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Explorative Implementation of Open-Source Peer-to-Peer Energy Trading Approaches

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Abstract—P2P energy trading pilots have proved some of their benefits for prosumer and renewable energy valorisations. Simultaneously, the electricity market regulations have been prepared to allow new business models in the electricity sector. However, P2P energy trading is not yet generalised, although the research literature is increasing and the integration of renewable energy production is inevitable. The authors assume this lack of adoption is partly due to few works on decision-making to select and implement an energy sharing scenario. This work aims to identify some major challenges with P2P energy trading to make decision-making based on simulations. The implementation presented in this article concerns the centralised communication aspects.

Keywords—Smart Grids, P2P Energy Sharing, Optimisation, Centralised architecture, Multi-agent architecture

I. INTRODUCTION

Controlling greenhouse gas emissions of the electricity industry has been a major concern of the European Union (EU) for over two decades. Climate change constraints the sector to massively introduce renewable sources. These new sources of energy are primarily intermittent and localised. It brings additional challenges to grid management. One of the solutions of the digitalisation of the energy sector is notably through the deployment of the smart grid. The combination of digital tools to power utilities allowed the emergence of new actors and business models that economically valorise every contribution to reducing greenhouse gas emission and energy consumption. For a decade, a new energy market was designed to allow commercial competition among companies all around the European Union and ease the introduction of new distributed power generation. In 2015, self-consumption was promoted [1], while, in 2019, a new directive reviewed the standard rules for the internal electricity market [2].

These evolutions have made possible new business models in the electricity sector and new services available on the energy infrastructure such as virtual power plants [3], flexibility markets [4], distributed energy resources (DERs) [5] and demand response (DR). Furthermore, new stakeholders, namely prosumers [6], have emerged, constraining historical actors to evolve. Alongside the concept of prosumer, the peer-to-peer (P2P) energy sharing/trading has perked up as a new energy market model that contributes to the valorisation of DERs, notably renewable energy sources owned by prosumers. The interest for this topic in scientific literature increased [7], and numerous pilot projects were realised, as listed in [7]–[9], and European projects, such as SHAR-Q [10] and P2P-SmarTest [11]. These technologies and engineering seem to strengthen the resilience of our society and our economy.

However, P2P energy trading remains mainly as pilot projects [9]. It can be quite surprising as regulation has been prepared to allow P2P energy trading, and the price of

equipment such as photovoltaic panel and battery storage is decreasing. Some of the locks that slow down the adoption of P2P energy trading are notably privacy and data protection, cybersecurity concerns, grid constraints and loss, the coexistence of conflicting stakeholders, post-settlement uncertainty, and scalability for a large number of participants [9], [12]. Another aspect is the awareness of professional actors concerning smart grid concepts and notably P2P energy trading. Initiatives such as the European project Smagrinet [13] contributes to spreading the word. However, the authors think there is another issue that is not tackled: supporting the decision-making process. Actors targeted by outreach programs like Smagrinet, such as policymakers and their team, have to deal with the evolution of the energy sector and need to make the right choice for the community without being an expert. Scientific literature provides various studies related to the P2P energy trading scenario; however, none seems to have a decision-making perspective. Besides, research such as [14] provides some insight in providing a tool to model and compare scenario, although it is not explicitly applied to P2P energy sharing.

The article aims to experiment with the feasibility of implementing P2P energy trading simulation using open-source tools. This experimentation is limited to centralised communications aspects, but it may identify difficulties a decision-maker may face when comparing scenarios. This research must be seen as a basis for implementing more complex frameworks in order to compare different P2P energy trading alternatives into a unique open-source tool.

The paper is organised as follows: Section II presents the concepts related to P2P energy trading, section III describes the research design, section IV gives the study findings. Finally, section V presents the conclusions and perspectives for future research.

