

## Operationally-Safe Peer-to-Peer Energy Trading in Distribution Grids: A Game-Theoretic Market-Clearing Mechanism

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Complete List of Authors:	Belgioioso, Giuseppe; ETH Zürich, Automatic Control Laboratory Ananduta, Wicak; Delft University of Technology, Delft Center for Systems and Control (DCSC) Grammatico, Sergio Ocampo-Martinez, Carlos; Universitat Politècnica de Catalunya, Institut de Robòtica i Informàtica Industrial (CSIC-UPC)
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# Operationally-Safe Peer-to-Peer Energy Trading in Distribution Grids: A Game-Theoretic Market-Clearing Mechanism

Giuseppe Belgioioso, Wicak Ananduta, Sergio Grammatico, and Carlos Ocampo-Martinez

**Abstract**—In future distribution grids, prosumers (i.e., energy consumers with storage and/or production capabilities) will trade energy with each other and with the main grid. To ensure an efficient and safe operation of energy trading, in this paper, we formulate a peer-to-peer energy market of prosumers as a generalized aggregative game, in which a network operator is only responsible for the operational constraints of the system. We design a distributed market-clearing mechanism with convergence guarantee to an economically-efficient and operationally-safe configuration (i.e., a variational generalized Nash equilibrium). Numerical studies on the IEEE 37-bus testcase show the scalability of the proposed approach and suggest that active participation in the market is beneficial for both prosumers and the network operator.

**Index Terms**—Prosumers, energy management, distributed algorithm, generalized Nash equilibrium

## NOMENCLATURE

Variables and Cost Functions		
$f^{\text{di}}$	[€]	cost of the dispatchable units
$f^{\text{mg}}$	[€]	cost of trading with the main grid
$f^{\text{st}}$	[€]	cost of the storage units
$f^{\text{tr}}$	[€]	cost of trading with other prosumers
$J$	[€]	total cost function of each prosumer
$\lambda^{\text{mg}}$	[€/kWh]	dual variable for grid trading constraints
$\mu^{\text{pb}}$	[€/kWh]	dual variable for power balance constraints
$\mu^{\text{tg}}$	[€/kWh]	dual variable for grid physical constraints
$\mu^{\text{tr}}$	[€/kWh]	dual variable for reciprocity constraints
$p^{\text{di}}$	[kW]	power generated by dispatchable units
$p^{\ell}$	[kW]	real power line of two neighboring busses
$p^{\text{mg}}$	[kW]	power traded with the main grid
$p^{\text{st}}$	[kW]	power delivered to/from the storage units
$p^{\text{tg}}$	[kW]	power exchanged between bus and main grid
$p^{\text{tr}}$	[kW]	power traded with another prosumer
$q^{\ell}$	[kVar]	reactive power line
$\sigma^{\text{mg}}$	[kW]	aggregate of active load on the main grid
$v$	p.u.	voltage magnitude
$x$	[%]	state of charge of the storage units
$\theta$	[rad]	voltage angle

Parameters		
$a$	-	efficiency of storage units
$\alpha, \beta, \gamma$	-	step sizes of the proposed algorithm
$b$	[kW]	aggregate of passive consumer demand
$B$	[ohm <sup>-1</sup> ]	line susceptance
$c^{\text{di}}$	[€/kWh]	linear coefficient (coeff.) on the cost of dispatchable units (DU)
$c^{\text{ta}}$	[€/kWh]	trading tariff
$c^{\text{tr}}$	[€/kWh]	per-unit cost of trading
$d^{\text{mg}}$	[€/kWh <sup>2</sup> ]	coeff. on the cost of trading with the main grid
$e^{\text{cap}}$	[kWh]	max. capacity of the storage units
$G$	[ohm <sup>-1</sup> ]	line conductance
$H$	-	time horizon
$p^{\text{ch}}$	[kW]	max. charging power of the storages
$p^{\text{d}}$	[kW]	power demand
$p^{\text{dh}}$	[kW]	max. discharging power of the storages
$\bar{p}^{\text{di}}, p^{\text{di}}$	[kW]	max. and min. power generated by DU
$\bar{p}^{\text{mg}}, p^{\text{mg}}$	[kW]	max. and min. total power traded with the main grid
$\bar{p}^{\text{tr}}$	[kW]	max. power traded between prosumers
$Q^{\text{di}}$	[€/kWh <sup>2</sup> ]	quadratic coeff. on the cost of DU
$Q^{\text{st}}$	[€/kWh <sup>2</sup> ]	coeff. on the cost of storage units
$\bar{s}$	[kVA]	max. line capacity
$T_s$	[hour]	sampling time
$\bar{v}, v$	p.u.	max. and min. voltage magnitude
$\bar{x}, x$	p.u.	max. and min. state of charge
$\bar{\theta}, \theta$	[rad]	max. and min. voltage angle
Sets		
$\mathcal{B}$		set of busses in the electrical network
$\mathcal{B}^{\text{mg}}$		set of busses connected to main grid
$\mathcal{C}$		coupling constraint set
$\mathcal{E}$		set of links in the trading network
$\mathcal{G}^{\text{t}}$		graph representing trading network
$\mathcal{G}^{\text{p}}$		graph representing physical network
$\mathcal{H}$		set of discrete-time indices
$\mathcal{L}$		set of power lines (links)
$\mathcal{N}$		set of prosumers
$\mathcal{N}^+$		set of prosumers and network operator
$\mathcal{N}_i$		set of trading partners of prosumer $i$
$\mathcal{N}_y^{\text{b}}$		set of prosumers of bus $y$
$\mathcal{P}$		set of passive consumers
$\mathcal{P}_y^{\text{b}}$		set of passive consumers of bus $y$
$\mathcal{U}$		local constraint set

G. Belgioioso is with Automatic Control Laboratory, ETH Zurich, Switzerland. W. Ananduta and S. Grammatico are with the Delft Center for Systems and Control (DCSC), TU Delft, The Netherlands. C. Ocampo-Martinez is with the Automatic Control Department, Universitat Politècnica de Catalunya, Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Barcelona, Spain. E-mail addresses: gbelgioioso@ethz.ch, carlos.ocampo@upc.edu {w.ananduta,s.grammatico}@tudelft.nl. This work was partially supported by NWO under research projects OMEGA (grant n. 613.001.702), P2P-TALES (grant n. 647.003.003), the ERC under research project COSMOS (802348) and the L-BEST project (Ref. PID2020-115905RB-C21) from the Spanish Ministry of Science and Innovation.

## I. INTRODUCTION

In recent years, there has been a fast growing penetration of distributed and renewable energy sources as well as storage units in distribution networks [1]. The parties who own these devices are called prosumers, i.e., energy consumers

with production and/or storage capabilities. Unlike traditional consumers, prosumers can have a prominent role in achieving energy balance in a distribution network, since they can contribute to energy supply. Therefore, currently there is a large research effort to study potential evolutions of electricity markets and decentralized energy management mechanisms that can enable active participation of prosumers [1]–[4].

Focusing on spot markets, i.e., day-ahead and intra-day markets, each prosumer has to decide its energy production and consumption over a certain time horizon, with the objective of minimizing its own economic cost while satisfying its physical and operational constraints. Most of existing works formulate such peer-to-peer (P2P) markets via game-theoretic or multi-agent optimization frameworks [2], [5]–[10]. For instance, the authors of [2] provide a literature survey of early works on game-theoretic P2P market models. More recently, [5] considers a coalition game approach for peer-to-peer trading of prosumers with storage units. Furthermore, [6]–[10] propose economic dispatch formulations where energy trading is incorporated as coupling (reciprocity) constraints and each prosumer has an objective that depends on local decision variables only.

Generalizing the previous papers, our preliminary work in [11] does not only consider multi-bilateral trading but also trading with the main grid, which extends the coupling to both constraints and objective functions. Mathematically, clearing the resulting P2P market corresponds to finding a generalized Nash equilibrium (GNE), namely, a configuration in which no prosumer has an incentive to unilaterally deviate. Similarly, [12] formulates a generalized Nash game of energy sharing or a multilateral (instead of bilateral) trading among prosumers, and moreover, a distributed GNE seeking algorithm is designed to find a solution of the market equilibrium problem. In parallel, we note that operator-theoretic approaches have been effectively exploited to design distributed methods that solve GNE problems under the least restrictive assumptions [13]–[17].

In practice, however, direct trading among prosumers might jeopardize system reliability, for which network operators are responsible. Therefore, when designing energy management mechanism for a distribution grid, one must also consider the role of network operators and the reliability of the system itself. For example, [18], [19] treat decentralized markets and operational reliability separately, and propose market-clearing mechanisms where decentralized market solutions must be approved by a network operator based on the system operational constraints. An alternative is based on incorporating network charges, which may reflect utilization fees and network congestion, into the market formulation, as discussed in [20], [21]. Differently, [8], [22] include network operators as players in the market and impose operational requirements of the network as constraints in the market problem, which is formulated as a multi-agent optimization. Nevertheless, none of these works simultaneously consider coupled objectives and constraints, implying the inapplicability of their decentralized mechanisms to our market formulation.

