexibility by peer n in period t
L_l	Line load level of line l
V_i	Voltage magnitude of node i

to run preventive management mechanisms that can use this flexibility to mitigate voltage and congestion issues if their own mechanisms are not sufficient [6].

The main aim of the work presented in this paper is to accommodate the inclusion of all these concepts in a set of models that can coordinate the negotiation of prosumers' flexibility in a P2P structure with the operation and coordination of the DSO and TSO systems.

1.2. State of the art

Some works are emerging in the literature to study how network operating issues can be solved using demand response (DR) flexibility and TSO/DSO coordination as key methods [7–11]. The methods proposed in the literature can be classified in two different ways. First, the mechanisms to solve grid constraints could be classified into two options, *(i)* conventional reinforcement of the grids and *(ii)* the use of flexibility to avoid or delay the investments in the reinforcement of the network [12]. The second classification is related to the types of flexibility that can be procured. In that case, two sources of flexibility can be identified, namely: *(i)* when the system operators use their own resources to solve network constraints such as reconfiguration, OLTC tap changing, etc., and *(ii)* the procurement of flexibility services (products) using market mechanisms or other alternatives (dynamic tariffs, connection agreements, bilateral contracts, etc.) [13]. Regarding markets, the TSO currently uses ancillary services markets to solve congestion and balancing problems [14], and, with regards to DSO, some initiatives are testing local markets (including P2P) to procure flexibility to solve congestion and voltage problems in the network. The present state-of-the-art is centred on the use of flexibility mainly the ones that are procured in P2P markets.

Concerning the activation of flexibilities, works that relate to P2P markets and DSO operation to solve either congestion or voltage constraints can be referred. Orlandini et al. [15] uses an iterative approach with a product differentiation mechanism to solve line congestion. This model penalizes trades causing congestion based on the Euclidean distance between the peers. Similarly, Botelho et al. [16] resorts to topological distribution factors to proportionally penalize only the trades causing congestion, ensuring a feasible solution. A different approach based on sensitivity analysis is proposed by Guerrero et al. [17] to solve voltage limit violation, by evaluating the impact of P2P trades in the grid operation. Another sensitivity-based analysis is provided by Dynge et al. [18] who studies the impact of P2P trading on voltage variations and network losses.

A completely different perspective to take into consideration these constraints is presented in [19], where a two-stage market is used: in the first stage a local P2P market (without product differentiation) is established, and in the second stage prosumers trade flexibility through a local market, in order to solve congestion and voltage issues.

Other works take into account the impact of DER in the grid frequency, which is regulated by the TSO. An example is the work in [20], where a multi-market nanogrid trading for real-time imbalance elimination and frequency regulation procurement is proposed, based on P2P architecture. This work considers the participation in three markets: P2P bilateral energy market, the balancing market and the ancillary services market.

Finally, it is important to mention works related to the TSO-DSO coordination for DER integration. Methodologies presented in [21] analyse the coordination, monitoring and dispatch of resources between aggregators, DSOs, and TSOs.

The coordination aspect is deepened in [22], contributing to two different coordination schemes between TSOs and DSOs: one centralized and another decentralized that facilitate the integration of distributed generation. In the resulting decentralized scheme, TSOs and DSOs collaborate to optimally allocate all resources in the system. Another methodology to coordinate TSOs and DSOs giving an active role to the DER is proposed in [23]. However, while the purpose of Najibi et al. [22] was to minimize operating costs and relieve congestion, Radi et al. [23] aims to provide balancing across different timescales.

1.3. Main contributions

Even though the works presented in the literature present a deep level of analysis within the topic presented in this paper, they mainly focus on solving a specific constraint. For example, in category *(i)* the works in [15,16] centre on solving congestion, and Guerrero et al. [17], Dynge et al. [18] pivot on solving voltage constraints. Only the work in [19] has the ability to solve both those constraints, but it lacks the implementation of a model such as product differentiation to fix the network operating issues without needing a flexibility market. A positive aspect of all works in this category is that they all deal with network constraints in a P2P market context.

Taking into account the works in category *(ii)*, Hu et al. [20] only aims to solve frequency issues in the presence of a P2P market.

Finally, in category *(iii)*, despite all works studying TSO-DSO coordination mechanisms, none of them do so considering a P2P market, but only considering the presence of DER. Furthermore, each work focus on solving only one network operating constraint: congestion [22] or frequency [23]. In summary, considering all the literature analysed and presented in this section, it is possible to mention that procurement of flexibility using a full P2P market model and TSO/DSO coordination is a gap in the existing state-of-the-art.

The proposed work focus on the implementation of methodologies to solve congestion, voltage and frequency constraints, always in the context of a P2P market. The proposed methodology is evaluated considering several network operating scenarios allowing the validation of the contribution to solve each constraint. The main contributions of the present work are threefold:

- To explore iterative coordination methods between the P2P market and the DSO, namely with product differentiation mechanism and reactive power control, to solve congestion and voltage issues;
- To conceptualize a frequency regulation service to be offered to the TSO, in the context of a P2P market;
- To explore an iterative coordination method between the TSO and the DSO to solve congestion, voltage and frequency issues through the P2P framework.

1.4. Paper organization

The paper is structured as follows: after this introduction, Section 2 introduces a P2P market formulation (basis) and the power flow method to check the feasibility of the market outcomes. Section 3 describes four P2P market models to solve different network operating issues based on the formulation presented in Section 2. A description of product differentiation strategies is also introduced in this section. A distribution network with 37 nodes is presented in Section 4 and is used as a study case, where the proposed models described in the previous sections are assessed and compared to a benchmark model (using a full P2P market model without differentiation). Section 5 assembles the main conclusions and some directions for future work.

2. Use of P2P trading in power systems

Even though different P2P market structures can be defined [3], such as full P2P, community-based and hybrid P2P markets, the present work focus on the first ones, namely, full P2P markets. In this market, peers are allowed to freely trade energy among themselves at the distribution grid level. The full P2P market is a completely unsupervised and decentralized market, where multiple peers can negotiate establishing bilateral trades. This is illustrated in Fig. 1.

For the correct implementation of a full P2P market, two components are essential: *(i)* the P2P market clearing process, which matches the selling and buying bids of the prosumers, and *(ii)* the power flow validation, performed by the DSO, to check if the technical and operational limits of the distribution network are respected. These components are explained in the following sub-sections.

2.1. P2P market model

The P2P market is solved for each period (one hour in the proposed method), where $\mathcal{T}$ corresponds to all hours of a single day. Note that all time-varying input data is updated every hour. Peers n, m are assumed to have full control over their consumption and DER assets. It was considered that they, in each hour, could only act as either producers or consumers in bilateral trades. If producers in the P2P market cannot supply all the demand, it is assumed that the consumers can buy energy from external suppliers (connected in the transmission network). The set of producers and consumers are given by Ω_p and Ω_c, respectively. Within Ω_p it can be considered a set exclusively for producers with renewable generation, $\Omega_{p_{RES}}$. The set of trading partners of n is given by ω_n.

The P2P mathematical model inspired on [24] can be formulated as,

$$\min_{D} \quad \sum_{n\in\Omega} C_n(P_n) + \tilde{C}_n(P_n) \tag{1a}$$

$$\text{s.t.} \quad P_n = \sum_{m\in\omega_n} P_{n,m} \qquad \forall n \in \Omega \tag{1b}$$

$$\underline{P_n} \leq P_n \leq \overline{P_n} \qquad \forall n \in \Omega \tag{1c}$$

$$P_{n,m} + P_{m,n} = 0 \qquad \forall (n,m) \in (\Omega, \omega_n) \tag{1d}$$

$$P_n \geq 0 \qquad \forall n \in \Omega_p \tag{1e}$$

$$P_n \leq 0 \qquad \forall n \in \Omega_c \tag{1f}$$

where $D = \{P_n, P_{n,m} \in \mathbb{R}\}$ and the decision variable is P_n, the net active power of peer n. Constraints are necessary to guarantee the correct functioning of the P2P market.

