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Peer to peer electricity markets

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Abstract

Driven by the energy transition and the development of distributed energy resources, peer-to-peer markets are the focus of much research. Because of their decentralised structure, they allow scaling up by multiplying the number of agents in a market. Moreover, they permit heterogeneous preferences between peers to introduce behaviours such as local exchanges or an environmentally friendly preference. Despite these attractive features, which make them good candidates for the evolution of power systems, they present several challenges that are still being investigated at present in order to become operationally viable. Supporting many agents is done by exchanging even more messages. Furthermore, integration with power systems requires adapting the interaction with the system operator. The aim is to ensure that the physical limits of the infrastructure are respected and to measure the completed trades. The decentralisation of the energy market also has an impact on the market for capacity reserves to deal with contingencies. Finally, the final challenge is how the end-user will deal with such a change. Despite these various difficulties, several pilot projects highlight the possibilities of these markets for the evolution of power systems.

Keywords: , peer to peer market, electricity market, distributed optimisation, grid control

1. Introduction

Electricity networks in the 21st century are facing a proliferation of connections from new protagonists. On the one hand, wind and photovoltaic power

plants, sometimes of very low power, have developed [1]. They constitute power
5 injections distributed throughout the network, sometimes at very low voltage
levels that were not planned for such uses. On the other hand, the drop in the
cost of Lithium Ion batteries is leading to the widespread adoption of electric
vehicles and even stationary domestic batteries [2]. These new uses, in par-
ticular the electrification of mobility, are very likely to generate an increase in
10 electrical consumption in the years to come [3]. Together with the possibility
to produce energy on their own via a rooftop PV power plant, this results in
the involvement of the user in their electrical behavior. The consumer becomes
a prosumer at various stages: from the monitoring of his consumption, to their
management, then to their balance with his domestic production [4].

15 This transition in electrical behaviour coincides with the development of
communication networks. Although impelled independently, power networks
and communication networks merge to constitute the concept of the smart grid
[5]. All the elements are now in place to mainstream the measurement and
remote control of production and consumption. In this context, the concept of
20 peer-to-peer exchanges is being put to new use: popularised by file exchange
protocols, it provides the possibility of exchanging electricity in a way that is
highly adapted to the new context of electricity networks. Indeed, it provides
the possibility for everyone to directly operate in a participative energy market,
capable of managing very large numbers of players, without any supervision by
25 a central manager [6].

Following a contextualisation presenting the role of electricity markets within
the current management of a power system – section 2 – this article attempts to
highlight the properties that make a P2P market such an attractive alternative
– section 3. The mathematical definition and an example of resolution will be
30 presented in section 4. The main remaining obstacles to its operational use will
be raised in the following sections: intrinsic communication and time cost in
section 5, coordination issues with power system management in section 6 and
adoption by the prosumer in section 7. Finally some examples of experimental
deployment in section 8 will be presented.

35 **2. Prologue: current functions of an electricity market**

A so-called market problem is defined by producers and consumers seeking to exchange a product by agreeing on a price and quantities. It is based on the assumptions that the good is substitutable and that the agents are so numerous and small that they cannot influence the outcome of the problem alone. In the case of power systems, the use of energy markets has become the hegemonic approach since the dismantling of vertically integrated operators [7]. They are classically defined as follows [8], with the purpose of optimizing the sum of the interests of all participants:

$$\min_{p_n \in \Omega} \sum_{n \in \Omega} f_n(p_n) \quad (1a)$$

$$\text{s.t.} \quad \sum_{n \in \Omega} p_n = 0 \quad (1b)$$

$$p_n^{\min} \leq p_n \leq p_n^{\max} \quad (1c)$$

where Ω denotes the set of agents participating in the market, p_n the power that agent n will produce – $p_n \geq 0$ – or consume – $p_n \leq 0$ – and f_n the function describing their costs, which are most often considered convex. Indeed such an assumption can be widely checked by real systems if using modelling of
 40 adequate complexity. Moreover it allows many efficient solving methods. These functions describe the costs of the power plants – fuel, maintenance, ... – and those of the consumers. In the context of today’s markets, these consumers are the suppliers with whom the final consumers have their supply contracts. The market crucial point is the coupling constraint imposing balance of transactions
 45 (1b). The latter also conveys the balance of power injected and subtracted into the network¹. Finally, the power injected by each agent is limited by their physical constraints (1c).

¹During the transport of electricity through the grid, losses are generated. These losses are compensated for by the system operator, who buys an amount equivalent to the losses on the market.

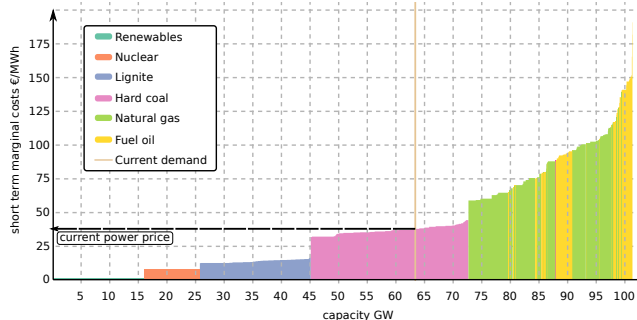


Figure 1: Example of merit order curve: production offers are ranked by increasing price. The crossing point with the consumption demand settles the electricity price [9]

The definition of such a market problem is independent of the choice of its resolution method. Currently, energy markets are solved in a centralised manner. This means that a market operator is responsible for collecting bids and offers and then setting the energy price for the current time period. Operationally this is done using a merit order method illustrated figure 1. The bids must be discrete rather than described in a continuous manner by functions. A resolution using a convex optimisation algorithm could also be used in this centralised optimisation framework.

A second approach of the resolution of a market problem is distributed optimisation. Indeed, the market problem is precisely a problem of optimal exchange of a resource between agents. A distributed iterative resolution is specifically provided [10] by the following algorithm, with $\rho > 0$ and \bar{p} the mean value among agents:

$$p_n^{k+1} := \operatorname{argmin}_{p_n} f_n(p_n) + \frac{\rho}{2} (p_n - p_n^k + \bar{p}^k + u^k)^2 \quad (2a)$$

$$\text{s.t. } p_n^{\min} \leq p_n \leq p_n^{\max}$$

$$u^{k+1} := u^k + \bar{p}^{k+1} \quad (2b)$$

This decomposition can be deduced from distributed optimisation algorithms, but is also equivalent to equilibrium search processes such as *tâtonement à la Walras*. Here, the central agent is still necessary because it must receive the p_n^{k+1} updates from the agents, compute their average \bar{p}^{k+1} value and update the dual

60 variable (2b). However, the agents can perform their own updates (2a) and keep their objective functions confidential. Such a distributed approach allows a parallel resolution. This is why, even in the case of a resolution completely carried out by the central agent, one can encounter distributed optimisation schemes, for example between the cores of a processor. An example of implementation is
65 proposed on the GitLab repository of the SATIE Laboratory².

Regardless of how this market has been resolved, several essential elements of a power system have not yet been taken into account. Firstly, market agents trade electricity without addressing the issue of its transmission. The grid is assumed to be a copper plate. It is therefore necessary that the power injection
70 plans drawn up by the market are passed on to the system operator, who must ensure that this plan is compatible with the physical limits of the infrastructure. If this is not the case, the markets have to decouple into different zones, each with different prices [11].

Moreover, an electricity market always takes place before real time in order
75 to predict and agree on trades. However, it is inevitable that not everything will go according to expectations: a generator suffering an outage or poorly forecasted weather conditions that are adverse to renewable plants for instance. All these unexpected events will create imbalances in the grid that will have to be compensated for. Other agents must be ready to adjust their own injection plans
80 to mitigate the deviation. To do this, a reserve market must be established [12]. The optimal solution for the system is obtained when the energy and reserve markets are resolved jointly.

