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A review of P2P energy markets and a possible application for remote areas

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***Abstract*—Peer-to-peer (P2P) markets are emerging as a promising alternative to the current centralized markets, especially for the management and operation of areas where traditionally passive electricity consumers become small-scale producers (prosumers). This solution may also be a more convenient alternative to an expensive extension of the existing grid infrastructure, to handle the increasing electric load. Thus, lately, extensive research work is aiming to provide efficient and reliable operation of local energy markets. This paper provides a review of current studies and decomposes the components required for P2P markets: price-formation, prosumers behavior, grid technical specifications, and peer-matching optimization algorithms. Furthermore, it examines some existing case studies that are moving towards P2P energy trading. Finally, we propose the interconnection of microgrids in a remote rural area as a possible application of P2P trading. A simple case study with two microgrids shows that peer-to-peer transactions may allow reducing generation capacities by 10% and storage system by 50%.**

***Index Terms*—peer-to-peer markets, microgrids**

I. Introduction

The deployment of renewable energy sources, along with the advances in Information and Communication Technologies (ICT), is triggering fundamental changes in the energy sector. In particular, a novel solution for the design and operation of electricity markets has recently emerged: the peer-to-peer (P2P) markets, in which the traditionally passive electricity consumers become prosumers, i.e. small-scale producers who can transact electricity and other services. This concept is an alternative to centralized electricity supply by utilities or third-party aggregators, and may potentially alleviate the need for investments in upstream generation and transmission infrastructure, increase network efficiency and energy security, promote renewable (therefore, environmentally friendly) production, and allow households to actively participate in electricity markets. The clear advantages have triggered extensive research in this field to design and develop innovative market models and peer-matching strategies. Nevertheless, the concept is still on its early stage and there are no rules of thumb for the operation of P2P markets yet.

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This paper is organized as follows. Section II gives an overview of current studies on P2P markets and describes the components required for modeling. Section III describes running projects and initiatives. Section IV reports on a simulation study, which confirms our hypothesis that a prospective application for P2P markets are microgrids operating in remote areas. Apart from a general review of the topic, such an idea is the main contribution of the present manuscript.

II. State-of-the-art

A. Market design

The term peer-to-peer energy market is widely applied to prosumer integrated markets, but it could refer to different market designs, depending on the degree of decentralization. The "pure" P2P markets completely eliminate third party agents, prosumers directly interact with each other and make sells agreements. Even if this design strategy gives a complete freedom to peers and does not raise security concerns, it causes major difficulties in the control of the system and needs a massive computational capacity, thus stimulating the research of more feasible solutions. For example, [1], along with pure P2P trading, proposed two possible market models: prosumer-to-grid integration and prosumer community groups. Classification of P2P markets formulated in [2] includes pool based, peer-to-peer based and community based. Although different markets models are actively discussed, it is widely recognized that the most promising models assume a presence of a third party agent [2]–[4], as it simplifies market regulation and communication with system operators. In different studies this agent may have a different name and set of duties. For example, in [5] it is the local grid controller, who manages the demand side response, optimizes and transfers the locally generated power to the main grid or to another microgrid via an aggregator. Instead, [6] suggested a presence of a retailer for invoicing, real-time metering, and local energy management, but also to participate to the P2P market on behalf of the consumers, who may, for example, prefer having stable prices. In [4], besides the general functions, the community manager is authorized to assess the fairness of market participants. A

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particular case of P2P markets is the so-called island-mode, when a microgrid is not connected to a distribution network and is completely isolated. In this case, the storage system plays a vital role in terms of security and continuity of supply. Researchers predicted the same evolution path for batteries as for photovoltaic (PV) panels [7], with a gradual reduction of the technology cost and a raise of government subsidies, which will contribute to the proliferation of electrical vehicles, batteries and other storage technologies. There are two commonly discussed configurations of storage in microgrids: households own individual set of batteries or storage belonging to the community [7]. Although microgrids and local generation are currently associated with renewable energy sources, traditional fuel-based generators could also be considered [8]; alongside with storage systems, these resources can help to keep the balance and to support independence from the main grid.