The objective function have to parcels. The first parcel considers the cost C_n for each peer as a quadratic curve, as proposed in [25,26]:

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

The product differentiation parcel of the cost function (3) is given by a combination of non-monetary preferences between peers n and m [27],

$$\tilde{C}_n = \sum_{m\in\omega_n} \sum_{g\in G} c_n^g \gamma_{n,m}^g P_{n,m} \tag{3}$$

where a particular preference $g \in G$ is monetized through the trade coefficient, c_n^g. The trade characteristic, $\gamma_{n,m}^g$, differentiates each peer m from the perspective of peer n. This differentiation will lead to variable shadow prices $\lambda_{n,m}$. The definition of the product differentiation parcel based on the impact that peers have in the network and system constraints is the main contribution of the present paper.

This work considers two preferences, both to solve constraints at the DSO level: *(i)* one based on the Euclidean distance between peers, to solve congestion constraints, and *(ii)* another to solve voltage constraints, based on the sensitivity between the peers that can offer flexibility and the node where the voltage constraint is located. As for the frequency regulation, which is managed by the TSO, product differentiation was not needed as all peers have the same impact on this service. For this service, a virtual load was added to the system, before HV/MV power transformer, in order to model the requirements of the TSO for frequency services. Product differentiation is only applied to this virtual load. More details about the product differentiation proposed in this work will be provided in Section 3.

The active power of each peer n is equal to the sum of all bilateral trades $P_{n,m}$ in which n is involved (1b) with peers m. P_n has a given degree of flexibility for both type of peers, hence the

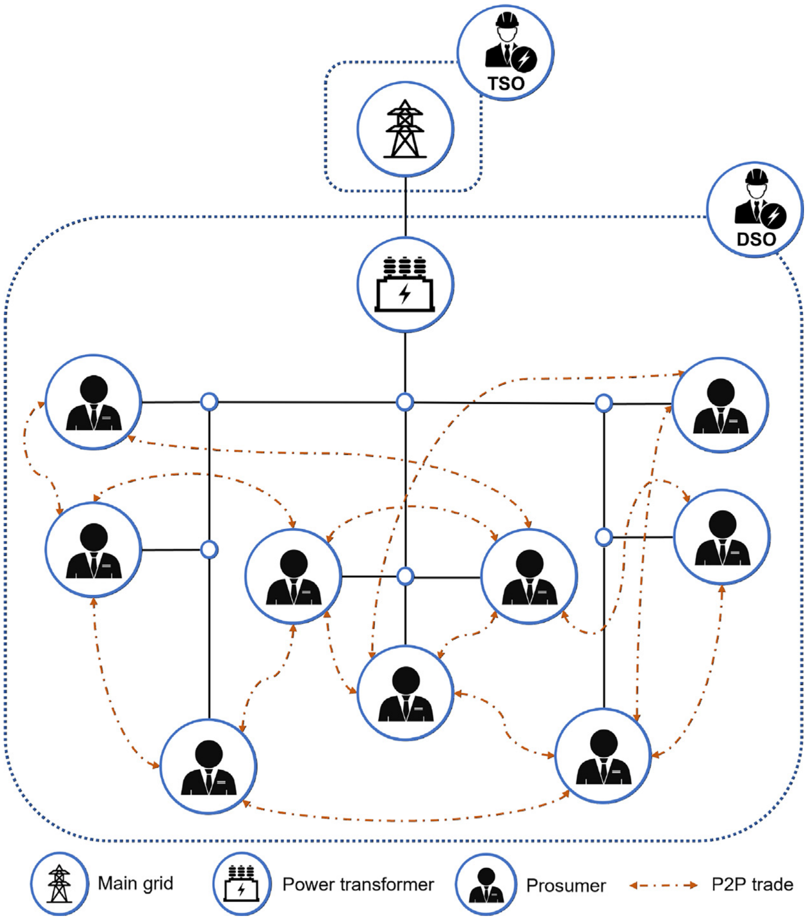


Fig. 1. Schematic representation of a full P2P market on a distribution grid.

lower and upper boundaries are defined in (1c). Constraint (1d) guarantees the bilateral agreements between peers n and m are respected. The price for each trade is obtained by calculating the dual variable $\lambda_{n,m}$ of constraint (1d). The producers will have a positive P_n (1e), while the consumers will have a negative P_n (1f).

2.2. Power flow modelling

The feasibility of P2P transactions should be validated using a power flow model. As this work is applied to distribution grids, an AC power flow model is used. This model is more accurate than the DC power flow which is used in many studies in the literature, such as in [28]. The present work considers a distribution network with radial topology, which can be represented as a graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$, composed by a set of lines $l \in \mathcal{L}$ which connect the nodes $i \in \mathcal{N}$. A short summary of the power flow model used in the present work and available in the PandaPower library is described in the following sentences.

Each peer n is located in a node, which has voltage magnitude, V_i, angle θ_i, and injects/consumes apparent power, S_i, where P_i and Q_i corresponds to the active and reactive components of S_i (4). Each node can have several prosumers.

$$S_i = P_i + \mathbf{j}Q_i \tag{4}$$

Line l connects a pair of nodes (i, j) and its impedance is characterized by (5), where $R_{i,j}$ is the resistance and $X_{i,j}$ is the reactance. Eq. (6) represents the active, $P_{i,j}$, and reactive, $Q_{i,j}$, components of the power flow, respectively.

$$Z_{i,j} = R_{i,j} + \mathbf{j}X_{i,j} \tag{5}$$

$$S_{i,j} = P_{i,j} + \mathbf{j}Q_{i,j} \tag{6}$$

Graph $\mathcal{G}(\mathcal{N}, \mathcal{L})$ starts with a root node that represents the transmission network, and which is used as a slack bus for the AC power flow model. The slack bus has voltage level and angle fixed in 1 pu and 0° and is connected to the distribution system by a power transformer that can be modelled in pu system as a line with specific characteristics.

The AC power flow model from the pandapower tool [29] was used, where P_n results from (1), described in Section 2.1, as a steady active power for each peer n. The consumers have a fixed $tg(\phi)$, while the producers reactive power is variable depending on the used technology: Combined Heat and Power (CHP) plants, Photovoltaic (PV) units or Wind farms.

Frequency constraints can be anticipated by TSO due to imbalances between production and consumption creating frequency variations. The other targeted constraints can be predicted by DSOs after the AC-PF validation. A line/transformer congestion occurs if the load level of a line l is above 100%, $L_{l_{max}}$ (7). A voltage constraint emerges when the voltage magnitude of a node i is not between the lower $V_{i_{min}}$ and upper limits $V_{i_{max}}$ of 0.95 p.u. and 1.05 p.u., respectively (8) [16].

$$L_l \leq L_{l_{max}} \quad , l \in \mathcal{L} \tag{7}$$

$$V_{i_{min}} \leq V_i \leq V_{i_{max}} \quad , i \in \mathcal{N} \tag{8}$$

To evaluate the highest possible social welfare (SW), a model which disregards grid constraints, the so-called benchmark, was developed. This model is non-iterative and consists of two steps. In the first step is executed the P2P market model. Here, the bilateral power traded and trading prices are obtained, along with the power that should be generated by the sellers and that should be consumed by the buyers. The second step is an AC power flow validation, to determine if the results from the P2P market respect (or not) the technical and operational limits of the distribution network.

The benchmark model will be compared with the models proposed in this work showing its capacity to solve the network constraints.

3. Participation of TSO and DSO in P2P market

To solve the P2P market taking into account the technical operating limits of the network, different methodologies were considered: *(i)* coordination between the P2P market and the DSO, to solve congestion and voltage constraints; *(ii)* coordination between the P2P market and the TSO, to solve frequency constraints; *(iii)* TSO-DSO coordination with the P2P market to solve all constraints simultaneously.

The following sub-sections will describe the modelling of the services that can be contracted by the DSO and TSO, for achieving both market clearing and grid feasibility.

