Impact of P2P Market Transactions on Distribution Network Congestion Considering Physical Constraints

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2023 International Conference on Smart Energy Systems and Technologies (SEST) | 979-8-3503-9790-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/SEST57387.2023.10257466

***Abstract*—The novel trend of peer-to-peer (P2P) transactions has allowed traditional consumers to become prosumers, capable of maximizing the usage of their energy production by sharing it with their neighbors. Thus, the P2P market has emerged to allow both prosumers and consumers to trade energy independently from the conventional market. However, while local energy transactions will allow for a more open and decentralized grid, they will nevertheless have a significant impact on the planning, control and operation of distribution grids. Hence, in this paper, an improved model is presented to evaluate the impact of P2P transactions on distribution grid congestion, considering its restrictions and the uncertainty associated with renewable energy sources generation and load. The objective function has been modeled to minimize the transaction costs of each prosumer/consumer. The model was tested on a branch adapted from a 119-bus IEEE test grid, in which different operational scenarios have been considered through case studies, considering the various RES technologies and energy storage systems (ESS) installed by each prosumer/consumer. Comprehensive simulation results indicate that the introduction of smart grid enabling technologies and P2P transactions has led to both technical (voltage profile and grid congestion) and economic benefits for the distribution grid and its users.**

Keywords: ***Distribution Network Congestion, Energy Community, Renewable Energy Sources, Smart Grid Enabling Technologies, Voltage Quality, Peer-to-Peer Transactions.***

I. INTRODUCTION

A. Background

The past decade has seen increased public awareness of the damage that will be caused by climate change, which has pressured governments and businesses to decarbonize the economy [1]. Recently, advances in renewable generation and telecommunications have allowed a new market participant to emerge, an active consumer or 'prosumer', that can generate its power supply and address some of its energy demand [2]. Consequently, peer-to-peer (P2P) markets have been developed to allow prosumers to trade energy independently from the conventional market [3].

The presence of many prosumers can not only facilitate the deployment of renewable energy sources (RESs), at a small scale by increasing the economic viability of small RES installations but also at a larger scale by allowing energy demand to fluctuate more and better match the variable and uncertain nature of renewable energy generation [4].

In addition, P2P transactions can affect distribution grid operation. Moreover, in conventional approaches to P2P transactions, grid restrictions are not considered in practice, but power flowing through the grid must follow the energy balance equations and grid restrictions. Implementing a P2P market that satisfactorily accounts for these restrictions, however, is a complex and difficult challenge. Therefore, this paper investigates the impact of P2P markets on distribution grid operation. Furthermore, it is necessary to develop an optimization model that is capable of operating under these restrictions and realistically simulates demand and generation, to study the technical and economic impacts of P2P markets.

B. Literature Review

Previous works [5]-[6] have developed some P2P markets wherein consumers can buy electricity on the P2P market or from the wider grid and prosumers may also sell their surplus power. Particularly, the authors of [7] have also included uncertainty trading. Moreover, [8] and [9] have employed blockchain technology in their work. Taking into account a utility's point of view, [10] and [11] have put forward utility-focused P2P market designs wherein energy transactions must be approved by the utility. Literature reviews have been presented in [12] and [13]. Also, [14] has looked at the implementation of a P2P trading mechanism to join wind power and reserve generation to compensate for uncertainty. The field of distribution network congestion has no singular point of focus, unlike previous categories like research on P2P markets. Indeed, works on this topic have studied problems such as voltage quality, cost optimization, intermittency, congestion, and the impact of data quality on system state estimation. Furthermore, besides [15] and [16], the presence of RES has been considered (either PV or Wind), with [17] also contemplating flexible loads. Munikoti et al. [18] have studied the impact of voltage profiles on a distribution grid of distributed generation sources. Nayak et al. [19] have studied the power flow of a wind farm equipped with a battery energy storage system (BESs), while [15] developed a two-level sensitivity analysis framework with the goal of such an analysis to allow system operators to quantify the sensitivity of their distribution system state estimation at a medium voltage (MV) level, to changes in low voltage (LV) data from home energy management system (HEMS) such as a demand response signal or appliance parameters. Finally, [20] has put forward models for coordinating electricity and heat/cooling demand with varying renewable generation.