B. Price formation

Despite the variety of market structures and components, a key objective of market design is to find a scalable peer-matching process, i.e. an agreement on electricity trades from which the involved agents do not want to deviate from [8]. An important instrument to find this equilibrium is price. Price formation does not just cover the production expenses, but also performs as an instrument to influence consumers' behavior and preferences, for example, to alleviate burden on distribution network or to smooth the demand peaks. In addition, in some models, the technical constraints are formulated via spatial and temporal varying tariffs [4] or as an additional network charge [9]. Also, as the prosumers are small-scale producers that exploit the services of the distribution infrastructure, they should be charged to contribute to the operation and maintenance of the network. While these charges are billed according to the electricity consumption in conventional grids, [9] studied possible solutions on how this service fees should be charged for prosumers selling their excess of energy. Furthermore, varying prices reflect the new vision of electricity as a heterogeneous good [10] to satisfy consumers' preferences – for instance they could like to buy electricity from their friends, relatives or neighbors or from a less polluting source – thus creating new characteristics (attributes), which are not strictly inherent to electricity. Nevertheless, no matter what is the reason for varying cost of energy, both [10] and [11] showed that the simultaneous negotiation among consumers make prices converging to similar values.

Three paradigms of price formation were proposed by [12]: bill sharing, mid-market rate and an auction-based. In the first case, all consumers pay the same price for the electricity according to their consumption and different export tariff. The mid-market rate assumes that the final price is the mean value of selling and buying price. In this case, the price during local generation will be lower, which stimulates electricity consumption. As auction strategy, each household provides bids or offers of its demand or generation, which, after a predefined bidding period, are matched together to define the clearing price. Simulations showed that an "order book" based market leads to lower electricity prices and that it is easier to support efficiency and reliability of the grid [13]. However, it assumes the presence of an operator or a centralized platform to collect bids and offers for price clearing.

C. Prosumers' behavior

Offering a choice of their energy supply to prosumers entails personal involvement with all respective features, such as bounded rationality, strategic behavior or risk aversion. The evaluation of different prosumers' behavior strategies was done in [13]; more in detail, it introduced intelligent and zero-intelligent agents, who make bids, either considering or not the history of transactions, to maximize their welfare. They also showed that, in a simulated P2P market, zero-intelligent agents obtain the highest electricity prices, while intelligent agents tend to achieve lower prices and higher levels of self-consumption. Morstyn and McCulloch, in [6] divided prosumers according to their preferences and proposed a market platform based on multi-class energy management: philanthropic prosumers agreed to provide energy to low-income consumers for reduced prices, while "green" prosumers preferred environmental friendly generators regardless the higher cost of electricity.

An algorithm that reveals true prosumers' preferences and eliminates "unfair behaviors", when some prosumers behave strategically, was developed by [4].

D. Real-time/forward market

The local market concept has appeared in correspondence to the spread of renewable energy sources, which are mainly related to intermittent generation. Hence, the presence of a balancing market is an essential factor of security of electricity supply. The conventional electricity trading system accommodates future and real-time markets, while, in the P2P trading literature, the majority of proposed market structures model just forward market [14]. Nevertheless, a couple of studies suggested a multi-settlement P2P market solution. A competitive market environment for prosumers using a forward market and a real-time balancing market was modeled in [15]; in this case, a combination of different contract types helps to guarantee system reliability and to maximize prosumers' profit, assuming that they strategically participate in energy markets. Another interesting example is provided in [8], by incorporating prosumers preferences and their risk attitudes in their model of forward and real-time markets.

