Real-time bidding in a Walrasian Local Energy Market

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Abstract— **This paper presents a Local Energy Market (LEM) model based on Walrasian Auctions for near real-time energy trading among peers in an Energy Community. The market operates with minimal information exchange, where peers only indicate trade decisions and quantities. The auctioneer updates prices iteratively to balance supply and demand. Two core algorithms support the LEM: (1) the Auctioneer Price Decision Algorithm, which adjusts prices based on past imbalances, and (2) a real-time bidding optimization algorithm, which optimizes peers' energy dispatch and local energy trading decisions based on expected demand, generation, storage, and opportunity costs of external trading. This work details the design and implementation of the bidding optimization algorithm and evaluates its performance through simulations. The results compare the LEM to a centralized pool-based market and individual optimizations, assessing its efficiency and imbalance control. The findings support the development of innovative and decentralized energy markets and smart grid applications.**

Index Terms-- **Local Energy Markets, Walrasian Auctions, Real-Time Energy Trading, Price Decision Algorithms, Bidding Optimization**

I. INTRODUCTION

Walrasian auctions are theoretical constructions designed by the French economist Léon Walras in the 19th century to explain market equilibrium through a tâtonnement process, where prices are adjusted iteratively by an auctioneer entity until supply equals demand. In contrast to typical auction-based markets, where prices are set through real time transactions at varying prices based on demand and supply dynamics, without waiting for a single equilibrium price, Walrasian markets find price and market equilibrium before all trades occur, which can lead to less volatility and inefficiencies under certain circumstances. For instance, Walrasian auctions are used in financial exchanges, as in the opening or closing of stocks trading sessions, where buying and selling orders accumulate, and a single price is determined to clear all market bids in a single moment.

In the context of electricity markets, typical day ahead pool markets, like the MIBEL[1], contain elements of Walrasian auctions, such as the use a centralized clearing mechanism to determine unique market prices in a single delivery period based on all supply and demand bids. However, it uses an optimization approach instead of an iterative *tâtonnement* process, and neither the real market equilibrium nor the real price of electricity is ever actually found, since literally all electricity markets are forward ones, i.e., they trade the expected energy supply and demand in future periods, and not the current ones. This is why liberalized electricity markets count on several forward market options, from long-term bilateral trades to short-term intra-day and other flexibility solutions. All of these are tools to provide market players with ways to reduce uncertainties as to what the real cost of energy will be. As pointed out by Steven Stoft in [2], the only moment where the real price of electricity could be theoretically found is during real-time operation by TSOs, since they operate in a process very similar to a Walrasian auction to guarantee supply and demand equilibrium of the grid.

The literature on Walrasian auctions for electricity markets is not extensive. A single imbalance settlement period (ISP) Walrasian auction is simulated in [3] to find the equilibrium of wholesale market (WSM) active and reactive power. Agents bid to supply and demand in real time until a stable price is found by the auctioneer. However, this work does not consider intertemporal choices. In [4], a similar single ISP is considered to clear a demand response market. A distributed unit commitment problem was also tackled with Walrasian auctions in [5]. In common, all these references assume a WSM logic where supply and demand are obligatory due to grid concerns, while agents do not have convex preferences or cost functions [6]. In this sense, and considering the recent regulation on collective self-consumption, CSC, in Europe [7], innovative LEMs without delivery commitment can be tested [8], [9], [10], since members can still trade with their own suppliers of not trading locally [11].

Building on Stoft's reflection and the reviewed literature, we identified that a real-time market could, in theory, operate within the constrained scope of local energy markets (LEM) under the CSC regulation, where grid safety—unlike in wholesale markets—is not a concern, since local transactions

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are virtual and peers do not have balancing responsibilities [12]. Based on this, we first introduced the concept of a continuously iterative, near-real-time Walrasian LEM in [13], followed by a proof of concept for the auctioneer price algorithm in [14]. This work is aligned with recent EU CSC regulations that allow local generation to be shared locally, using the REC LEM models designed in [9]. In this work we finally close the gap and simulate the whole Walrasian LEM proposal by incorporating a Mixed-Integer Linear Programming (MILP) to model the peers' decision-making, i.e., how to program their storage systems dispatch while bidding to buy or sell locally in each imbalance settlement period (ISP), i.e., each LEM iteration, given the proposed auctioneer price.