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Based on the reviewed works, it is possible to verify the absence of works that simultaneously take into account the effect of smart grid enabling technologies with P2P transactions by way of analyzing their impact on the grid.

C. Contributions

This paper proposes a model based on stochastic mixed-integer linear programming (SMILP). The model aims at minimizing the total costs of the prosumers over 24 hours while accounting for grid restrictions and the operation of smart grid enabling technologies and P2P transactions. The distribution network and the interactions among the consumers/prosumers can be seen, where several actors utilize smart grids enabling technologies. These technologies allow the existence of P2P transactions and the possibility of selling energy to the grid. These transactions are analyzed in terms of costs, energy mix, P2P transactions, congestion, and voltage while considering network constraints to assess the impact of these transactions on network operation.

The main contributions of this paper are:

- To create a mathematical formulation to understand the impact of P2P transactions on the distribution grid, taking into account its physical restrictions.
- To evaluate the impact of P2P markets on the operation of the distribution grid in terms of costs, transaction behaviors, voltage profiles, and grid congestion.

II. MATHEMATICAL FORMULATION

This chapter presents the mathematical formulation used to model user behavior in a P2P environment with the presence of distributed energy resources. The model is formulated as a stochastic mixed-integer linear programming (MILP) optimization problem, where General Algebraic Modeling System (GAMS) is used to simulate the model.

A. Objective function

In the present work, the objective function aims to minimize the total cost of each prosumer, as shown in equation (1). Essentially, the formula is the difference between the cost of total acquired power by each prosumer w, during a period ΔT, and the cost of total injected power by each prosumer w, during a period ΔT.

$$\sum_s \rho_s \sum_w \sum_t (\lambda_{t,s}^{bought} . P_{w,t,s}^{bought,T} . \Delta T - \lambda_{t,s}^{sold} . P_{w,t,s}^{sold,T} . \Delta T) \tag{1}$$

B. Energy Transactions

The following equations present restrictions regarding energy transactions on the energy market between prosumers and with the wider grid. Equation (2) states that for a given prosumer, w, bought energy must come either from the grid or another prosumer. The following restriction (3) asserts that for each prosumer, w, energy sold must go to the grid or another prosumer. Finally, equation (4) states that, for the community as a whole, the total energy bought must equal the total energy sold.

$$P_{w,t,s}^{bought,T} = P_{w,t,s}^{bought,grid} + P_{w,t,s}^{bought,local} \tag{2}$$

$$P_{w,t,s}^{sold,T} = P_{w,t,s}^{sold,grid} + P_{w,t,s}^{sold,local} \tag{3}$$

$$\sum_w P_{w,t,s}^{bough,local} = \sum_w P_{w,t,s}^{sold,local} \tag{4}$$

Equations (5 to 7) represent the energy transactions among prosumers and the grid. Equation (5) states that the total power sold by each of the community's prosumers equals all the power sold by PV systems and the discharge of EVs and ESS systems. Equations (6 and 7) establish a possible limit on the total power acquired by the community, where N can impose a maximum on energy obtained from the grid as a complementary strategy to demand response.

$$P_{w,t,s}^{sold,T} = P_{w,t,s}^{sold,PV} + P_{w,t,s}^{sold,EV} + P_{w,t,s}^{sold,ESS} \tag{5}$$

$$P_{w,t,s}^{bought,T} \leq N . x_{w,t',s}^2 \tag{6}$$

$$P_{w,t,s}^{bought,T} \leq N . (1 - x_{w,t',s}^2) \tag{7}$$

Equation (8) shows the balance of power. It states that each prosumer must have a balance between its acquired energy from various sources and its load. In other words, the sum of total power acquired, either from the grid or the local market, plus power from its PV panels, ESSs systems, and EVs must equal the sum of inflexible loads, flexible loads, such as controllable appliances, and the charging demands of its EV and ESSs systems.

