Analysis of consumer-centric market models in the Brazilian context

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***Abstract*—In recent years, the large deployment of distributed energy resources (DERs) in low voltage networks is changing the traditional approach to power systems. This massive change is pushing towards new solutions to improve energy trading in low voltage networks. Consumer-centric options, such as full peer-to-peer (P2P) and energy community markets (CM) are seen as viable options to increase the active participation of end-users in the electricity markets. This work studies the full P2P and CM market approaches applied to the actual regulatory framework in Brazil, evaluating and comparing both approaches to be potentially applied in Brazil. A case study based on a typical Brazilian neighborhood is designed, allowing to assess the behavior of consumers and prosumers in both markets. The results show the economic viability of both models, considering the social welfare and the penetration of distributed generation in the system. An important conclusion under the current regulatory framework is that the full P2P can have greater benefits over the CM, as long as the distributed generation is enough to confer near self-sufficiency to the peer's demand.**

***Index Terms*—Electricity markets, Peer-to-peer markets, Optimization, Distributed generation.**

Nomenclature

α_n	Power imported by an agent from external supplier
β_n	Power exported by an agent to a external supplier
γ_{exp}	Power exported by a community to a external supplier
γ_{imp}	Power imported by a community from external supplier
Ω	Peer-to-peer community of agents
Ω_c	Set of peer-to-peer community consumers
ω_n	Set of trade partners of agent *n*
Ω_p	Set of peer-to-peer community producers
$\overline{P_n}$	Represents an agent's minimum trade value
Φ_n	Power traded within community by an agent
$\underline{P_n}$	Represents an agent's maximum trade value
a_n	Quadratic coefficient associated to agent's *n* trade cost function
b_n	Linear coefficient associated to agent's *n* trade cost function
c_{exp}	Trade cost associated to exportation to external supplier
c_{imp}	Trade cost associated to importation from external supplier
P_{nm}	Trade between agents *n* and *m*

I. Introduction

Due to the appeal and growth of distributed energy resources in markets around the world, passive consumers now have the alternative to become active members of a more decentralized market design. By means of their growing participation in the electricity generation process, consumers are gradually breaking down the power scales that have existed so far in more traditional markets.

Aside from the growing accessibility to technological advances, which enables the creation of new categories of electricity consumers and producers, the increasing economic integration between basic utilities and the commitment to the energy communities must also be taken into account. This economic integration is supported by the collaborative economy principle that fosters energy community initiatives and flexible market configurations when it comes to the energy exchange agreements between peers [1].

Establishing new market designs focused on decentralized management and the collaborative principle would consequently empower the proactive consumers (*prosumers*), who in turn could dynamically influence market trades by means of the imposition of prosumer's preferences during agreements. Therefore, it is imperative to redefine current electricity markets, given that a new system is needed to properly organize the engagement and responsibilities of prosumers in these competitive electricity markets. In this case, this new market configuration named as *consumer-centric electricity markets* might lay the foundations for Peer-to-Peer (P2P) and community-oriented structures [1]. Through P2P, prosumers are able to engage into trade agreements among themselves, as peers and with players that fit the traditional definitions of supplier and consumer.

Although one of the first proposals for multilateral trades on electricity networks was made in 1999 by [2], only recently, in light of the challenges related to the many changes needed to decentralize electricity markets, works such as [3] and [4] that discuss grid operation under P2P markets have become more recurrent in literature.

Furthermore, works such as [5] and [6] have proposed different approaches towards the organization of market designs and the proper cost allocation to prosumers who are members in P2P structures, respectively.

Following the aforementioned advances for empowering prosumers integration in the electricity markets, the present paper contributes to the adaptation of new consumer-centric markets to the Brazilian context. More precisely, it assesses the applicability of the full P2P and CM market models under the Brazilian regulatory framework. In addition, a detailed and comparative analysis of the market models through a test case based on actual Brazilian data is provided. In this context, the main contributions are:

- To explore the P2P and CM market models under the current Brazilian regulation;
- To test, compare and validate P2P markets through a test case supported by actual Brazilian data;
- To discuss prosumers integration in Brazil from the regulatory framework standpoint.