3.1. DSO related services

Regarding grid operation, the DSO can contract services to manage congestion and voltage level violations. Two iterative models were developed, one for each type of constraint. The mathematical model for the P2P market used in both methods can be presented as an improvement of P2P model (1), described in Section 2.1:

$$\min_{D} \sum_{n\in\Omega} C_n(P_n) + \tilde{C}_n(P_n) + \alpha P^{Flex_{Ext}}_{n,t} \tag{9a}$$

$$\text{s.t.} \quad \text{constraints in (1)} \tag{9b}$$

$$0\%.P^{max}_n \leq P_n + P^{Flex_{Ext}}_{n,t} \leq 100\%.P^{max}_n \quad , n \in \Omega_c,\ t \in \mathcal{T} \tag{9c}$$

$$\alpha \gg 1 \tag{9d}$$

At the beginning of every time period t, the flexibility offered by the loads is at 30% of their baseline, in both upward and downward directions. This flexibility is already modelled in Eq. (1c) where the variable P_n is limited between $\underline{P_n}$ and $\overline{P_n}$. The extra load flexibility is initially set at 0% of the maximum active power P^{max}_n. In every hour, if when the iteration k limit is reached the constraint has not been solved, then $P^{Flex_{Ext}}_{n,t}$ will update the total flexibility offered. This flexibility is limited by (9c), and its increase is penalized by coefficient α (9d). This forces the system to use as little of the extra flexibility as possible.

During every time period t and at any iteration k, the flexibility offered by the RES is of 100% in the downward direction, meaning the operation point can be anywhere between zero and their forecast power.

It is important to notice that, nowadays, activation of flexibility services are not allowed in most of the systems. The proposed methodology implies a change in the policies and regulatory framework to allow the use of flexibility services and, consequently, the increase of DER connected in the system.

3.1.1. Congestion management services

The iterative model that deals with grid congestion, *P2P_Cong*, is presented in Fig. 2.

The first step of *P2P_Cong* is the P2P market to obtain optimal trading between peers (9a) through the bilateral trades, $P_{n,m}$, and the shadow prices, $\lambda_{n,m}$. Initially, the market is cleared without any differentiation of market offers. The second step is the DSO operation, where an AC power flow is used to determine if the network technical limitations are respected.

In case a line congestion is detected, violating (7), the product differentiation mechanism will penalize every trade causing the congestion using the euclidean distance between peers through c^g_n and $\gamma^g_{n,m}$. Then, new values of c^g_n and $\gamma^g_{n,m}$ are sent to the P2P market, initiating the first step again, until the network limits are finally respected. This allows the process to move to step four.

The choice of c^g_n and of the parameter that will penalize $\gamma^g_{n,m}$ in each iteration are of utmost importance as they control the penalization given to the trades. If given a low value, a big computational effort may be needed to differentiate market offers in order to solve the constraints. However, if this value is too high, the penalization given to the generators further away from the loads may be higher than needed to solve the constraint.

If the product differentiation is not enough to solve the congestion, iteration k limit is reached. So, in step three, the flexibility adjustment enforces that the loads flexibility increases and the P2P market is run from step one. The adjustment of the flexibilities is made in fixed steps defined by each peer. Once the congestion is solved, the process moves to step four and the market results under grid constraints are obtained.

3.1.2. Voltage control services

The iterative model that deals with grid voltage constraints, *P2P_Volt*, is presented in Fig. 3.

Similarly to model *P2P_Cong*, *P2P_Volt* uses the P2P market in step one, and starts the DSO operation (step two) with the AC power flow. However, in *P2P_Volt*, the product differentiation penalizes the trades causing voltage issues by violating (8), using a sensitivity criteria. As this constraint may be found in different nodes, the node with the worst constraint was considered for this mechanism. The sensitivity was based on resistance of the common path of two paths: the one between the node with worst constraint and the slack bus, and the one between the node with the peers that can offer flexibility and the slack bus.

In case the product differentiation is not enough to solve the voltage constraint, the iteration k limit is reached. This initiates step three, where a flexibility adjustment enforces the loads flexibility to increase. The new flexibility bids will be used in step one, resetting the number of iterations k. Once the voltage constraint is solved, the process moves to step four and the market results complying network constraints are obtained.

An extra stage is considered in step 2, by applying reactive power control to the peers with most impact on the existing constraint. For example, in case there is a low voltage constraint, the value of $tg(\phi)$ on the loads could be reduced. This would be done for every load in the feeder where the constraint is located, from the load with most impact until the load with less impact. This impact is known from the sensitivity criteria in the product differentiation mechanism. In the case of a high voltage constraint, the same process is applied but to the $tg(\phi)$ of the RES. In reality, this process could be done to the RES, but not to the loads, as they correct their power factor in order to not pay for reactive power. Therefore, rules for the payment of reactive power for the loads would be needed, as well as capacitor banks in the loads, to allow them to go over the correction of the minimum power factor.

The methodologies in both *P2P_Cong* and *P2P_Volt* assume a feedback mechanism from the DSO operation to the P2P market, with peers having the chance to re-negotiate the transactions made. This mechanism is used until a solution is obtained, satisfying the DSO and peers in the market.

In case both constraints come up simultaneously, the mechanisms meant to solve each constraint will be applied and market transactions will be renegotiated. If one of the problems is not

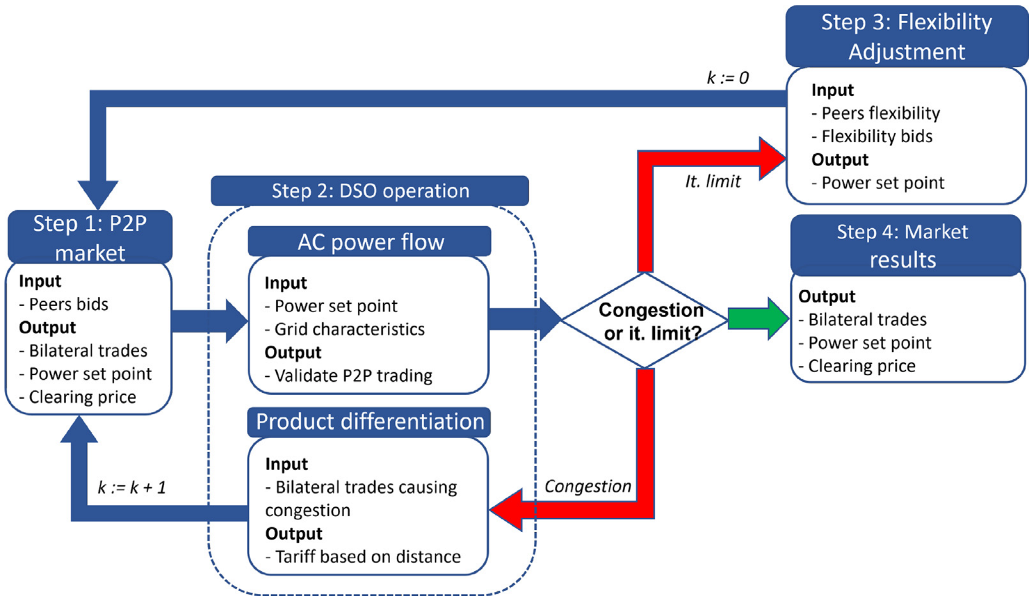


Fig. 2. Flowchart of the P2P market model, handling congestion issues at the DSO level, *P2P_Cong*.
Source: Adapted with authorization from [24].

