FEASIBILITY STUDY ON THE ADOPTION OF PEER-TO-PEER TRADING INTEGRATED ON EXISTING RETAIL MARKET AND DISTRIBUTION GRID

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ABSTRACT

The increasing penetration of prosumers, as well as the decentralized nature of power system management, are supporting the emergence of so-called consumer-centric electricity markets based on peer-to-peer and community-based concepts. The regulation of both market and distribution grid influence how a country is ready to integrate consumer-centric markets. Therefore, this paper proposes a methodology that performs a feasibility study on whether a consumer-centric market can be deployed at a specific location. The proposed methodology is divided into three steps that starts with enumerating the relevant data, then moving to choose the consumer-centric market model, finally providing the recommendation based on evaluation indicators. A test case based on a neighborhood in Denmark is carried out to assess our methodology. An important conclusion is that Denmark can integrate consumer-centric markets under deregulation of the Danish electricity market.

INTRODUCTION

In distribution grids, the figure of prosumers has steadily gained relevance [1] due to advances in Distributed Energy Resources (DERs) and digitalization in power systems. The energy sector has not entirely caught up this ongoing transition [2] and Distribution System Operators (DSOs) can no longer use the 'fit-and-forget' approach to integrate DERs and prosumers (individually or as energy communities). A consumer with assets for production and storage is designated as a prosumer. Their active participation is essential to reach a decarbonized power system as suggested in [1]. Alternatively, restructuring electricity markets under Peer-to-Peer (P2P) concept [3] has recently proposed, which would empower prosumers' choice while facilitating the grid operation for DSOs. Moreover, P2P markets could support private customer investment into renewable DERs integration in the distribution grid. Besides that, a P2P consumer-centric market paradigm can redesign the role of prosumers and DERs into an integral part of the market ecosystem.

Consumer-centric P2P market is in its early stage with proposals for microgrids and small communities [3]. So far, one can find three distinct designs as discussed in [2, 3], i.e. full P2P, community-based and hybrid P2P model. The full P2P model assumes that every peer directly trades with others without a centralized structure (as the wholesale market) or intermediary entities (as the retail market). On the other hand, peers can form energy communities under the community-based model. A supervision node manages the trading between members, as well as supervises the trading between the community and the rest of the system. The hybrid P2P model is the combination of the two previous ones. Independently of the P2P model, every agent owning or operating an asset (e.g. production, consumption, storage) is seen as a peer. Moreover, one cannot forget the virtual agents in existing markets without owning and operating assets that can also be peers.

Following these P2P designs, [4] proposes prosumers coalition based on P2P trading to form a federated virtual power plant. One can also find pilot tests of P2P energy trading conducted across the world, e.g. Piclo in UK [5], and Vandebron in Netherlands [6]. Both companies have an online platform that allows consumers to virtually buy electricity from producers in a P2P system. [7] proposes an architecture to identify the key elements in a microgrid P2P energy trading. A framework is proposed in [8] that integrates prosumer communities into the existing day-head and intraday markets using a two-stage stochastic programming approach. In summary, these studies show that a consumer-centric market based on P2P energy trading requires key elements to be met, such as regulatory and smart grid environment. Future research has to focus on proposals that investigate the potential of P2P trading into a specific location. This research question should consider the coexistence between P2P trading with the existing market organizations (wholesale and retail).

Thus, our paper contributes with a methodology that evaluates the conditions to deploy P2P markets, considering the DERs available, smart grid environment and regulatory framework applicable in a specific location. The proposed methodology performs feasibility studies that assess the conditions to the P2P markets deployment. A decision-maker can use such methodology to evaluate what kind of conditions have to be met for deploying P2P energy trading in a location. For example, the type of DERs that is necessary to integrate, or the time latency of the historical data, finally, which P2P design achieves better results. Besides that, the paper uses the methodology as a feasibility study of a local market based on P2P energy trading, while guaranteeing the coexistence with the existing retail market and distribution grid. This is done through a realistic setup of an energy community inside the new neighborhood of Nordhavn [9] in Copenhagen.

After this introductory section, the paper follows to the next section that explains the proposed methodology on feasibility studies, elaborating on the key aspects of the methodology. The third section describes the test case as a proof-of-concept towards the coexistence between P2P trading and existing retail market, which includes the results of the feasibility study to this test case. The next section discusses the results as well as the contribution of the methodology to the field. The last section summarizes the work conducted in this paper.