$$\begin{aligned} P_{w,t,s}^{bought,T} + P_{w,t,s}^{PV,used} + P_{w,t,s}^{EV,used} + P_{w,t,s}^{ESS,used} \\ = P^{CargaInf}{}_{w,t,s} + P_{w,t,s}^{EV,load} \\ + P_{w,t,s}^{ESS,load} + \sum_c P_{w,t',c,s}^{apliences} \end{aligned} \tag{8}$$

Finally, a prosumer's PV production is defined in (9) and must be either used or sold in its entirety at all times.

$$P_{w,h,s}^{PV,uso} + P_{w,h,s}^{vend,PV} = P_{w,h,s}^{PV,prod} \qquad \forall w, t \tag{9}$$

C. Controllable Appliances

Controllable appliances include devices such as a dishwasher or washing machine. These typically operate in pre-defined cycles which means that the durations and load profiles of their work cycles are known. Thus, considering the presence of demand response their work periods can be shifted to a time of lower prices. This type of load is modeled using equations (10 to 16). Equation (10) defines the power consumed by a controllable appliance as the sum of the power consumed by the appliance during each phase. The device can operate at distinct phases such as startup, running, finishing, and stopping. Restriction (11) states that each piece of controllable equipment cannot be simultaneously operating at more than one phase of its work cycle. Expressions (12 to 15) enforce the logical sequence among the operating phases. Finally, equation (16) sets the number of times a specific appliance should operate during the optimization period.

$$P_{w,t',c,s}^{appliance} = \sum_f (x_{w,t,f,c,s}^{fase} . P_{w,f,c,s}^{fase}) \tag{10}$$

$$\sum_f x_{w,t,f,c,s}^{fase} \leq 1 \tag{11}$$

$$y_{w,t,f,c,s}^{fase} \leq 1 \tag{12}$$

$$y_{w,t,f,c,s}^{fase} = y_{w,f,c,s,(t+T_{w,f,c,s}^{duration})'}^{fase} \tag{13}$$

$$y_{w,t,f,c,s}^{fase} - z_{w,t,f,c,s}^{fase} = x_{w,t,f,c,s}^{fase} - x_{w,f,c,s,(t-1)'}^{fase} \tag{14}$$

$$z_{w,t,f,c,s}^{fase} = y_{w,t',f+1,c,s}^{fase} \tag{15}$$

$$\sum_t y_{w,t,f,c,s}^{fase} = N_{w,c,s} \tag{16}$$

D. Electric Vehicles

Equations (17 to 23) describe the behavior of Electric vehicles (EVs).

In (17) a balance is defined among the power provided by an EVs for its prosumer's self-use together with the sold by the EVs and the power discharged by the EVs affected by its discharge efficiency.

Charging and discharging limits are presented in (18) and (19), respectively. During the period between EV's arrivals and departures, its charging or discharging power is bounded by 0 and a maximum value is used to represent a previously defined charging or discharging rate. State-of-charge (SOC) conditions are set in (20) to (23). In addition, EVs must be fully charged by departure time.

$$P_{w,t,s}^{EV,used} + P_{w,t,s}^{sold,EV} = \eta_{w,s}^{EV,disch} . P_{w,t,s}^{EV,disch} \tag{17}$$

$$0 \leq P_{w,t,s}^{EV,charg} \leq R_{w,s}^{EV,charg} . x_{w,t}^{3}, \quad w \in [T_{w,s}^{a}, T_{w,s}^{d}] \tag{18}$$

$$0 \leq P_{w,t,s}^{EV,disch} \leq R_{w,s}^{EV,disch} .(1 - x_{w,t}^{3},) \quad w \in [T_{w,s}^{a}, T_{w,s}^{d}] \tag{19}$$

$$SOC_{t,w,s}^{EV} = SOC_{t,w,s}^{EV,ini} + CE_{w,s}^{EV} . P_{w,t,s}^{EV,charg} . \Delta T - P_{w,t,s}^{EV,disch} . \Delta T \;\; \forall w, if\ t = T_{w,s}^{a} \tag{20}$$