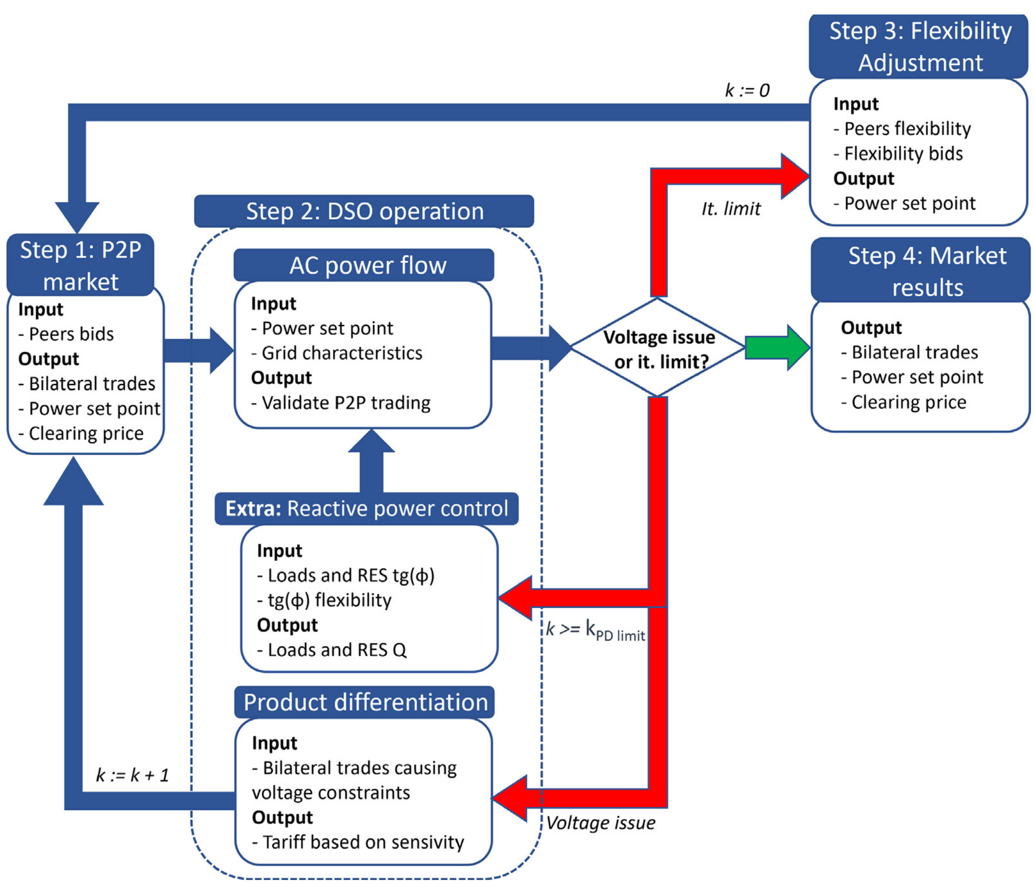


Fig. 3. Flowchart of the P2P market model, handling voltage issues at the DSO level, *P2P_Volt*.

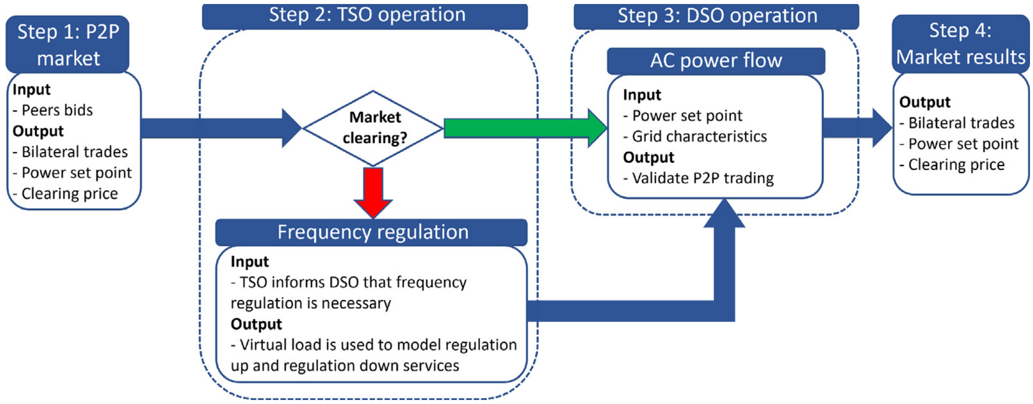


Fig. 4. Flowchart of the P2P market model, handling frequency issues at the TSO level, *P2P_Freq*.

solved, the flexibility offered in the system will be increased and the new offers will be used in the P2P market. The coordination required between these services for this mechanism to work is described in Section 3.3.

3.2. TSO related services

In the case there is imbalance between generation and consumption in the system, a frequency regulation service can be provided to the TSO. The mathematical model for this P2P market can be presented as in (1).

As the TSO can ask for upward or downward frequency regulation, a virtual load with the ability to have either positive or negative consumption has been add in the primary of the power transformer. In case of regulation up service the virtual load should be positive and in the case of regulation down services the load should be negative.

The model that deals with frequency regulation, *P2P_Freq*, is presented in Fig. 4.

Similarly to models *P2P_Cong* and *P2P_Volt* in Section 3.1, *P2P_Freq* starts in the P2P market to obtain the optimal trading between peers (1a). Entering the second step, TSO operation, TSO can request frequency regulation services to the market. As mentioned, this regulation service is modelled by a virtual load located in the TSO bus.

The third step relates to the DSO operation, where an AC-PF is ran to determine if the network limitations are obeyed. This methodology does not assume a feedback mechanism from the DSO to the P2P market place, as the TSO contracts a service to solve the frequency problem. Once this is done, the process moves to step four, containing the final market results.

Coordination between services offered to the TSO and DSO for situations where all targeted constraints can exist is studied in Section 3.3.

3.3. TSO-DSO related services coordination

The TSO and DSO can be coordinated in order to solve all previous mentioned problems simultaneously. The mathematical model for the P2P market model used in this method can be presented as an improvement of the results from (1) described in Section 2.1, given by

$$\min_{D} \sum_{n\in\Omega} C_n(P_n) + \tilde{C}_{nT}(P_n) + \alpha P^{Flex_{Ext}}_{n,t} \tag{10a}$$

$$\text{s.t.} \quad \text{constraints in (1)} \tag{10b}$$

$$0\% \le P^{Flex_{Ext}}_{n,t} \le 100\% \qquad , n \in \Omega_{P_{RES}},\ t \in \mathcal{T} \tag{10c}$$

$$\alpha \gg 1 \tag{10d}$$

where the product differentiation is now the sum of two parcels: the one that solves congestion issues, and the one that solves voltage issues. As mentioned in Section 2.2, product differentiation is not applied for frequency regulation, as every peer has the same impact on this constraint.

At the beginning of every time period t, the flexibility offered by the RES is at 0%, as is the extra flexibility from RES, $P^{Flex_{Ext}}_{n,t}$. In every time period t, when the iteration k limit is reached and the constraints have not been solved, then $P^{Flex_{Ext}}_{n,t}$ will be updated, making the total flexibility offered increase in the downward direction. The RES flexibility is limited by (9c) and its increase is penalized through α (10d), to enforce the system to use as little extra flexibility as possible.

In each period t and in any iteration k, the flexibility offered by the loads is at 30% of their baseline, in both upward and downward directions.

The model presented in Fig. 5, *P2P_Full*, has the purpose of solving all possible grid constraints at once.

The described steps work as explained in Sections 3.1 and 3.2. After the P2P market optimization (step one), the services offered to the TSO (step two) take place, to regulate grid frequency. Then, come the services that can be contracted by the DSO (step three), with the AC-PF to check if network limits are respected. In case there are congestion or voltage issues, then it is applied product differentiation to solve these problems. If only voltage issues are found, an extra stage for reactive power control is included. Only if the flexibility negotiated in the P2P market to support the DSO services is insufficient to solve both constraints will the RES flexibility be increased (step four). The new flexibility bids will be sent to step one, and the number of iterations k is reset. The process will be completed once no grid operating issues are detected, and the market results are obtained (step five). It is noteworthy that the proposed process can deal with different directions of TSO and DSO needs, as it is an iterative process that aims to find a compromise solution between the different requests.