FEASIBILITY STUDY METHODOLOGY

This section starts by describing the methodology on which the feasibility study is based. The proposed methodology is divided into three steps that are illustrated in Figure 1.

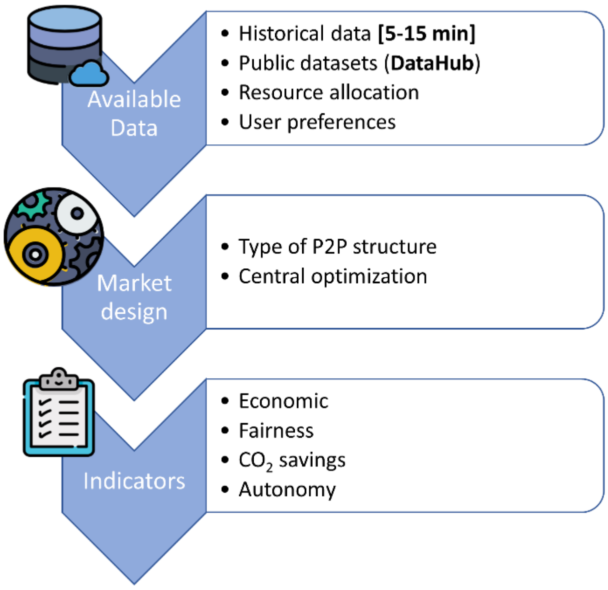

Figure 1. Methodology on feasibility studies.

The first step is collecting and filtering the available data, this is followed by defining the P2P market design. Finally, a set of indicators are calculated to assess the feasibility study of a specific location. Each step will be explained in the following subsections.

Available Data

The feasibility study requires historic data from prosumers and DERs of the selected location. The required data should be energy consumption and production, flexibility characteristics and customer preferences towards electricity usage (e.g. CO_2 emission). The later data corresponds to how customers are willing to pay for the electricity, which can depend on the CO_2 emission and location. Ideally, the time step should be within 5 to 15 minutes.

This historical data is usually recorded by measurement devices such as smart meters, which are the first source of data in the feasibility study. One can also use other sources of data in case the measurement devices option is unavailable. Public datasets are a source of available data for feasibility studies, such as the Danish repository of electric consumers [10]. Methods on resource allocation assessment are another potential source of data. For example, one can use such methods to determine the expected solar production of a specific location.

The dataset in this paper uses historic data collected from the Nordhavn neighborhood in Copenhagen [9]. The dataset considers electricity consumption from 10 residential consumers and solar production from a service building. The data is logged every minute. Figure 2 shows the solar production from the service building.

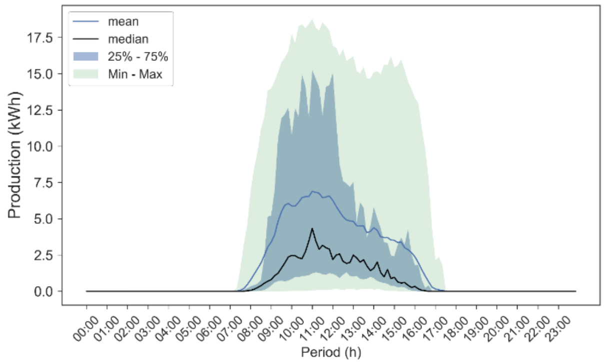

Figure 2. Solar production from the service building in February 2017 [9].

Market Design Model

The choice of the market design model under consumer-centric market is the next step. As described in the introduction, one can choose between a full P2P, community-based and hybrid P2P model. For comparison purposes, the benchmark model assumes that prosumers trade individually in the existing markets (retail or wholesale). Naturally, this business-as-usual model is a benchmark option in most feasibility studies, however, one may not need the benchmark when the study only pretends to compare different P2P market structures.

The full P2P model is selected in the test case for the Nordhavn neighborhood in Copenhagen, as shown in Figure 3.