The main contributions of this work include:

- A near-real-time innovative LEM proposal compatible with CSC regulation and WSM settlement, and that could operate at very small ISPs to potentially provide different services to the grid.
- The proof of a LEM concept that clears with very little information exchange, since peers only need to inform the auctioneer if they want to trade or not. This is a significant advantage in relation to other pool markets, that often need full information.
- A working peer decision making algorithm using MILP optimization to decide whether to trade or not locally in each ISP, while programing storage dispatch and expected future trades.
- Provides a decentralized LEM solution fit for REC with large number of members, where centralized decisions can be too costly.

II. THE WALRASIAN LEM

A. General overview

As conceptualized in [13], the proposed Walrasian LEM consists of successive single step Walrasian auctions illustrated in Figure 1. For each interval t (defined as 15-minute ISP in this work), the auctioneer sends a price λ_t to the peers, in step 1, who maximize their revenue in t by either trading locally ($E_{n,t}^{LEM}$) or trading with the grid ($E_{n,t}^{GRID}$), in step 2.

In step 3, the auctioneer sums up all peers' bids to the LEM $E_{n,t}^{LEM}$ in this single time interval t and computes a new price for the next time interval based on the imbalance between supply and demand. Instead of several iterations to find the optimal price in each period t when a stable equilibrium is found, as in most of the reviewed literature, a single iteration is done at each period and the unavoidable imbalance is used to adjust the price in $t+1$. As such, in this LEM imbalances are a tool to adapt prices in real time according to changing peers' needs. Relying on imbalances is an adaptation of the Walrasian concept to operate this market at a very reduced ISP, like minutes or even seconds, which can be very useful to frame the provision of flexibility services. To simulate the Walrasian LEM [15] an initial LEM price (λ_0) is arbitrarily set to 0.06 €/kWh, starting the iteration process. As proven in [14] and in this work's result, the Walrasian prices follow a predictable path between the peers' opportunity costs.

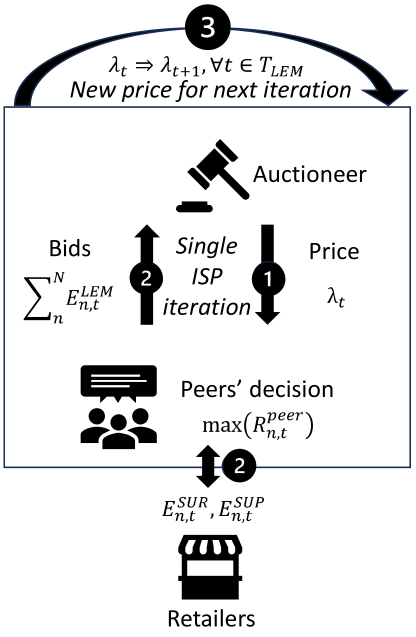

Figure 1: Illustration of the Walrasian LEM concept

The auctioneer mechanism in step 3 already presented in [14] uses a price adjustment factor A to obtain the next period price based on the previous period LEM imbalance ($\sum_n^N E_{n,t}^{LEM}$), as in (1). Also from [14], the auctioneer is responsible for these LEM imbalances, i.e., it trades with the grid the imbalances generated in the Walrasian LEM, which causes costs that must be share among all peers through a trading fee or other means. This sharing mechanism was not simulated in this work and should be subject of future research.

$$\lambda_{t+1}^{LEM} = \lambda_t^{LEM} + A * \sum_n^N E_{n,t}^{LEM} \tag{1}$$

From [11], $E_{n,t}^{LEM}$ is the energy bought from the LEM by a peer n, or sold if negative.

B. The peers' decision algorithm

The peer's decision algorithm corresponds to a MILP optimization problem that every peer having a storage system runs in each period t to decide their LEM bid $E_{n,t}^{LEM}$ in the initial period t. This problem is also used to reschedule the dispatch of the storage assets in the following t periods. This is done via the maximization of the welfare MILP objective function given by (2).

$$max \sum_{t \in T} \big(E_{n,t}^{SUR} \cdot \lambda_{n,t}^{g\_sell} - E_{n,t}^{SUP} \cdot \lambda_{n,t}^{g\_buy} - E_{n,t}^{LEM} \cdot \lambda_t^{LEM}\big) \tag{2}$$

In this welfare function each peer can be supplied ($E_{n,t}^{SUP}$) or can sell its surplus ($E_{n,t}^{SUR}$) to its Retailer at the grid prices $\lambda_{n,t}^{g\_buy}$ and $\lambda_{n,t}^{g\_sell}$, respectively. Conversely, the peer can trade locally with the LEM, paying the auctioneer's price λ_t^{LEM}. Note that, while only $E_{n,t}^{LEM}$ for t (the ISP just dispatched) is sent to the auctioneer, peers do simulate all periods $t \in T_{peer}$ to take intertemporal decisions regarding their storage assets future dispatch. If the peer has no storage assets, expression (2) is still applied although the decision is simply to trade locally if $\lambda_{n,t}^{g\_sell} < \lambda_t^{LEM} < \lambda_{n,t}^{g\_buy}$ in the initial t.