II. EXISTING THEORIES & PREVIOUS WORKS

A. Concept of P2P energy trading

Peer-to-peer energy trading defines a decentralised structure where all peers co-operate with what they have available for commons-based producing, trading or distributing a good or service [12]. It is enabled by distributed cyber and physical devices, also known as eIoT, which allows the remote control and monitoring of electric components [15]. Digitalisation and eIoT are enablers of P2P energy trading which is available when the electricity production and consumption devices are connected to the network and checks how much energy the prosumer produces and consumes and the information on energy other consumers need [8]. It is a platform that can facilitate the independent decision-making process of prosumers to trade their energy within a connected community [9]. The common principle of P2P energy trading is a web service providing a window for

electricity suppliers and consumers to acquire information and conduct transactions [8].

B. Characteristics of P2P energy trading

Although the principle is similar regardless of the implementation, various characteristics distinguish one implementation from another. The first one is the market design, a combination of trading process and communication process that can be either coordinated or centralised [9]. Here are some of the configurations identified in the literature and can be classified into Table I:

- Coordinated market is when both the trading process and the communication of information are done in a centralised way [9].
- Decentralised market is a configuration where peers communicate directly with each other [9]. As a result, they have full control of their decision-making process. It is also known as a full P2P market [12].
- Community market combines a centralised communication between prosumers, although the trading process is done in a decentralised way [9]. The centralised coordinator only communicates price signals and does not control the export and import of energy [9]. Each prosumer's part of the community solves its own optimisation problem [12].
- Hybrid P2P market appoints a larger system where both community and decentralised markets are implemented [12].

TABLE I. DIFFERENT TYPES OF MARKET FOR P2P ENERGY SHARING [3]

		Communication process	
		Centralised	Distributed
Trading process	Centralised	Coordinated Market	/
	Distributed	Community Market	Decentralised Market

Aside from the market design, other aspects characterise the P2P energy sharing scenario, such as the communication technology and the protocol used to secure communication, the controllability of the DERs, the algorithm used for trading calculation [16], the technology used to measure the consumption and the quality of the data provided [9].

Another perspective to see the P2P energy sharing is to split it into two layers [9]:

- The physical layer that gathers the electric infrastructure, the communication infrastructure and the metering devices.
- The virtual layer of the information system, the energy management system and all decision part including market operation and pricing mechanism.

It means that when a P2P energy trading system is simulated, it focuses on the virtual layer.

C. Simulating P2P energy trading

In the scientific literature related to P2P energy sharing, two main approaches were identified: multi-agent system [3], [17] and multi-objective optimisation [14], [18]. The optimisation provides the best parameters to the system, whereas the multi-agent system eases the interaction between prosumers and a potential central coordinator. Both can be

used to simulate or deploy a system as the multi-agent system presented in [19].

III. METHODS

A. Study objectives and approach

There are various aspects to consider regarding the P2P energy trading scenario before choosing those that will be implemented. The best way to do it is to simulate and generate indicators that will contribute to the decision-making process. However, although scientific publications use simulations for their studies, few of them provide the source code. It provides a framework to simulate a distribution network, but no clue is provided concerning the P2P energy sharing community. Meanwhile, the replicability of P2P energy trading works to anyone who wants to implement it in its specific localisation and territory is an issue. Therefore, the authors think it would be beneficial for the research community and the economic actors to have access to resources that compare different strategies to implement P2P energy trading according to local specificities. However, preliminary works have to be done to check feasibility and identify issues that someone may face when starting it from scratch. So, the research questions of this work can be formulated as follows:

What does it imply to make an open-source P2P energy trading simulation from a decision-making perspective?

This work aims to explore the feasibility of P2P energy trading simulations with open-source tools. The approach adopted is inspired by the research action method. It means the authors explore the topic while the source code is made freely available to be integrated into outreach programmes as quickly as possible.