3. Motivations for a transition to a peer-to-peer market

The mechanisms for managing electricity networks as described in the previ-
85 ous section allow for efficient regulation of these highly complex systems. They have been proven to provide good quality electricity with a very high availability

²https://gitlab.com/satie.sete/p2p_electricity_markets

rate. Nevertheless, there are several points that trigger a desire for evolution in these management mechanisms.

To begin with, the energy transition, together with the omnipresence of an efficient communication network, is driving the massive deployment of distributed
90 generators and new consumption practices [2]. The outlook for this transition is a metropolis whose roofs are covered with photovoltaic panels and whose electricity distribution infrastructures could not carry the consumption of electric vehicle recharging without demand response mechanisms [3]. Consequently, the
95 inhabitants would actively participate in their electricity consumption. By definition, such a situation would make everyone both an electricity producer and a consumer seeking to minimise their purchasing costs. It would then become difficult to persevere with standard electricity supply contracts. Instead, each household would tend to become a small market agent [13], attempting to sell
100 its production, buy its consumption and be rewarded for providing ancillary services [14]. This solution offers the most flexibility and allows for optimal control of the system: decision-making is transferred to each actor who can act according to his preferences and his particular situation. However, this comes up against a scaling-up hurdle.

105 Indeed, energy markets were not designed to coordinate thousands or even millions of agents. At present, only a few approved players are allowed to participate. The centralised form of a market presents a bottleneck that does not allow for scaling up, if only because of communication concentration issues. Peer to peer – P2P – markets provide an answer to this precise issue of scaling up
110 as each agent trades electricity directly with its peers, without global supervision. There is therefore no bottleneck in the negotiation because all peers can negotiate in parallel. It should be noted that scaling is also addressed by other approaches in the literature. Aggregators, for example, propose to coordinate a large number of actors in order to value their overall behaviour in existing mar-
115 kets. Additionally, small but interconnected markets, as illustrated in figure 2, have been proposed [15]. However, it has been shown that all market topologies can be considered as particular cases of a P2P market: each central agent can

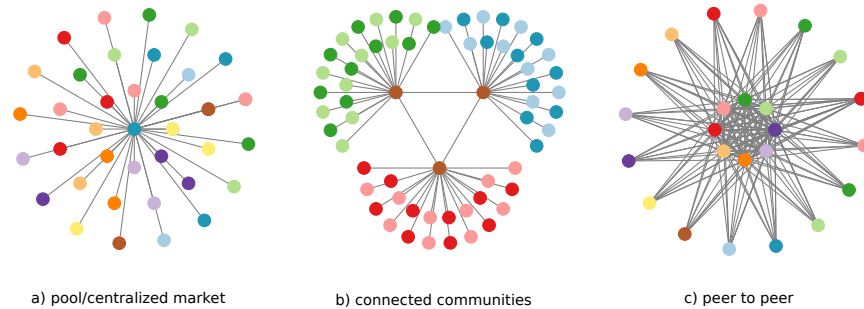


Figure 2: Examples of market structures [15]: each dot represents an agent and each line a communication. Physical connections are not represented here.

be described as a particular peer, in communication with all the others. This property is a considerable safeguard in the context of current research activities. It is still unclear what operational solutions will emerge from the energy transition. Proposing methods for managing electrical systems on the basis of a P2P market therefore provides the guarantee that the method developed will be adaptable to any context using a market – which is a very loose characteristic.

Furthermore, in this trade organisation centered around the prosumer, there is a strong desire which is already at work today in many areas of consumption: one wants to identify the origin of its purchases and to be assured of its fairness in terms of human rights, carbon impact or geographical origin for instance [16]. In the case of electricity, this differentiation between two suppliers can only be achieved through contracts or certificates of origin as there is no physical difference and no way to track electrons on a grid. However, in a centralised electricity market and by definition, the quantities offered are equivalent and interchangeable. Such differentiation is therefore impossible. On the contrary, in the case of P2P markets, it is very feasible to specify that one is willing to pay more for the product of a particular seller. A preference is then given to a renewable producer or to locally produced electricity. Several prices for the same asset can then go along within the same market, depending on agents preferences [17].

Moreover, electricity exchange will probably be just one of the components of future networks. Indeed, the forecasting of production and consumption
140 is of vital importance for the anticipative management, in particular of storage facilities. However, this forecast can only be made accurately by aggregating the local data and measurements of each agent. A shared good – the forecast – will therefore be calculated by aggregating individual contributions. An adequate value will therefore have to be given to each contribution in order to redistribute
145 fairly the benefits obtained thanks to the forecast [18]. Such a data market could then come along with the electricity market, also under a P2P structure.

4. Mathematical definition of a peer-to-peer market and example of resolution

A peer-to-peer market [19] consists of a set of agents who aim to minimize
150 their objective functions by exchanging contracts. By agents, we mean producers – owning production plants – consumers, or prosumers. The latter combine both behaviors, either simultaneously or at different times. Storage units in particular belong to this category. Their objective functions reflect their operating costs, the services they have committed to provide, or a quantification
155 of the inconvenience they would suffer if they could not consume. This last point can be objectively quantified in the case of industrial consumption, but is much more subjective in the case of domestic consumers. Finally, the notion of contract refers here to the fact that a market takes place upstream of real time, no electrons are circulating at the moment. Ensuring that power flows
160 according to the proposed contracts will be addressed at a later stage. For a peer-to-peer market, the contracts do not relate to power injected or subtracted at the agent’s connection point. Instead, it is a quantity of electricity exchanged between two agents. This is called a bilateral exchange. The power injected by an agent will therefore be the sum of all the exchanges it has contracted with
165 its peers.

The peer-to-peer market among agents of the set Ω is stated as the following

problem:

$$\min_{(p_{nm})} \sum_{n \in \Omega} f_n \left(\sum_{m \in \omega_n} p_{nm} \right) \quad (3a)$$

$$\text{s.t. } \forall n, m, p_{nm} = -p_{mn} \quad (3b)$$

$$\forall n, m, p_{nm}^{\min} \leq p_{nm} \leq p_{nm}^{\max} \quad (3c)$$

$$\forall n, p_n^{\min} \leq p_n \leq p_n^{\max} \quad (3d)$$

The problem has many similarities with a centralized market problem. The power of agent n has been replaced by a sum of trades contracted with his peers. ω_n stands for the set of peers of agent n . Limits on the trades have been added. The major difference lies in the market equilibrium constraint (1b) which is not compatible with a decentralized framework. Indeed its verification would require that everyone communicates their trades to everyone else. It is therefore replaced by a stronger, but decentralizable, constraint (3b), that of the reciprocity of each trade: the buyer must agree to buy the same quantity as the seller wishes to sell. The agents' f_n functions are assumed to be convex. However the problem is not strictly convex with respect to the trades p_{nm} . The optimal social welfare value may be achieved by several trades configurations. If desired, the problem can be strictly convexified by adding to (1a) a negligible term minimizing the trades $\alpha \sum_{n,m} p_{nm}^2$.

Like any optimization problem, it may be solved by several different algorithms. Strictly speaking, it would be an option to centralize the objective functions of the agents and solve the problem by the same algorithms as a centralized market. In the case of a simulation, this is a viable solution. The number of variables being much larger, the time performance could only be inferior to a pool market. Moreover, such a centralized resolution would be unnatural for a P2P market which should, intrinsically, remove any bottleneck and be decentralized. In an operational ambition, it is mandatory to systematically adopt a decentralized optimization method. Several algorithms are possible: Consensus+Innovation [20], Alternating Direction Method of Multipliers [10] for example. This last option is very frequently chosen [21, 22]. The example

190 of resolution presented below uses this versatile method, which in the present case, is equivalent to the simpler method of multipliers.