This paper is structured as follows: the general framework of the Brazilian electricity sector with a focus on small consumers is presented in section II. Afterwards, the consumer-centric market structures (namely, full P2P and CM) along with their respective mathematical models are outlined in section III. The case study based on data from the Brazilian power system and the results from simulations are discussed in section IV. Finally, noteworthy conclusions are presented in section V.

II. Brazilian Electricity Sector Framework

The Brazilian electricity sector has over 80% of renewable generation, with hydroelectricity being the main resource, representing over 65% of the electricity generation in 2017 and 2018 [7]. With the increasing difficulties to install new hydro generation plants, the last years have significantly increased the participation of the wind and solar generation in Brazil. Forecasts shown by the national operator of the electric system (ONS) estimate that, by the end of 2024, the wind generators participation will be nearly 11% of the total electricity installed capacity in the Brazilian system [8]. Similar forecasts estimate that photovoltaic generators will represent around 2% of the country's total capacity [8]. Also, [8] and [9] indicate a constant growth of the load until the year 2024.

In a general manner, the Brazilian electricity sector is composed of about 30% of free consumers, those able to purchase in the wholesale electricity market. Concerning the incentive to small consumers insertion of distributed generation, the Brazilian Electricity Regulatory Agency, ANEEL, released a Normative Resolution in 2012, (RN 482/2012), with a net-metering scheme. This resolution was improved in 2015 (RN 687/2015) [10]. The main points can be summarized as (i) definition of micro-generation, with a maximum capacity of 75 kW and mini generation, up to 5 MW; (ii) compensation of energy credits are given a 60 months deadline; (iii) the definition of the distributed generation business models related to the small consumers, the so called prosumers.

The business models for DGs are divided mainly in the following possibilities [10]: (i) to install the systems as a condominium; (ii) to install as a cooperative, where the energy generated is shared among the cooperative members; and (iii) to define a remote self-consumption, where the credits are compensated in a different location with the same registration (commercial or personal entity), but within the same utility area. It is important to mention that distributed generators are not allowed to trade production higher than their installed capacity.

It is even more important to highlight that over the past few years, the Brazilian government also proposed different tariff schemes focusing on household consumers [11]. Especially, a Time of Use (ToU) scheme has been recently released for small consumers as an option for the fixed tariff. A broader view of the Brazilian system with the main challenges towards a smart grid environment is presented by [12].

Nowadays, the Brazilian government is engaged to promote a set of reforms in the electricity sector. One of the main points is the expansion of the free market by a progressive reduction in the lower limit of the installed capacity of consumers. Another central idea of these reforms is to loosen the regulation in order to allow small consumers to increase their participation in those markets. Thus, the present work makes a first attempt to evaluate the main aspects related to a consumer-centric market simulated in the Brazilian electricity environment, intent on helping intensify future discussions on the subject and further the improvements to the Brazilian market.

Significant changes are expected to happen in the Brazilian power system regulation in the near future, as a set of laws are under evaluation comprising the improvement of the electricity market.However, in none of the proposed changes, alternatives that contemplate the active participation of consumers in full P2P and CM models are analysed. Therefore, this paper evaluates a possible scenario for future changes in the Brazilian regulation.

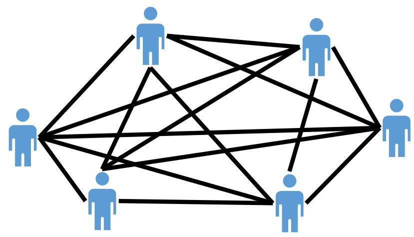
In particular, some of the DG's business models may actually fit the basic concepts and requirements for consumer-centric markets, which are based on the sharing economy principle. Once a consumer with small-scale generation can share and trade energy with other consumers either inside or outside a community, P2P mechanisms can be a way to empower consumers to play a more active role in the Brazilian electricity market. Thus, this model might present a possible transition from the current model in Brazil.