$$SOC_{t,w,s}^{EV} = SOC_{t-1,w,s}^{EV,ini} + CE_{t,s}^{EV} . P_{w,t,s}^{EV,charg} . \Delta T - P_{w,t,s}^{EV,disch} . \Delta T \quad \forall w, t \in t = [T_{w,s}^{a} - T_{w,s}^{b}] \tag{21}$$

$$SOC_{w,s}^{EV,min} \leq SOC_{t,w,s}^{EV} \leq SOC_{w,s}^{EV,max} \tag{22}$$

$$SOC_{t,w,s}^{EV} = SOC_{w,s}^{EV,max} \forall w, if\ t = T_{w,s}^{d} \tag{23}$$

E. Energy Storage Systems

Each prosumer's ESS system is modeled using (24) to (29). These equations work similarly to the previously described EVs.

Charging and discharging limits are defined in (25) and (26). SOC is defined in (27) to (29).

$$P_{w,t,s}^{ESS,used} + P_{w,t,s}^{sold,ESS} = \eta_{w,s}^{ESS,disch} . P_{w,t,s}^{ESS,disch} \tag{24}$$

$$0 \leq P_{w,t,s}^{ESS,charg} \leq R_{w,s}^{ESS,charg} . x_{w,s,t}^{4}, \qquad \forall w, t \tag{25}$$

$$0 \leq P_{w,t,s}^{ESS,disch} \leq R_{w,s}^{ESS,disch} .(1 - x_{w,s,t}^{4},) \; \forall w, t \tag{26}$$

$$SOC_{t,w,s}^{ESS} = SOC_{t-1,w,s}^{ESS} + CE_{t,s}^{ESS} \cdot P_{w,t,s}^{ESS,charg} . \Delta T - P_{w,t,s}^{ESS,des} . \Delta T \quad \forall w, t \geq 1 \tag{27}$$

$$SOC_{t,w,s}^{ESS} = SOC_{w,s}^{EV,ini} \forall w\ if\ \ t = 1 \tag{28}$$

$$SOC_{w,s}^{ESS,min} \leq SOC_{t,w,s}^{ESS} \leq SOC_{w,s}^{ESS,max} \forall w, t \tag{29}$$

F. HVAC systems

Equations (30) to (32) define a simplified model for Heating, Ventilating, and Air Conditioning (HVAC) which aims primarily at maintaining the temperature within defined parameters. Temperature variation is calculated based on (30) which is in turn based on an equivalent thermal system.

Furthermore, the temperature may change in-between minimum and maximum values according to the defined scenarios and their power.

$$\theta_{w,t+1} = \beta_{w,s} * \theta_{w,t,s} + \left(1 + \beta_{w,s}\right)(\theta_{w,t,s}^{0} + COP_{w,s} * R_{w,s} * P_{w,t,s}^{HVAC}) \tag{30}$$

$$\theta_{w}^{min} \leq \theta_{w,t+1} \leq \theta_{w}^{max} \qquad \forall w, t \tag{31}$$

$$0 \leq P_{w,t}^{HVAC} \leq P_{w,t}^{HVAC,max} \qquad \forall w, t \tag{32}$$

G. Kirchhoff's Current and Voltage Laws

A major technical requirement for grid operation is Kirchhoff's current law, wherein the sum of all currents entering a bus must be equal to the sum of all outward flows. Also, all feeders must comply with Kirchhoff's voltage law. Power losses are considered in the model.

H. Power flow limits

Apparent power flow cannot be greater than or equal to the nominal value on any given line. In addition, the maximum flow capacity of each line must respect the power flow limits.

III. CASE STUDY AND RESULTS

The system used to validate the methodology proposed in the previous chapter is based on a branch of a 119-bus IEEE test grid, depicted in Fig. 1, chosen to represent a typically structured distribution grid, with two branches downstream of a feeder bus. Table I indicates each prosumer/consumer's location in the grid.

A. Case Study

In this work, three case studies were considered. Case 0 is the benchmark, meant to represent the current status of the distribution grid. There is no P2P, all clients are consumers and there is no distributed generation or storage. Moreover, the total demand is lower since flexible loads and HVAC aren't considered, along with the inefficiencies associated with the use of energy storage.