In this paper, we consider a P2P energy market in which each prosumer is capable of not only generating and storing

energy but also directly trading with other prosumers as well as with the main grid. Similarly to [22], we include a network operator, whose objective is to ensure safe and reliable operation of the system. However, we formulate the market clearing as a GNE problem, in which the players (i.e., prosumers and network operators) have coupling objective functions and constraints (Section II). Our market formulation extends our preliminary work [11] by including nonlinear network operational constraints and system operators in the model, which considerably complicate the analysis.

The main advantage of our decentralized market design is that its equilibria are not only economically-optimal but also operationally-safe and reliable. Furthermore, we propose a provably-convergent, scalable and distributed market-clearing algorithm based on the proximal-point method for monotone inclusion problems [23, § 23] (Section III). Finally, we investigate via extensive numerical studies: (i) the effectiveness of the proposed market framework; (ii) the impact of distributed generation, storage and P2P tradings in distribution grids; and (iii) the scalability of the proposed market-clearing mechanism with respect to both the number of prosumers and the number of P2P tradings in the distribution network (Section IV).

*Basic notation:*  $\mathbb{R}$  denotes the set of real numbers,  $\mathbb{N}$  denotes the set of natural numbers, and  $\mathbf{0}$  ( $\mathbf{1}$ ) denotes a matrix/vector with all elements equal to 0 (1); to improve clarity, we may add the dimension of these matrices/vectors as subscript.  $A \otimes B$  denotes the Kronecker product between the matrices  $A$  and  $B$ . For a square matrix  $A \in \mathbb{R}^{n \times n}$ , its transpose is  $A^\top$ ,  $[A]_{i,j}$  represents the element on the row  $i$  and column  $j$ .  $A \succ 0$  ( $\succeq 0$ ) stands for positive definite (semidefinite) matrix. Given  $N$  vectors  $x_1 \in \mathbb{R}^{n_1}, x_2 \in \mathbb{R}^{n_2}, \dots, x_N \in \mathbb{R}^{n_N}$ ,  $x := \text{col}(x_1, \dots, x_N) = [x_1^\top, \dots, x_N^\top]^\top$ .

*Operator theoretic definitions:* For a closed set  $S \subseteq \mathbb{R}^n$ , the mapping  $\text{proj}_S : \mathbb{R}^n \rightarrow S$  denotes the projection onto  $S$ , i.e.,  $\text{proj}_S(x) = \arg\min_{y \in S} \|y - x\|$ . A set-valued mapping  $\mathcal{F} : \mathbb{R}^n \rightrightarrows \mathbb{R}^n$  is (strictly) monotone if  $(u-v)^\top(x-y) \geq (>) 0$  for all  $x \neq y \in \mathbb{R}^n$ ,  $u \in \mathcal{F}(x)$ ,  $v \in \mathcal{F}(y)$ .

## II. PEER-TO-PEER MARKETS AS A GENERALIZED NASH EQUILIBRIUM PROBLEM

We denote a group of  $N$  prosumers connected in a distribution network by the set  $\mathcal{N} = \{1, 2, \dots, N\}$ . Each prosumer might have the capability of producing, storing, and consuming power, depending on their devices and assets. Furthermore, each prosumer might also trade power directly with the main grid and with (some of) the other prosumers, which we will refer to as *trading partners*. The trading partners of an agent might be defined based on geographical location or on bilateral contracts [4]. We model the trading network of prosumers as an undirected graph  $\mathcal{G}^t = (\mathcal{N}, \mathcal{E})$ , where  $\mathcal{N}$  is the set of vertices (agents) and  $\mathcal{E} \subseteq \mathcal{N} \times \mathcal{N}$  is the set of edges, with  $|\mathcal{E}| = E$ . The unordered pair of vertices  $(i, j) \in \mathcal{E}$  if and only if agents  $j$  and  $i$  can trade power. The set of trading partners of agent  $i$  is defined as  $\mathcal{N}_i = \{j | (j, i) \in \mathcal{E}\}$ .

Moreover, we also consider the electrical distribution network, to which the prosumers are physically connected. This network consists of a set of  $B$  busses, denoted by  $\mathcal{B} :=$

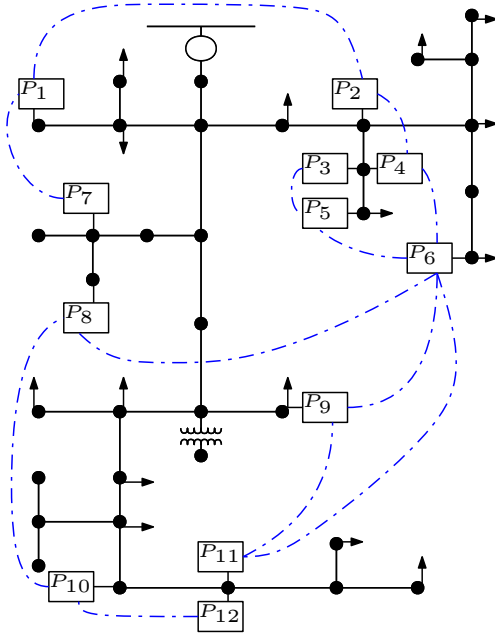


Fig. 1: A modified IEEE 37-bus network with 12 prosumers (boxes) and 15 passive loads (black triangles). Busses are represented by black circles, physical lines in  $\mathcal{L}$  by solid lines, whereas trading relations ( $\mathcal{E}$ ) by dash-dotted blue lines.

$\{1, 2, \dots, B\}$ , connected with each other by a set of power lines, denoted by  $\mathcal{L} \subseteq \mathcal{B} \times \mathcal{B}$ . Thus, we represent the physical electrical network as a connected undirected graph  $\mathcal{G}^p = (\mathcal{B}, \mathcal{L})$ . In  $\mathcal{G}^p$ , each prosumer is connected to a bus and, in general, one bus may have more than one prosumer. Figure 1 illustrates an example of trading and physical electrical networks. Furthermore, we assume that a distribution network operator (DNO) is responsible to maintain the reliability of the system, i.e., to ensure the satisfaction of the physical constraints of the electrical network [18], [19], [22].

We focus on P2P spot markets, i.e., day-ahead and intra-day markets, similarly to [4], [6], [22]. Thus, we denote the time horizon for which the decisions are computed by  $\mathcal{H} = \{1, 2, \dots, H\}$ . For instance, in a day-ahead market, typically, the sampling period is one hour and the time horizon is  $H = 24$  hours. Moreover, as in [22], we also include the physical constraints of the distribution network to ensure that a solution is not only economically optimal but also meets the standards of the DNO.

Let us model such a P2P market as a generalized game. Specifically, we assume that each prosumer, or agent,  $i \in \mathcal{N}$  aims at selfishly minimizing its cost function, which might involve decisions of other agents, subject to local and coupling constraints. Furthermore, we consider the DNO as an additional agent, i.e., agent  $N + 1$ , whose objective is to ensure the constraints of the physical network are met. In this regard, let  $u_i \in \mathbb{R}^{n_i}$  denote the decision of agent  $i$ , for all  $i \in \mathcal{N}^+ := \{1, \dots, N + 1\}$ , for the whole time. Furthermore, we denote by  $u$  the decision profile, namely, the stacked vectors of the decisions of all agents, i.e.,  $u := \text{col}(\{u_j\}_{j \in \mathcal{N}^+})$ , and by  $u_{-i}$  the decision of all agents except agent  $i$ , i.e.,

$$u_{-i} = \text{col}(\{u_j\}_{j \in \mathcal{N}^+ \setminus \{i\}}).$$

Each agent  $i$  wants to selfishly compute an optimal decision,  $u_i^*$ , of its local optimization problem, as follows:

$$u_i^* \in \begin{cases} \arg \min_{u_i} J_i(u_i, u_{-i}) & (1a) \\ \text{s.t. } u_i \in \mathcal{U}_i & (1b) \\ (u_i, u_{-i}) \in \mathcal{C}, & (1c) \end{cases}$$

where  $J_i$  is the cost function of agent  $i$ ,  $\mathcal{U}_i$  is the local constraint set, and  $\mathcal{C}$  is the set of coupling constraints.

In the remainder of this section, we describe  $J_i$ ,  $\mathcal{U}_i$ , and  $\mathcal{C}$ , upon which we postulate standard assumptions, as formalized in the next statement.

*Assumption 1:* For each agent  $i \in \mathcal{N}^+$ , the function  $J_i(\cdot, u_{-i})$  is convex and continuously differentiable, for all fixed  $u_{-i}$ ; the set  $\mathcal{U}_i$  is nonempty, closed and convex. The global feasible set  $\mathcal{X} := (\prod_{i \in \mathcal{N}} \mathcal{U}_i) \cap \mathcal{C}$  satisfies the Slater's constraint qualification [23, Eq. (27.50)].  $\square$

#### A. Model of prosumers in the network

In this section, we introduce the prosumer model. We consider that power might be generated by non-dispatchable generation units, e.g. solar and wind-based generators, or dispatchable units, e.g. small-scale fuel-based generators. Moreover, we also consider the slow dynamics of storage units. We restrict the model of each component such that Assumption 1 holds, that is, we avoid non-convex formulations and provide a convex approximation instead. Not only this approach is common in the literature, see e.g. [22], [24], [25], but also practical especially for real-time implementation, which requires fast and reliable computations.