4. Evaluation of P2P flexibility markets and TSO/DSO operation

This sections intends to assess the models described in previous section. The main goal is to demonstrate that the proposed architecture allows the trading between peers and, at the same time, provides services to DSO (congestion management and voltage control) and TSO (frequency regulation). After the description of the distribution network that is used in this case study, three DSO service scenarios considering, *(i)* power transformer boundaries, *(ii)* lines thermal limits constraints, and *(iii)* bus voltage constraints are presented. In the end, a scenario considering TSO

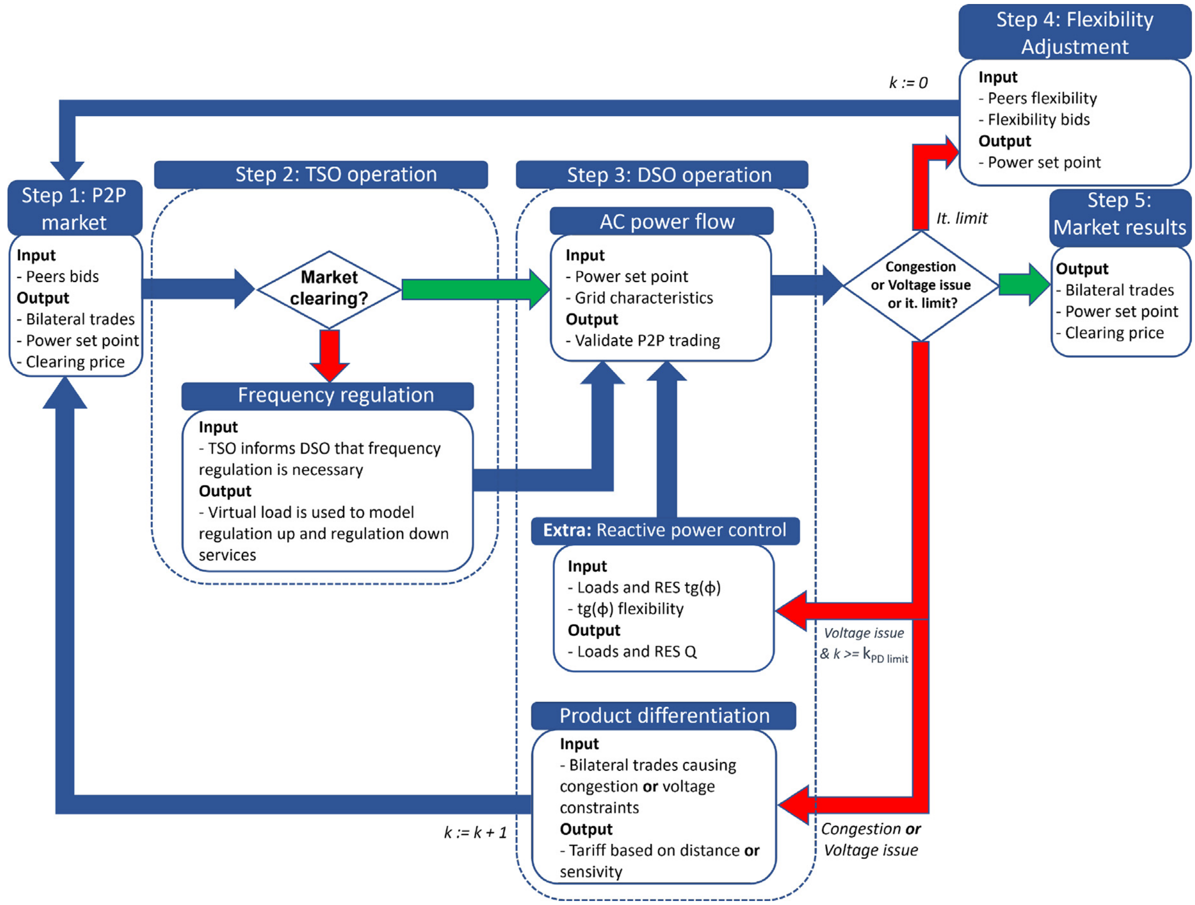


Fig. 5. Flowchart of the P2P market model, handling congestion and voltage issues at DSO level, and frequency issues at the TSO level, *P2P_Full*.

Table 1
Considered scenarios and respective characteristics.

Scenario Model	Benchmark	1 *P2P_Cong*	2 *P2P_Cong*	3 *P2P_Volt*	4 *P2P_Freq*	5 *P2P_Full*
24 hours	✓	✓	✓	✓	✓	×
Reduced power transformer capacity	×	✓	×	×	×	×
Reduced distribution lines capacity	×	×	✓	×	×	✓
Increased distribution lines impedance	×	×	×	✓	×	✓
Frequency regulation need	×	×	×	×	✓	✓

service and another including all the DSO and TSO services are illustrated.

To have different constraints in each scenario, consumption and production profiles were changed and limits of lines and power transformers have been adjusted. An overview of the considered scenarios and their characteristics is given in Table 1.

4.1. Distribution network description

This work uses a 37-bus MV distribution network, with a bus voltage of 11 kV, as in Fig. 6. The original network is presented in [30], the update of the network is taken from [31], including an energy mix in 2050 proposed in [32]. There is generation from 27 flexible DERs, specifically 3 CHP units, 2 wind turbines and 22 PV systems. The network is connected to the high voltage network through an upstream connection, which is limited by a 20 MVA power transformer.

There are 22 consumers on the network who have 30% upward and downward flexibility from their baseline in every scenario. Their reactive power is set with a $tg(\phi)$ equal to 0.3 [24].

The RES are non-dispatchable but can be given flexibility on the downward direction from their forecast power. Spatial–temporal scenarios were generated based on the forecast data for the PV and wind systems from [34] and [35], respectively. For the RES a $tg(\phi)$ of 0.4 was used.

The CHP units are considered dispatchable units with a maximum and minimum power capacities of 0.5 MW and 0.1 MW. For these units, a $tg(\phi)$ up to 0.3 was assumed.

In addition, the CHP units use quadratic cost functions, while RES and the external supplier follow linear cost functions. All the loads have a linear marginal cost function [24].

The data used for all models can be found in [36].

4.2. DSO services participation in P2P market

This section aims to analyse and compare the results of scenarios 1, 2 and 3 with the benchmark case, both from a technical and economic point of view.

