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Call-options in Peer-to-Peer Energy Markets

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***Abstract*—This paper proposes the novel application of *call-options* for financial loss mitigation in a *peer-to-peer* (P2P) energy market. P2P energy markets present the opportunity for end-users to trade electricity among themselves by managing their electricity usage and production capabilities. But variability characteristics of renewable resources pose a fundamental challenge to their integration into the grid as well as participating in emerging P2P energy markets. The growing penetration of renewable supply will increase the need for tools to mitigate potential energy traders' financial losses. This paper proposes and evaluates the application of call-option contracts in P2P markets to hedge against financial losses related to power shortfall in renewable supply. A case study is presented, showing that P2P traders might have to bear financial losses when they cannot meet their market obligations, and how options can be used to mitigate such losses.**

***Index Terms*—Call-options, distributed energy resources, local energy markets, smart grids, peer-to-peer energy trading, transactive energy.**

I. Introduction

The electricity energy sector is experiencing a transition paradigm characterised by decentralisation and the increasing uptake of *distributed energy resources* (DER). The emergence of prosumers, users with DER who both produce and consume energy, along with advances in information and communication technology have led to new *transactive energy* (TE) frameworks, characterised by proactive users' participation [1]. This context brings new opportunities to increase the potential value-stack delivered to users, and the systems as a whole.

Given this context, *peer-to-peer* (P2P) energy markets have been proposed as new decentralised energy market platforms in which users take the role of buyers and sellers in a local market to trade electricity among them [1], [2]. The energy surplus of sellers can be seen as an opportunity to trade with those users who are willing to buy in the local market.

However, there is a growing concern that benefits from P2P markets can be diminished by emerging challenges [3], [4]. The inherent variability and limited controllability of renewable resources, as well as the stochastic nature of end-users consumption pose a fundamental challenge to deploy P2P markets [5]. Uncertainty in generation and demand can be translated to uncertainty in the amount of energy to trade in the market. In particular, the uncertainty of renewable resources, such as wind and photovoltaic (PV) systems, make it difficult to guarantee that the energy committed in a P2P market for a given time-slot will be actually delivered [6]. Consequently, P2P traders are likely to face financial losses and end up cash negative after they participate in the market due to erroneous bids and penalty fees. Indeed, the introduction of penalty mechanisms in transactive energy markets has been suggested as a tool to force participants to fulfill their contractual market obligations and avoid unrealistic bids in the market. Nevertheless, penalty mechanisms in TE markets may lead to adverse outcomes, including conservative market participation, blocked DER value and unsafe system operation [7]. Although state-of-art techniques can reduce forecast errors, reduce potential penalty payments and limit other implications to a certain extent, additional techniques and tools need to be developed to manage such uncertainty that can adversely affect the users' participation in P2P markets.

Despite the importance of this emerging challenge, so far it has attracted little attention. Some studies assume that P2P market agents trade based on their actual generation and demand, avoiding the need to manage uncertainty and potential penalty fees. Existing works on P2P markets have mainly focused their attention on developing new market mechanisms, evaluating network constraints and blockchain, as reviewed in [1]. An interesting approach is proposed in [8], in which forward and real-time network contracts are introduced for P2P trading. A real-time market allows balancing of supply and demand requirements, reducing deviations caused by forecast errors. However, traders cannot adequately hedge against financial losses when they cannot meet their market obligations.

Given this context, we focus our analysis on energy trading in a P2P market, where agents need tools to mitigate potential financial losses when they cannot fulfill their market obligations. In doing so, the concept of *call-options* contracts is introduced as an adequate instrument to hedge against the financial risk. A call-option contract gives the right, but not the obligation, to its holder to buy/sell a specified amount of energy during a certain future period at the so-called *strike price*. Whether the holder of a call-option decides to call its right under the contract depends on the real-time price and the availability of its production units [9]. Previous studies have assessed the use of call-options in electricity markets [9], [10], [11]; however, to our knowledge, call-options have not been tested under the P2P market framework. In order to evaluate the economic implications of call-option contracts in P2P markets, we adopt the P2P market design proposed in [8]. Thus, this paper seeks to demonstrate how call-option contracts can be used as an instrument to mitigate potential financial losses.

The rest of this paper is organised as follows. Section II describes the different components of the adopted P2P market design and the proposed call-option market framework. Sections III presents a case study verifying the operation of the proposed market design. Section IV concludes the paper.