Equations (3) to (8) represent the main constraints of the MILP problem. The trading energy equilibrium constraint in (3) enforces that all energy physically exchanged with the grid is traded either with the grid or with the LEM. The physical energy equilibrium in (4) ensures that $E_{n,t}^{MET}$ reflects the peers' assets' physical exchanges with the grid.

$$E_{n,t}^{SUP} - E_{n,t}^{SUR} + E_{n,t}^{LEM} = E_{n,t}^{MET} \qquad (3)$$

$$E_{n,t}^{MET} = E_{n,t}^{C} + E_{n,t}^{BC} - E_{n,t}^{G} - E_{n,t}^{BD} \qquad (4)$$

Constraints (5) to (7) are the main storage system constraints, where E_t^B is the energy stored in each battery, $E_{n,t}^{BC}$ and $E_{n,t}^{BD}$ are the charging and discharging decisions and η^{BC} and η^{BD} are corresponding efficiencies.. The state of charge $SOC_{n,t}$is limited between SOC^{min} and SOC^{max}, while P^{BMax} sets the power limit of batteries charge and discharge. Finally, (8) sets that the MILP variables are non-negative. Additional parameters are considered, as explained in the following section.

$$E_t^B = E_{t-1}^B + \left(E_{n,t}^{BC} \cdot \eta^{BC} - \frac{E_{n,t}^{BD}}{\eta^{BD}} \right) \qquad (5)$$

$$SOC^{min} \leq SOC_{n,t} = \frac{E_{n,t}^{B}}{E_n^{BN}} \times 100\% \leq SOC^{max} \qquad (6)$$

$$\frac{E_{n,t}^{BC}}{\Delta t}, \frac{E_{n,t}^{BD}}{\Delta t} \leq P^{BMax} \qquad (7)$$

$$E_{n,t}^{BC}, E_{n,t}^{BD}, E_{n,t}^{B}, E_{n,t}^{SUP}, E_{n,t}^{SUR}, SOC_{n,t} \geq 0 \qquad (8)$$

The MILP optimization is in fact a slight adaptation of the individual Self-consumption (ISC) stage one MILP described in [9].

III. DATA GATHERING AND SCENARIOS TO ANALYSE

As depicted in Figure 2, the LEM horizon (T_{LEM}) consists of the LEM simulation itself, i.e., all periods $t \in T_{LEM}$ the auctioneer and peers iterate to compute the local trading and prices. The peers' decision model ISC MILP horizons, however, runs sequentially in a moving window horizon where the initial t_{init} of the ISC MILP is always the current t of the LEM horizon, and the last initial ISC MILP t_{init} is the last period of the LEM horizon.

Since peers need the full ISC MILP horizon period to take a decision in the initial ISC period, the last ISC simulation stretches further than the LEM simulation.

Seven days were simulated in the LEM and each ISP is a 15-minute period according to the Portuguese CSC regulation, so T_{LEM} consists of 672 periods. The ISC MILP horizon was defined as 6h, therefore T_{MILP} equals 24 periods from current LEM t. To approximate the SOC to 50% by the end of the ISC LEM simulation, a constraint was included to set the final $SOC_{n,t_{final}}$ in each ISC MILP to $0.5 \times SOC_{n,t_{initial}} + 25$.