Constraints (3c) and (3d) being local to each agent, they are not taken into account in the problem decomposition approach below. The first step is to develop the augmented Lagrangian of the problem (3) with $\rho > 0$:

$$L_\rho(\mathbf{P}, \mathbf{\Lambda}) = \sum_{n \in \Omega} f_n \left(\sum_{m \in \omega_n} p_{nm} \right) + \sum_{m \in \omega_m} \lambda_{nm} (p_{nm} + p_{mn}) + \frac{\rho}{2} (p_{nm} + p_{mn})^2 \quad (4)$$

where \mathbf{P} refers to the set of trades (p_{nm}) and $\mathbf{\Lambda}$ the set of dual variables associated with each reciprocity constraint. The principle of the multiplier method consists in performing a gradient descent according to the following iterations:

$$\begin{aligned} (P_{nm})_{m \in \omega_n}^{k+1} = & \underset{(P_{nm})_{m \in \omega_n}}{\operatorname{argmin}} \quad f_n(\sum_{m \in \omega_n} p_{nm}) + \\ & \sum_{m \in \omega_n} \left[\lambda_{nm}^k \left(p_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} \right) + \frac{\rho}{2} \left(p_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} \right)^2 \right] \\ \text{s.t. } \forall m \in \omega_n & \quad p_{nm}^{\min} \leq p_{nm} \leq p_{nm}^{\max} \\ & \quad p_n^{\min} \leq \sum_{m \in \omega_n} p_{nm} \leq p_n^{\max} \end{aligned} \quad (5a)$$

$$\lambda_{nm}^{k+1} = \lambda_{nm}^k + \rho (p_{nm}^{k+1} + p_{mn}^{k+1}) \quad (5b)$$

Both steps (5a) and (5b) can be performed by each agent independantly, although one has to wait for peers decisions p_{mn}^{k+1} . Note that the reciprocity constraint has been modified: the trade p_{nm} is compared to the mean $\frac{p_{mn}^k - p_{nm}^k}{2}$ at the previous iteration rather than to the sole peer decision p_{mn}^k . Once the convergence is reached, both expressions are equivalent and the latter avoids oscillations during the iterative resolution. The above iterative resolution highlights that the P2P market can be solved in a completely decentralised way, i.e. without any concentration of information in a single computational node, as opposed to a distributed resolution.

200 The global stopping criteria associated to (5) are such as

$$\sum_{n \in \Omega} r_n^{k+1} \leq \epsilon^{\text{pri}^2} \quad \text{and} \quad \sum_{n \in \Omega} s_n^{k+1} \leq \epsilon^{\text{dual}^2} \quad (6)$$

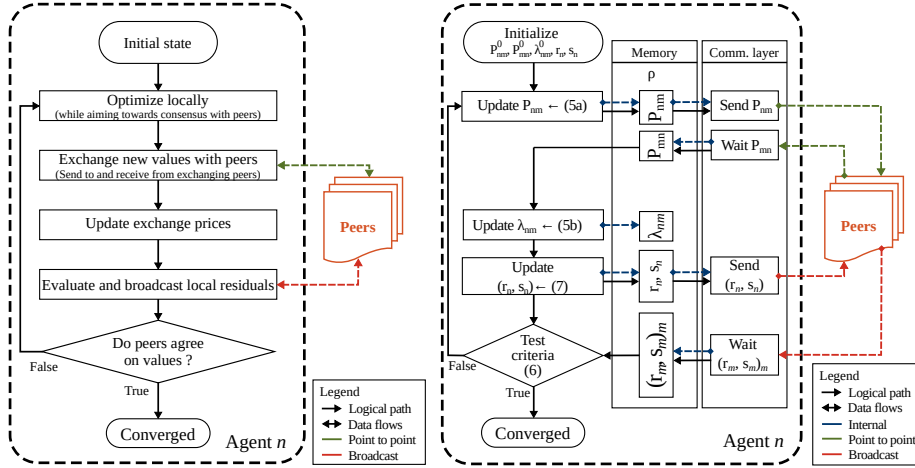


Figure 3: Decentralized algorithm for P2P market and associated dataflow, adapted from [23]

with, respectively, primal and dual local residuals

$$r_n^{k+1} = \sum_{m \in \omega_n} (p_{nm}^{k+1} + p_{mn}^{k+1})^2 \quad (7a)$$

$$s_n^{k+1} = \sum_{m \in \omega_n} (p_{nm}^{k+1} - p_{nm}^k)^2. \quad (7b)$$

Parameters ϵ^{pri} and ϵ^{dual} denotes primal and dual global feasibility tolerances, respectively. Figure 3 depicts the information exchanges that must take place during this resolution. In this version, checking the stopping criterion still requires a broadcast step, which is problematic for scaling. However, section 205 5.1 will show that stopping criteria local to each trade also allow convergence, without broadcasting and with much less message exchange.

In order to perform the algorithm (5), the minimisation step (5a) still needs to be addressed. Here again many methods are applicable. As this convex problem is local to each agent, a centralised solution using an interior point algorithm is for example possible. Since it is strictly a sharing problem, a solution by ADMM is also possible, either explicitly coded or via an Operator Splitting Quadratic Program type solver [24]. Again for illustrative purposes, an iterative resolution by ADMM is presented here, using the structure of the

problem (5a). This one is indeed a sharing problem of the form :

$$\min_{(p_{nm})_{m \in \omega_n}} f_n \left(\sum_{m \in \omega_n} p_{nm} \right) + \sum_{m \in \omega_n} g_{nm}(p_{nm}) \quad (8)$$

with

$$\begin{aligned} g_{nm}(p_{nm}) &= \lambda_{nm}^k \left(p_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} \right) + \frac{\rho}{2} \left(p_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} \right)^2 \\ &= \frac{\rho}{2} \left(\left(p_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} + \frac{\lambda_{nm}^k}{\rho} \right)^2 - \left(\frac{\lambda_{nm}^k}{\rho} \right)^2 \right) \end{aligned} \quad (9)$$

Since the minimisation is on the variable p_{nm} , the last term may not be taken into account. The direct application of ADMM on such a sharing problem requires a reformulation with a new variable:

$$\min_{(p_{nm}, q_{nm})_{m \in \omega_n}} f_n \left(\sum_{m \in \omega_n} q_{nm} \right) + \sum_{m \in \omega_n} g_{nm}(p_{nm}) \quad (10a)$$

$$\text{s.t. } \forall n, m, p_{nm} = q_{nm} \quad (10b)$$

Hence the following algorithm, where μ is the dual variable associated to (10b), l denotes the second iteration variable, M_n is the number of peers in the set ω_n , ρ_n is the coefficient of the augmented Lagrangian of this local problem and $\bar{\cdot}$ denotes the mean value :

$$P_{nm}^{l+1} = \underset{P_{nm}}{\operatorname{argmin}} \frac{\rho}{2} \left(P_{nm} + \frac{p_{mn}^k - p_{nm}^k}{2} + \frac{\lambda_{nm}^k}{\rho} \right) + \frac{\rho_n}{2} \left(P_{nm} - P_{nm}^l + \bar{P}^l - \bar{Q}^l + \frac{\mu^l}{\rho_n} \right)^2 \quad (11a)$$

$$\bar{Q}^{l+1} = \underset{\bar{Q}}{\operatorname{argmin}} f_n(M_n \cdot \bar{Q}) + \frac{M_n \cdot \rho_n}{2} \cdot \left(\bar{Q} - \bar{P}^{l+1} - \frac{\mu^l}{\rho_n} \right)^2 \quad (11b)$$

$$\mu_n^{l+1} = \mu_n^l + \rho_n \left(\bar{P}^{l+1} - \bar{Q}^{l+1} \right) \quad (11c)$$

These minimisation steps can be solved analytically in the case of quadratic functions. An example of an implemented resolution is available on the GitLab repository of the SATIE Laboratory³.