B. Case study

The simulation requires a use case, so the authors decided to consider four buildings with photovoltaic power generation and battery-based storage systems. In order to have realistic data, the use case was based on the infrastructure and data of the city of Lorient, France. Given the low maturity of energy ecosystems to collect and capitalise on reliable data in large quantities, several weeks were spent with French local authorities and start-ups between June and August 2020. Inspired by small case studies such as [20], the authors arbitrary decided to do the simulation with four buildings according to the structure shown in Figure 1. Each building was fictively equipped with a photovoltaic (PV) panel and a battery energy storage system (BESS).

The characteristics of the PV and BESS are detailed in Table II. Outside this information, batteries are considered similar to a minimal and a maximal state of charges of respectively 0.2 and 0.8. In order to simplify the optimisation issue, other parameters of the battery are considered perfect, meaning both charging efficiency and discharging efficiency are equal to 1, and self-discharging is 0. Concerning the PV's array, the information provided by Table II allows the calculation of the power production with the irradiance provided by the Solcast API [20].

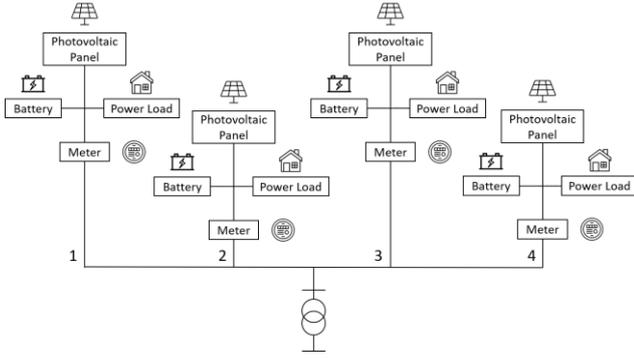


FIGURE 1. ARCHITECTURE OF THE NETWORK SIMULATED

TABLE II. CHARACTERISTICS OF GENERATION AND STORAGE EQUIPMENT

ID	PV panel	BESS
1	Efficiency: 0.16 Surface: 180 m ²	Nominal capacity: 3.99 kW
2	Efficiency: 0.153 Surface: 650 m ²	Nominal capacity: 2.98 kW
3	Efficiency: 0.144 Surface: 250 m ²	Nominal capacity: 29.4 kW
4	Efficiency: 0.16 Surface: 150 m ²	Nominal capacity: 18.83 kW

C. Methodology

As presented previously, two paradigms are considered: multi-agent system and optimisation problem. For example, balancing the power between prosumers and the grid can be considered an optimisation problem, whereas prosumers can be considered agents in the balancing system. The energy flow that an agent has to manage is schematised by Figure 2.

The optimisation problem aims to determine the quantity of energy exchanged with the grid at each time slot Pg_t as well as the power stored by the battery W_t . The prosumer or the cluster of prosumers can import or export energy, which means $Pg_t \in \mathbb{R}$. The energy stored by the battery is limited by its specification $W_{min} \leq W_t \leq W_{max}$.

a) Objective function

The problem is characterised by an objective function that tends to minimise the cost of energy. When energy is imported ($Pg_t \in \mathbb{R}^+$), the tariff of the energy is those of the grid (GT_t), whereas when energy is exported ($Pg_t \in \mathbb{R}^-$), it is the feed-in-tariff (FIT_t) that is applied. This function is formalised by the formula 1, where N is the number of time slots.

$$\min \sum_{t=0}^{N-1} (Pg_t \times 1_{\mathbb{R}^+}(Pg_t) \times GT_t + Pg_t \times 1_{\mathbb{R}^-}(Pg_t) \times FIT_t) \quad (1)$$

$$1_I(x) = \begin{cases} x & \text{if } x \in I \\ 0 & \text{else} \end{cases} \quad (2)$$

b) Constraints

As with most of the energy system, the prosumer or the cluster of prosumers has to be balanced. It means the inputs and the outputs represented by Figure 2 have to be equal. The mathematical representation of this constraint is given in formula 3, where Pbd_t and Pbc_t are the energy that discharge (\mathbb{R}^+) and charge the battery (\mathbb{R}^-), Ppv_t is the energy produced by PV panels (\mathbb{R}^+) and Pc_t is the energy consumed