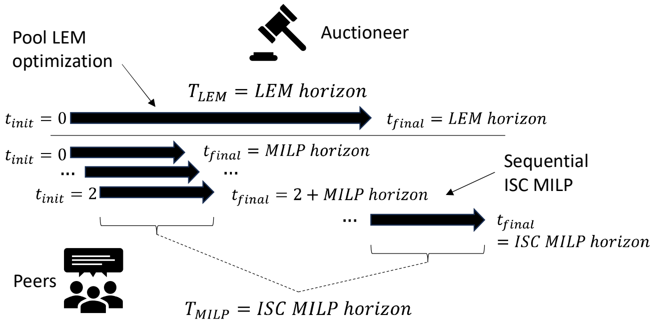

Figure 2: LEM and MILP time intervals simulation

TABLE I: PEERS PROFILE

	Contracted Power	Storage				PV Power kWp
		Power limit kW	Capacity kWh	SOC min	SOC max	
Peer1	3,45	-	-	-	-	-
Peer2	6,90	-	-	-	-	2,2
Peer3	6,90	2	6,40	15%	95%	-
Peer4	10,35	5	13,50	15%	95%	4,4

Four peers were simulated. Peer 1 is a consumer only, Peers 2 and 4 have PV generation assets and Peers 3 and 4 own storage assets, with the specs depicted in I. All data was estimated considering the Portuguese market background of February 2025. The load and generation profiles were estimated from [16], while the opportunity costs $\lambda_{n,t}^{g_{buy}}$ and $\lambda_{n,t}^{g\_sell}$ were estimated from Portuguese retailers, taking into consideration different grid-tariffs choices [17]. Since peers 3 and 4 own storage systems, they face flexible tariffs. Peers 1 and 2 opted for simple one price tariff for the whole simulation. In Portugal, all members of a CSC sell together the community surplus at the same price. The initial λ_t^{LEM}price was purposedly set to 0,06 €/kWh to be distant to the initial $\lambda_{n,t}^{g_{buy}}$ values and force an Auctioneer correction right in the first steps.

Since the ISC MILP needs LEM prices for the full ISC MILP horizon, an optimal community dispatch considering a Pool LEM optimization, as in [9], was simulated. This provides an optimal benchmark scenario, since the post-delivery Pool LEM optimizes the whole community dispatch for all $t \in T_{LEM}$. This is a strong assumption that peers can predict LEM prices, and it is useful to help simulate the core of this paper: the peers decision algorithm ISC MILP. Future research should analyze other solutions, such as using extended simulation periods and developing peers' decision algorithms that learn from past LEM iterations. The Pool LEM MILP is also used by the auctioneer in the strictly bounded decision algorithm described below.

Regarding the auctioneer algorithm, price factor $A = 0.1$ was considered. As expected, the Walrasian LEM prices fluctuate close to the opportunity costs with a certain delay since the auctioneer algorithm relies on imbalances to accelerate the price adjustment.

Two different auctioneer scenarios were initially tested in the LEM simulation. First a scenario with flexible price fluctuations where prices face no limitation and may stretch far beyond the optimal prices set by the Poll MILP, i.e., may reach values that are far beyond peers' opportunity costs to trade locally. This is a very crude application of the auctioneer algorithm (1), since the auctioneer has some inertia, i.e., a significant imbalance is required to correct the price mismatch.