E. Technical specifications

Among the advantages of P2P market implementation, one of the most used arguments is the reduced utilization and, therefore, the congestion of the transmission network. However, as a consequence, a significant burden on the distribution network can occur, so that an analysis of the technical constraints of the distribution grid in P2P markets is a relevant subject. In real-life situations, the power flow should be controlled to guarantee the security of supply. Considering that the existing distribution infrastructure was not built

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for bidirectional power flows, to avoid voltage and capacity problems, additional constraints should be incorporated in the models [11]. In the latter study, [11] proposed to integrate coefficients, such as Voltage Sensitivity Coefficients, Power Transfer Distribution Factors and Loss Sensitivity Factors, to guarantee bilateral transactions and to internalize the external costs associated with the power flows. On the other hand, [9] suggested a model in which P2P market transactions are matched relying on conventional optimal power flow calculations and distributional locational marginal prices.

F. Optimization problem

Optimization can be formulated based on different objective functions. Usually they aim to minimize the price, to reduce losses, to smoothen the peak demand [16], etc. According to these objectives, different constraints for the energy trading algorithms are applied, such as electricity price, physical distance, and technological constraints. For example, two alternative objective functions were studied by [9], who assessed the peer-matching schemes by applying either system-centric or peer-centric configurations. In the first case, the utility function oversees maximizing social welfare, while in the latter one, peers act according to their individual preferences. The simulation showed that in the peer-centric set, the producers sell energy to the closest neighbors, which significantly reduces system charges, while system-centric configurations lead to transactions among remote nodes and fully utilize line capacity.

A classification of optimization methods based on the mathematical framework was suggested in [17]. The authors grouped all possible computational solutions into three categories: the first one exploits single objective maximization tools, such as convex stochastic or swarm optimization, and is mainly used in the presence of a third-party agent; the second one is based on game theoretic approaches to find the optimal solution for the direct interaction among peers; finally, the third category finds the optimal solution based on simulations. Due to the nature of P2P markets, distributed price-directed optimization mechanisms are applied. Currently, the most well-known and applied method for distributed optimization in P2P markets is ADMM [4], [6], [8]. An alternative was suggested by [10], who applied a relaxed consensus + innovation (RCI) approach to match peers in a fully decentralized manner. The agents exchange both price and amount of energy in every iteration. A primal-dual gradient method was applied by [14], which needs lower information exchange (sellers send solely the price to the buyers, and the buyers provide only demanded energy to the sellers), therefore reduces number of iterations and convergence time.

III. Existing projects and possible novel applications

A. Existing projects

The first attempts to get closer to P2P markets are already presented by several companies. "The first-ever peer-to-peer energy transactions" were made in US in April 2016 and further developed to the project named Brooklyn Microgrid [18]. Nowadays, analogical projects have appeared in different countries. Nevertheless, as [19] noticed in their review, the existing projects are focused either on business models and marketplaces for P2P trading or on ICTs and control systems. To the first category belongs the Dutch company Vandebron, matching households with independent renewable energy suppliers. The English company Piclo follows the same strategy and presents itself as "The independent marketplace for trading energy flexibility online". Other examples of business-based companies are SonnenCommunity (Germany), Yeloha (US) and Mosaic (US) [19], [20]. On the other hand, TransActive Grid (US) and Electron (UK) mainly focus on innovative metering and billing systems and introduced blockchain technologies. Finally, Smart Watts is a German project that uses modern ICTs to optimize energy supply and to reach cost efficiency and secure supply [19].

B. Possible novel applications

A P2P market concept originates from microgrid deployment. However, the majority of existing trials are concentrated in Europe or US, where the distribution grid is already developed and the presence of microgrids is not forced by circumstances. Thereby, the connection of new producers to the grid is relatively easy. However, a completely different situation occurs in remote areas, where microgrids based on renewable sources may be the only possible solution. A particular case is represented by developing countries, where the transmission and distribution networks are not developed, the villages are insulated from the grid with kilometers of rainforests (like in the Amazonia region), or the transport infrastructure is not sufficient to build the network [21]. Hence, most likely, the grid extension to these regions will never happen due to both high capital costs and low electricity demand [22]. An alternative and a more economical solution nowadays is to develop microgrids for the remote rural areas. The proximity to loads and use of renewable energy make them a feasible solution for remote villages.