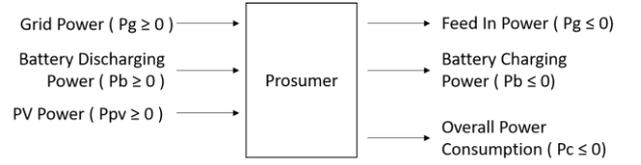


FIGURE 2. PROSUMER ENERGY FLOW

by the prosumer or the cluster (\mathbb{R}^-). However, to reduce the calculation, boundaries can be defined for Pg_t . In the worst case, all the energy consumed by the prosumer is imported from the grid, meaning $Pg_t \leq \max(Pc_t)$. The opposite scenario consists of exporting both the produced and stored energy, meaning $Pg_t \leq -\max(Pbd_t) - \max(Ppv_t)$.

$$Pg_t + Pbd_t + Pbc_t + Ppv_t + Pc_t = 0 \quad (3)$$

Ppv_t is the production of energy by the photovoltaic panel for the time slot t . Its value is either positive or null ($Ppv_t \in \mathbb{R}^+$) and can be calculated with formula 4, where A_i is the surface of the PV panel, μ_i is the efficiency of the panel and GHI_t^i is the global horizontal irradiance that varies according to the time slot considered and the localisation of the panel.

$$Ppv_t^i = A_i \times \mu_i \times GHI_t^i \quad (4)$$

As represented by Figure 2, Pbd_t and Pbc_t are respectively the discharging and charging energy of the battery. The energy from the discharge of the battery is considered positive ($Pbd_t \in \mathbb{R}^+$), whereas the energy that charges the battery is negative ($Pbc_t \in \mathbb{R}^-$). However, the charging and discharging energy are limited by the battery capacity. The battery state of charge is bounded as formula 5, where SOC_t^i is the state of charge of the battery i at the time slot t . SOC_{min} and SOC_{max} are respectively the minimum percentage of discharge and the maximum percentage of charging.

$$SOC_{min} \leq SOC_t^i \leq SOC_{max} \quad (5)$$

These bounds allow the reduction of the limit for the charging and discharging energy as in formulas 6 and 7, where W_{NC} is the nominal capacity of the battery.

$$0 \leq Pbd_t \leq W_{NC} - W_{min} - W_{max} \quad (6)$$

$$0 \geq Pbc_t \geq W_{NC} - W_{min} - W_{max} \quad (7)$$

However, in order to identify the power stored by the battery, Pbd_t and Pbc_t have to be reformulated according to the power charge or discharge from the battery (formulas 9 and 10). W_{t-1-t} represents the energy charge ($W_{t-1-t} \in \mathbb{R}^-$) or discharge ($W_{t-1-t} \in \mathbb{R}^+$) between two time slots $t-1$ and t . It allows the inclusion of the self-discharge rate (σ) as well as the charging and discharging rate, $\eta_{C,t}$ and $\eta_{D,t}$, respectively.

$$W_{t-1-t} = W_{t-1} \times (1 - \sigma) - W_t \quad (8)$$

$$Pbd_t = \begin{cases} W_{t-1-t} \times \eta_{D,t} & \text{if } W_{t-1-t} > 0 \\ 0 & \text{else} \end{cases} \quad (9)$$

$$Pbc_t = \begin{cases} W_{t-1-t} / \eta_{C,t} & \text{if } W_{t-1-t} < 0 \\ 0 & \text{else} \end{cases} \quad (10)$$

The objective function and the constraints provide the main elements to optimise one prosumer. The next section will detail how it has been implemented.