III. Future Market Designs

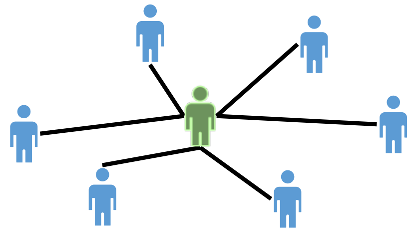
Over the last years, several new electricity market designs, the so-called consumer-centric markets, have been proposed and discussed in the literature [1]. Among them, the full P2P and CM markets are two distinct market designs that best fit the context of the Brazilian regulatory framework. Therefore, these two market designs are described and compared in this work. The main difference between both markets is the inclusion of a central manager in the CM market, which receives and establishes the trades within the community. Figure 1 depicts a graphical representation of the exchanges between peers for each market [5].

A. Full P2P markets

This design is based on the premises that all peers and market members are allowed to commercialize electrical energy between themselves, agreeing on the price and the amount to be traded. The absence of a central supervisor is also an important characteristic of this design, since it increases the peer's freedom to decide on matters regarding their trade agreements (e.g., price). Although relatively anarchic, this design is becoming popular in academic and industrial areas. This market model can



(a)



(b)

Figure 1. Graphical representation of exchanges in: (a) *Full P2P Market* and, (b) *Community Market* (adapted from [5]).

be mathematically described through Equations 1a - 1e based on the assumptions and designs presented in [1], [13].

$$\min_{D} \sum_{n\in\Omega} \frac{a_n}{2}\Big(\sum_{m\in\omega_n} P_{nm}\Big)^2 + b_n\Big(\sum_{m\in\omega_n} P_{nm}\Big) \quad (1a)$$

$$s.t. \quad P_{nm} + P_{mn} = 0 \qquad \forall \ (n,m) \in (\Omega, \omega_n) \quad (1b)$$

$$\underline{P_n} \le \Big(\sum_{m\in\omega_n} P_{nm}\Big) \le \overline{P_n} \qquad \forall \ n \in \Omega \quad (1c)$$

$$P_{nm} \le 0 \qquad \forall \ (n,m) \in (\Omega_c, \omega_n) \quad (1d)$$

$$P_{mn} \ge 0 \qquad \forall \ (n,m) \in (\Omega_p, \omega_n) \quad (1e)$$

where 1a is the objective function aiming to minimize the operating costs for the peers. The balancing equation for the exchanges between consumers and producers is represented by 1b. Equation 1c represents the minimum and maximum limits for each peer. It is assumed that the variable with the exchanges in the consumer point of view is negative (1d), while for producers is positive (1e). It is important to point out that the external supplier is represented as one of the peers in this simulation. Therefore, the cost coefficients associated to trade with such peers are: zero for the quadratic term and equal to the market value for the linear term.

B. Community-oriented market

Similarly to the design described in subsection III-A, the CM market allows the commercialization of electrical energy between peers within an energy community. This organization splits peers into communities coordinated or controlled by a manager, as can be seen in Figure 1(b). That is, all the exchange between peers are supervised and decided by the community manager. Aside from this change that prioritizes trades between peers belonging to the same community, both systems operate in a relatively similar fashion.

The mathematical modelling for the community-oriented approach is given by Equations 2a - 2i.

$$\min_{D} \sum_{n\in\Omega} \frac{a_n}{2} \cdot \Big(\sum_{m\in\omega_n} P_{nm}\Big)^2 + b_n \cdot \Big(\sum_{m\in\omega_n} P_{nm}\Big) + \\ + \gamma_{exp} \cdot c_{exp} - \gamma_{imp} \cdot c_{imp} \quad (2a)$$

$$s.t. \quad \underline{P_n} \le \Big(\sum_{m\in\omega_n} P_{nm}\Big) \le \overline{P_n} \qquad \forall \ n \in \Omega \quad (2b)$$

$$\underline{P_n} \le \Big(\sum_{m\in\omega_n} P_{nm}\Big) - \beta_n \le \overline{P_n} \quad \forall \ n \in \Omega_p \quad (2c)$$