³https://gitlab.com/satie.sete/p2p_electricity_markets

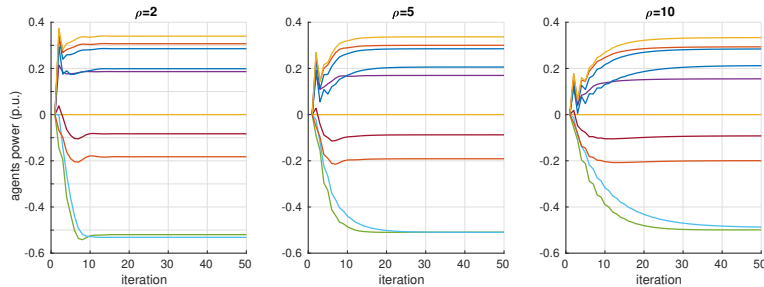


Figure 4: Impact of ρ on the convergence speed of a 10 agent, fully connected P2P market.

210 Although this solution scheme converges systematically for convex functions, the different coefficients of the augmented Lagrangians have a strong impact on the convergence speed. Figure 4 illustrates this influence for a 10-agent P2P market, where each agent can trade with everyone else.

It is crucial to clarify that the resolution presented in this section only ad-
 215 dresses the market problem (3) and that the behaviours of real economic actors are far more complex. It is required to assume that the interests of market players will be uniquely described by the objective functions f_n and that they will behave rationally and not strategically [25]. Although such assumptions can be applied to economic actors whose impact on the market is marginal
 220 [26], the section 7 will discuss the limits of such an assumption in the case of a participative P2P market.

5. Intrinsic challenges to operational use

Despite their many interesting properties, P2P markets raise several complexities that ought to be addressed to allow their operational deployment –
 225 5. Moreover, in the particular case of electricity markets, several mechanisms must be redesigned since the market is only one part of the management of this complex system – section 6. Finally, as the prosumer is brought to the centre of grid management by P2P markets, the crucial issue of his reaction to such tools remains largely to be investigated – section 7.

230 *5.1. Increasing communication needs*

A peer-to-peer organisation allows the number of agents to be amplified by eliminating the bottleneck of a central agent. During the iterative resolution process, information is exchanged directly between agents without concentration at a regulator. This decentralised organisation of communications allows for
235 scaling up. However, it considerably increases the overall number of messages during the resolution process. Indeed, in the case of a centralised market, each agent sends a single message to the central agent. For a distributed resolution, each agent sends a message to the central agent at each iteration. The number of messages is therefore proportional to the number of agents and the number of
240 iterations, which in turn depends on the desired resolution accuracy. Conversely, in the case of a P2P market, each agent must send a message to each of its M peers at each iteration. The total number of messages is therefore multiplied by M , assuming the number of iterations is not significantly affected.

To guarantee convergence to the globally optimal solution – similar to that
245 obtained by a centralized or distributed market – the P2P market must be completely connected, i.e., each agent must be connected to all others. The number of communications is then proportional to N^2 . This is an upper bound that is only realized in cases of proof of concept and research. Indeed, such an increase in the number of messages would make any operational deployment hardly fea-
250 sible. The communication protocols considered to manage these exchanges can be the classic Internet layer, 5G and low-power protocols such as LoRa. The choice of a communication protocol is however outside the scope of this article.

Faced with this issue of increasing communication needs, several approaches should be explored in the remainder of this section.

- 255 • section 5.2: how to choose one's peers to achieve a solution close to the global optimum without the assumption of full connectivity of the communication graph?
- section 5.3: how to speed up the overall resolution time?

- continuation of this section: how to limit the number of necessary iterations to reach the optimum?

In order to limit as much as possible the number of iterations needed to reach the optimum, we will point out here two approaches. First of all, a P2P market is operationally expected to be used repeatedly, with a market for a time slot succeeding the one dedicated to the previous slot. During this succession, knowing the solution obtained by the previous market is an obvious hint to predict the solution of the current market. Indeed, production and consumption behaviours have an inertia which limits the variations of strong amplitude. The solutions of the two markets will probably be very close. Initializing the iterative resolution of the current market to the solution obtained by the previous market is therefore a simple and very efficient solution to reduce the number of iterations. This idea is referred to as warm start.

Furthermore, the number of messages exchanged in a P2P market can be greatly reduced by noticing that the speed of convergence of trades is very diverse. Some trades converge in a few iterations, while others will take much longer to conclude. This property strongly depends on the market configuration and cannot be generically formalised. However, the use of alternative stopping criteria can only improve the speed of convergence. For example, figure 5 presents the results obtained when the stopping criterion is fixed agent by agent or trade by trade [27]. The idea is then that as soon as the dual residue of a trade –respectively of an agent– falls below a certain tolerance, which can be fixed in a relative or absolute way, this trade – respectively agent – is considered as settled. No more messages are then exchanged about it, even if the market continues globally to establish the remaining trades. These alternative stopping criteria strategies have been implemented on a P2P market with 25 agents, whose objective functions are randomly drawn 1000 times. The overall market imbalance $-\sum_{nm} P_{nm}$ is plotted as a function of the number of messages exchanged, in blue for the baseline situation. The stopping criterion on each trade, according to an absolute tolerance, allows notably a reduction by a

factor of 10 of the number of messages to be exchanged.

290 *5.2. Choosing one's peers*

P2P markets feature the fundamental capability of managing a very large number of agents since each agent does not communicate with all the others, but only with a few. The issue of choosing these few peers among all the market players is therefore unavoidable. In the context of an energy market, it is all the more crucial as it will affect the final solution. A market is indeed very different
295 from a file sharing system where all peers share the same resource. In a market, all agents have different cost functions. Choosing the wrong partners therefore results in a cost overrun as shown figure 6. The reference situation is a market where all peers can trade with all. This is the only configuration where the
300 P2P market is demonstrated to converge to the optimal solution obtained by a centralized market. A Monte Carlo simulation is then performed by removing random links from the market connection matrix. The final price obtained as well as the social welfare are then plotted as a function of the sparsity of the communication matrix.

305 For an operational P2P market where agents must respect a maximum number of partners, there is to the best of our knowledge no explicit method that guarantees the best choice. This open problem seems very suitable for greedy heuristics or reinforcement learning. However, the validation of such methods will require to be evaluated against the optimal solution which can only be
310 determined by an exhaustive search.

5.3. Market resolution time

Any parallel calculation benefits from an acceleration due to the tasks carried out simultaneously by several calculation nodes. Since a P2P market is inherently built so that the agents are independent, they can therefore carry
315 out their local calculations in parallel, provided that they synchronise at each iteration to exchange their offers with their peers. During an operational deployment, however, this synchronisation stage presents a great risk of slowing

down because it is necessary to obtain messages from all the peers. Waiting times will therefore be necessary until the last one arrives. These messages
320 will have to be routed via a multiplexed communication network with many other purposes. Communication times cannot therefore be uniform between all agents, but moreover they can neither be guaranteed nor repeatable. Indeed, remote agents will have longer communication times due to propagation times and more repeaters on the route. Depending on the load of the communication network, messages may be delayed due to the packet switching paradigm
325 on which the widely multiplexed networks that make up the internet are built. When a message is lost, the communication protocols are able to detect it and retransmit it. However, this results in a higher overall transmission delay. For these reasons, an operational resolution of a peer-to-peer market with decentralised calculations is likely to spend most of its time waiting for the arrival of
330 messages from peers.