II. Problem description

We consider a smart energy system for P2P energy trading. As this is a preliminary study, we do not yet consider network constraints, in effect assuming a copper-plate network model. A full representation will be integrated as part of future work. The market consists of autonomous agents acting on behalf of end-users. Agents can behave as buyers or sellers and can trade energy among themselves in a decentralised manner. Formal definitions of the adopted P2P market platform and call-option settlements are described below.

A. P2P market platform

We adopt the market design proposed in [8], which encompasses a forward market and real-time market for energy trading. A set of contracts describes the potential trading between agents. Each contract specifies a price and power amount during a particular time-slot. We assume all contracts have the same power level and interval duration. Agents negotiate energy ahead of the delivery of the power in the forward market. Also, agents can negotiate energy in the real-time market based on the actual demand and generation. Nonetheless, any seller who is unable to deliver the quantity agreed can be subject to penalty payments or have to buy it from an upstream entity (e.g. aggregator or utility network).

Let $\mathcal{A}$ be the set of agents. let Ω be the set of contracts in the P2P market, such that the number of potential contracts (trades) in the market is $|\Omega| = |\mathcal{A}_b| \times |\mathcal{A}_s|$. The set of underlying contracts $\Omega_b \subseteq \Omega$, in which a buyer b is involved is given by $\Omega_b := \{\omega \in \Omega | \omega(b) = b\}$. Similarly, the set of underlying contracts $\Omega_s \subseteq \Omega$, in which a seller s is involved is given by $\Omega_s := \{\omega \in \Omega | \omega(s) = s\}$. A contract $\omega \in \Omega$ is a four-tuple $\langle b, s, \alpha_\omega, \mu_\omega \rangle$, which is the underlying matching between a seller $\omega(s) = s$ and a buyer $\omega(b) = b$. Associated with each possible trade ω, $\alpha_\omega \in \mathbb{R}_+$ denotes the transaction price and $\mu_\omega \in \mathbb{R}_+$ denotes the amount of power to exchange.

Each buyer b has a valuation function $v_b : \mathbb{R}_+ \to \mathbb{R}_+$, where $v_b(d_b)$ is the value of b for a level of demand, $d_b \in \mathbb{R}_+$, over a set of contracts Ω in the P2P market. The bid price of a buyer b for a contract ω is denoted by α^b_ω. Formally, we can define a utility function u_b to combine their values and cost for buying electricity in the P2P market as follows

$$u_b(d_b) \triangleq \begin{cases} v_b(d_b) - \sum_{\omega \in \Omega_b} \alpha^b_\omega \mu_\omega, & \text{if } \Omega_b \notin \varnothing; \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Then, if a buyer b is unmatched in the market, then $u_b = 0$. Equivalently, each seller s has a valuation function $v_s : \mathbb{R}_+ \to \mathbb{R}_+$, where $v_s(g_s)$ is the value of s for a level of supply, $g_s \in \mathbb{R}_+$,over a set of trades Ω in the P2P market. The ask price of a seller s for a trade ω is denoted by α^s_ω. Then, we can define a utility function u_s to combine their values and cost for selling electricity in the P2P market as

$$u_s(g_s) \triangleq \begin{cases} \sum_{\omega \in \Omega_s} \alpha^s_\omega \mu_\omega - v_s(g_s), & \text{if } \Omega_s \notin \varnothing; \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Then, if a seller s is unmatched, $u_s(g_s) = 0$.

Note that (1) and (2) show that buyers' and sellers' decisions are coupled through their dependence on their utilities on the trades ω. Thus, their interaction results in a game, and since each agents' preferences and reward functions are private, it is a game of incomplete information.