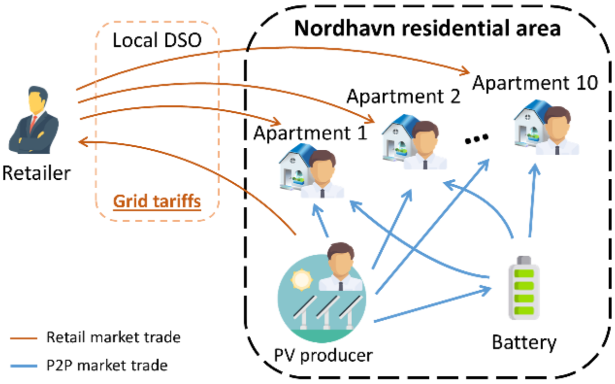

Figure 3. Full P2P model in the residential area of Nordhavn.

This setup assumes 10 consumers, a single photovoltaic (PV) producer, a battery and an external retailer. Bilateral real-time trading is allowed among the peers in Nordhavn residential area, maximizing the use of endogenous resources (PV and battery). This P2P trading requires the access of the Low Voltage (LV) distribution grid in Nordhavn owned by the DSO in Copenhagen. Thus, P2P trades are charged by a local grid tariff. The peers (apartments and PV producer) can also trade energy with an external retailer, where these exchanges are charged by the grid tariff scheme of the DSO in Copenhagen. This grid tariff corresponds to the use of the MV and LV grid. In this setup, peers are freely choosing who they buy or sell energy, as well as testing the feasibility between a local P2P model and the existing retail market in Copenhagen. The full P2P market from [11] is a multi-bilateral economic dispatch with product differentiation that allows non-monetary preferences on each market participant. The mathematical formulation of the full P2P model is presented below,

$$\min \sum_{t \in T} \left[\sum_{n \in \Omega} \left(\frac{1}{2} a_n (P_n^t)^2 + b_n P_n^t \right) + \sum_{n \in \Omega} \left(\sum_{m \in \omega_n} \gamma_{n,m} P_{n,m}^t \right) \right] \tag{1a}$$

s.t.

$$P_n^t = \sum_{m \in \omega_n} P_{n,m}^t \qquad \forall \ n,m,t \in \Omega, \omega_n, T \tag{1b}$$

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

$$P_{n,m}^t + P_{m,n}^t = 0 \qquad \forall \ n,m,t \in \Omega, \omega_n, T \tag{1d}$$

$$P_{n,m}^t \geq 0 \qquad \forall \ n,m,t \in \Omega_p, \omega_n, T \tag{1e}$$

$$P_{n,m}^t \leq 0 \qquad \forall \ n,m,t \in \Omega_c, \omega_n, T \tag{1f}$$

where, $P_{n,m}^t$ is the set of decision variables that corresponds to the bilateral trade between peers n and m. A positive value $P_{n,m}^t$ corresponds to a sale/production (1e) and a negative value $P_{n,m}^t$ to a purchase/consumption (1f). Ω, Ω_p and Ω_c are sets for all peers, producers and consumers, respectively (hence, Ω_p, $\Omega_c \in \Omega$). The net power P_n^t of each peer n is equal to the sum of bilateral trades $P_{n,m}^t$ (1b), where ω_n contains the trading partners m. Upper $\underline{P_n^t}$ and lower $\overline{P_n^t}$ boundaries are defined (1c) for every peer n. The set of trading constraints (1d) imposes equal bilateral trades between peers n and m. The objective function (1a) maximizes the social welfare, which can be formulated as minimizing the utility curves. T is the set of periods. A quadratic function is commonly selected to represent the utility curve [12]. The product differentiation in [11] defines a bilateral trading cost through the parameter $\gamma_{n,m}$. Peer n can impose a prority to each bilateral trade $P_{n,m}^t$. One can think $\gamma_{n,m}$ based on the geographical distance between peers n and m, or the type of technology used by peer m (renewable or traditional source). This paper uses $\gamma_{n,m}$ to impose consumer preference on the type of technology (wind, solar, conventional).

Indicators

The last step is the evaluation of the market clearing results through indicators, which determine the potential of the selected location to deploy P2P markets. The evaluation indicators can be divided into 4 categories:

- Economic
- Fairness
- Environment
- Autonomy/resilience

In the economic category, the social welfare, profit for producers and energy cost savings for consumers should be analysed. The fairness category analyses the impact of the P2P market clearing results among the single peers. One should use the quality of service, Quality of Experience (QoE) and Min-Max fairness, which are normally used in communication networks [13, 14].