First, we suppose that the components of the decision vector of prosumer  $i \in \mathcal{N}$ ,  $u_i$ , are the power generated from a dispatchable unit ( $p_i^{\text{di}} \in \mathbb{R}^H$ ), the power delivered to/from a storage unit ( $p_i^{\text{st}} \in \mathbb{R}^H$ ), the power traded with the main grid ( $p_i^{\text{mg}} \in \mathbb{R}^H$ ), and the power traded with its neighbors  $j \in \mathcal{N}_i$  ( $p_{(i,j)}^{\text{tr}} \in \mathbb{R}^H$ ), for all  $j \in \mathcal{N}_i$ . For simplicity of exposition, we assume that each prosumer only owns at most one dispatchable unit and/or one storage unit. Next, we present the model for these devices.

*Dispatchable units:* The objective function of a dispatchable unit, denoted by  $f_i^{\text{di}} : \mathbb{R}^H \rightarrow \mathbb{R}$ , is typically a convex quadratic function [10], [24], [26], e.g.

$$f_i^{\text{di}}(p_i^{\text{di}}) = \|p_i^{\text{di}}\|_{Q_i^{\text{di}}}^2 + (c_i^{\text{di}})^\top p_i^{\text{di}}, \quad (2)$$

where  $Q_i^{\text{di}} \succcurlyeq 0$  and  $c_i^{\text{di}}$  are constants. Furthermore, the power generation  $p_i^{\text{di}}$  is limited by

$$\begin{aligned} \underline{p}_i^{\text{di}} \mathbf{1}_H &\leq p_i^{\text{di}} \leq \bar{p}_i^{\text{di}} \mathbf{1}_H, & \forall i \in \mathcal{N}^{\text{di}}, \\ p_i^{\text{di}} &= 0, & \forall i \notin \mathcal{N}^{\text{di}}, \end{aligned} \quad (3)$$

where  $\bar{p}_i^{\text{di}} > p_i^{\text{di}} \geq 0$  denote maximum and minimum total power production of the dispatchable generation unit, and  $\mathcal{N}^{\text{di}} \subseteq \mathcal{N}$  the subset of agents that own dispatchable units.

*Storage units:* Each prosumer might also minimize the usage of its storage units, for instance, in order to reduce its degradation. The corresponding cost function is denoted by  $f_i^{\text{st}} : \mathbb{R}^H \rightarrow \mathbb{R}$ , defined as in [26]:

$$f_i^{\text{st}}(p_i^{\text{st}}) = \|p_i^{\text{st}}\|_{Q_i^{\text{st}}}^2, \quad (4)$$

where  $Q_i^{\text{st}} \succcurlyeq 0$ . The battery charging/discharging profile  $p_i^{\text{st}} = \text{col}((p_{i,h}^{\text{st}})_{h \in \mathcal{H}})$  is constrained by the battery dynamics

$$\left. \begin{aligned} x_{i,h+1} &= a_i x_{i,h} - \frac{T_s}{e_i^{\text{cap}}} p_{i,h}^{\text{st}}, \\ \underline{x}_i &\leq x_{i,h+1} \leq \bar{x}_i, \\ -p_i^{\text{ch}} &\leq p_{i,h}^{\text{st}} \leq p_i^{\text{dh}}, \\ p_i^{\text{st}} &= 0, \end{aligned} \right\} \forall i \in \mathcal{N}^{\text{st}}, \forall h \in \mathcal{H}, \quad (5)$$

where  $x_{i,h}$  denotes the state of charge (SoC) of the storage unit at time  $h \in \mathcal{H}$ ,  $a_i \in (0, 1]$  denotes the efficiency of the storage and  $T_s$  and  $e_i^{\text{cap}}$  denote sampling time and maximum capacity of the storage, respectively. Moreover,  $\underline{x}_i, \bar{x}_i \in [0, 1]$  denote the minimum and the maximum SoC of the storage unit of prosumer  $i$ , respectively, whereas  $p_i^{\text{ch}} \geq 0$  and  $p_i^{\text{dh}} \geq 0$  denote the maximum charging and discharging power of the storage unit. Finally, we denote by  $\mathcal{N}^{\text{st}} \subseteq \mathcal{N}$  the set of prosumers that own a storage unit.

*Local power balance:* The local power balance of each prosumer  $i \in \mathcal{N}$  is represented by the following equation:

$$p_i^{\text{di}} + p_i^{\text{st}} + p_i^{\text{mg}} + \sum_{j \in \mathcal{N}_i} p_{(i,j)}^{\text{tr}} = p_i^{\text{d}}, \quad (6)$$

where  $p_i^{\text{d}} \in \mathbb{R}^H$  denotes the local power demand profile over the whole prediction horizon. The power demand  $p_i^{\text{d}}$  is defined as the difference between the aggregate load of prosumer  $i$  and the power generated by its non-dispatchable generation units, e.g., solar or wind-based generators<sup>1</sup>. Finally, it is worth mentioning that a prosumer that does not own a dispatchable nor storage unit can satisfy its power balance (6) by importing (trading) power from other prosumers and/or the main grid.

*Passive consumers:* In addition, we assume that some busses in the distribution network might also be connected to some (traditional) passive consumers that do not have storage nor dispatchable units, and do not trade with other prosumers. Let us denote the set of such passive consumers by  $\mathcal{P}$ . For each passive consumer  $i \in \mathcal{P}$ , its power demand  $p_i^{\text{d}} > 0$  is balanced conventionally, namely, by importing power from the main grid. Nevertheless, these passive loads will play a role in the trading process between prosumers and main grid, and in the power-balance equations of the physical network.

## B. Modelling the P2P trading

In this section, we present the cost and constraints of bilateral tradings between prosumers.

<sup>1</sup>If a component of  $p_i^{\text{d}}$  is positive, then the load is larger than the power produced by its non-dispatchable units.

*Power traded with neighbors:* Recall that each prosumer  $i \in \mathcal{N}$  has a set of trading partners denoted by  $\mathcal{N}_i$ . The corresponding cumulative trading cost is

$$f_i^{\text{tr}}(\{p_{(i,j)}^{\text{tr}}\}_{j \in \mathcal{N}_i}) = \mathbf{1}_H^\top \sum_{j \in \mathcal{N}_i} (c_{(i,j)}^{\text{tr}} p_{(i,j)}^{\text{tr}} + c^{\text{ta}} |p_{(i,j)}^{\text{tr}}|), \quad (7)$$

where  $p_{(i,j)}^{\text{tr}} \in \mathbb{R}^H$  is the power that prosumer  $i$  trades with prosumer  $j$ ,  $c_{(i,j)}^{\text{tr}} \geq 0$  is the per-unit cost of trading [6], and  $c^{\text{ta}}$  is a tariff imposed by the DNO for using the network [9]. In practice, the parameters  $c_{(i,j)}^{\text{tr}}$  can be agreed through a bilateral contract [4] or model taxes to encourage the development of certain technologies [6]. Furthermore, for each P2P trade it must hold that

$$-\bar{p}_{(i,j)}^{\text{tr}} \mathbf{1}_H \leq p_{(i,j)}^{\text{tr}} \leq \bar{p}_{(i,j)}^{\text{tr}} \mathbf{1}_H, \quad \forall j \in \mathcal{N}_i, \quad (8a)$$

$$p_{(i,j)}^{\text{tr}} + p_{(j,i)}^{\text{tr}} = 0, \quad \forall j \in \mathcal{N}_i, \quad (8b)$$

where  $\bar{p}_{(i,j)}^{\text{tr}}$  denotes the maximum power can be traded with neighbor  $j$ . Equations (8b), commonly known as *reciprocity constraints* [4], impose the agreement on the power trades.

*Power traded with the main grid:* Let  $p_i^{\text{mg}}$  be the power prosumer  $i$  imports from the main grid at time  $h \in \mathcal{H}$ . As in [24], we assume that the electricity unit price at each time step  $h \in \mathcal{H}$  depends on the total consumption and is defined as a quadratic function, i.e.,

$$c_h^{\text{mg}}(\sigma_h^{\text{mg}}) = d_h^{\text{mg}} \cdot (\sigma_h^{\text{mg}} + b_h)^2, \quad (9)$$

where  $\sigma_h^{\text{mg}}$  and  $b_h$  denotes the *aggregate active* and *passive load on the main grid*, respectively, i.e.,

$$\sigma_h^{\text{mg}} = \sum_{i \in \mathcal{N}} p_{i,h}^{\text{mg}}, \quad b_h = \sum_{i \in \mathcal{P}} p_{i,h}^{\text{d}}, \quad \forall h \in \mathcal{H}, \quad (10)$$

and  $d_h^{\text{mg}} > 0$  is a constant. Therefore, the cost incurred by prosumer  $i$  over  $\mathcal{H}$  for trading with the main grid is

$$\begin{aligned} f_i^{\text{mg}}(p_i^{\text{mg}}, \sigma_h^{\text{mg}}) &= \sum_{h \in \mathcal{H}} c_h^{\text{mg}}(\sigma_h^{\text{mg}}) \frac{p_{i,h}^{\text{mg}}}{\sigma_h^{\text{mg}} + b_h} \\ &= \sum_{h \in \mathcal{H}} d_h^{\text{mg}} (\sigma_h^{\text{mg}} + b_h) p_{i,h}^{\text{mg}}, \end{aligned} \quad (11)$$

where  $p_i^{\text{mg}} = \text{col}((p_{i,h}^{\text{mg}})_{h \in \mathcal{H}})$  and  $b = \text{col}((b_h)_{h \in \mathcal{H}})$ . Finally, we bound the aggregative loads (10) as follows:

$$\underline{p}^{\text{mg}} \mathbf{1}_H \leq \sigma^{\text{mg}} + b \leq \mathbf{1}_H \bar{p}^{\text{mg}}, \quad (12)$$

where  $\bar{p}^{\text{mg}} > \underline{p}^{\text{mg}} \geq 0$  denote the upper and lower bounds. Typically, the latter is positive to ensure a continuous operation of the main generators that supply the main grid.