In order to find a stable outcome,[1] a distributed price-adjustment process can be used, like an ascending auction. The ascending auction is an iterative simultaneous auction, in which the prices in the bidding can only increase. Specifically, there is a sequence of $k \geq 1$ auction iteration. Each iteration consists of a price adjustment step, proposals steps, and acceptance or rejection steps. Each agent bids in the market and chooses the bids that maximize its utility given their values and cost. For trades $\omega \in \Omega$, let $\Omega^* := \bigcup_{\omega \in \Omega} (\Omega^*_b \cap \Omega^*_s)$ be the set of all optimal matches. Then, the set of trades $\Omega^*_b \subseteq \Omega$ that maximize the utility of buyers is given by

$$\Omega^*_b = \arg\max_{\Omega_b} \left\{ v_b(d_b) - \sum_{\omega \in \Omega_b} \alpha^b_\omega \mu_\omega \right\}, \quad \forall b \in \mathcal{A}_\text{b}, \tag{3}$$

where $d_b = \sum_{\omega \in \Omega} \alpha_{b,s}$. Similarly, the set of trades $\Omega^*_s \subseteq \Omega$ that maximize the utility of sellers is given by

$$\Omega^*_s = \arg\max_{\Omega_s} \left\{ \sum_{\omega \in \Omega_s} \alpha^s_\omega \mu_\omega - v_s(g_s) \right\}, \quad \forall s \in \mathcal{A}_\text{s}, \tag{4}$$

where $g_s = \sum_{\omega \in \Omega} \alpha_{b,s}$. In this process, both buyers and sellers update prices in response to bids in the market, depending on the set of trades that maximize their utilities, i.e. (3) and (4). Then, buyers or sellers update their bids in response to the new prices. As such, private information is only partially revealed during the iterative process.

Note that the price adjustment is monotonic, with prices beginning low and rising until a contract ω is selected by both buyer $\omega(b)$ and seller $\omega(s)$, then the transaction price α_ω is defined, i.e. $\alpha_\omega = \alpha^b_\omega = \alpha^s_\omega$. Specifically, in this model, in which buyers make the proposals, all of the possible transaction prices, $\boldsymbol{\alpha}^b$ and $\boldsymbol{\alpha}^s$, are initialized in zero. Since buyers would prefer the cheapest value, this is a reasonable value (this algorithm is buyer-optimal as buyers are making offers to sellers). Prices stop ascending if both a set of buyers and sellers are satisfied. Then, the process continues until no price changes occur during an iteration. The allocation of the resources is based on the last held set of contracts Ω^*. Note that there will be some agents who do not match.

A summary of the P2P market mechanism adopted is outlined in Fig. 1. For the sake of compactness, a detailed explanation of the adopted P2P market platform is not provided, but interested readers are referred to [8].

[1] Stable outcome is an agreed set of contracts no group of agents wish to mutually deviate from.

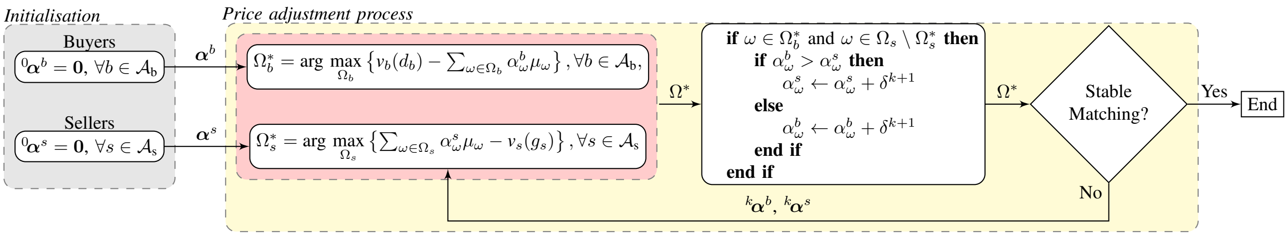

Fig. 1. Schematic of the price adjustment process in bilateral matching contracts configuration.

B. Call-option contracts

Network contracts in the forward market involve a commitment to sell the agreed amount of power during the delivery time-slot. Hence, an agent may need to buy the non-available power from the utility, if the agent cannot fulfill its contract commitments. When the utility import price is higher than the negotiated price, financial losses will be incurred. These losses can be exacerbated when penalty fees are incorporated.

Given this context, we propose introducing call-option contracts into the market framework. A call-option is an agreement that gives the buyer the right, but not the obligation, to buy or sell a particular amount of electricity during a certain future time at a specified price [9]. It is worth noting that buying a call-option represents an additional cost, which has to be paid even if the option is not called.

Fig. 2 shows the timeline of the proposed market design. Thus, call-options contracts are negotiated between the forward and real-time market. In this way, agents can use the forward market outcome to decide on purchasing call-options. Moreover, agents can purchase options prior to the real-time market, so the agent can strategically avoid potential financial losses. How call-options are negotiated is out of the scope of this paper, but the adopted P2P market mechanism can also be used to trade options among agents.