D. Implementation

The introduction referred to a multi-agent system because an energy system comprises several actors and prosumers, and they may interact with each other. So, the architecture of the implementation is based on the multi-agent principle, where each prosumer is an agent. The MESA framework [21] was used to do this. This framework was chosen from the framework available in Python that was reviewed in [22]. Each prosumer agent embeds the ability to run the optimisation described previously and implement with the Pymoo [23] library. The source code of this experimentation can be found on GitHub [24].

The study case set four buildings with BESS and PV panels simulated over one day. The duration of the time slots was defined as 10 minutes according to the data consumption data collected. It means the simulation was done for 144 time slots to cover one day. The case study defines some constant values, such as the PV panel and BESS characteristics shown in Table II. In addition, it required the load profile for each building, provided by partners, and the grid price, the feed-in-tariff and the global horizontal irradiance.

To simplify, for the first time, the implementation and the interpretability, BESS is considered as ideal, meaning the self-discharge is null ($\sigma = 0$), and the charging and discharging efficiency are perfect so $\eta_{C,t} = 1$ and $\eta_{D,t} = 1$.

The optimisation was done at the beginning of the first day (the first time slot),

In order to identify and interpret the impact of the optimisation in the simulation, two other configurations were simulated. The first was the most basic; each prosumer was only equipped with a PV panel, meaning they had to consume or sell the energy produced. The second scenario added BESS to prosumers, with the priority to store energy and only sell energy to the grid when they are full of charge.

IV. FINDINGS

A. Collected Data

The two main output observed are the energy transferred from or to the grid ($P_{g,t} \in \mathbb{R}^+$) and the state of the battery ($W_{NC} \times SOC_{min} \leq W_t^i \leq W_{NC} \times SOC_{max}$). However, additional indicators have to be defined to observe the impact of the optimisation of energy systems. The first one is the self-sufficiency index that measures the energy autonomy that can be formulated as 11, where $P_{C_{total}}$ is the total energy consumed by the prosumer and $P_{g_{total}}$ is the total energy imported from the grid. In the case of a positive building