C. The case study

Even if microgrid solutions have been widely discussed for the developing countries [22]–[24], the P2P concept has still not been considered in such a context. Nevertheless, trading among close-by villages could provide higher benefits than islanded microgrids and could cost less that the connection to the main grid. In this work, we present a simulation study to highlight the advantages of a small P2P network that links the two villages. Due to the underdevelopment of the infrastructure and to the limited choice of generators in remote areas, the remote rural P2P markets significantly differ from the ones in the developed countries. Indeed, the main aim of the energy systems is to provide reliable and economically viable electricity supply, while other attributes of P2P markets, e.g. a choice of supplier, different electricity tariffs, presence of balancing market, etc. are still not a strict priority for the villagers. Therefore, on the current stage, the P2P network

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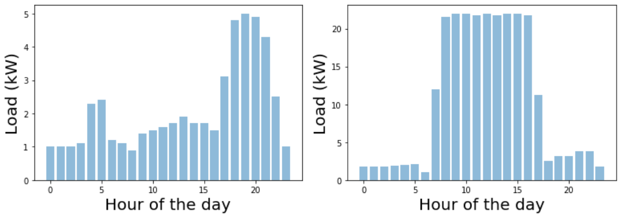

Fig. 1. Reference loads of Village A (left) and Villlage B (right)

could be regarded as an instrument to decrease the overall price of the energy system, and, following this statement, in the study we assess how interconnections can help to reduce the installation of generation capacities.

D. The villages

Compared to the traditional grid, microgrids in underserved communities have some distinct features. The load curves are atypical, since the peak of consumption often is during the day, while the evening is relatively calm [22]. Moreover, a unique microgrid design does not exist, hence the technology and the structure of the microgrid should be applied individually to each community, based on its loads and available resources. In this work, in order to create a basic P2P market example and to assess possible benefits, two Rwandan villages are taken as prototypes of underserved communities to design microgrids.

Rwanda is a commonly used case study in this field, due to its low level of electrification, lack of fossil fuel resources and 75% of the population living in remote rural areas [22]. Particularly, two villages modelled by [25] and [24] were already used to design microgrids. The authors analyzed the electricity need of the villagers to supply typical appliances for that region (lightning, phone, computer, etc.), available sources of energy and the most feasible energy mix. The load of Village A (Fig. 1 left), 50kWh per day with a 5kW-peak during the evening, is due to residential houses and a small store. Instead, Village B, based on the load profile of the existing village Nyakabanda (Fig. 1 right), has a significantly higher load, 250 kWh per day with a 22kW-peak during day-time, due to two coffee milling stations, alongside with residential houses and a restaurant. According to [25] and [24], the microgrid in Village A can rely on PV and diesel generation, while Village B can be supplied by hydro energy coupled with PV; both villages are equipped with storage systems, which are essential in islanded networks based on intermittent generation. According to [22], on a monthly time horizon, the river flow is constant and can stably supply energy.

E. Modeling and optimization

The stand-alone energy systems of the villages and their interconnection were modelled in ‘Python for Power System Analysis (PyPSA)’, a freeware developed by [26], which defines the optimal installed capacities of different resources by minimizing “the total system costs, which include the variable and fixed costs of generation and storage given technical and physical constrains”. The optimization tool GNU Linear Programming Kit [27] was employed. On a one-month horizon, the optimizer minimizes capital and operational costs of generation and storage, with the constraints of no load curtailment (except in case of faults) and assuming deterministic RES/load profiles and non-flexible users. It is worth highlighting that, during optimization, the minimum energy production from PV was set to cover half of the daily consumption (25kWh) to balance intermittent and constant generation.