The CO_2 savings should be consider as environment indicator, which can be relevant to users with environmental concerns. In the last category, the level of locally produced energy that is consumed will indicate the autonomy level regarding the retail market. Before calculating the indicators, one has to decide which categories are priority over others.

TEST CASE

This section presents the results for the test case using the dataset and P2P model described in the previous section. It starts by describing the simulation conditions in this paper, moving on to the results with this feasibility study.

Description

As described previously, the test case is composed by 10 consumers with controllable loads, 1 PV producer with 20 kWp capacity, a battery with 20 kWh capacity and an external retailer. We assumed a DSO grid tariff equal to 0.84 DKK[1]/kWh between 5-8 pm and 0.33 DKK/kWh for the remaining time. This grid tariff is charged to the energy trading between peers and retailer (see Figure 3). Since the DSO has no information about which grid tariff to consider for the local LV grid in the Nordhavn neighborhood. We assumed a local grid tariff equal to 0.3 DKK/kWh that is charged to local P2P trading. The time step in this test case is 10 minutes, which for one day the P2P model (1) comprises 34,704 variables and 12,106 constraints. Due to the computational burden, we chose 1 representative week

[1] DKK – Danish krone (currency of Denmark)

(i.e. 7 days) for summer and winter. Specifically, one week in February and July of 2017 is considered. The full P2P model (1) is solved by Gurobi Optimizer in Python. The results are compared with the benchmark model that consumers and PV producer individually trade energy with the retailer.

Results

Table 1 presents the indicators for both P2P and benchmark models. Results show that the P2P model has a social welfare of around 1993.8 DKK, compared to a social welfare of around 1390.2 DKK achieved in the benchmark model. These results correspond to the 2 representative weeks.

These results also show potential cost savings of around 9.2% to the residential consumers by engaging in P2P trading. Similarly, an increase of around 8.5% is achieved in the PV revenue when compared to the benchmark model. Besides the P2P model achieving better economic indicators, the autonomy level increases because the locally PV produced energy supports approximately 34% of the consumed energy during these 2 representative weeks. The QoE indicator evaluates consumers satisfaction on the perceived price of energy. The QoE is calculated per time step that results on a mean around 0.85 (shown in the table) and a standard deviation of 0.12. The P2P market fairness is higher as the QoE is close to 1, meaning the price variation among the 10 consumers is smaller in the 2 representative weeks. Our results show that fairness is reached when assuming a local P2P model among consumers in Nordhavn neighborhood.

Figures 4 and 5 depict the energy exchange by the consumers and PV producer for a single day, respectively. These 10 consumers benefit from the efficient use of the local DERs available in their neighborhood, either by consuming directly from the PV producer or by the charge/discharge of the battery. Their response towards the periods with high grid tariff is improved due to the local P2P energy trading.

The test case also analyzed the effect of consumers preference on getting more locally PV produced energy. For that purpose $\gamma_{n,m}$ in (1a) is set to 0.5 DKK/kWh between consumer at apartment 2 and PV producer. So, consumer 2 is willing to pay extra more 0.5 DKK for every PV produced energy. Figure 6 shows the result of consumer preference.

Table 1. Results for the 2 representative weeks.

Indicator	Benchmark	P2P
Social welfare (DKK)	1390.2	1993.8
Consumers cost (DKK)	2806.7	2548.3
PV revenue (DKK)	488.3	529.6
Local PV production consumed	0%	34%
QoE	-	0.85

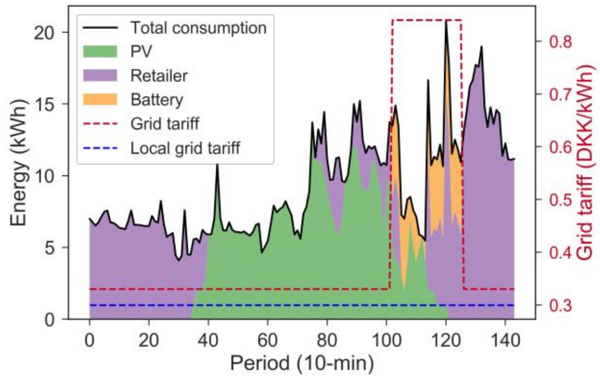

Figure 4. Consumers energy trading in the P2P model.