## C. Physical constraints

To ensure that the solutions to our decentralized market design are not only economically-efficient but also operationally-safe and reliable for the entire system, we impose the physical constraints of the electrical network, namely, power-flow-related constraints.

Firstly, recall that  $\mathcal{G}^{\text{p}} = (\mathcal{B}, \mathcal{L})$  is a graph representation of the physical electrical network that connects the prosumers. We denote by  $\mathcal{B}_y = \{z \mid (y, z) \in \mathcal{L}\}$  the set of neighbouring

busses of bus  $y \in \mathcal{B}$ , whereas we denote by  $\mathcal{N}_y^b \subseteq \mathcal{N}$  and  $\mathcal{P}_y^b \subseteq \mathcal{P}$  the set of prosumers and passive consumers that are connected to bus  $y \in \mathcal{B}$ , respectively. Additionally, we denote the set of busses that is connected to the main grid by  $\mathcal{B}^{\text{mg}} \subseteq \mathcal{B}$ .

Secondly, we define decision variables, for each bus  $y \in \mathcal{B}$ , which are used to define the physical constraints. Denote by  $v_y \in \mathbb{R}^H$  and  $\theta_y \in \mathbb{R}^H$  the voltage magnitude and angle over  $\mathcal{H}$ . Moreover,  $p_y^{\text{tg}} \in \mathbb{R}^H$  denotes the real power exchanged between bus  $y \in \mathcal{B}$  and the main grid, whereas  $p_{(y,z)}^\ell$  and  $q_{(y,z)}^\ell \in \mathbb{R}^H$ , for each  $m \in \mathcal{B}_y$ , denote the real and reactive powers of line  $(y, z) \in \mathcal{L}$  over  $\mathcal{H}$ , respectively.

We consider a linear approximation of power-flow equations, which is standard in the literature of P2P markets, e.g., [22], [27]. Specifically, for each bus  $y \in \mathcal{B}$ , it must hold that

$$\sum_{i \in \mathcal{P}_y^b} p_i^{\text{d}} + \sum_{i \in \mathcal{N}_y^b} (p_i^{\text{d}} - p_i^{\text{di}} - p_i^{\text{st}}) - p_y^{\text{tg}} = \sum_{z \in \mathcal{B}_y} p_{(y,z)}^\ell, \quad (13)$$

which indicates local power balance of bus  $y$ , similarly to (6) although now it relates power generation, consumption and line powers. Moreover, it must hold that

$$p_{(y,z)}^\ell = B_{(y,z)} (\theta_y - \theta_z) - G_{(y,z)} (v_y - v_z), \quad \forall z \in \mathcal{B}_y, \quad (14a)$$

$$q_{(y,z)}^\ell = G_{(y,z)} (\theta_y - \theta_z) + B_{(y,z)} (v_y - v_z), \quad \forall z \in \mathcal{B}_y, \quad (14b)$$

which represent the power flow equations of line  $(y, z)$  from the perspective of bus  $y$ , with  $B_{(y,z)}$  and  $G_{(y,z)}$  denoting the susceptance and conductance, respectively, of line  $(y, z)$ . Note that by (14a) and (14b), for each pair  $(y, z) \in \mathcal{L}$ , it holds that  $p_{(y,z)}^\ell = -p_{(z,y)}^\ell$  and  $q_{(y,z)}^\ell = -q_{(z,y)}^\ell$ .

Furthermore, we also impose reliability constraints for each bus  $y \in \mathcal{B}$ , i.e.,

$$(p_{(y,z),h}^\ell)^2 + (q_{(y,z),h}^\ell)^2 \leq \bar{s}_{(y,z)}^2, \quad \forall z \in \mathcal{B}_y, \quad \forall h \in \mathcal{H}, \quad (15a)$$

$$\underline{\theta}_y \mathbf{1} \leq \theta_y \leq \bar{\theta}_y \mathbf{1}, \quad (15b)$$

$$\underline{v}_y \mathbf{1} \leq v_y \leq \bar{v}_y \mathbf{1}, \quad (15c)$$

where (15a) represents the line capacity constraint at each line, with maximum capacity of line  $(y, z) \in \mathcal{L}$  denoted by  $\bar{s}_{(y,z)}$ , and (15b)-(15c) represent the bounds of the voltage phase angles and magnitudes, respectively, with  $\underline{\theta}_y \leq \bar{\theta}_y$  denoting the minimum and maximum phase angles and  $\underline{v}_y \leq \bar{v}_y$  denoting the minimum and maximum voltage magnitude. Note that, when linearizing the power flow equations, we take one of the busses as reference bus. Without loss of generality, we suppose the reference is bus 1 and assume  $\underline{\theta}_1 = \bar{\theta}_1 = 0$ .

Finally, related with the power exchanged with the main grid, we impose the following constraints:

$$p_y^{\text{tg}} = 0, \quad \forall y \notin \mathcal{B}^{\text{mg}}, \quad (16a)$$

$$\sigma_h^{\text{mg}} + b_h = \sum_{y \in \mathcal{B}} p_{y,h}^{\text{tg}}, \quad \forall h \in \mathcal{H}, \quad (16b)$$

where (16a) is imposed by definition that the busses that are not directly connected with the main grid do not exchange power with the main grid, whereas (16b) ensures that the power traded by the prosumers with the main grid (in the trading network) corresponds to the power exchanged between the whole distribution network and the main grid.

### III. A DISTRIBUTED MARKET-CLEARING MECHANISM

By letting the decision variables related to the physical constraints handled by a DNO (agent  $N+1$  in the game), the P2P market model can be compactly written as the problem of finding  $u_i^*$  in (1), for all  $i \in \mathcal{N}^+$ , where the decision variable  $u_i$  is defined as

$$u_i = \begin{cases} \text{col}\left(p_i^{\text{di}}, p_i^{\text{st}}, p_i^{\text{mg}}, \{p_{(i,j)}^{\text{tr}}\}_{j \in \mathcal{N}_i}\right), & \forall i \in \mathcal{N}, \\ \text{col}\left(\{\theta_y, v_y, p_y^{\text{tg}}, \{p_{(y,z)}^\ell, q_{(y,z)}^\ell\}_{z \in \mathcal{B}_y}\}_{y \in \mathcal{B}}\right), & i = N+1; \end{cases}$$

the cost function is defined as

$$J_i(u_i, u_{-i}) = f_i^{\text{di}}(p_i^{\text{di}}) + f_i^{\text{st}}(p_i^{\text{st}}) + f_i^{\text{tr}}\left(\{p_{(i,j)}^{\text{tr}}\}_{j \in \mathcal{N}_i}\right) + f_i^{\text{mg}}(p_i^{\text{mg}}, \sigma^{\text{mg}}), \quad \forall i \in \mathcal{N}, \quad (17)$$

whereas<sup>2</sup>  $J_{N+1} = 0$ ; the local action set is

$$\mathcal{U}_i = \begin{cases} \{u_i \mid (3), (5), (6), (8a) \text{ hold}\}, & \forall i \in \mathcal{N}, \\ \{u_i \mid (14), (15), (16a) \text{ hold}\}, & i = N+1; \end{cases} \quad (18)$$

and finally, the set of coupling constraints is

$$\mathcal{C} = \{u \mid (8b), (12), (13), (16b) \text{ hold}\}. \quad (19)$$

*Remark 1:* Our definitions of  $J_i$ ,  $\mathcal{U}_i$  and  $\mathcal{C}$  satisfy Assumption 1. Moreover, these definitions can be expanded by incorporating additional cost terms, for example, related to the degradation of storage units and constraints (e.g. ramping constraints of dispatchable generation units), as long as Assumption 1 remains satisfied.  $\square$

From a game-theoretic perspective, the inter-dependent optimization problems in (1) constitute a *generalized game* [28] and a set of decisions  $\{u_1^*, \dots, u_{N+1}^*\}$  that simultaneously satisfy (1), for all  $i \in \mathcal{N}^+$ , corresponds to a GNE [28, § 1]. In other words, a set of strategies  $\{u_1^*, \dots, u_{N+1}^*\}$  is a GNE if no agent  $i \in \mathcal{N}^+$  (prosumers and DNO) can reduce its cost function  $J_i(u_i^*, u_{-i}^*)$  by unilaterally changing its strategy  $u_i^*$  to another feasible one, i.e.,  $u_i \in \mathcal{U}_i$  s.t.  $(u_i, u_{-i}^*) \in \mathcal{C}$ .