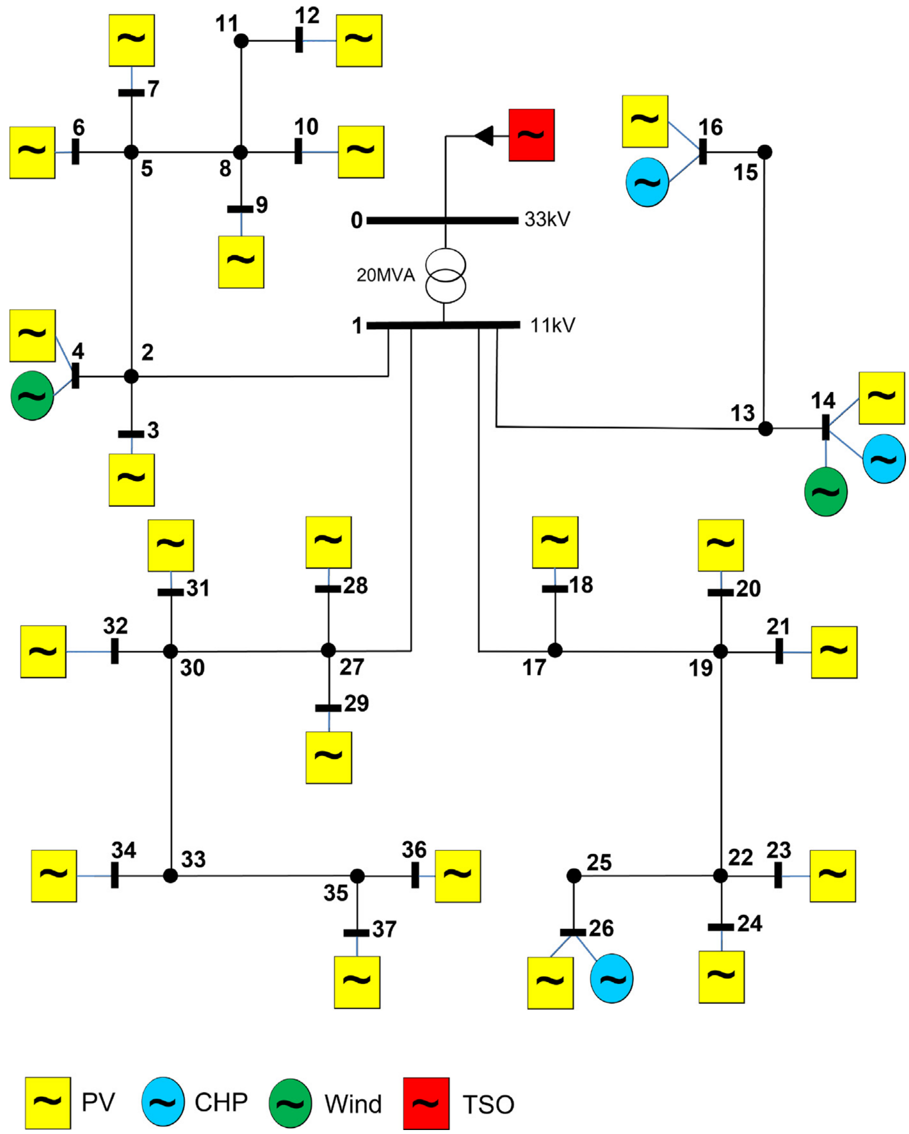


Fig. 6. 37-bus distribution network used.
Source: Adapted with authorization from [33].

4.2.1. Scenario 1 — Power transformer boundaries

The first scenario studies the behaviour of model *P2P_Cong* when there is congestion in the power transformer, i.e., assuming that the power transformer capacity is reduced by three times.

As seen in Fig. 7(a), the transformer presents congestion in hours 20 and 21, where (7) is violated, since these are the hours in which there is more power being supplied by the high voltage network. After applying the *P2P_Cong* model, the bottlenecks in the transformer in these hours were solved, as verified in Fig. 7(b).

In these hours, the lack of RES penetration is directly related to the inefficiency of the product differentiation mechanism, as more injection from the external supplier is required. In order to solve the congestion, load flexibility must be increased, as seen in Table 2.

A cumulative representation of the results from Scenario 1 is presented in Table 3, to establish a comparison between the scenario and the benchmark model.

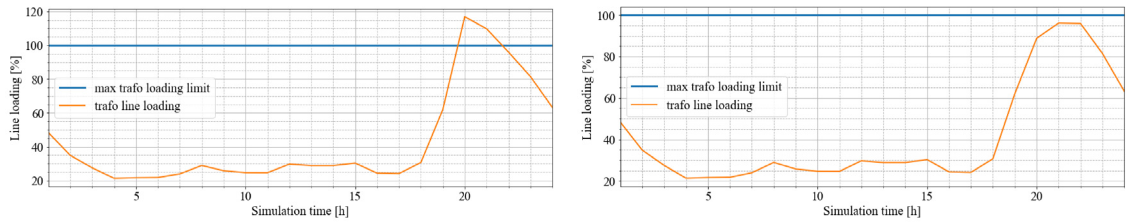
As expected, the increase of flexibility leads to a reduction in the consumption. By increasing flexibility, the first iteration

Table 2
Scenario 1 — load flexibility results after the application of *P2P_Cong*.

Hour	20	21
Load flex (%)	40	35

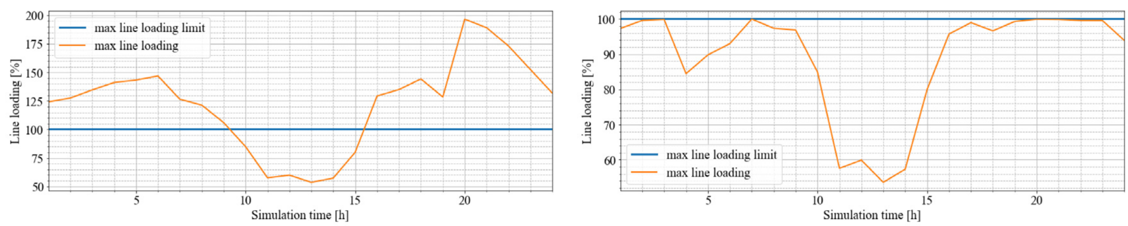
Table 3
Comparison between the energy dispatch and economic results in Scenario 1, and the benchmark over a 24-hour period.

Result	Benchmark	Scenario 1
Grid (MWh)	47.47	44.10
CHP (MWh)	24.09	24.09
Wind (MWh)	114.06	114.06
PV (MWh)	171.20	171.20
Consumption (MWh)	356.82	353.45
Losses (%)	0.61	0.60
SW (€)	22 025.8	21 675.1



(a) Before $P2P\_Cong$.   (b) After $P2P\_Cong$.

Fig. 7. Scenario 1 — maximum transformer line capacity before (a) and after (b) the application of *P2P_Cong* model.



(a) Before $P2P\_Cong$.   (b) After $P2P\_Cong$.

Fig. 8. Scenario 2 — maximum distribution line capacity before (a) and after (b) the application of *P2P_Cong* model.

Table 4
Scenario 2 — load flexibility results after the application of *P2P_Cong*.

Hour	1	2	3	4	5	6	7	8	9	16	17	18	19	20	21	22	23	24
Load flex. (%)	40	35	30	30	30	30	40	30	30	30	30	30	45	65	65	60	55	50

of the P2P market does not use product differentiation. As RES generation is prioritized in the P2P market, since its cheaper, a reduction in the supply from the external supplier is observed. Reducing the power flow in the transformer is shown to be the solution for the adjustment of the power transformer limit. It was noticed that reducing the capacity did not impact the relative losses in the network. The slight decrease verified is due to the lower power flow, given by the increase in load flexibility to solve the congestion issue. This load flexibility increase leads to a decrease in the SW.

4.2.2. Scenario 2 — Lines thermal limits constraints

The second scenario studies the behaviour of model *P2P_Cong* when there is congestion in the distribution lines, i.e., assuming that all the distribution network lines are at half of their capacity. This happens when (7) is violated.

This leads to congestion in hours 1 to 9 and 16 to 24, as seen in Fig. 8(a). Note that these are periods with low PV injection, which is the generation with most presence in the network. It is important to notice that the maximum values presented in the graphics happen in different lines in each one of the simulation periods. Not having these generators supplying power means less DER and, consequently, more likely to have congestion issues. After applying *P2P_Cong*, the congestion issues in the distribution lines in these periods will have been solved, as it can be seen in Fig. 8(b).

The results in Table 4 shows that the product differentiation mechanism is effective in solving congestion issues in the distribution lines. For instance, in hour 3 the congestion was solved by maintaining the load flexibility at 30%. Even though in some hours the loads flexibility had to be increased, the obtained results for these hours still relied in the differentiation applied to the market offers. For example, in hour 20 the load flexibility had to be increased to 65% for the differentiation mechanism to be effective. By optimizing the product differentiation parameters, the penalization applied to the "bad" trades was just enough to solve the congestions, as intended.

Table 5
Comparison between the energy dispatch and economic results in Scenario 2, and the benchmark over a 24-hour period.

Result	Benchmark	Scenario 2
Grid (MWh)	47.47	29.63
CHP (MWh)	24.09	21.05
Wind (MWh)	114.06	102.05
PV (MWh)	171.20	171.28
Consumption (MWh)	356.82	324.00
Losses (%)	0.61	0.37
SW (€)	22 025.8	18 946.3

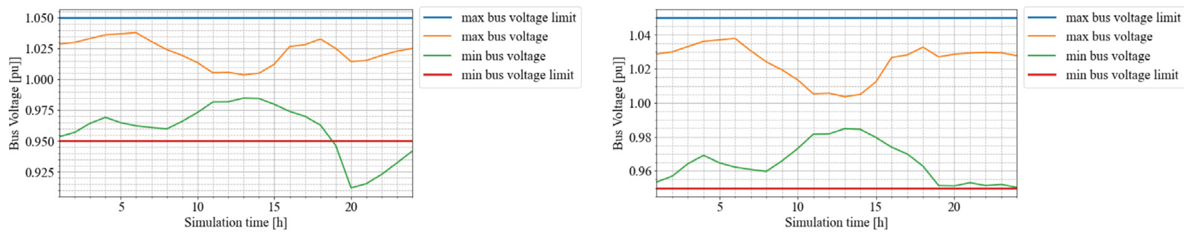
A cumulative representation of the results from Scenario 2 is presented in Table 5, establishing a comparison between the scenario and the benchmark model.