Faced with this problem, one possible solution is an asynchronous implementation of the resolution. Indeed, during a distributed resolution where an agent must wait for responses from several peers, the waiting times are deter-
335 mined by the slowest of the peers, as illustrated in figure 7. However, this longest waiting time depends not only on the distance to be covered and the performance of the network, but also on its load rate and packet losses. As soon as a packet is lost, the transport protocols – TCP – automatically cause a retransmission, but this results in at least double the waiting time. A P2P
340 market algorithm capable of updating itself without waiting to receive all the messages from its peers therefore allows a significant acceleration. As illustrated in figure 7, as soon as an agent receives a message, it updates its local problem without waiting. A new adjustment parameter is therefore introduced, the asynchronous rate δ . It is defined as the ratio between the number of messages
345 we wait to receive before updating and the total number of messages we should receive. $\delta = 1$ corresponds to a synchronous implementation because all messages must be expected. Figure 8 then represents the speedup that is achieved by an asynchronous implementation. Not only can an acceleration of about

40% be observed, but this acceleration is very little affected by communication
350 hazards. σ represents here the risk that a message gets lost and thus generates
retransmission delays, $\sigma = 0$ stands for a perfectly reliable network. While the
synchronous version is strongly affected by such a degradation of the network
reliability, the asynchronous version is almost completely immune to it.

6. Coordination challenges with other power system operation fea- 355 tures

The previous section has raised some of the inner problematics of solving
a P2P market. However, as the section 2 has highlighted, an energy market
is not the only brick in the operation of a power system as a whole. Several
coordination mechanisms must therefore be rethought. We will first address the
360 issue of contractualization of exchanges and their measurement. Second, the
coordination between the P2P market and the grid operator will be discussed.
Finally, the evolution of the reserve market will be outlined.

6.1. Contractualisation of exchanges and measurement

The decentralised structure of a P2P market raises the issue of the contrac-
365 tualisation of trades. With no central trusted agent, it is necessary to find a
process that ratifies trades also in a decentralised manner. The blockchain is
currently an approach that is attracting considerable interest [30, 31]. It allows
contracts to be verified by everyone by concatenating them in a chain of which
everyone has a copy and whose authenticity can be verified by everyone using a
370 cryptographic hash signature.

There are already many examples of contributions to implement different
economic models. The situations of microgrids [32], fleets of electric vehicles
[33, 34], optimal power flow [35], flexibilities aggregator [36] and network service
[37] have been proposed. The implementation of a P2P marketplace exchange
375 is the most emblematic application [35, 38]. Moreover, the blockchain is not
limited to the implementation of distributed control of a system upstream of real

time. It also allows the validation of exchanges that have physically happened by harvesting the measurements of the power meters [39]. It is then possible to validate whether the behaviours have been consistent with the commitments.

380 These proposals are based on a variety of blockchains, but Ethereum is the most frequently observed solution. In order to ensure the authenticity of the blockchain, a consensus must be reached between all participants. This consensus is most often still achieved by a proof of work. This solution is highly energy intensive. However, other mechanisms such as a proof of stake
385 are becoming increasingly adopted.

6.2. Interaction with the system operator

As described in the section 2, in the current regulatory context, the grid operator receives a power injection forecast from the market operator in order to identify potential risks to the physical infrastructure. In the context of a
390 decentralised market, several approaches are possible to replace this interaction:

- the P2P market is marginal enough not to change the current operating rules. This is the case for the examples of experimental deployment that exist so far.
- a channel of interaction between the P2P market and the network operator
395 is created. This is then an exogenous signal – from outside – sent to the P2P market that the operator must adjust in order to ensure the safety of the physical infrastructure.
- the system operator is coordinated directly with the market at each iteration – endogenous approach.

Exogenous approach. The endogenous approach therefore consists of injecting a signal into the P2P market. This signal takes the following form:

$$\min_{(p_{nm})} \sum_{n \in \Omega} \left[f_n \left(\sum_{m \in \omega_n} p_{nm} \right) + \sum_{m \in \omega_n} \gamma_{nm} p_{nm} \right] \quad (12a)$$

$$\text{s.t. } \forall n, m, \quad p_{nm} = -p_{mn} \quad (12b)$$

$$\forall n, m, \quad p_{nm}^{\min} \leq p_{nm} \leq p_{nm}^{\max} \quad (12c)$$

$$\forall n, \quad p_n^{\min} \leq p_n \leq p_n^{\max} \quad (12d)$$

400 with γ_{nm} a fee imposed by the network operator. The only purpose of this fee is to force the agents to reduce their trades in order to respect the network's operating constraints. It can therefore be adjusted from one time step to the next to be zero when the network is not overloaded. Moreover γ can be determined according to many different metrics. For example, by taxing trades according
 405 to the distance separating the agents: the closer they are, the less the trade stresses the network. Or according to zones defined by the most fragile lines. Figure 9 represents an example of a market subjected to such exogenous policies. Depending on the γ policy, trades can be reduced uniformly or partitioned.

As a result of this fee, the system operator will collect money. This money
 410 would be used to cover operating costs, but would also be redistributed among the market agents according to the flexibility service they have provided to the community. As the purpose of the γ fee is to force the agents to respect the network's operating constraints, an example is shown in Figure 10. The initial configuration of the market resulted in a violation of the capacity of some lines
 415 – the most problematic represented in dotted line. The introduction of a fee restores operation compatible with the physical infrastructure, although it is more or less efficient depending on the policies chosen. The additional cost to the market, collected by the network operator, is shown in the bottom panel of the figure. The most efficient policy is considered to be the one that enforces
 420 the network constraints, at the lowest cost. This best choice highly depends on the configurations. Its judicious adjustment would in the future requires a good grid observability and would depend on the expertise of the system operator

and its acquired experience [41].

Endogenous approach. In contrast to an exogenous approach, the endogenous
425 approach strives to involve the system operator as closely as possible in the
resolution of the P2P market. At each iteration of the market – or each few
iterations – the system operator receives a copy of the trades in order to signal
violations, as illustrated figure 11. Such a scheme proves to be as effective as
an optimal power flow as illustrated figure 12.

430 However, endogenous resolution presents several operational difficulties. First
of all, it increases even more the number of messages to be transmitted and the
risks of associated delays. This last effect can be limited by using an asyn-
chronous implementation as illustrated figure 12. Furthermore, the computa-
tional cost and real time constraints for the system operator are not currently
435 viable on a large scale. In the future, decentralising the computation of the
system operator could allow an operational use of this scheme.

6.3. Coupling with a reserve market

The purpose of the energy market is to anticipate the exchanges that will
take place at a given moment on the electricity network. However, these ex-
changes never take place exactly as expected, as explained section 2. Since the
purpose of the reserve market is to provide for the compensation of discrepan-
cies, it is necessary to adapt it to a P2P process as well [43]. Otherwise, the
decentralisation of the management would not be complete. Ideally, the energy
and capacity markets are solved jointly, otherwise there is a sub-optimality.
A coupled pool market consists of the following chance constrained problem,
where p_n is the power that an agent forecasts on the market, p_n^* is the power
that will actually be realised, r_n^+ is the reserves that allow to increase production

or decrease consumption and r_n^- is the opposing reserves:

$$\min_{p_n, r_n^+, r_n^-} \sum_{n \in \Omega} f_n(p_n, r_n^+, r_n^-) \quad (13a)$$

$$\text{s.t.} \quad \sum_{n \in \Omega} p_n = 0 \quad (13b)$$

$$\forall n, \quad p_n^{\min} + r_n^- \leq p_n \leq p_n^{\max} - r_n^+ \quad (13c)$$

$$\mathbb{P} \left(\sum_{n \in \Omega} r_n^- \leq \sum_{n \in \Omega} p_n^* \leq \sum_{n \in \Omega} r_n^+ \right) \geq \delta \quad (13d)$$

Such a market should be transposed to a P2P scheme. Trades on reserves $r_{nm}^{+,-}$ can be introduced with no difficulty. However the challenge comes from the coupling probabilistic constraint (13d). The uncertainty on the power balance depends on everyone's incertitudes. To be able to decentralise this market, this constraint will need to be altered [23]. It must therefore be replaced by a constraint local to each agent: each agent must guarantee to be able to respect his commitments with a certain degree of confidence δ_n :

$$\mathbb{P} \left(r_n^- + \sum_{m \in \omega_n} r_{nm}^- \leq p_n^* \leq r_n^+ + \sum_{m \in \omega_n} r_{nm}^+ \right) \geq \delta_n \quad (14)$$

To do this, he can buy reserves from his peers in order to improve his self reliability, or sell them if he is very reliable. There are many different ways of
440 distributing the global uncertainty δ to local confidence levels δ_n . The problem is not straightforward, especially because the uncertainties may be dependent on each other: if there is less wind than expected, all wind producers will produce less.