Note that, the cost functions in (17) are not influenced by some specific prosumers, but only by the local decisions and by the aggregative quantity  $\sigma^{\text{mg}}$  in (10), namely, the active load on the main grid. Therefore, for each agent  $i \in \mathcal{I}$ , we can define a function  $\tilde{J}_i$  such that

$$\tilde{J}_i(u_i, \sigma^{\text{mg}}) =: J_i(u_i, u_{-i}). \quad (20)$$

Games with such special structure are known as *aggregative games* [29], [30], and have received intense research interest, within the operations research and the automatic control communities [13]–[17].

#### A. Nash Equilibrium Seeking in Aggregative Games

Several semi-decentralized and distributed algorithms are available in the literature to find a solution of the generalized aggregative game in (1), e.g. [13]–[17]. Among these methods, semi-decentralized ones [16] have been shown to be particularly efficient in terms of convergence speed.

<sup>2</sup>Here, we assume that the DNO does not have preferences on the outcome, provided that it is a feasible solution for the network.

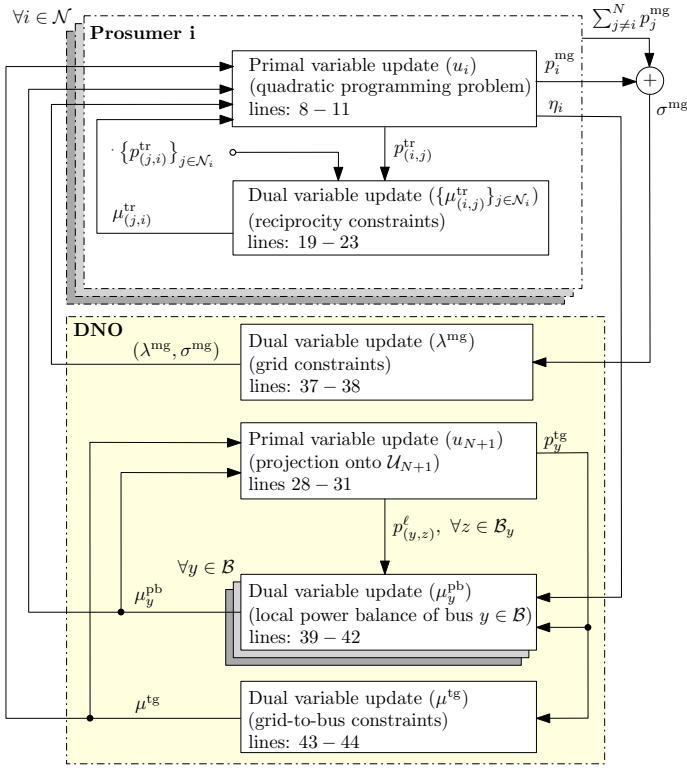


Fig. 2: Information flow of Algorithm 1 for each prosumer  $i \in \mathcal{N}$  (top boxes) and the DNO (bottom box).

Here, we tailor Algorithm 6 in [16] for our P2P market game in (1). Before presenting the algorithm, let us introduce, for each prosumer  $i \in \mathcal{N}$ , the dual variable  $\mu_{(i,j)}^{tr} \in \mathbb{R}^H$ , for all  $j \in \mathcal{N}_i$ , which are associated with the trading reciprocity (8b). For the DNO, we introduce  $\lambda^{mg} \in \mathbb{R}^{2H}$ ,  $\mu^{tg}$ , which are dual variables associated with the grid constraints (12) and (16b), respectively; moreover, for all  $y \in \mathcal{B}$ , let us introduce  $\mu_y^{pb}$ , namely, the dual variable associated with the power balance constraint on bus  $y$  (13).

The proposed market-clearing algorithm is summarized in Algorithm 1 and its information flow is illustrated in Fig. 2. In the following proposition, we state the global convergence of Algorithm 1 to a variational<sup>3</sup> GNE of the P2P market game in (1).

**Proposition 1:** The following statements hold:

- (i) There exists a variational GNE of the game (1), with cost functions and constraints sets defined in (17)-(19).
- (ii) The sequence  $(u_1(k), \dots, u_{N+1}(k))_{k \in \mathbb{N}}$  generated by Algorithm 1 converges to a variational GNE of (1).  $\square$

**Remark 2:** The main properties of the proposed market-clearing mechanism (Algorithm 1) are listed below:

- (i) The step sizes are fully-uncoordinated, i.e., they can differ across the prosumers. Moreover, each prosumer can set the local step sizes based on local information only (see lines 2–3);

<sup>3</sup>Variational GNEs (v-GNEs) are a special subclass of GNEs that enjoys the property of “economic fairness”, namely, the marginal loss due to the presence of the coupling constraints is the same for each agent, and coincides with the solutions to a specific variational inequality [31].

- (ii) Algorithm 1 is semi-decentralized, i.e., the prosumers rely on a reliable central coordinator (i.e., the DNO) that gathers local variables in aggregative form and then broadcasts signals, such as dual variables, to all prosumers, see Figure 2. Such communication architecture is particularly efficient to design fast and scalable equilibrium seeking algorithms in games [16];
- (iii) The local primal update of each prosumer (lines: 8–11) involves the solution of a quadratic programming problem<sup>4</sup>, for which very efficient solvers are available, e.g. [32];
- (iv) The primal update of the DNO (lines: 26–29) requires projecting onto  $\mathcal{U}_{N+1}$ , which is a convex but nonlinear set. This operation can be computationally expensive if naively solved. Therefore, we propose and use an efficient ad-hoc algorithm to calculate  $\text{proj}_{\mathcal{U}_{N+1}}$  based on the celebrated *Douglas–Rachford splitting* for monotone inclusion problems [23, §. 26.3], [33, § 4.3].

#### IV. NUMERICAL STUDIES

We perform an extensive numerical study on the IEEE 37-bus distribution network to validate the proposed game-theoretic market design and market-clearing algorithm. Specifically: (a) we evaluate the importance of having physical constraints in the model; (b) we evaluate the economical benefits of trading; (c) we show how storage units owned by prosumers might affect power consumptions; and (d) we test the scalability of the proposed algorithm. All the simulations are carried out in MATLAB and use the OSQP solver [32] for solving the quadratic programming problems.

In all simulations<sup>5</sup>, we consider heterogeneous networks, where the power demand profile of a prosumer or passive user is either that of single household, multiple household, restaurant, office, hospital, or school. Moreover, some prosumers may have solar-based power generation. The demand and solar-based generation profiles are based on [34]. We also arbitrarily select a set of prosumers to own dispatchable generation units with different sizes and to own homogeneous storage units. We randomly generate the trading networks and place each prosumer and passive user in one of the busses of the IEEE 37-bus network.

Some of the default cost parameters are set as in [24], i.e.,  $Q_i^{\text{di}} = 0$ ,  $c_i^{\text{di}} = 0.045 \text{ €/kW}$ , for all  $i \in \mathcal{N}^{\text{di}}$ ,  $Q_i^{\text{st}} = 0$ ,  $c_i^{\text{st}} = 0$ , for all  $i \in \mathcal{N}^{\text{st}}$ , and  $d_h^{\text{mg}} = 0.1624/b_h \text{ €/kW}$ , whereas the trading cost parameters  $c_{(i,j)}^{\text{tr}} = 0.08 \text{ €/kW}$ , for all  $(i,j) \in \mathcal{E}$ , and  $c^{\text{ta}} = 0.01 \text{ €/kW}$ . The parameter  $c_{(i,j)}^{\text{tr}}$  is set larger than  $c_i^{\text{di}}$  to encourage trading between prosumers with and without dispatchable units, but is smaller than the average unit-price of importing power from the main grid. Note that, in some simulations, we vary these cost parameters.

##### A. Achieving operationally-safe solutions

In the first simulation study, we compare the solutions obtained from solving a P2P market model with and without

<sup>4</sup>Up to a fairly-standard reformulation of the absolute value term in (7).

<sup>5</sup>The codes and data sets used for all simulations are available at <https://github.com/ananduta/P2Penergy>.