In all hours with congestions, the differentiation mechanism implemented had impact on the result. By doing so, a major impact on the SW was verified, as the differentiation gives priority to the energy provided by external suppliers instead of local RES generation. Therefore, it is visible a decrease mainly in the Wind generation, instead of just in the supply from the external supplier. By no longer having preference over the cheapest generators, the SW decreased significantly. The reduction in this value is also affected by the increase in load flexibility. This increase also lead to a reduction in the overall consumption. Furthermore, the reduction in the networks power flow allowed a significant decrease in the losses.

4.2.3. Scenario 3 — Bus voltage constraints

The third scenario studies the behaviour of the *P2P_Volt* model when there are nodal voltage constraints. By increasing the impedance of the distribution lines, e.g., in three times, the voltage throughout the network will be affected, and consequently leading to the violation of (8).

In the hours without PV generation, the most predominant technology, the overall generation in the network will be lower



(a) Before $P2P\_Volt$. (b) After $P2P\_Volt$.

Fig. 9. Scenario 3 — maximum and minimum node voltage before (a) and after (b) the application of *P2P_Volt* model.

Table 6
Scenario 3 — $tg(\phi)$ and load flexibility results after the application of *P2P_Volt*.

Hour		19	20	21	22	23	24
P2P_Volt	Load flex. (%)	35	60	60	55	50	40
	Flex. $tg(\phi)$	−0.3	−0.3	−0.3	0	−0.3	−0.3
P2P_Volt w/ Q control	Flex. $tg(\phi)$ load location	12	37,36,34,32,31	37,36,34,32	37,36,34,32	37,36,34,32	37,36,34,32
	Load flex. (%)	30	50	50	50	40	30

Table 7
Comparison between the energy dispatch and economic results in Scenario 3 and the benchmark, over a 24-hour period.

Result	Benchmark	Scenario 3
Grid (MWh)	47.47	22.57
CHP (MWh)	24.09	24.09
Wind (MWh)	114.06	114.06
PV (MWh)	171.20	171.20
Consumption (MWh)	356.82	331.92
Losses (%)	0.61	1.60
SW (€)	22 025.8	20 287.3

Table 8
Comparison between the energy dispatch and economic results in Scenario 4 and the benchmark, over a 24-hour period.

Result	Benchmark	Scenario 4
Grid (MWh)	47.47	47.47
CHP (MWh)	24.09	24.09
Wind (MWh)	114.06	127.10
PV (MWh)	171.2	187.75
Consumption (MWh)	356.82	386.41
Virtual load consumption (MWh)	–	29.59
Losses (%)	0.61	0.62
SW (€)	22 025.8	21 937.1

than the consumption. Then, the compensation is made by the external supplier. So, considering a greater line impedance, low voltage issues arise, as it can be seen between periods 19 to 24 in Fig. 9(a). After applying *P2P_Volt*, the voltage constraints in these hours were solved, as depicted in Fig. 9(b).

Even though the product differentiation mechanism can differentiate the market offers, it was not effective in impacting the voltage level in the network. So, the load flexibility had to be increased in hours 19 to 24, to solve the existing constraints. The highest load flexibility is at 60% in hours 20 and 21. The results are presented in Table 6.

In the case reactive power control is taken into account, reducing the $tg(\phi)$ of the loads that have more impact on the (low) voltage constraint allows less flexibility to be needed in order to solve the constraints.

A cumulative representation of the results from Scenario 3 is presented in Table 7, establishing a comparison between the scenario and the benchmark model.

Increasing load flexibility to solve the constraints leads to lower consumption in the network. Similarly to Scenario 1, without differentiation RES will be prioritized and the injection from the external supplier is lower. The increase in line impedance leads to an increase in the relative losses. This value is then reduced when solving the constraints by increasing load flexibility, since these mechanisms contribute to a reduction in the power flow. Increasing load flexibility leads to a reduction of the SW.

4.3. TSO services participation in the P2P market (scenario 4)

The fourth scenario studies the behaviour of the model *P2P_Freq* when there are frequency constraints requested by the TSO. A positive virtual load simulating a regulation up service is included. The consumption the virtual load can be seen in Fig. 10.

The maximum line capacity and nodal voltage level is now slightly higher between the periods 9 and 16, in comparison to the benchmark case. This is due to the higher power flow originated by consumption from the virtual load, as the RES do not have flexibility. The results can be seen in Fig. 11.

A cumulative representation of the results from Scenario 4 is presented in Table 8, to establish a comparison between the scenario and the benchmark model.

The consumption in the network increases by 29.59 MWh through the virtual load to create the need for the regulation up service. Consequently, RES generation is now higher, since these generators are forced to operate at their forecast power. The need for the regulation service makes the SW decrease. Furthermore, in this scenario, this service showed to lead to an increase in the losses, as the solution requires the power flow in the network to increase.

4.4. DSO and TSO services participation in the P2P market (scenario 5)

In the last model, *P2P_Full*, TSO/DSO coordination is needed to solve all grid problems at the same time. An extreme scenario was created in order to obtain high voltage, line congestion, and frequency constraints. Even though the scenario is extreme, it is necessary to obtain the aimed constraints. For that reason, it was only studied the solution for one single hour, e.g., hour 12.

To create this scenario, Scenario 4 from Section 4.3 was taken, and then all distribution lines capacity was reduced to half and their impedance was increased five times. This allowed to obtain congestion and high voltage constraints, respectively, in this hour. Therefore, the result of hour 12 in Scenario 4 is seen as the

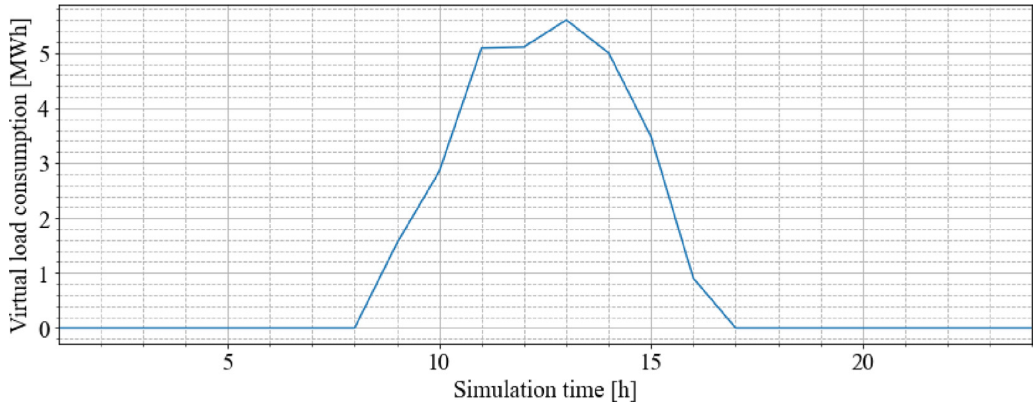
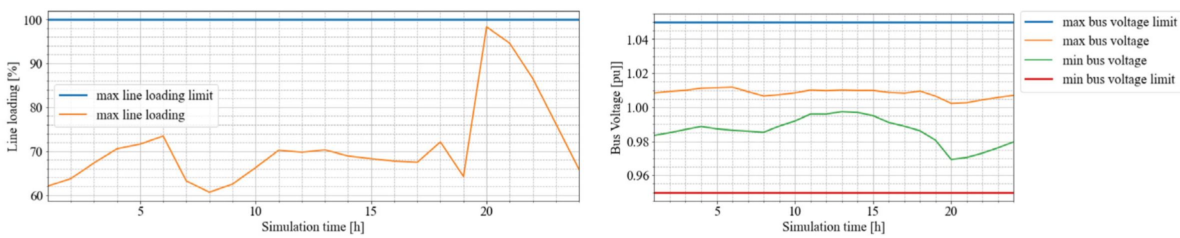


Fig. 10. Scenario 4 — virtual load consumption after application of *P2P_Freq*.