$$\Big(\sum_{m\in\omega_n} P_{nm}\Big) + \beta_n + \Phi_n = 0 \quad \forall \ n \in \Omega_p \quad (2d)$$

$$\underline{P_n} \le \Big(\sum_{m\in\omega_n} P_{nm}\Big) + \alpha_n \le \overline{P_n} \quad \forall \ n \in \Omega_c \quad (2e)$$

$$\Big(\sum_{m\in\omega_n} P_{nm}\Big) - \alpha_n + \Phi_n = 0 \quad \forall \ n \in \Omega_c \quad (2f)$$

$$\sum_{n\in\Omega} \Phi_n = 0 \quad (2g)$$

$$\sum_{n\in\Omega_c} \alpha_n = \gamma_{imp} \quad (2h)$$

$$\sum_{n\in\Omega_p} \beta_n = \gamma_{exp} \quad (2i)$$

where Equation 2a represents the objective function of this market design considering the costs of exchange within the community, and the costs for importing and exporting from the community. Equation 2b establishes the lower and upper bounds for each peer in the community. In addition, Equations 2c through 2f depict the energy balance within the community, taking into account internal peer exchanges and the imported (α) and exported energy (β). Equation 2g ensures that all the transactions between peers within the community are accounted. Similarly, Equation 2h and Equation 2i ensure that only the producers and consumers can export and import from outside the community, respectively.

IV. Brazilian Test Case

In order to create a study case considering the Brazilian electricity sector, some characteristics must be considered. The Brazilian power sector consists of a centrally dispatched system, with a settlement price defined on a weekly basis as the wholesale market price. This system is operated by the National System Operator (ONS), the Brazilian ISO [14]. In a recent effort, computer models that run the central dispatch have been upgraded to release hourly prices. However, this hourly prices are set to become operational only in 2021.

A. Case characterization

This study considers a set of consumers/prosumers whose data were collected from smart meters installed in a city in Brazil. The data set is comprised of twenty Brazilian consumers, five of which are commercial establishments and another fifteen residential consumers. It also considers data acquired during one typical day, which is replicated in order to represent a week. The general load behaviour for this day and its correspondent limits is represented by Figure 2.

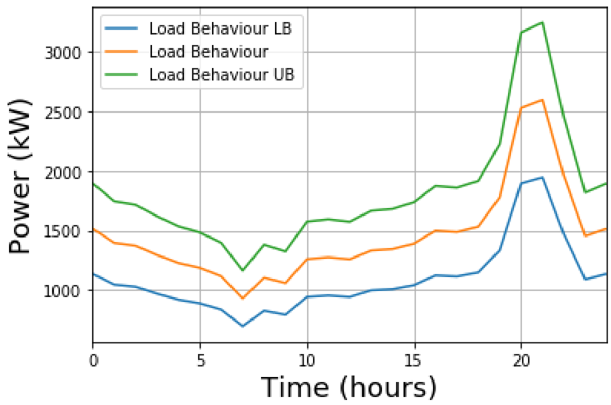


Figure 2. Load behaviour and its limits during a typical day.

Furthermore, two 75 kWp photovoltaic generators based on a real solar plant capacity factor in Brazil were considered. Additionally, a set of 4 micro CHP, summing up 345 kW of installed capacity were included to improve the prosumers capability to participate in this local electricity market. Finally, one wind generator is considered, with the installed capacity varied in order to create low and high generation scenarios. Three different scenarios for wind power capacity (low - 1000 kW, medium - 3000 kW and high - 5000 kW) were considered. Concerning the prices, the present study takes into account the hourly prices available in [15]. Figure 3 presents the hourly prices adopted during the simulated week.