## Algorithm 1: Distributed P2P Markets Clearing Mechanism

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1: Initialization
2:   Prosumers. For all  $i \in \mathcal{N}$ : set  $u_i(0) \in \mathcal{U}_i$ ,  $\mu_{(i,j)}^{\text{tr}}(0) = \mathbf{0}$ ,  $\forall j \in \mathcal{N}_i$ ;  $\alpha_i < 3 + N \max_{h \in \mathcal{H}} d_h^{\text{mg}}$ ,  $\beta_{(i,j)}^{\text{tr}} = \beta_{(j,i)}^{\text{tr}} < \frac{1}{2}$ ,  $\forall j \in \mathcal{N}_i$ .
3:   DNO. Set  $u_{N+1}(0) \in \mathcal{U}_{N+1}$ ,  $\lambda^{\text{mg}} = \mathbf{0}$ ,  $\mu^{\text{lg}} = \mathbf{0}$ ,  $\mu_y^{\text{pb}}(0) = \mathbf{0}$ ,  $\forall y \in \mathcal{B}$ ;  $\alpha_{N+1} < 2$ ,  $\gamma^{\text{mg}} < \frac{1}{N}$ ,  $\beta^{\text{lg}} < \frac{1}{|\mathcal{N}|+|\mathcal{B}|}$ ,  $\beta_y^{\text{pb}} < \frac{1}{1+2|\mathcal{N}_y^{\text{b}}|+|\mathcal{B}_y|}$ ,  $\forall y \in \mathcal{B}$ .
4: end initialization
5: While convergence is not achieved do:
6:   for all  $i \in \mathcal{N}$  do
7:     Prosumer  $i$  routine
8:       primal update ▷  $u_i = \{\text{generation, storage, main grid, trades}\}$ 
9:          $\psi_i(k) = \text{col} \left( -\mu_y^{\text{pb}}(k), -\mu_y^{\text{pb}}(k), \begin{bmatrix} I_H \\ -I_H \end{bmatrix}^\top \lambda^{\text{mg}}(k) + \mu^{\text{lg}}(k), \left\{ \mu_{(i,j)}^{\text{tr}}(k) \right\}_{j \in \mathcal{N}_i} \right)$  ▷ auxiliary vector
10:         $u_i(k+1) = \begin{cases} \underset{\xi \in \mathbb{R}^{n_i}}{\text{argmin}} & \tilde{J}_i(\xi, \sigma^{\text{mg}}(k)) + \psi_i(k)^\top \xi + \frac{1}{2\alpha_i} \|\xi - u_i(k)\|^2 \\ \text{s.t.} & \xi \in \mathcal{U}_i \end{cases}$  ▷ quadratic programming
11:      end
12:      communication (to DNO and trading partners)
13:         $\eta_i(k+1) = p_i^{\text{d}} - p_i^{\text{di}}(k+1) - p_i^{\text{st}}(k+1)$  ▷ auxiliary vector: local load unbalance
14:         $p_i^{\text{mg}}(k+1), \eta_i(k+1) \longrightarrow \text{DNO,}$  ▷ forward to DNO
15:        for all prosumer  $j \in \mathcal{N}_i$  do
16:           $p_{(i,j)}^{\text{tr}}(k+1) \longrightarrow \text{prosumer } j$  ▷ forward trade estimate to prosumer  $j$ 
17:        end for
18:      end communication
19:      dual update ▷ reciprocity constraints
20:        for all  $j \in \mathcal{N}_i$  do
21:           $\zeta_{(i,j)}^{\text{tr}}(k+1) = p_{(i,j)}^{\text{tr}}(k+1) + p_{(j,i)}^{\text{tr}}(k+1)$  ▷ auxiliary vector
22:           $\mu_{(i,j)}^{\text{tr}}(k+1) = \mu_{(i,j)}^{\text{tr}}(k) + \beta_{(i,j)}^{\text{tr}} \left( 2\zeta_{(i,j)}^{\text{tr}}(k+1) - \zeta_{(i,j)}^{\text{tr}}(k) \right)$  ▷ reflected dual ascent
23:        end for
24:      end
25:    end prosumer  $i$  routine
26:  end for
27:  DNO routine
28:    primal update ▷ angels, voltages, power on grid and buses
29:     $\psi_{N+1}(k) = \text{col} \left( \{\mathbf{0}, \mathbf{0}, -\mu^{\text{lg}}(k) - \mu_y^{\text{pb}}(k), \{-\mu_y^{\text{pb}}(k), \mathbf{0}\}_{z \in \mathcal{B}_y}\}_{y \in \mathcal{B}} \right)$  ▷ auxiliary vector
30:     $u_{N+1}(k+1) = \text{proj}_{\mathcal{U}_{N+1}} \left( u_{N+1}(k) - (\alpha_{N+1})^{-1} \psi_{N+1}(k) \right)$  ▷ solved via Algorithm 2 (see Appendix)
31:  end
32:  aggregation update
33:     $\sigma^{\text{mg}}(k+1) = \sum_{i \in \mathcal{N}} p_i^{\text{mg}}(k+1)$  ▷ aggregate active load, eqn. (10)
34:     $\sigma^{\text{lg}}(k+1) = \sum_{y \in \mathcal{B}} p_y^{\text{lg}}(k+1)$  ▷ aggregate grid-to-buses power
35:  end
36:  dual update
37:     $\eta_{N+1}(k+1) = \begin{bmatrix} 1 \\ -1 \end{bmatrix} \otimes (2\sigma^{\text{mg}}(k+1) - \sigma^{\text{mg}}(k)) - \begin{bmatrix} \bar{p}^{\text{mg}} \mathbf{1}_H - b \\ -\bar{p}^{\text{mg}} \mathbf{1}_H + b \end{bmatrix}$  ▷ auxiliary vector
38:     $\lambda^{\text{mg}}(k+1) = \text{proj}_{\mathbb{R}_{\geq 0}^{2H}} (\lambda^{\text{mg}}(k) + \gamma^{\text{mg}} \eta_{N+1}(k+1))$  ▷ grid constraints
39:    for all buses  $y \in \mathcal{B}$  do
40:       $\zeta_y^{\text{pb}}(k+1) = \sum_{i \in \mathcal{P}_y^{\text{b}}} p_i^{\text{d}} + \sum_{i \in \mathcal{N}_y^{\text{b}}} \eta_i(k+1) - p_y^{\text{lg}}(k+1) - \sum_{z \in \mathcal{B}_y} p_{(y,z)}^{\ell}(k+1)$  ▷ auxiliary vector
41:       $\mu_y^{\text{pb}}(k+1) = \mu_y^{\text{pb}}(k) + \beta_y^{\text{pb}} (2\zeta_y^{\text{pb}}(k+1) - \zeta_y^{\text{pb}}(k))$  ▷ local power balance of bus  $y$ 
42:    end for
43:     $\zeta^{\text{lg}}(k+1) = \sigma^{\text{mg}}(k+1) + b - \sigma^{\text{lg}}(k+1)$  ▷ auxiliary vector
44:     $\mu^{\text{lg}}(k+1) = \mu^{\text{lg}}(k) + \beta^{\text{lg}} (2\zeta^{\text{lg}}(k+1) - \zeta^{\text{lg}}(k))$  ▷ grid-to-buses constraints
45:  end
46:  communication (broadcast to all prosumers)
47:     $\{\sigma^{\text{mg}}(k+1) + b, \lambda^{\text{mg}}(k+1), \mu^{\text{lg}}(k+1)\} \longrightarrow \mathcal{N}$ 
48:    for all buses  $y \in \mathcal{B}$  do
49:       $\mu_y^{\text{pb}}(k+1) \longrightarrow \mathcal{N}_y^{\text{b}}$  ▷ only to prosumers on bus  $y$ 
50:    end for
51:  end communication
52:  end DNO routine
53: end while

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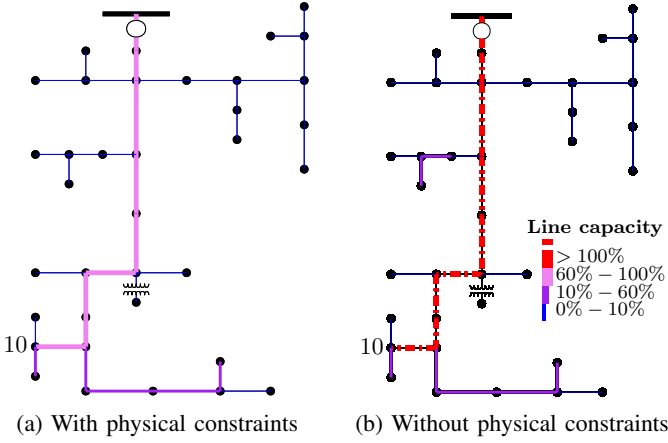


Fig. 3: Power line capacities of the physical network. The solutions of the P2P market might cause overcapacity in some lines of the physical network when capacity constraints (15a) are not taken into account.

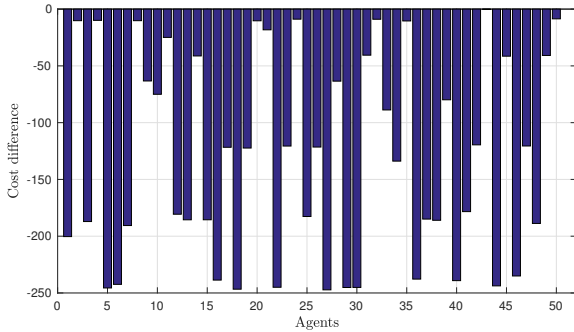


Fig. 4: Total cost improvement (€) of each prosumer by trading ( $c_{(i,j)}^{\text{tr}} = 0.08\text{€/kW}$ ).

capacity constraints (15a). We specifically create an extreme case with 25 prosumers, where the load of prosumer 10 (see Figure 3) is very high. We solve both market designs using Algorithm 1. Figure 3 shows the resulting power-line saturations between busses for both designs. Some equilibrium solutions of the P2P market cause overcapacity in some lines when capacity constraints (15a) are not taken into account in the model, as illustrated in Figure 3 (b).