Table I summarizes this case, individually highlighting which technologies are present as well as the type of P2P transactions available. Case 1 introduces the P2P market structure. There is a mix of residential consumers and prosumers, along with a service prosumer (school). Except for the latter, these users will have similar load profiles, the consequences of which shall be discussed later. Moreover, residential prosumers will have similarly sized PV generation and ESS/EV storage capacity, whereas w10 won't have EVs but will own larger ESS and PV systems. Case 1 is summarized also in Table I.

In this case, two residential users (w2 and w9) are now industrial prosumers. This is meant to introduce a greater variety of load profiles, and thus more varied transactional behavior, and evaluate their impact on the developed model. Furthermore, it can be inferred that having a monotonous set load profile, among all users, due to a lack of user diversification, will discourage P2P transactions since all users would want to buy and sell power at the same time. Consequently, introducing two new low-voltage industrial users adds more heterogeneous demand, thus increasing the opportunities for P2P transactions. A description of this case is shown also in Table I.

Despite the differences between cases, there are some common aspects to all cases:

- Unless specified, the client (consumer/prosumer) type is residential by default;
- In cases 1 and 2, both prosumers and consumers have controllable loads and HVAC;
- In the P2P market, prosumers can buy and sell energy (from their PV generation and/or EV/ESS storage);
- Consumers may only buy energy from the P2P market or the grid, i.e., can't sell to the P2P market;

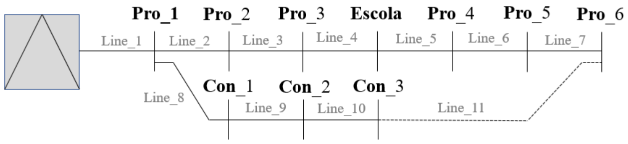

Fig. 1. Test System.

TABLE I. CLIENT'S CORRESPONDING BUS AND CASE STUDYS: AVAILABLE TECHNOLOGIES AND P2P TRANSACTION PER CLIENT

Bus	Client	Case 0: available technologies and P2P transactions per client					Case 1: available technologies and P2P transactions per client					Case 2: available technologies and P2P transactions per client				
		Type	EV	ESS	PV	P2P	Type	EV	ESS	PV	P2P	Type	EV	ESS	PV	P2P
Pro_1	w1	1	No	No	No	No	2	Yes	No	Yes	Both	2	Yes	No	Yes	Both
Pro_2	w2	1	No	No	No	No	2	No	No	Yes	Both	3	No	No	Yes	Both
Pro_3	w3	1	No	No	No	No	2	Yes	Yes	Yes	Both	2	Yes	Yes	Yes	Both
Pro_4	w4	1	No	No	No	No	2	Yes	Yes	Yes	Both	2	Yes	Yes	Yes	Both
Pro_5	w5	1	No	No	No	No	2	Yes	Yes	Yes	Both	2	Yes	Yes	Yes	Both
Pro_6	w6	1	No	No	No	No	2	No	Yes	Yes	Both	2	No	Yes	Yes	Both
Con_1	w7	1	No	No	No	No	1	Yes	No	Yes	Buy	1	Yes	No	Yes	Buy
Con_2	w8	1	No	No	No	No	1	Yes	No	Yes	Buy	1	Yes	No	Yes	Buy
Con_3	w9	1	No	No	No	No	1	No	No	Yes	Buy	3	No	No	Yes	Buy
School	w10	1	No	No	No	No	2	No	Yes	Yes	Both	2	No	Yes	Yes	Both

Type: 1 → Consumer; 2→Prosumer Residencial; 3→Prosumer Industrial

B. Results

To review the change in energy costs among the cases, they were compared with each other in terms of the total costs per user, the average cost per unit of energy (case vs. case and consumer vs. prosumer), and the total cost for the community.

As seen in Fig. 2, the costs decreased for all actors, from Case 0 to Case 1, with a 16.1% reduction in total costs, on average. Regarding Case 2, due to w2 and w9 becoming industrial prosumer and industrial consumer, respectively, their total costs have increased, while all other participants experienced no change. This can be justified by the increased energy demand of the industrial actors.