With option contracts in place, the market platform allows agents to negotiate options before delivering the negotiated power. Note that we only consider call-option for sellers in this paper, option contracts for all agents will be assessed in future research. Formally, the profit of a seller s with call-option contracts $o^s \in \Theta_s$ is given by:

$$U_s(g_s, \mu_o^s, \alpha_o^s) = u_s(g_s) - \sum_{o\in\Theta_s} \mu_o^s \alpha_o^s - \left(I(x^s)\alpha_p(x^s)\right), \quad (5)$$

where α_o^s is the option strike price, μ_o^s is the amount purchased with call-options, α_p is a penalty fee, x is the difference between the power shortfall and the amount of power purchased with call-options, defined by $x = \sum_{\omega\in\Omega_s}\sum_{o\in\Theta_s}(\alpha_\omega^s - g_s - \mu_o^s)$, and $I(\cdot)$ equals 1 for positive arguments and 0 otherwise. Note that the penalty fee α_p can take the value of the utility import price, or a penalty payment for power shortfall, or incorporate both. Also, note that $U_s(g_s, \mu_o^s, \alpha_o^s) = u_s(g_s)$ if $\Theta_s \in \varnothing$ and $\alpha_\omega^s \geq g_s$.

III. Case Study and Discussion

Case study simulations were carried out to assess the proposed P2P market framework with call-options. In particular, we divide our analysis into two parts. First, we simulate a P2P market platform to examine the operation of the forward and real-time markets. Second, we present a comparative analysis to evaluate the implications of call-options in the market.

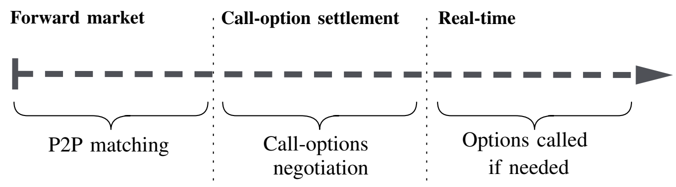

Fig. 2. Timeline of the proposed market design.

A. P2P market simulations

Specifically, we consider a smart grid system for energy trading at a local level, which comprises six agents for trading and one utility agent who acts as an intermediary between the agents and upstream entities such as generators or network operators. In more detail, our case study considers:

- Two agents as solar generation sources, which are rated at 200 kWp and 180 kWp;
- Two agents as EV parks of 25 EVs, each with 36 kWh batteries. It is assumed that EV arrivals and departures are uniformly distributed between 6 am to 10 am, and 3 pm to 9 pm, respectively; and
- Two agents as aggregators, one combines a set of consumers and behaves as a large uncontrollable load, and the other aggregates PV systems, loads and a *community electricity storage* (CES) of 130 kW and 232 kWh.

Load and PV generation profiles are obtained from a dataset [12]. Fig. 3 shows the total base load and PV generation of the agents. Note Fig. 3 does not include the flexible load related to EVs and battery storage systems, which are defined through energy management systems and trading preferences. The price of energy imports is 0.15 \$/kWh and 0.05 \$/kWh is paid for energy exports.

Energy trading occurs at each hour over a day, with 5 kWh energy trades, and a price increment of 0.05 \$/kWh. It is assumed that agents may export more energy to the grid than the amount traded in the P2P market. Note that in this case the energy is paid at the export price. Additionally, the proposed market design considers a forward market and real-time market for each energy trading interval during the day. In

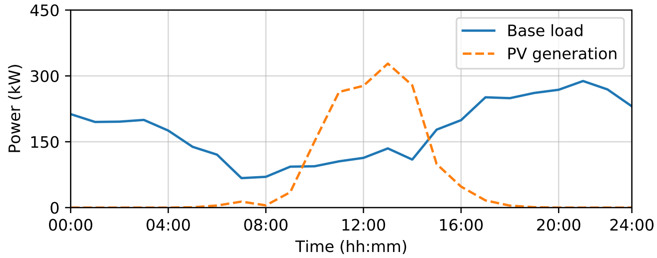

Fig. 3. Base load and PV generation profiles.