### B. Peer-to-Peer trading

In this section, we evaluate whether energy trading is economically beneficial for the prosumers. To this end, we generate a network of 50 prosumers and consider two scenarios: (a) where trading is not allowed, i.e.,  $\bar{p}_{(i,j)}^{\text{tr}} = 0$  in (8a); (b) where trading is allowed with  $\bar{p}_{(i,j)}^{\text{tr}} = 30$  kW, and the default cost parameters are homogeneous. The other parameters of the network are kept constant in both scenarios. Figure 4 shows the individual costs difference between the equilibrium configurations of the market designs with (a) and without P2P tradings (b). In particular, all prosumers gain economical benefits when they can trade.

Then, we evaluate the sensitivity of the total traded power with respect to the trading cost parameter  $c_{(i,j)}^{\text{tr}}$  and the trading

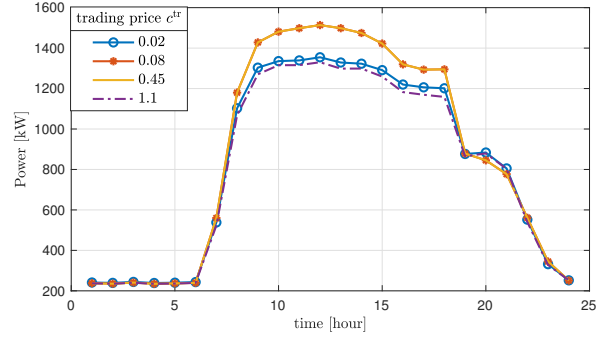


Fig. 5: Aggregated P2P trading for different cost coefficients ( $c_{(i,j)}^{\text{tr}}$  in €/kW).

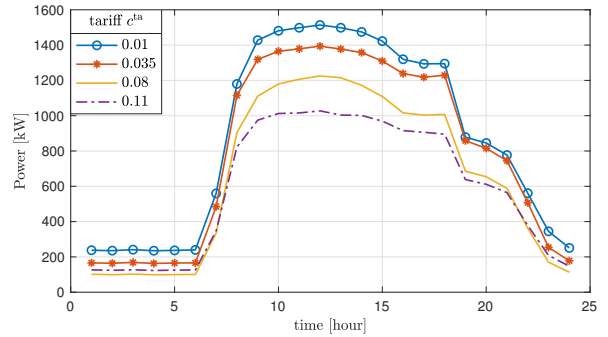


Fig. 6: Aggregated P2P trading for different penalty coefficients ( $c^{\text{ta}}$  in €/kW).

tariff,  $c^{\text{ta}}$ . Figure 5 shows that  $c_{(i,j)}^{\text{tr}}$  must be set appropriately to maximize trading among prosumers. In other words, when  $c_{(i,j)}^{\text{tr}}$  is either too high or low, trading is less attractive. On the other hand, the higher the tariff is, the less power is traded, as shown in Figure 6. Therefore, the DNO may adjust this tariff to encourage or discourage trading in the network. Discouraging trading might be needed when the capacity of the network is close to its limit.

### C. The impact of storage units

In this set of simulations, we investigate the advantages of distributed storage in the network. We generate a test case of 50-prosumer network and consider two extreme scenarios: (a) no prosumers own storage units and (b) all prosumers own storage units. Furthermore, we also allow some of the prosumers to own distributed generation units. Figures 7-8 summarize the simulation results. From Figure 7, we can see how the storage units help in shaving the peak of total power imported from the main grid and locally generated by distributed generators.

Interestingly, the trading between prosumers is also affected, as shown by the top plot of Figure 8. From this plot, we observe that the existence of storage units reduce the total power traded during the peak hours as the prosumers have reserved energy in their storages. Note that the prosumers charge their storage units during the first off-peak hours by buying energy from the main grid and/or from other prosumers

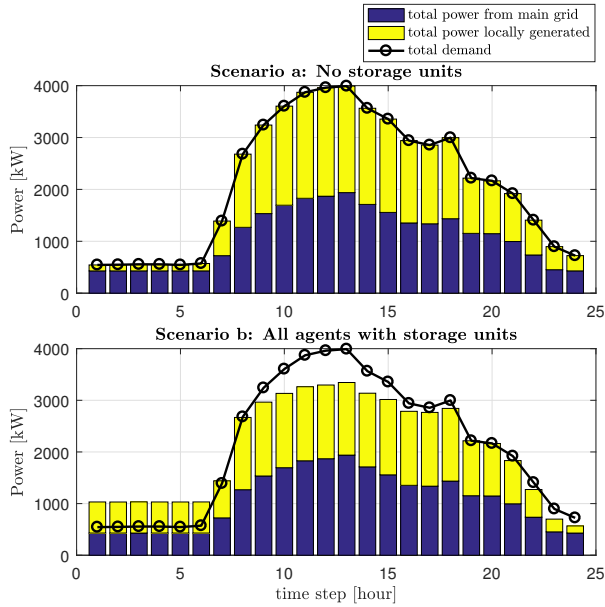


Fig. 7: Incorporating storage units causes a peak-shaving effect on the aggregate demand on the main grid.

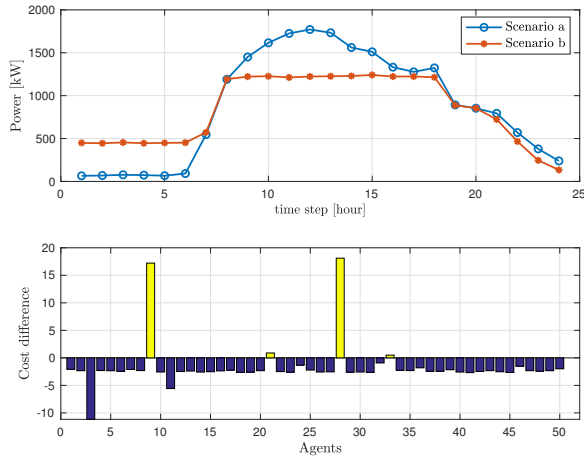


Fig. 8: Aggregated P2P trading (top plot), and individual cost difference (bottom plot), in scenarios (a) and (b).

that own dispatchable generation units (see the first six hours of the bottom plot of Figures 7 and those of the top plot of Figure 8). Additionally, the bottom plot of Figure 8 shows the cost difference between both scenarios. There, we observe that most of the prosumers gain economical benefits by owning a storage unit. The ones that have positive cost differences are those that also own dispatchable generation units. They gain more profit in scenario (a) since the prosumers that do not own any active components prefer to buy energy from their trading partners that own dispatchable generation units than importing from the main grid. This preference becomes less attractive when these buying prosumers own a storage unit.

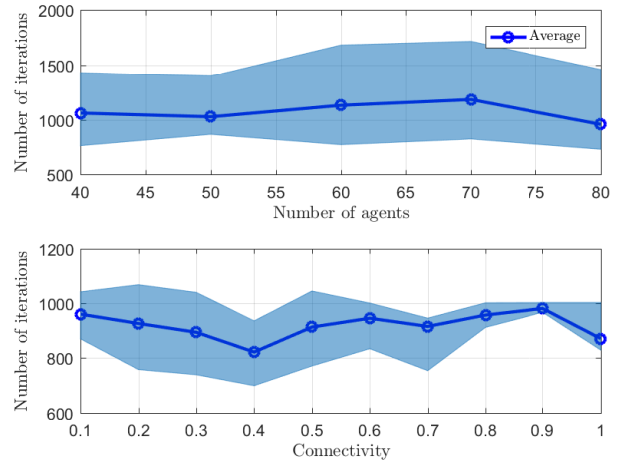


Fig. 9: Total number of iterations for convergence of Alg. 1 vs number of prosumers (top) and the connectivity level (the number of trading links) (bottom).

#### D. Scalability of the algorithm

Finally, we perform a scalability test for the proposed algorithm. Specifically, we evaluate the convergence speed, in terms of the total number of iterations required to meet a predetermined stopping criterion, when the size of the population of prosumers  $N$  and the connectivity of the trading network (the number of trading links) grow. We carry out two sets of simulations. For the former, we consider five different values of  $N$  and a fixed connectivity level of 0.6 and we run ten Monte Carlo simulations for each  $N$ , whereas in the latter, the connectivity of the trading network of 50 prosumers varies in the range  $[0.1, 1]$ , where connectivity 1 means that the trading network is a complete graph. Similarly, we also run ten Monte Carlo simulations for each connectivity value. Figure 9 shows the numerical results. We can see that Algorithm 1 suitably scales with respect to both the number of prosumers and the connectivity level of the trading network. These results highlight that our algorithm is suitable to be applied to large-scale systems.

#### V. CONCLUSION

Energy management and peer-to-peer trading in future energy markets of prosumers can be formulated as a generalized aggregative game, where the network operator is an extra player in charge of handling the network operational constraints. A provably-convergent operationally-safe distributed market-clearing mechanism is obtained by solving the game with a Nash equilibrium seeking algorithm based on the proximal-point method. Numerical studies show that the computational complexity of the proposed mechanism is independent of the prosumer population size, and suggest that active participation in the market is economically advantageous both for prosumers and network operators.