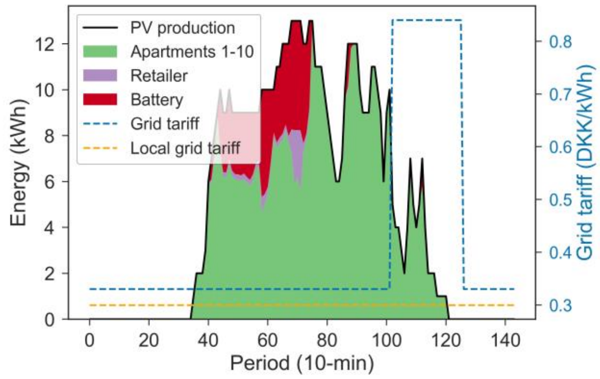

Figure 5. PV production in the P2P model.

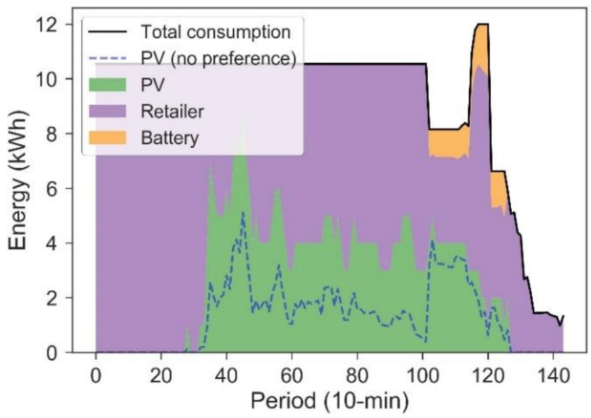

Figure 6. Consumer 2 consumption with PV preference.

Following the consumer 2 preference, the level of PV consumed energy is almost twice than the PV energy obtained in the simulation without preference (blue line). However, the introduction of consumer preference increases the cost on the remaining consumers. This simulation achieves 2648 DKK of consumers cost and 1989 DKK of social welfare. Since consumer 2 gets most of PV produced energy, the other consumers have to consumer their energy from the retailer with a higher price due to the grid tariffs in the peak periods. The cost savings are reduced to around 5.7% (compared to the benchmark). The QoE reduced to a mean of 0.44 showing a higher price variation and less fairness among the 10 consumers.

DISCUSSION

The results of this feasibility study support the necessary adoption of a new local market environment in the Nordhavn neighborhood, and in general in the residential areas within the distribution grid. A P2P model allows consumers getting locally produced energy instead of expensive energy from retailers due to the high grid tariff in peak periods. Besides the economic benefit introduced by P2P trading as shown in Table 1, one should also take into account the social aspect of being part of a community. In particular, this local P2P market helps consumers to be aware on how their energy is produced, as well as where it comes from (inside or outside of Nordhavn neighborhood). This can be seen in Figure 6 with the energy consumption following the consumer preference. This social aspect and fairness among consumers play a bigger role than the economic aspect, because the sense of ownership is enhanced to private consumers in energy projects, as the ongoing project in Nordhavn neighborhood [9].

The proposed methodology on feasibility study is central to evaluate the potential of prosumers and DERs adopting a P2P market in a specific location. The paper emphasizes the required steps to perform a correct feasibility study on P2P markets integrated into existing retail market and distribution grid. This methodology can support a community of private consumers to investment on local DER solutions. In fact, [1] concludes that the empowerment of private consumers (individually or collectively) is crucial to future investments on renewable projects. The limitation of the proposed local market concerns the existing legal barriers to perform real-time P2P negotiation between neighbor prosumers in a local distribution grid.

SUMMARY

The future paradigm will be a decentralized power system management with large-scale integration of prosumers. Current electricity market requires new organizational approaches based on P2P trading. Feasibility studies are necessary to assess the potential of a certain location before adopting P2P markets. This paper proposes a methodology that identifies the data, P2P models and indicators essential to perform feasibility studies. A neighbourhood in Denmark is selected as showcase, which presents potential of deploying a local P2P market. The local P2P market enables cost savings around 9.2% to consumers in Nordhavn neighbourhood.

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