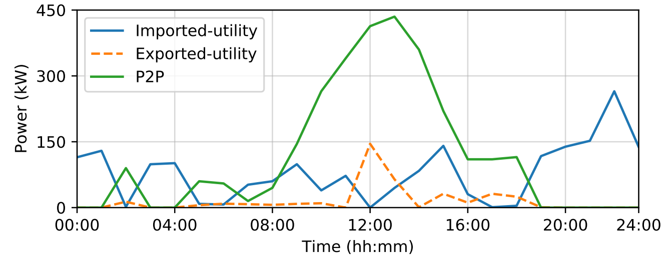

Fig. 5. Power traded in the real-time market and power imported/exported from/to the utility.

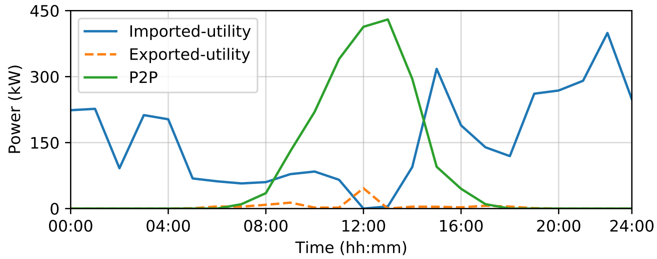

Fig. 4. Power traded in the forward market and power imported/exported from/to the utility.

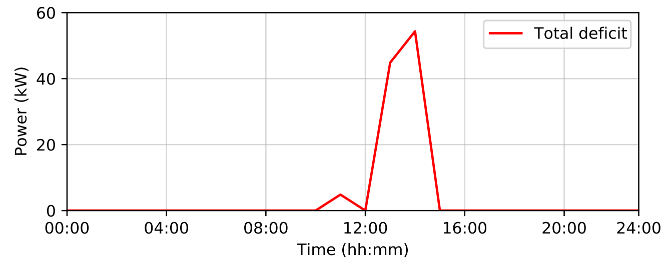

Fig. 6. Total traded power deficit due to forecast errors.

the forward market, agents buy/sell energy based on the import and export price and their individual electricity consumption. Note that PV generation forecast errors are introduced in order to evaluate the proposed method on a challenging yet realistic scenario. For this study, the forecast errors are assumed to follow a normal distribution $\mathcal{N}(0, 0.2)$ per time interval [3]. Hence, agents must generate energy, or buy it from the utility, to meet their P2P market obligations from the forward market.

Fig. 4 shows the power traded in the forward market, the total power exported to the utility, and the total power imported from the utility during one day. The results show that most of the energy traded in the P2P market occurs around midday, when PV generation peaks. A close observation of the results in Fig. 4 reveals that the EV parks bought in the market from 8 am to 4 pm, taking advantage of the lower prices that can achieve in the P2P market in comparison with purchasing energy at the utility import price. Following a similar trend, the aggregator with uncontrollable loads purchased energy from 7 am to 5 pm, obtaining affordable prices in the P2P market.

The traded energy in the real-time market and the power imported/exported from/to the utility is presented in Fig. 5. Note that the output of the real-time market presents some differences in comparison with the forward market output. This stems from the fact that PV generation forecast errors result in changes in the energy traded in the market. Also, Fig. 5 shows that there is an extension on the trading periods. In other words, there are P2P trades before 8 am and after 4 pm, in which the agent with the CES behaves as a seller.

To complement our analysis, Fig. 6 shows the total power deficit. That is, the amount of power that agents committed in the forward market that could not be meet in the real-time market due to their energy production shortfall. Specifically, two agents have to purchase energy from the utility or other agents to meet their P2P forward market obligations.

B. Comparative analysis

Now, since our interest is to evaluate the operation of the proposed call-option contracts and their financial implications, we compare five potential scenarios that may occur to agents who cannot meet their forward market obligations. Specifically, the scenarios considered in this study are:

- *Scenario 1*: The negotiated power deficit is covered by the utility and agents do not have to buy power from the utility, nor are penalised (i.e. $\alpha_p = 0$ \$/kWh);
- *Scenario 2*: Agents have to purchase the traded power to the utility (i.e. $\alpha_p = 0.15$ \$/kWh);
- *Scenario 3*: Agents are charged with a penalty fee;
- *Scenario 4*: Agents buy power from the utility and pay a penalty fee (i.e. a mix of Scenarios 2 and 3); and
- *Scenario 5*: Call-options contracts are considered. In this scenario, agents have purchased options and are used to cover any power shortfall if they need. The assumed call-option price is $\alpha_o = 0.05$ \$/kWh, which is lower than the import utility price 0.15 \$/kWh. Thus, agents would prefer buying options instead of buying from the utility.