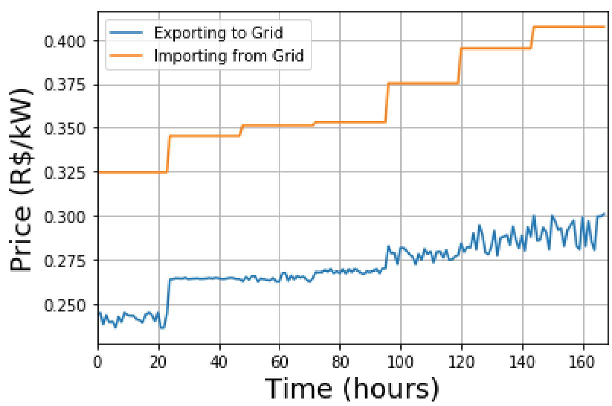


Figure 3. Hourly costs related to the exportation and importation of energy from the grid over the period of one week.

As a wholesale price, it must be subject to some tariffs due to the transmission and distribution systems usage. In a recent study of regulatory impact in Brazil, conducted by ANEEL, the Brazilian Electricity Regulatory Agency, the distribution costs were considered about 28%, without considering losses [16], [17]. Thus, in the present work, the import price considers the price from the wholesale market increased by a fixed surplus of 30% to account for the grid usage. On the other hand, the export prices are considered to be the average daily price, with a uniform deviation that may reach up to 10%.

One important aspect of the proposed P2P and CM market models is the possibility of a local arrangement before injecting in the distribution system. Although the export price must be subject to a tariff for the use of the system, in this first approach, the network costs will not be considered for exporting energy, since the proposed models prioritize local arrangements.

It is worth mentioning that it is assumed the consumers have elasticity, and therefore, a demand offer curve for each consumer has been built. These offer curves follow a quadratic function with the base price discussed above.

B. Results

The full P2P and CM market models have been validated in the aforementioned test case, for different penetration scenarios (low, medium and high) of wind energy. Taking the medium scenario (3000 kW of installed wind power capacity) as a basis for comparison, Figure 4 shows the social welfare of each market model. One can see that in most periods,the P2P has greater social welfare than the CM market, which is due to the self-sufficiency of the community during the periods of the day when renewable energy is considerably high. On average, the social welfare of the P2P is 39% higher than the CM market. As expected, the dispatch of distributed generation is higher in the full P2P than in the CM, and this can be seen clearly in Figure 5. However, the supplied load (depicted in Figure 6) in the full P2P is smaller than the CM, as P2P exports more energy to the external supplier (representing the wholesale market).

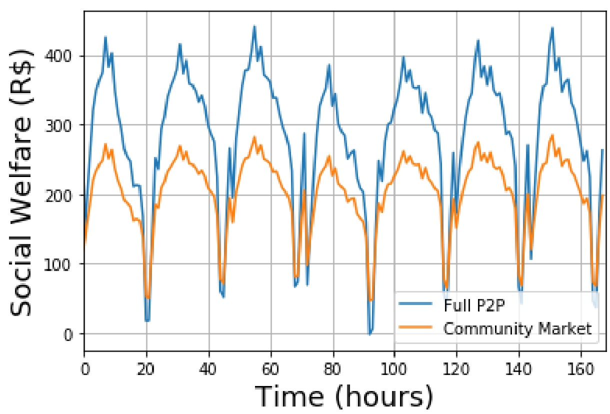


Figure 4. Hourly social welfare optimization results over the period of one week for each model.

Results for the three scenarios considering both P2P and CM are presented in Table I. One can see that the dispatched load in any scenario in the P2P model is almost always the same and as much as possible. The P2P market model always tries to provide

Table I
DISPATCHED ENERGY OVER THE WEEK

	Full P2P			Community Market		
Wind Power Capacity (MW)	Load (MWh)	Distributed Generation (MWh)	External Supplier (MWh)	Load (MWh)	Distributed Generation (MWh)	External Supplier (MWh)
1 (low)	183.531	134.451	49.079	178.847	172.361	6.486
3 (medium)	184.006	357.593	-173.587	191.224	299.846	-108.622
5 (high)	184.006	588.080	-404.073	191.224	415.090	-223.865