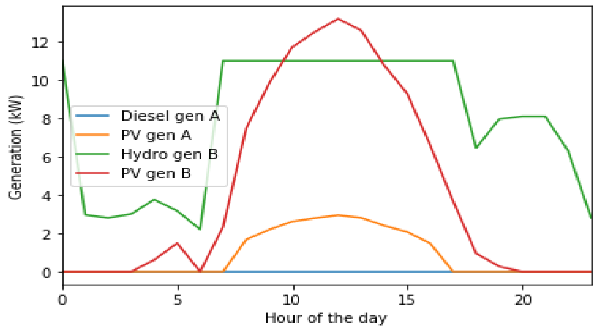

Fig. 2. Generation profile of interconnected villages

F. Reference component costs

The reference costs are presented in Table 1. According to [24], the reference costs of the connection line were taken from [23], since authors suggested that, even if corresponding to a Kenyan scenario, such costs can be extended to other Sub-Saharan African countries.

TABLE I
COST ASSUMPTIONS

	Capital cost	*O&M*	*Fuel cost*	*Lifetime*
PV	$2700/kW	$80/kW/year	-	20 years
Hydro	$4200/kW	$130/kW/year	-	25 years
Diesel	$640/kW	$50/kW/year	$0.70/kWh	10000 hours
Battery	$900/kWh	$14/kWh/year	-	10 years

G. Results

As summarized in Table 2, for the stand-alone energy systems, we obtained that in Village A the optimal choice is to cover the electricity demand by installing a 3-kW PV plant, a 2.3-kW diesel generator, and a 5-kW 11-kWh storage system. On the other hand, hydro energy will supply steadily 11 kW for Village B, together with a 14.5-kW of PV plant and a 5-kW 7.8-kWh storage system. On the other hand, assuming to interconnect the two systems, in the optimal design of minigrids we obtained:

1) No need for diesel generation in Village A. The evening load peak, which was originally met by diesel generation, can be covered by electricity transferred from Village B and produced by hydro energy. In addition, PV installation of Village B is reduced by 1 kW (up to 13.5 kW).

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2) A significant reduction of the size of the storage systems. The overall stored energy could be limited by 9.5 kWh. Therefore, the batteries could be completely removed from Village B and be reduced in Village A, leading to a correspondent reduction of operation and maintenance costs.

TABLE II
ENERGY SYSTEMS BEFORE AND AFTER INTERCONNECTION

	Village A	*Village B*	*Village A connected*	*Village B connected*
PV	3kW	14.5kW	3kW	14.5kW
Hydro	-	11kW	-	11kW
Diesel	2.3kW	-	-	-
Battery	11kWh 5kW	7.8kWh 5kW	9.3kWh 5kW	-

Considering the cost of the line, assumed to connect the two villages, we obtained that the maximum distance that makes this interconnection economically viable is 2.05 km if realized in Medium Voltage and 3.88 km if in Low Voltage (although this maximum length is not realistic for a LV connection). In addition, the removal of the diesel generator allows breaking the dependency from fuel transportation. Beyond monetary saving, interconnection also increases the reliability of supply: if an emergency and an outage of a generator occur, the load can be partially supplied by transferred electricity to fill the basic needs of the villagers.

IV. Conclusion

A large penetration of small-scale renewable energy production and a solid base of ICT is triggering the integration of P2P markets into the current power systems. The process has already silently started: a number of research works already suggest possible designs and specialized marketplace platforms have already appeared in several countries. This review examined the concept of P2P markets from different angles, drawing attention to existing research gaps and suggested possible applications.

The case study described in this paper showed that P2P markets could find wide applications in remote areas, where the distribution grid is not developed yet. Nowadays, part of these regions is not electrified and another part is supplied by small microgrids. Therefore, these markets could become a "white sheet" for peer trading and gain the highest benefits from them.

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