Fig. 7 shows how the revenue of an individual P2P transaction is affected when an agent cannot meet their market obligation. For the sake of demonstration, we assume the price of the individual transaction is equal to the average transaction price in the simulated P2P market in Section III-A, which was 0.1 $/kWh (i.e. 0.5 $ for each P2P contract). Scenario 1 is the benchmark case in which the agent keeps the profit achieved by its trading in the P2P market. It is worth noting that most

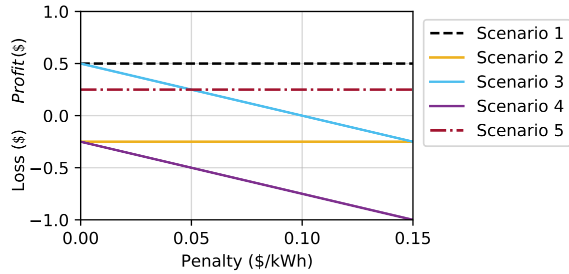

Fig. 7. Resulting profit or losses of one P2P transaction when the agent cannot meet its market obligation.

of the work on the P2P market considers this scenario, but it is not very realistic as other entities or agents will have to fulfill the power deficit. When additional charges and penalties are included, participation in the P2P market might result in losses for agents. In particular, purchasing the traded power deficit to the utility (Scenario 2) results in losses, which might be exacerbated when a penalty fee is included (Scenario 4). Interestingly, the agents can still achieve economic benefits when the penalty fee is low and no other charges are added (Scenario 3); however, high penalty fees lead to loss outcomes. Now, the inclusion of call-option contracts would reduce or limit the losses by ensuring a profit margin (Scenario 5). Therefore, if the agent experiences a power shortage, the option contract can be called to meet the agent's market obligations and still get economic benefits.

The comparative analysis of the scenarios is complemented with the simulation results presented in Table I, which summarises the profit that two agents achieved using the case study parameters presented in Section III-A and having 0.06 $/kWh penalty fee. It is worth noting that Scenario 5 considers the settlement of call-option contracts between the agent with the CES and the two agents with the PV systems. Notably, call-option contracts (Scenario 5) allowed agents to mitigate the reductions in their profits when they experienced a power deficit to trade. In comparison with Scenario 1 (which does not consider any additional fee), agents in Scenario 5 only reduced their profits by around 2.6%. In contrast, agents reduced their profit by approximately 9% and 11% in scenarios 2 and 4, respectively. Finally, a close observation of Table I reveals that agent 2 achieves almost the same profit in Scenario 3 and 5. This is because the penalty fee is just over the call-option price. In fact, as shown in Fig. 7, if the penalty fee is lower than the call-option price, Scenario 3 would be more profitable than Scenario 5. Consequently, in this particular case, Scenario 5 is the most profitable. Our simulation results suggest that call-option contracts are a valuable tool to mitigate financial losses in the context of P2P markets.

IV. Conclusions and Future Research Directions

This paper presented a new application of call-options in P2P energy markets. Call-options can be used as financial tools to mitigate energy traders' financial losses. It has been shown that call-options can create value for traders, by reducing their exposure to potential penalty fees due to scarce production or forecast errors in supply. Future works might take different directions. The proposed market design can be extended by incorporating more relevant elements, such as network constraints, modeling agent risk preferences (e.g. value-at-risk and conditional-value-at-risk), sophisticated forecast techniques, modeling uncertainty in the real-time market prices. Moreover, trading call-options can be modeled as a multi-stage stochastic optimisation problem to determine an agent's optimal trading strategy that incorporates options, forward and real-time contracts. Robust and chance-constrained optimisation techniques are interesting approaches to explore. Another area for future work is to assess how aggregators could make profit by offering options to risk averse generators. Finally, agents with battery storage systems can play an important role in the proposed market. Hence, further research is required to evaluate the technical and economic implications of their role.

TABLE I
Profit of agents with power traded deficit

Scenarios	1	2	3	4	5
Agent 1	$ 101.50	$ 93.13	$ 98.15	$ 89.78	$ 98.71
Agent 2	$ 93.27	$ 86.04	$ 90.38	$ 83.14	$ 90.86

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