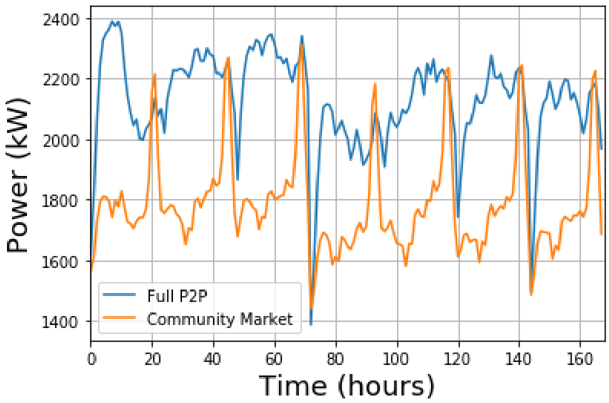


Figure 5. Hourly generator dispatch over the period of one week for each model.

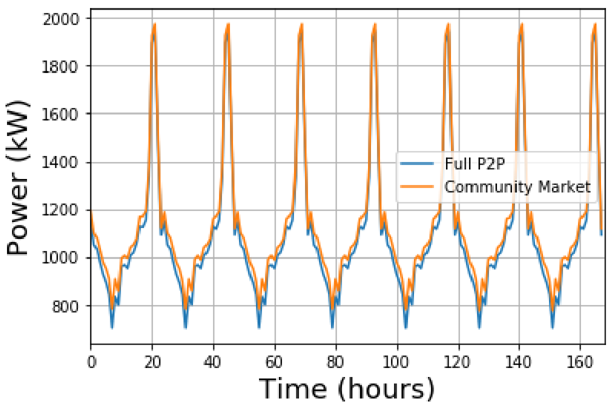


Figure 6. Hourly load dispatch over the period of one week for each model.

the maximum possible load, depending on the agreements between peers. As the external supplier is a peer that can exchange individually with other peers, a significant amount of energy (especially in low wind penetration scenarios) is supported by that peer, even though that is the most expensive producer. In contrast, the CM avoids exchanges with this expensive peers, prioritizing internal exchanges within the community. In the CM, community self-sufficiency is prioritized, and therefore, in situations where the community does not have self-sufficiency, energy imported from expensive resources is minimized. Thus, the flexibility of the community's internal demand is maximized, which results in less dispatched demand.

A comparison of the Social Welfare of both P2P and CM market models, for the three renewable penetration scenarios is presented in Table II. It can be seen that the CM has greater social welfare over the P2P for the low wind penetration scenario. However, for medium and high wind power scenarios, P2P performs better than the CM. The reason for such behavior is based on the lack of self-sufficiency of the CM in low penetration scenarios of DER, especially renewable energy sources. This forces the CM to import energy at higher prices.

Table II
SOCIAL WELFARE

Wind Power Capacity (MW)	Full P2P (R$)	Community (R$)
1	-20,305.82	1,985.14
3	47,011.38	33,799.13
5	109,288.28	64,937.57

V. CONCLUSIONS

This paper presents a first attempt to evaluate the consumer-centric approach considering some data from the Brazilian electricity sector, especially to evaluate the feasibility of these markets schemes by considering the social welfare optimization of this proposition under real data.

The P2P and CM market models were applied considering the actual regulatory framework in Brazil. The market models were assessed and compared for different wind penetration scenarios. The results show that the CM model performs better than the P2P in terms of social welfare and dispatched distributed generation for the low wind penetration scenario. In contrast, considering medium and high wind penetration scenario, the full P2P market model performs better than the CM model.

As final remark, this work concludes that the CM model is suitable for encouraging the emergence of small energy communities with reasonable degree of self-sufficiency. Additionally, the full P2P model fits better into a future distribution system with high integration of DER.

In order to properly evaluate the proposed consumer-centric option in Brazil, further studies should be carried out, starting with the economical comparison comprising the return on investment and the impacts for the current players in the power sector, consumers and utilities. In particular, a comparison with the current adopted tariff schemes should be conducted. In addition, an improved policy study must be drawn to outline propositions considering the P2P and community models as a transition from the current regulatory rules in the Brazilian system.

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