The tests are carried out on a 14-bus network, to experiment with different
445 methods of uncertainty allocation. Figure 13 represents the temporal trajectories of the exchanged power and the constituted reserves. The performances of these allocation policies are compared figure 14. Although respecting their local confidence level, the two first allocations Rel. α^μ and Rel. α^σ does not constitute enough reserve to respect the global confidence level. Rel. α^1 and Abs. α^σ
450 provide both a sufficient confidence and a social welfare close to the centralised performance. Joint reserve and energy P2P markets therefore seem a viable outcome.

7. User behaviour within a P2P market

After discussing the internal concerns of the P2P algorithm and the issues
455 raised by its coordination with other elements of power system regulation, the
most sensitive aspect is undoubtedly how users will seize such tools. Indeed,
the market's decentralisation is designed to bring the prosumer to the centre by
giving him as many levers as possible. This empowerment must, however, be
accompanied by the prosumer's desire and commitment, otherwise it will all be
460 in vain. At present, there is only a limited experience of this issue. However, the
studies carried out are very encouraging [44, 45, 46]. Furthermore, the way users
are involved distinguishes a vast majority who wish to actively participate in the
experimental P2P markets, either by setting their own prices at any given time
or by using proposed automatic profiles. These elements are crucial because the
465 willingness of participants is essential to improve the overall performance [47].

In addition to the ergonomics of the devices and interfaces offered to the
prosumer, several points need to be taken into account in the design of P2P
systems so that the user adopts them. As a P2P market is not intended to be all-
knowing about the consumer's life, some of his decisions may appear irrational,
470 such as the deliberate choice to pay more. This lack of knowledge of true
motivations can be addressed from the perspective of the bounded rationality of
economic agents [48]. The impact of these unexpected decisions must necessarily
be evaluated [49] and taken into account in order for regulations to be effective.
Moreover, real world use of markets will give rise to behaviours that are at
475 worst malicious, at least strategic [50]. Coalitions of agents will naturally form
by affinity if not by economic interest [51]. Preventing such behaviour would
probably be illusory and would be a brake on the adoption of P2P approaches.
In order for them to remain marginal, the design of market mechanisms [52]
and the redistribution of possible taxes – see section 6.2 – must ensure their
480 fairness [53]. When it is a question of a service rendered by an agent to preserve
a common infrastructure, the contribution of each one should be evaluated from
collaborative games approaches [54].

8. Examples of pilot projects

Due to both the involvement desire of users and technical efficiency issues,
485 many P2P projects have emerged in recent years. The purpose of this section
is not to propose an exhaustive review, which is an increasingly wide-ranging
exercise [55, 56, 19]. Moreover, regulatory constraints currently limit the actual
deployment of P2P markets. Rather, it is a matter of using a few examples of
projects to illustrate the concepts mentioned in the previous sections.

490 One of the most representative projects of P2P exchanges in terms of its
scale and background is the Brooklyn Micro Grid project [57], operated by
LO3 Energy. Within the context of often congested distribution networks, this
community with a significant amount of decentralised production has installed
smart meters capable of making purchase and sale contracts via a blockchain.
495 The market mechanisms are online matching or experimental P2P. These trades
are achieved via the main distribution network. However, a physically separable
microgrid has been added in case of congestion of the main grid so as to isolate
a neighbourhood of 10 by 10 housing blocks. This example is emblematic of
the possible coexistence between several management paradigms. Such a coex-
500 istence between several types of management is also illustrated in the Nordhavn
district in Copenhagen [58]. The approach there is also multi-energy and ex-
plicitly addresses the charging of electric vehicles. Here again, at the current
stage, the management deployed is more community than P2P.

The coordination of a community to manage both its flexibilities and its
505 network is also illustrated by the CONSORT project on the island of Bruny
[59]. The focus is there on the optimal management of a weakly interconnected
island network. The problem solved is a distributed optimal power flow which
is a premise close to an endogenous P2P market. Project leaders highlight user
information is a crucial acceptance factor that allows the implementation of
510 the most efficient pricing rules. This importance of participants support is a
common thread running through all the projects we know of [60].

Regarding this citizen's will that drives many projects, regulation is often the

blocking obstacle. Its evolution is underway [61] at a very heterogeneous pace from one country to another. For example, the evolution in 2018 of the Euro-
515 pean directive "Renewable Energy Directive" indicates that *Renewable Energy Communities are entitled to self-arrange sharing of renewable energy within the community and to access all suitable energy markets directly or through aggregation in a non discriminatory manner* [62]. Meanwhile its transposition into national laws gives rise to many disparities. France, Germany, the Netherlands
520 and the United Kingdom have adopted the drafts that are perceived to be the most favourable to prosumers. However a tool such as virtual net metering is only allowed in the UK and Germany although it is a key element for collective self-consumption and P2P trading.

9. Conclusion and prospects for evolution

525 The development of the concept of peer-to-peer markets is one of the main innovations capable of addressing the energy transition in power systems. Their theoretical tools are a generalisation of the usual market problem. They provide answers to the multiplication of agents and the heterogeneous behaviour of prosumers. Their formalisation and a decentralised resolution were presented.
530 Implementation issues remain before their operational use, in particular concerning the communication network. Many answers are being investigated and the increase in bandwidths is easing their pressure. The issue of P2P markets opens up the question of the evolution of grid management as a whole. Distribution grid in particular are the focus of the energy transition and are facing
535 the same challenges that led to the emergence of P2P markets. The project examples thus highlight that congestion management often was their starting point. Furthermore, the key element is the support of users and their desire for using this new tool. Here again, current projects are encouraging.

The current legislative evolutions will open further possibilities. This is
540 leading to an increasing number of projects, each focusing on specific issues and proposing ad hoc mechanisms. The transition between this current proliferation

and the emergence of new standards is likely to be the next milestone. Moreover, P2P markets will not remain limited to electricity. To this may be added the control of network constraints, flexibilities, reserves, and so forth. The opening
545 up to multi-energy networks and the inclusion of mobility is a logical extension. This increase in the complexity of the products offered on P2P markets requires vigilant attention to price design and fairness, as well as to the opinion of the prosumer.

P2P markets provide a more comprehensive approach to the problems of
550 large-scale networks. Although one cannot know what the future will be made of, the intellectual framework of peer-to-peer markets is relevant to identify the obstacles and propose solutions to the problems involved in enabling the evolution of power systems.