In Fig. 2, an increase in the load is visible with every case, which is due to the introduction of new flexible loads (washing machines, dishwashers, HVAC) that were not previously present, i.e., Case 0's total load corresponds only to Case 1's inflexible loads. Furthermore, in Case 2, users w2 and w9 are changed into industrial prosumers which have a higher inflexible demand.

However, the most notable change among the cases is the 22% decrease in the unit cost of energy, which can be attributed to the presence of PV generation, decreasing the amount of energy that needs to be acquired, and the deployment of ESS and EV V2G systems, which allow energy to be bought during periods of lower prices to be consumed throughout periods of higher prices. Additionally, there was a 16.1% reduction in total costs from Case 0 to Case 1 despite the overall increase in load.

Here, an analysis of each user's source of energy is made. The purpose was to discover which mechanism (storage, PVgen, or P2P market) had the greatest contribution and on what grounds. As previously stated, in Case 0, all energy is purchased from the grid, whereas in Cases 1 and 2, power may also be procured from PV generation, storage (EV and ESS), or the P2P market.

Fig. 3 shows each prosumer's energy mix by source. Most of the consumed energy is directly provided by the grid (as opposed to indirectly, i.e., through storage), supplying an average of 72.5% of each prosumer's energy, followed by PV generation, with about 17%, and storage (8.5%), and the P2P is responsible for the smallest proportion, only 2%.

Moreover, all the energy discharged by the storage systems (EV+ESS) has been charged from grid power, with most power traded on the P2P market coming from the community's storage systems. The transactional activity in the P2P market is studied, and the major trading periods are identified as well as the source and destination of traded energy, namely which users and systems (PV, ESS, EV) provide power.

Fig. 4 shows the hourly P2P market activity. Market transactions are concentrated around two periods of the day: one smaller midday period from 8:00 to 14:00, with a peak at 13:00 hours, and a larger evening period from 15:00 to 24:00, peaking at 18:00. These largely correspond to the two load peaks.

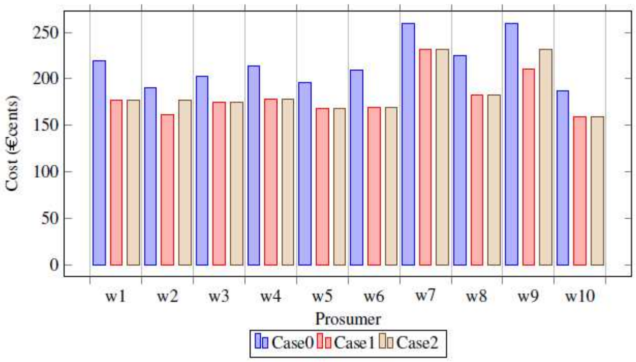

Fig. 2. Cost comparison between cases.