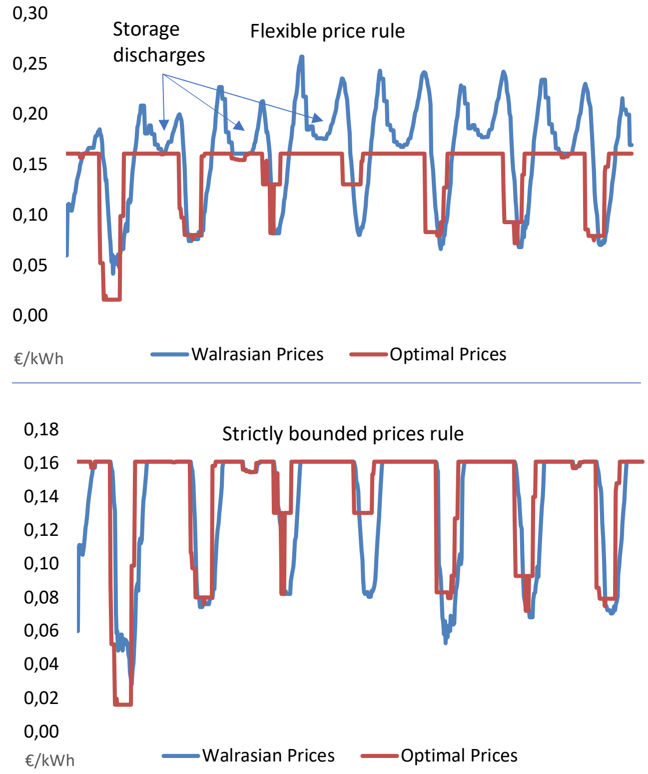

Figure 3: Walrasian LEM prices scenarios

As depicted in Figure 3, where the blue lines are the Walrasian LEM simulated scenarios prices and the red lines are the optimal prices from the Poll LEM MILP, the main problem in the flexible price simulation is the sharp price increment when PV generation from peers 2 and 4 ends after everyday evening. The rapid net-demand burst forces the auctioneer to respond quickly by increasing LEM prices; however, peers 3 and 4 who own the storage systems are slow in their discharge decisions. Since storage assets have a capacity limit, and since peers estimate future Walrasian LEM prices based on the optimal Pool MILP there is an inertia that holds peers 3 and 4 willingness to increase their discharge as soon as the Auctioneer price surpassed the optimal one. If they expected prices to be this high in the next periods they would have expected to discharge more. This is a clear limitation of the simulated bidding decision making algorithm, which is foresighted regarding future periods price signals. Although inefficient in terms of general market outcome, this strategy is lucrative for Peers 3 and 4, since they are guaranteed to trade with the auctioneer at these high prices. They are simply maximizing their own benefits at the cost of the auctioneer revenue. The flexible prices scenario price trends corroborates with the results in [14], where peers had no storage system and decision where not intertemporal. However, in the current work the price fluctuations also reflect peers 3 and 4 use of storage systems to earn improved profits.

To avoid such behavior, a strictly bound prices rule is included in the model where a limitation to LEM prices fluctuation is imposed assuming the auctioneer can also buy and sell energy with the grid at prices similar to peers 1 and 2. With this, it avoids proposing unreasonable prices that are too separate from the optimal equilibrium obtained in a community optimization. Although arbitrary in the simulation, this limitation makes sense, since it assumes that the auctioneer may also contract its own retailer to trade with the grid the LEM imbalances. It also assumes that, even if they could not trade with the grid, given time the auctioneer could learn the peers' behavior and avoid setting prices too distant from their actual opportunity costs. Of course, this would require a more complex auctioneer algorithm. The strictly bound prices scenario is the one considered in the results discussion.

IV. RESULTS

Each peer's trading decision is depicted in Figure 4. The middle yellow line is the LEM prices along the full 672 periods simulated. On the upper part are the periods the peers decided to trade with the auctioneer in the LEM. In the lower part are the periods peers decided to trade with the grid through their retailers. These trades can either be buy or sell bids, not differentiated here to simplify the representation.

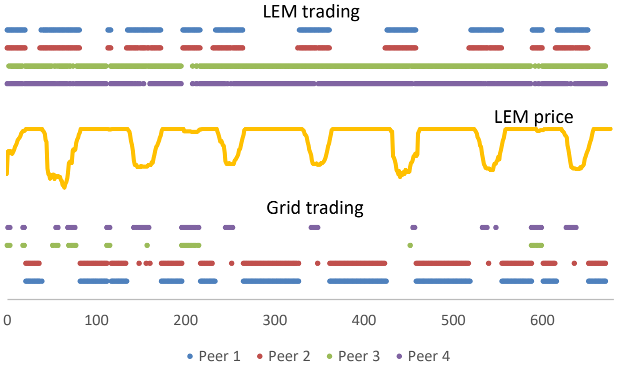

Figure 4: Peers' trading choices and Walrasian LEM prices behavior

Interestingly, peers 3 and 4 trade in the LEM on most of the periods. In part, this is due to the use of storage systems to maximize intertemporal benefits, storing energy when prices are low and discharging when they increase. Another reason is because these peers also face variable grid prices and often LEM prices are better for them. In fact, during valley price periods, peers 3 and 4 often buy energy from the grid to charge their batteries and sell in the LEM when prices peak in the next hours. Peers 1 and 2, who don't own storage systems, always trade locally when prices are lower than the upper boundary set to the LEM price. Peers 2, who owns a PV, sells some surplus in the LEM and to the grid during some price valley periods.

Table II summarizes the energy costs including LEM trades and grid exchanges of the Walrasian LEM, Pool LEM and a ISC MILP only scenario during the seven days period. The Walrasian LEM considered the strictly bound price rule.