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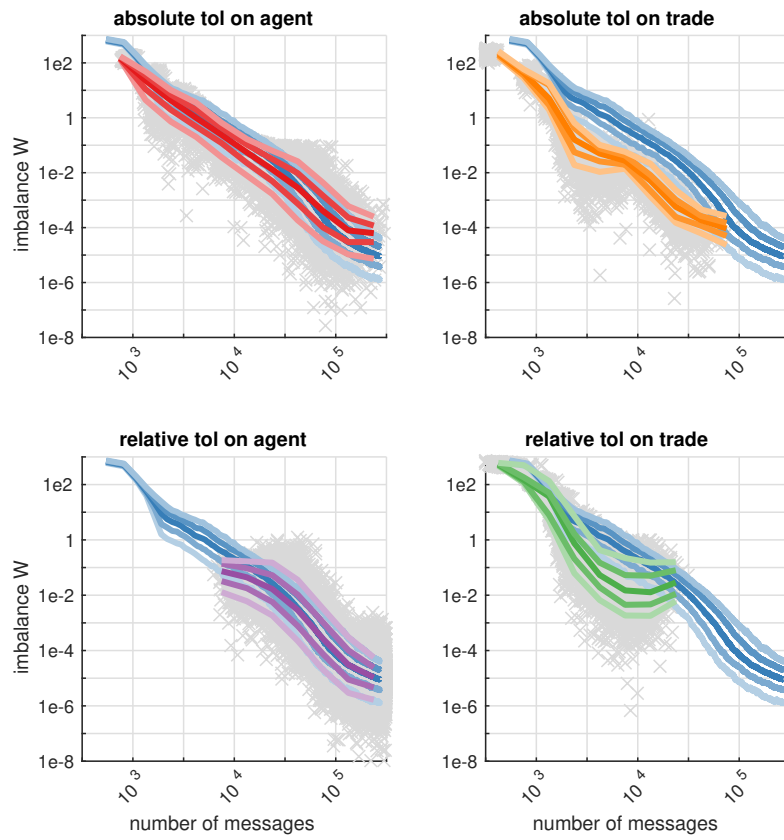


Figure 5: Imbalance of a P2P market depending on the number of messages according to different stopping criterion - average, 1st and 3rd quartiles, 1st and 9th deciles. The reference behaviour is displayed in blue [27]. Grey crosses : each result of the MonteCarlo simulation.

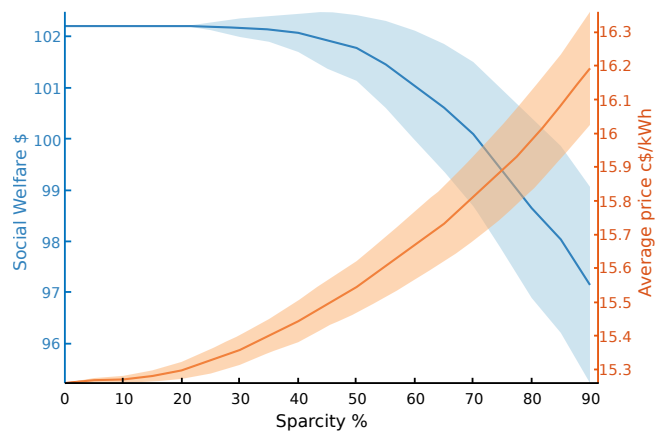


Figure 6: Evolution of a P2P market efficiency depending on the sparsity of the communication matrix – mean value in plain line and decile in colour [28]

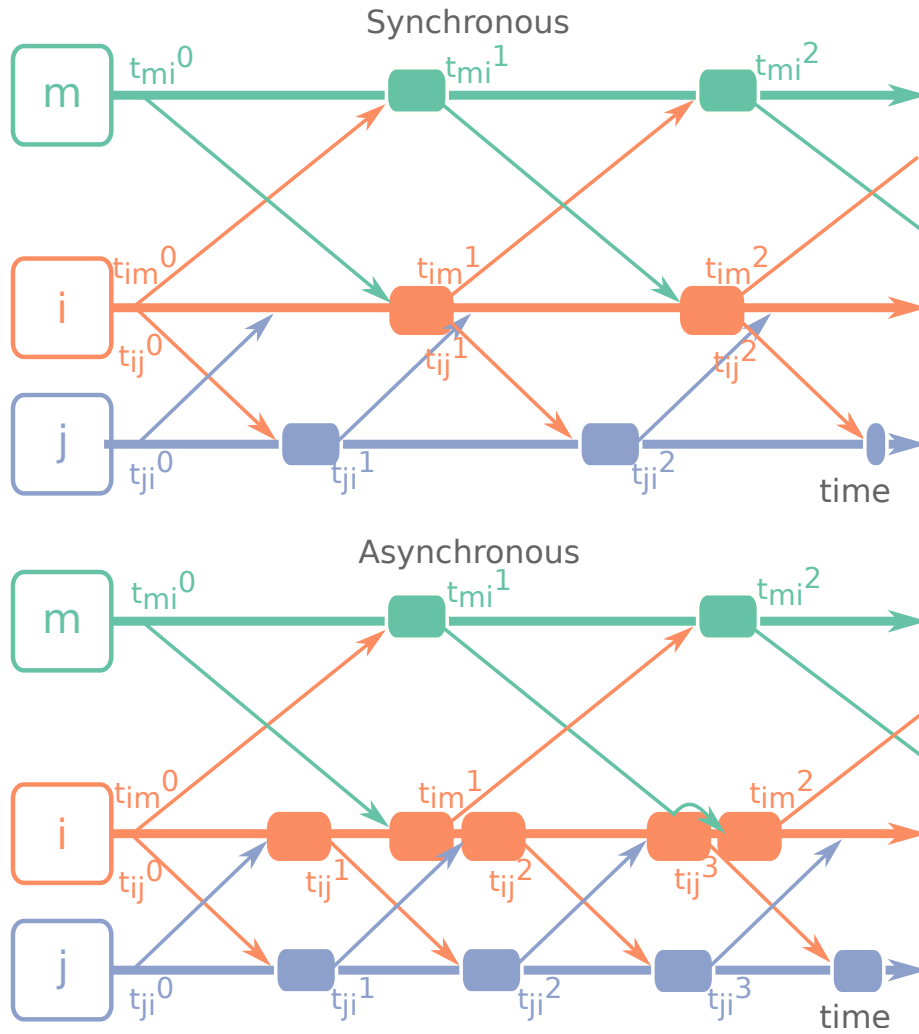


Figure 7: Message exchanges diagram in a three agent market: i, j and m , with $\omega_i = \{j, m\}$ and $\omega_j = \omega_m = \{i\}$ in synchronous and asynchronous cases. The diagonal arrows represent the message exchanges over time and the colored rectangles represent the processing time of a local iteration. The asynchronous case here consists of agent i only waiting for one message instead of two before performing its calculation [29]

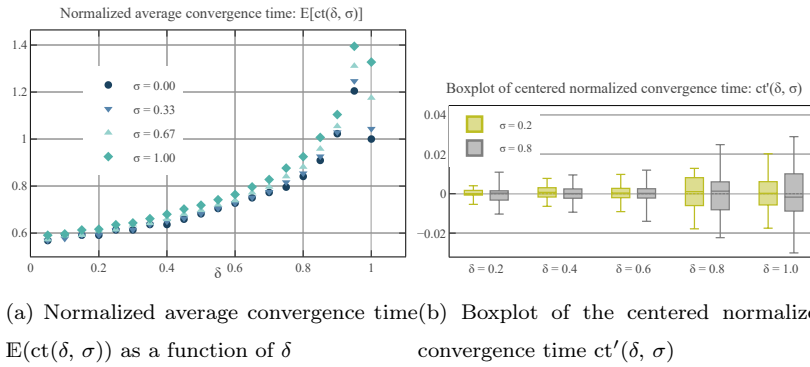


Figure 8: Values of the convergence time ct as a function of the asynchronism parameter δ for several values of σ , using the gaussian communication delay model. Figure (a) represents the average value of $ct(\delta, \sigma)$ while figure (b) represents the quartiles of $ct'(\delta, \sigma)$ [29].