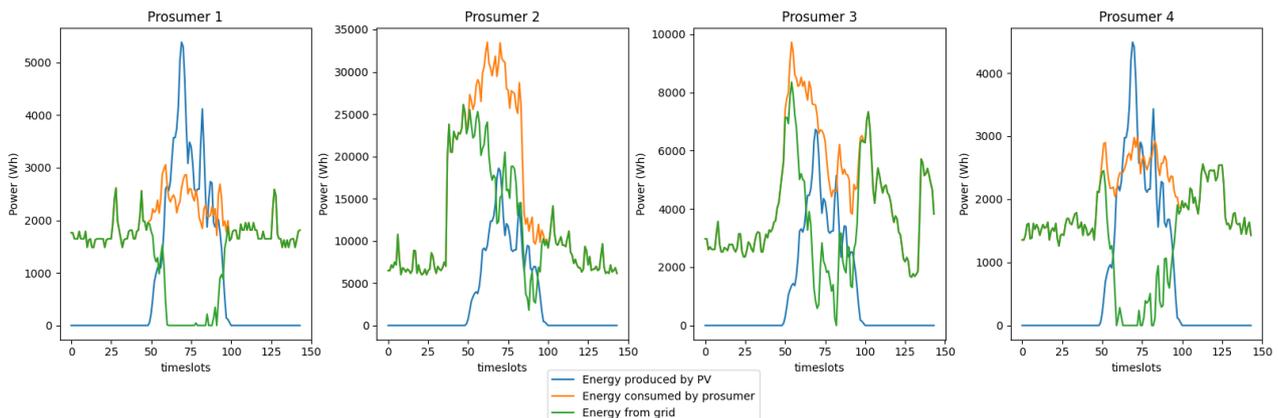


FIGURE 3. CONSUMPTION, PRODUCTION AND IMPORT FOR THE PV ONLY SCENARIO

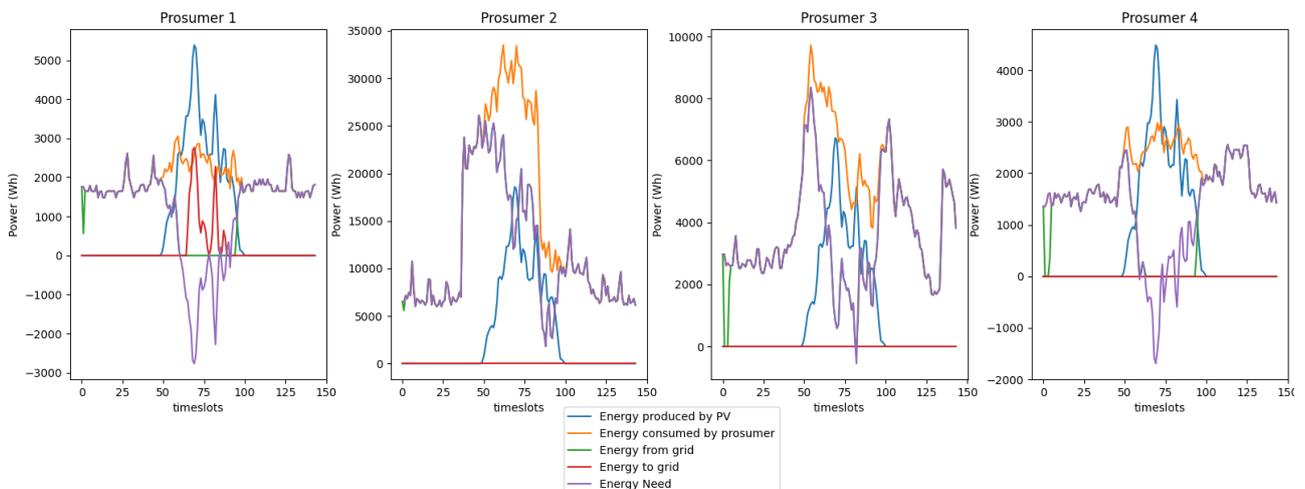


FIGURE 4. CONSUMPTION, PRODUCTION AND IMPORT FOR THE PV + BATTERY SCENARIO

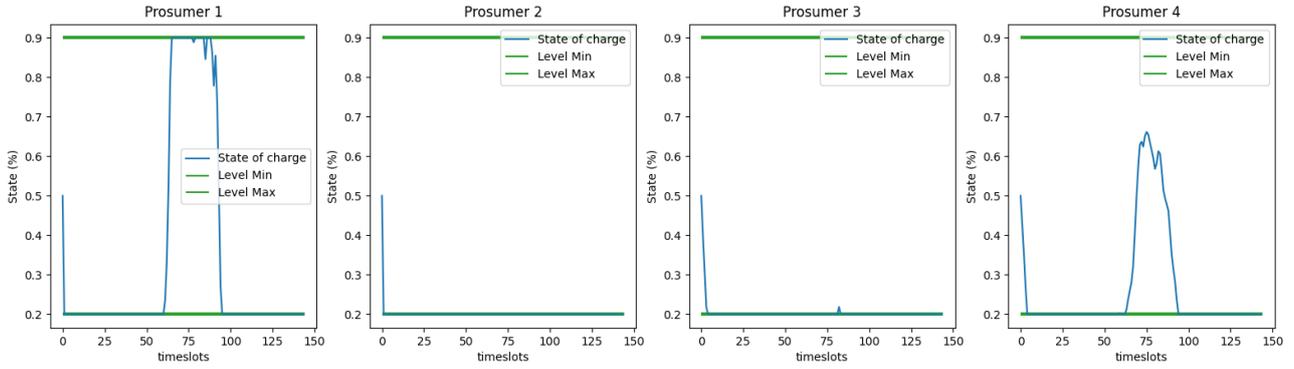


FIGURE 5. STATE OF THE BATTERY FOR THE PV + BATTERY SCENARIO