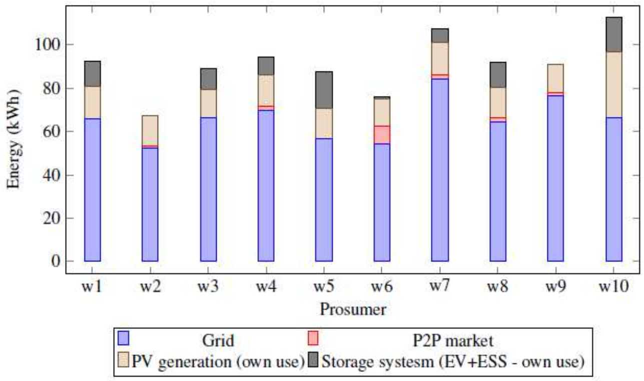

Fig. 3. Case 1: energy mix by the prosumer

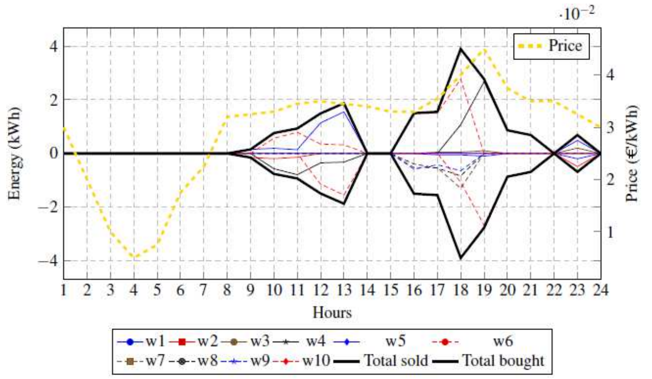

Fig. 4. Case 1: P2P transactions (sold - positive axis; bought - negative axis)

However, the first period sees a significantly smaller trading volume because PV generation is the highest, and thus, a consumer/prosumer's need for "imported" energy is lower. The opposite is true for the second, evening period, which involves almost no solar generation. Consequently, since prosumers can't produce their own energy, they must buy it, which results in a greater trading volume. Notably, the energy being sold during the evening is almost entirely supplied by the storage systems, either ESS or EV.

Finally, the price tends to follow demand, with peaks at 12:00 and 19:00, with the midday period having lower prices. This is, once more, due to the presence of PV generation at this time, which reduces the demand for "imported" energy, and thus price.

Fig. 5 indicates P2P market transactions depending on the source and destination user. Prosumers w1, w2 and w6 together with consumers w7, w8 and w9 only bought energy, whereas prosumer w4 was the only market participant to buy and sell power, with the rest only selling. Prosumer w10, the school, was responsible for 45% of the total energy sold, largely due to the larger capacity of its PV and ESS systems. Concerning Case 2, simulations have resulted in a very similar outcome and, as such, the same principles apply as in Case 1.

The last analysis was conducted on the congestion of each line and the voltage deviation in each bus where the different cases were compared.

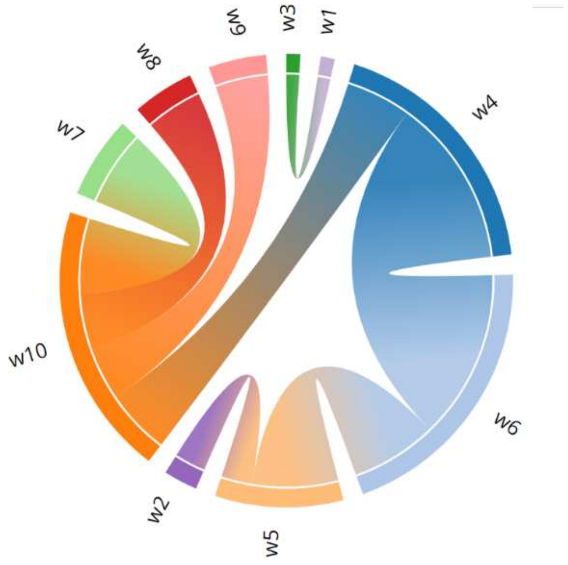

Fig. 5. Case 1: P2P market transactions.

Fig. 6 displays the load through each line for all three cases, In Case 0, 6 of the 10 lines were overloaded with an average capacity factor of 1.13 across all lines, whereas there were only 1 and 2 lines overloaded in Cases 1 and 2, respectively. There was a 15.37% decrease in line capacity factor from Case 0 to Case 1, with the most notable improvements being on lines 4 and 7. This is due to the presence of distributed generation, which decreased the amount of energy that has to be imported, coupled with smart grid facilitating technologies, which allow the community to waste less of their distributed generation that would otherwise be lost to the mismatch between demand and supply. The difference between Cases 1 and 2 is the presence of industrial players, w2 and w9, which are characterized by higher energy demand. This results in a slight increase in the capacity factor of those lines that are directly upstream from them.