Future research directions include: efficiently incorporating non-linear convex approximation of power flow in the algorithm; handling the physical constraints in a fully-distributed

manner, i.e., without the action of a network operator; and dealing with uncertainties in the model, e.g., renewable energy production, as well as those from information exchange processes required by our algorithm.

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## APPENDIX SUPPLEMENTARY MATERIAL

### A. Algorithm 1: Derivation and Convergence Analysis

The derivation and convergence analysis of Algorithm 1 relies (for the most part) on the *customized preconditioned proximal-point (cPPP)* algorithm for generalized aggregative games proposed in [16, Algorithm 6]. The objective of this appendix is to show that the proposed market-clearing game (1), with cost functions and constraints sets defined in (17)–(19), satisfies all the technical conditions in [16, Theorem 2], among which is the existence of a variational GNE, i.e., item (i) of Proposition 1. Therefore, we invoke [16, Theorem 2] to prove convergence of Algorithm 1, i.e., item (ii) of Proposition 1. For a complete convergence analysis of the cPPP algorithm for aggregative games we refer to [16, Appendix C].

*Aggregative cost functions:* First, we show that the cost functions (17) can be cast as in [16, Eqn. (30)], i.e.

$$J_i(u_i, u_{-i}) = g_i(u_i) + (C \text{avg}(u))^T u_i, \quad (21)$$

where  $\text{avg}(u) := \frac{1}{N} \sum_{i \in \mathcal{N}} u_i$  denotes the average strategy. Let  $\mathcal{N}_i = \mathcal{N}$ , for all  $i \in \mathcal{N}$ , without loss of generality<sup>6</sup>. In this case,  $u_i \in \mathbb{R}^{(3+N)H}$ , for all  $i \in \mathcal{N}$ . Moreover, let  $\Xi^{\text{mg}} \in \mathbb{R}^{H \times (3+N)H}$  denote the matrix that selects the  $p_i^{\text{mg}}$ -component from the decision vectors  $u_i$ 's, and define the matrix  $D := N \text{diag}(d_1^{\text{mg}}, \dots, d_H^{\text{mg}})$ , where  $d_h^{\text{mg}}$  is the price coefficient for the main grid power. Then, the cost functions in (17) can be recast as [16, Eqn. (30)], or (21), with

$$g_i(u_i) = f_i^{\text{di}}(p_i^{\text{di}}) + f_i^{\text{st}}(p_i^{\text{st}}) + f_i^{\text{tr}}\left(\{p_{(i,j)}^{\text{tr}}\}_{j \in \mathcal{N}_i}\right) + \frac{1}{N}(Db)^T p_i^{\text{mg}}, \quad (22a)$$

$$C = (\Xi^{\text{mg}})^T D \Xi^{\text{mg}}. \quad (22b)$$

*Technical assumptions:* Next, we show that all the assumptions in [16, Theorem 2] are satisfied.

- (i) For all  $i \in \mathcal{N}^+$ , the cost function  $J_i(u_i, u_{-i})$  in (22a) is convex in  $u_i$ , since all the components of  $g_i$  are convex. Hence, [16, Assumption 1] holds.
- (ii) For all  $i \in \mathcal{N}^+$ , the local set  $\mathcal{U}_i$  in (18) is nonempty, closed and convex. Moreover, Slater's constraint qualification on the global feasible set  $(\prod_{i \in \mathcal{N}^+} \mathcal{U}_i) \cap \mathcal{C}$  holds under an appropriate choice of the parameters. Therefore, [16, Assumption 2] is satisfied.
- (iii) The *pseudo-subdifferential* mapping of the game (1) reads as  $F : u \mapsto \prod_{i \in \mathcal{N}} (\partial_{u_i} J_i(u_i, u_{-i})) \times \mathbf{0}$ , since  $J_{N+1} = 0$ . It follows by [30, Corollary 1], that the first term of  $F$ , i.e.,  $u \mapsto \prod_{i \in \mathcal{N}} \partial_{u_i} J_i(u_i, u_{-i})$ , is maximally monotone, since  $C$  in (22b) is positive semidefinite, i.e.,  $C = (\Xi^{\text{mg}})^T D \Xi^{\text{mg}} \succeq 0$ . Moreover, also the second term of  $F$ , i.e., the zero mapping  $\mathbf{0}$ , is maximally monotone. Therefore, it follows by [23, Proposition 20.23] that their cartesian product  $\prod_{i \in \mathcal{N}} (\partial_{u_i} J_i(u_i, u_{-i})) \times \mathbf{0} = F$  is maximally monotone. Hence, [16, Assumption 6] holds.
- (iv) By [16, Lemma 1 (i)], there exists a variational GNE of the game in (1), since the constraint sets  $\mathcal{U}_i$  in (18) are

bounded, and the pseudo-subdifferential mapping  $F$  is monotone. Hence, [16, Assumption 4] is satisfied. ■

### B. Alternating Projection for Operational Feasibility

In this appendix, we propose an efficient algorithm to compute the projection onto the set  $\mathcal{U}_{N+1}$  (line 30 in Algorithm 1). First, let us recall the structure of  $u_{N+1}$ , i.e.,

$$u_{N+1} = \text{col} \left( \{\theta_y, v_y, p_y^{\text{tg}}, \{p_{(y,z)}^{\ell}, q_{(y,z)}^{\ell}\}_{z \in \mathcal{B}_y}\}_{y \in \mathcal{B}} \right),$$

and let us define the sets

$$\mathcal{S}_1 := \{u_{N+1} \mid (15) \text{ and } (16a) \text{ hold}\}, \quad (23)$$

$$\mathcal{S}_2 := \{u_{N+1} \mid (14a) \text{ and } (14b) \text{ hold}\}, \quad (24)$$

such that  $\mathcal{U}_{N+1} = \mathcal{S}_1 \cap \mathcal{S}_2$ . The proposed method, summarized in Algorithm 2, is essentially a *Douglas–Rachford splitting* (DRS) [23, § 26.3] applied to the *best approximation problem*  $\text{argmin}_{\xi \in \mathcal{S}_1 \cap \mathcal{S}_2} \|\xi - u_{N+1}\| = \text{proj}_{\mathcal{S}_1 \cap \mathcal{S}_2}(u_{N+1})$ , see e.g. [33, § 4.3] for a formal derivation of the algorithm.

Unlike  $\mathcal{U}_{N+1}$ , the projections onto  $\mathcal{S}_1$  and  $\mathcal{S}_2$  have closed-form expressions, hence Algorithm 2 only involves elementary operations. Specifically,  $\text{proj}_{\mathcal{S}_1}(u_{N+1}) = u_{N+1}^+$ , where

$$\theta_y^+ = \begin{cases} \underline{\theta}_y, & \text{if } \theta_y < \underline{\theta}_y \\ \bar{\theta}_y, & \text{if } \theta_y > \bar{\theta}_y \\ \theta_y, & \text{otherwise} \end{cases}, \quad v_y^+ = \begin{cases} \underline{v}_y, & \text{if } v_y < \underline{v}_y \\ \bar{v}_y, & \text{if } v_y > \bar{v}_y \\ v_y, & \text{otherwise} \end{cases},$$

$$p_y^{\text{tg}+} = \begin{cases} p_y^{\text{tg}}, & \text{if } y \in \mathcal{B}^{\text{mg}} \\ 0, & \text{otherwise} \end{cases},$$

and for all  $y \in \mathcal{B}$ ,  $z \in \mathcal{B}_z$ , and  $h \in \mathcal{H}$

$$L_{(y,z),h} = \max \left\{ \|\text{col}(p_{(y,z),h}^{\ell}, q_{(y,z),h}^{\ell})\|, \bar{s}_{(y,z)} \right\},$$

$$(p_{(y,z),h}^{\ell})^+ = \frac{\bar{s}_{(y,z)}}{L_{(y,z),h}} p_{(y,z),h}^{\ell},$$

$$(q_{(y,z),h}^{\ell})^+ = \frac{\bar{s}_{(y,z)}}{L_{(y,z),h}} q_{(y,z),h}^{\ell}.$$

Whereas, since  $\mathcal{S}_2$  is an affine set, a closed-form expression for  $\text{proj}_{\mathcal{S}_2}$  is given in [23, Example 29.17(ii)].

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#### Algorithm 2: DRS for computing $\text{proj}_{\mathcal{U}_{N+1}}(u_{N+1})$

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- 1: Initialize  $\xi(0) \in \mathbb{R}^{n_{N+1}}$ , and set  $\eta \in (0, 2)$
  - 2: **While convergence is not achieved do:**
  - 3:      $z(k) = \text{proj}_{\mathcal{S}_1}(\frac{1}{2}\xi(k) + \frac{1}{2}u_{N+1})$
  - 4:      $\xi(k+1) = \xi(k) + \eta(\text{proj}_{\mathcal{S}_2}(2z(k) - \xi(k)) - z(k))$
  - 5: **end while**
- 

<sup>6</sup>For example, by defining, for all  $i \in \mathcal{N}$ , the “dummy variables”  $\{p_{(i,j)}^{\text{tr}}\}_{j \in \mathcal{N} \setminus \mathcal{N}_i}$  for all the prosumers that do not trade with  $i$ .