Table II: Energy costs with LEM trades and Grid exchanges

	Peer1	Peer2	Peer3	Peer4	Auctioneer	Total
Walrasian LEM	5,45 €	5,13 €	16,35 €	8,23 €	7,90 €	**43,05 €**
Pool LEM	6,60 €	3,67 €	20,14 €	6,75 €	- €	**37,16 €**
ISC MILP	6,65 €	8,00 €	20,39 €	10,15 €	- €	**45,18 €**

As expected, Pool LEM obtained the lowest cost. However, the Walrasian LEM was only slightly better than the ISC MILP. The auctioneer faced significant costs due to the imbalances of the Walrasian LEM, consuming most of the peers' cost reductions in comparison to the ISC MILP. In future research, these imbalance costs must be included in peers' decision algorithm to adequately incorporate the actual opportunity costs of LEM trades. Peer 3 obtained the best savings from Walrasian LEM, from 20.39 € to 16.35 €, also surpassing the Pool LEM. This occurs because in the input scenario, in some periods, Peers 1 and 2 had supply prices from the grid lower than Peers 3 and 4 surplus prices to sell to the grid. This generated some odd behaviors in the pool mechanism, but interestingly not in the Walrasian LEM due to the natural inertia of the Auctioneer price algorithm. In fact, all peers are better off in the Walrasian LEM comparing to the ISC MILP. Oddly, the ownership of PV of peers 2 and 4 made them increase costs in comparison to the Pool LEM, while peers 1 and 3 reduced their costs. This happened due to the lower boundary price cap used in the strictly bounded prices rule scenario being lower than the optimal Pool LEM price, as shown in Figure 3, meaning that peers 2 and 4 sold to peers 1 and 3 at very low prices during peak PV generation.

Out of a total of 194 kWh consumed in the week in the Walrasian LEM scenario, only 49 kWh, or 25%, is procured locally, and 75% is supplied from the grid. A total of 44 kWh is exported to the grid, instead of sold locally. The Walrasian LEM results show that it is unable to efficiently use locally the peers' generation. The Pool MILP, optimal by definition, trades locally 101 kWh of its total 219 kWh local consumption. Note that the higher consumption in Pool LEM is due to the abundant use of batteries to arbitrage with the different peers' opportunity costs, i.e., peers are often charging and discharging their storage systems to allocate to others. This phenomena was explored in [10]. The Pool LEM is an optimal solution, so it is expected to generate more local trades in comparison to the Walrasian LEM. However, this may also reflect limitations regarding the peers' bidding algorithm, as well as the fact that price fluctuations rely on imbalances and imbalances are also partially missed trade opportunities.

V. CONCLUSIONS

This work is the first attempt to fully simulate a Walrasian LEM combining an Auctioneer pricing mechanism with Peers' biding mechanism and storage systems. The results are still preliminary, and some relevant limitations were pointed out, such as the difficulty in including forecast of future LEM prices in the Peers decision MILP, the missed LEM trades issue, and the high price inertia which may lead to temporary out of boundary pricing trajectories.

However, it was proven that the Walrasian LEM with complex peers' decision-making algorithms still leads to well-behaved price fluctuations and may be used to operate flexible systems reflecting opportunity costs from the grid. This has high potential to provide grid services as implicitly flexibility. This LEM is also decentralized and was simulated with very limited exchange of information between peers and Auctioneer, although a strong assumptions regarding future LEM prices using an optimal MILP is used. In realistic LEM applications, this may be a significant advantage, since peers often resist providing the sort of information required by Pool like LEM to optimize trades.

The next paragraphs enumerate some prospects for future work:

- The Walrasian *tâtonnement* can be improved by considering additional iteration rounds within each ISP. This may reduce the price inertia at the cost of more iteration rounds. Also, the auctioneer can provide more information to the peers, like, for instance, the price factor A, or total imbalance that was obtained in the previous round. This, however, could be used by peers to infer the competitors' bids.
- The auctioneer algorithm can also be improved by using a Newtonian model [15], or other innovative rules.
- A mechanism to share the auctioneer imbalance costs among the peers should be incorporated into the peers' decision algorithm.
- Additionally, more intelligent decision-making MILP algorithms can be tested, especially regarding new methods to forecast future auctioneer LEM prices.
- A key advantage of the Walrasian LEM is its decentralized decision-making structure, which allows it to scale to larger LEMs. Further testing with a higher number of participants having more distinct characteristics should be conducted to gain more insight into the behavior of the algorithm.

ACKNOWLEDGMENTS

This work was financed by ENPOWER ("Energy Activated Citizens and Data-Driven Energy-Secure Communities for a Consumer-Centric Energy System") project that has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement 101096354. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

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