Fig. 7 shows the voltage profiles across the different cases. In all cases, voltage drops more when nodes are farther away from the feeder bus. Thus, the most downstream bus, w6, presents the greatest voltage drop. However, with the introduction of Case 1 to the grid, there was a remarkable improvement in voltage quality across all buses, with the biggest benefits, in absolute terms, occurring in buses w4 to w6. Moreover, there was an average improvement of 37.19% in voltage quality from Case 0 to Case 1. In Case 2, once more there was a worsening of performance on the buses directly upstream of w9 and w2, again due to their increased load. Despite the greater load, voltage deviations in Case 2 were still smaller than in Case 0. Thus, based on the results, it can be concluded that the deployment of smart grid technologies, including P2P transactions, has generally led to improvements in the congestion and voltage profiles.

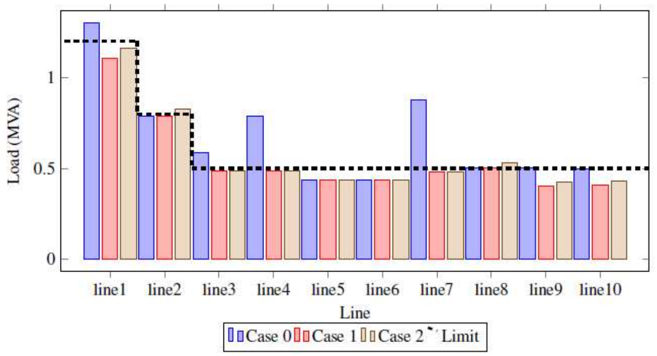

Fig. 6. Line congestion.

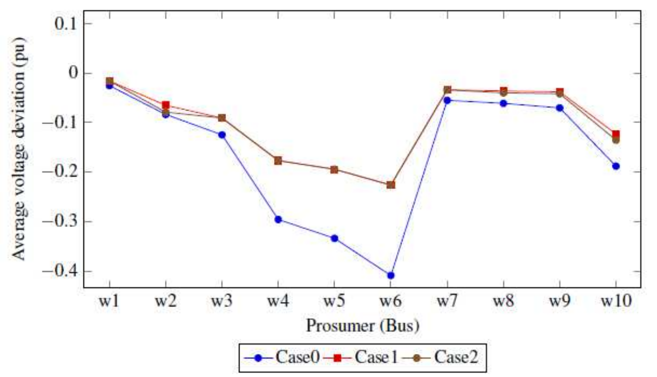

Fig. 7. Voltage profiles

Finally, while it wasn't the case in the case studies analyzed in this work, an argument could be made that excess PV output might lead to greater congestion. For example, in a radial network P2P transactions, the lines connecting these two branches might become congested. However, the presence of energy storage can mitigate this effect by absorbing excess PV generation and distributing it throughout the day, thus limiting congestion while avoiding wasting PV power.

IV. CONCLUSIONS

In this paper, a stochastic MILP model was developed that is capable of simulating the operation of a distribution grid with smart grid technologies and P2P transactions, which takes into account the grid's physical restrictions and aims to minimize the users' total costs. This model was used to simulate three case studies that represented different load and generation scenarios based on several mixes of prosumer and consumer types. The numerical results were obtained by applying the developed mathematical formulation on an adapted branch of a 119-bus IEEE test grid with 10 users. From the analysis made of the model, it was possible to see that the total cost was reduced on a collective basis since the energy cost of every user was lowered. Moreover, it was noted that, while the unit cost of energy was lower for everyone after the introduction of smart grid enabling technologies and P2P transactions, prosumers paid less per kWh on average than consumers. Regarding the community's overall load profile, the two major demand peaks that were initially present were significantly reduced. However, a new load peak was created after introducing the charging demand of the ESSs and EVs. Transactions on the P2P market were concentrated during the demand peaks, contributing to their reduction. Finally, after introducing the smart grid enabling technologies and P2P transactions, the voltage profiles and grid congestion were both improved. Therefore, this paper has highlighted the benefits of introducing smart grid enabling technologies, such as distributed generation and energy storage, together with P2P transactions, which provide both technical and economic benefits to the distribution grid and its users.

ACKNOWLEDGMENTS

S.F. Santos and G.J. Osório acknowledge the financial support from REMIT through the UIDB/05105/2020 Program Contract funded by FCT.

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