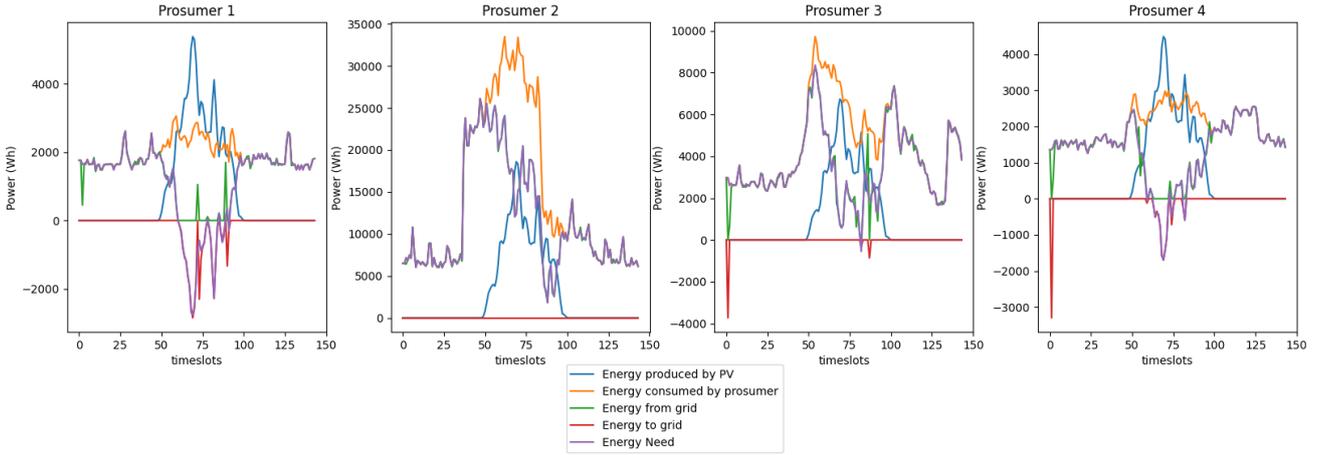


FIGURE 6. CONSUMPTION, PRODUCTION AND IMPORT FOR THE OPTIMISATION SCENARIO

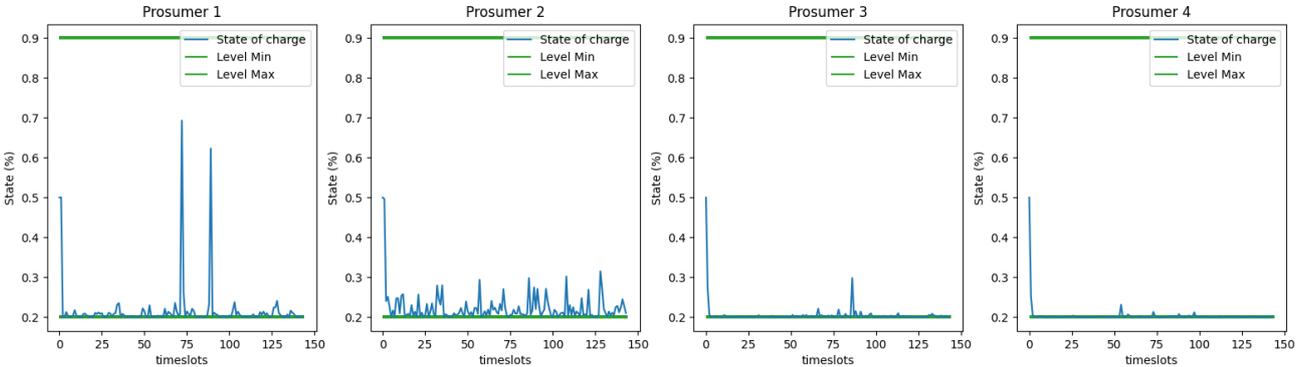


FIGURE 7. STATE OF THE BATTERY FOR THE OPTIMISATION SCENARIO

where production is higher than consumption, the self-sufficiency index may be higher than 100%.