(a) Maximum distribution line loading after application of *P2P_Freq*.

(b) Maximum and minimum node voltage after application of *P2P_Freq*.

Fig. 11. Scenario 4 — (a) maximum distribution line loading, (b) maximum and minimum node voltage after the application of *P2P_Freq* model.

Table 9
Scenario 5 — results with application of *P2P_Full* model.

Hour 12	Scenario 4	Scenario 5	
	After *P2P_Full*	Before *P2P_Full*	After *P2P_Full*
RES flex. (%)	0	0	20
Worst congested line	13	13	13
Worst congested line (%)	69.75	133.97	97.62
Worst constraint node	14	14	14
Worst constraint node (pu)	1.010	1.051	1.029
Grid (MW)	0	–	0
CHP (MW)	0.3	–	0.3
Wind (MW)	5.37	–	4.,31
PV (MW)	21.58	–	17.52
Consumption (MW)	27.24	–	22.13
Virtual load consumption (MW)	5.11	–	0
Losses (%)	0.23	–	0.96
SW (€)	1 274.6	–	1 289.9

reference, as described in Table 9. Thus, let us assume the RES generation initially has a flexibility of 0%.

In this scenario, line 13, at $L_{13} = 133.97\,\%$, will have the highest loading. Node 14 will have the worst voltage constraint, with a magnitude rated at $V_{14} = 1.051\,pu$. Due to the lack of flexibility in the system regarding the imposed limitations, the product differentiation mechanisms were considered ineffective. For instance, in this situation, the power flow in the network is too high for congestion to be solved even with product differentiation. To solve both constraints simultaneously *P2P_Full* model increases RES flexibility from 0% to 20%. The loading percentage of line 13 will decrease to $L_{13} = 97.62\,\%$, and the voltage magnitude of node 14 will decrease to $V_{14} = 1.029\,pu$. By doing this, however, it is not possible for the DSO to complete the request from the TSO to perform the regulation service. So, the total consumption will decrease to 22.13 MW. As the product differentiation mechanisms are ineffective and load flexibility is not increased, the SW can only be affected by the use of the virtual load. Therefore, the SW will increase. The losses will be higher than in Scenario 4, even though the power flow is lower, due to the higher impedance considered in the distribution lines.

The dispatch results before the application of *P2P_Full* were not considered, as the grid results were not feasible. Only afterward they were taken into account. The hour considered was hour 12, a daylight hour, where RES generation is predominant. Therefore, there is no supply from the external grid and the CHP is at its minimum operating point.

4.5. Results analysis

The possibility of choosing their source of energy enables customers to get the best solution from an economy sharing standpoint. Comparisons between each scenario and the benchmark case, described in Section 2.2, were presented through the cumulative results for one day, in Tables 3, 5, 7 and 8, to validate the proposed models.

The results show that the higher price makes the grid (external supplier) and CHP the least dispatched technologies. When they are predominant, the loads consumption is taken to their lower flexibility limit, in order to decrease consumption and avoid high costs. Despite this, these technologies are essential for the proper operation of the network, as they can cover the load consumption when RES are unavailable.

Since the price for RES is very low, they will be the most dispatched technologies. In the hours where these technologies are the most dispatched, the consumption is pushed to the upper limit of its offered flexibility, i.e., consumers are encouraged to consume at their maximum available capacity.

As anticipated, the developed methods present a lower SW than the benchmark, in order to meet the network constraints. The use of product differentiation mechanism gives preference to generation which is local rather than cheaper, as the "distance" preference is considered. As RES generation is not prioritized, the cost is higher, reducing the SW. Furthermore, after the increase of flexibility being penalized, a decrease in SW is expected. Moreover, the need for balancing makes the market non "ideal", making the SW decrease.

Regarding the losses, even though the reduction of capacity did not impact this result, the increase of line impedance did. By solving the constraints, the losses relative to the dispatched consumption were reduced. In general, this reduction comes from a reduction in the network power flow originated by these mechanisms. However, using the regulation up service contributed to an overall increase in these losses, since the scenario created (Scenario 4) requires an increase in the power flow to solve the constraint.

4.6. General discussion

The study highlights the importance of designing new market mechanisms focused on the proliferation of prosumers towards the decarbonization of the power system, while assessing the impact of integrating them into the power system operation performed by the system operators. Such developments are needed to promote prosumers' flexibility integration and make it useful to support system operation. More precisely, prosumers' flexibility could be crucial in future power systems not only to decarbonize the system, but also to keep the distribution networks running smoothly. In this case, better coordination of the TSO/DSO operation is essential for the maximum integration of these small-scale energy resources.

However, the authors acknowledge that the proposed models have limitations that must be taken into account. The proposed models are based on an iterative process between market and system operation. The models successfully found feasible market and system operation solutions, however, the iterative solving can be slow depending on several factors, such as the initial flexibility made available by peers in the market and the product differentiation preferences. More precisely, when running the product differentiation mechanism, the penalization factor in each iteration must be tuned according to the characteristics of the problem. On the one hand, if a low penalty value is set, a large computational effort may be required to differentiate market offers to solve network constraints. On the other hand, a high penalty factor may induce generators to further away from consumers, leading to feasible but less economically efficient solutions.

Another limitation is the flexibility made initially available by the peers, which may not be enough for the product differentiation mechanism to solve all voltage and congestion issues. In this case, the iteration k limit is reached, then the loads are enforced to provide flexibility, and the process is restarted from that point. The iteration limit number can also be tuned and, for that, heuristics can be used.

In this context, it is clear that the proposed iterative models can take a little or a long time to solve the problems, depending on several intrinsic factors related to the characteristics of the system they are solving. It should be noted that in the present test case, the proposed models took less than 30 seconds to find the solution and up to 15 minutes.

5. Conclusions

Recent literature has been giving increased importance to the coordination between markets and system operators, mostly because of the spread of flexibility services and, consequently, P2P markets.

In the present work, P2P market models considering product differentiation representing network and system constraints are proposed and several scenarios have been designed to demonstrate the effectiveness of the mentioned models.

For each scenario, an optimization of the parameters has to be performed, even if in a heuristic manner. Since every scenario takes into account different grid constraints, their results cannot be compared between each other. They can, however, be compared to a benchmark case.

In general, the product differentiation mechanism is effective in solving line congestion. On the other hand, it is not as effective to deal with voltage control, even though it can differentiate the market offers. However, adding a mechanism for reactive power control creates a greater impact in this type of constraint. The increase of flexibility offered in the system was effective in solving any of these grid constraints. It was also shown that it is possible to provide a frequency regulation service in a P2P market context.

An important conclusion is that, even though all the proposed models are effective to solve their specific network operating issues, the TSO/DSO coordination is essential to assure an overall feasible techno-economic solution.

Future work can go in different directions, such as: *(i)* using different criteria in the product differentiation mechanism suitable to solve voltage issues more smoothly, *(ii)* include storage systems in the distribution network, addressing their impact on network operation and flexibility availability, *(iii)* improve TSO/DSO coordination to prevent TSO requests from causing constraints at the DSO level, and *(iv)* adoption of improved information exchange platforms to facilitate coordination between stakeholders and P2P markets.

CRediT authorship contribution statement

João Marques: Conceptualization, Methodology, Software, Writing – original draft. **Tiago Soares:** Data curation, Software, Supervision, Validation, Conceptualization, Writing – reviewing. **Hugo Morais:** Conceptualization, Visualization, Investigation, Supervision, Validation, Editing.

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.

Data availability

The authors do not have permission to share data.

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