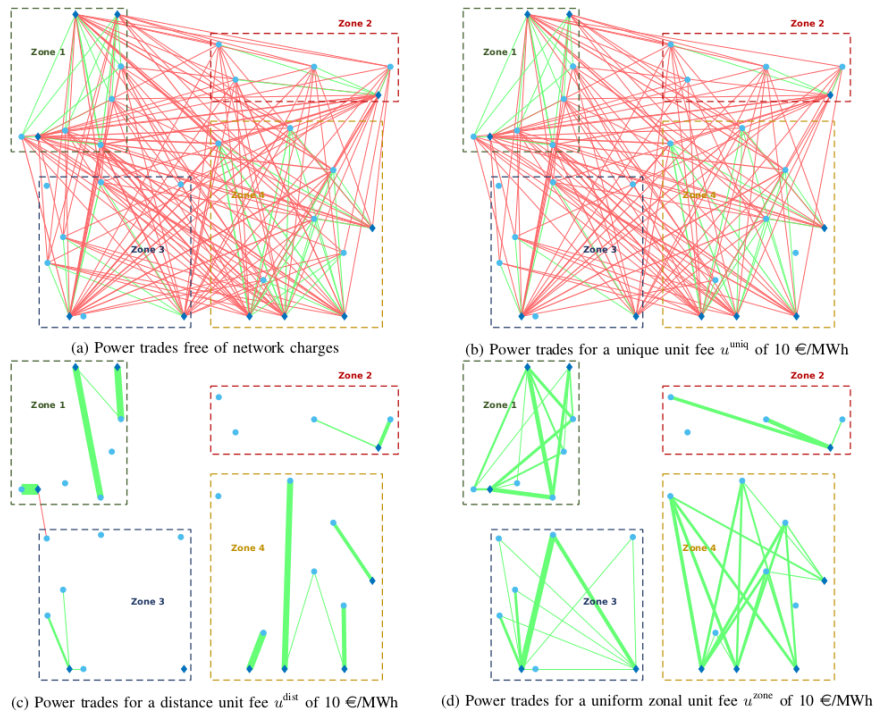


Figure 9: Cost allocation policies' influence on trades (red lines: interzone exchanges, green lines: intrazone exchanges) [40]

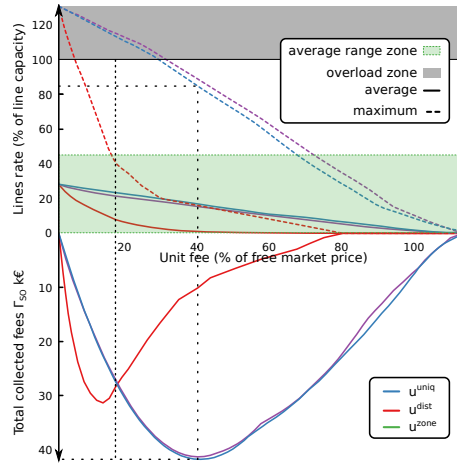


Figure 10: Effects of unit fees on line rates (upper part) and total money collected by the system operator (lower part) [40]

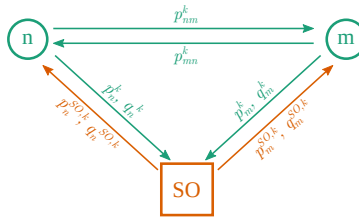


Figure 11: Diagram of the various data exchanges between peers and system operator during the k -th iteration. In this example, agents n and m are the only two market peers [42].

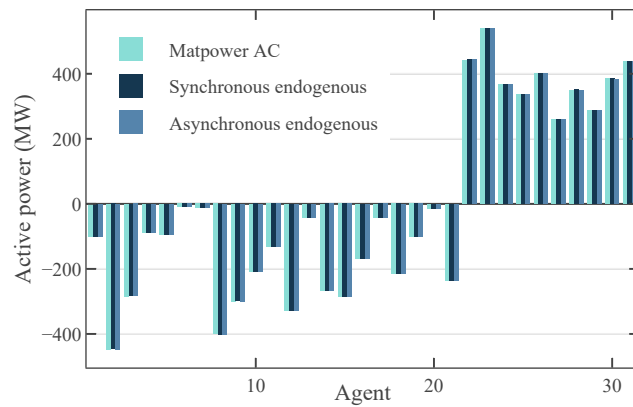


Figure 12: Power injection comparison between Matpower and endogenous negotiation mechanisms. Asynchronous case with $\delta_{peers} = \delta_{SO} = 0.2$ [42].

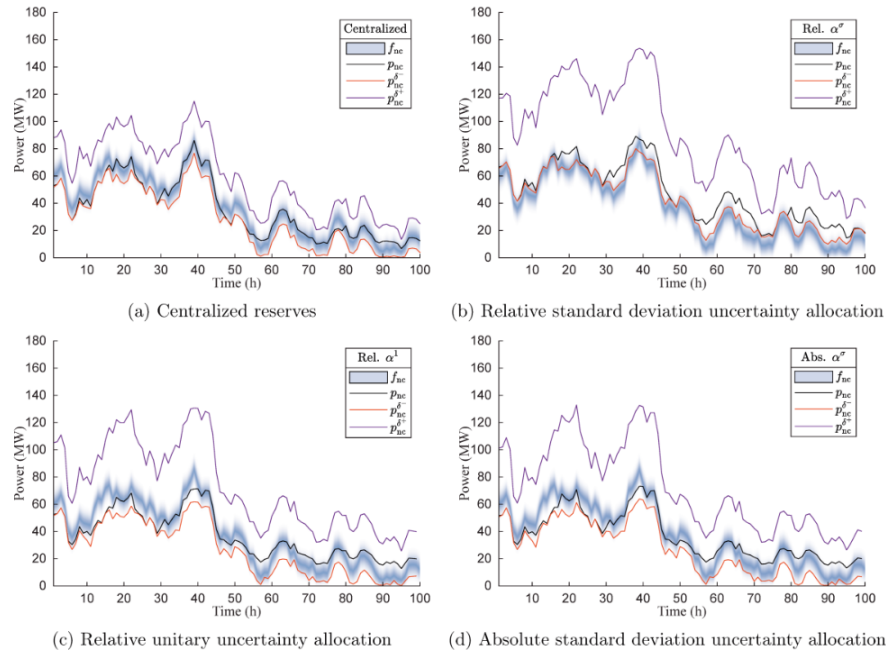


Figure 13: Evolution of reserves – up and down – for a confidence level of 95%, according to various repartitions of the uncertainty among peers [23].

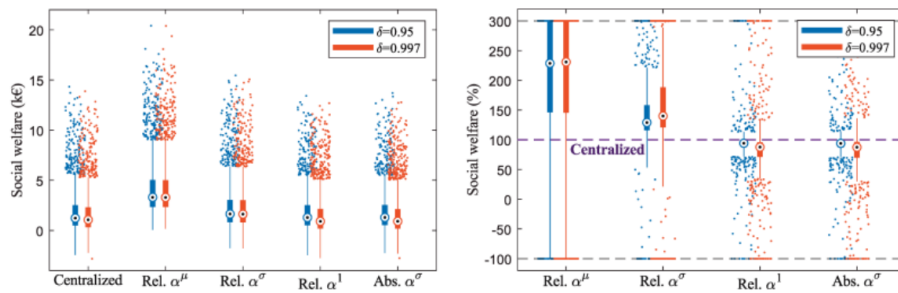


Figure 14: Joint market social welfare for a centralized resolution and with various repartitions of the uncertainty among peers [23]. Allocations Rel. α^μ and Rel. α^σ does not respect the global confidence level.