$$SS = \frac{P_{c_{total}} - P_{g_{total}}}{P_{c_{total}}} \quad (11)$$

The second indicator to compare is the total cost of energy. This cost is induced by the price of the energy imported from the grid. In order to provide further flexibility in the optimisation, the grid price evolves with the time slots according to an extraction of the spot market. So, there are two ways to reduce the global cost, using stored energy when it is cheaper to use it and when energy is more expensive or selling energy when there is an excess.

a) Scenario Without Battery

This scenario simulates prosumers that only possess PV panels. Their consumption and production profile is shown in Figure 3. The self-sufficiency index was 21.94%, and the global cost of energy was 154.53 €.

b) Scenario With Battery

In this case, the battery was added to PV panels with the simple rule of prioritising charging the battery over selling energy to the grid. It led to the profile illustrated by Figure 4, and the self-sufficiency index was calculated to 23.81%, and the global cost was around 152.70€. Figure 5 illustrates the usage of the battery.

c) Scenario With Optimisation

This scenario tries to minimise energy cost by running an optimisation for each prosumer at the beginning of the simulation and using this optimisation as a reference for the

battery state. It led to a consumption profile shown in Figure 6, a self-sufficiency index of 22.55% and a global cost of 153.97€. The usage of the battery is provided in Figure 7.

B. Analysis of Collected Data

All of the graphs generated by the simulation lead to several comments. It can be noticed that the BESS of prosumer 2 and 3 are unused in the PV + battery scenario (Figure 5). It does not mean the BESS is useless, but the day's consumption is likely so important that the production does not even allow partial charging of the battery. In this scenario, the top time slots are objecting to reducing the energy importation from the grid; it is due to the initial state of batteries set to 50%. It is done at the beginning of the simulation as no rules have been set to do it smarter. Similar behaviour can be seen in the optimisation scenario, but this time, the energy is sold to the grid (red line on Figure 6 for prosumer 3 and 4). Although the objective of the optimisation is to minimise the cost, it also explains why the battery maintained its minimal state of charge (Figure 7).

Regarding the other indicators, the evolution of the self-sufficiency index (summarised in Table III) is quite surprising. The optimisation scenario is worse than the battery scenario without optimisation for self-sufficiency. The optimisation function may explain it. From the global cost perspective, there are few differences between the scenarios, but as shown, the optimised scenario is not the best one.

TABLE III. THE SUMMARISATION OF THE DIFFERENT SCENARIOS

Scenario	Self-sufficiency index	Global cost
Only PV panel	21.94 %	154.53 €
PV panel & BESS	23.81 %	152.70 €
PV panel & BESS with optimisation	22.55 %	153.97 €

C. Discussion

It was expected that using an optimisation approach to identify energy exchange and batteries state of charge; however, neither the self-sufficiency index and the global cost is not improved. It means the optimisation problem is either poorly formulated or poorly implemented. Several difficulties were met when implementing optimisation using Pymoo. At first, the behaviour of the genetic algorithm did not reach a suitable solution due to the poor implementation of the vectorial calculation. However, once the optimisation problem was properly transposed into the vectorial calculation, it was compatible with Pymoo. The second challenge was to implement this optimisation into the multi-agent system. The optimisation problem can be improved to valorise better the energy stored in the battery to avoid an empty battery.

This implementation shows the feasibility of simulating an energy system for P2P energy trading; however, the actual implementation only covers the communication process in a centralised way using the multi-agent system. Nothing has been done on the trading aspects.

V. CONCLUSION

A. Limitations

This work aims to experiment with implementing a P2P energy trading simulation system from an open-source

perspective. Three simulations were done and released on GitHub [24]; however, it only covers the centralised communication aspects of P2P energy trading. Due to development difficulties, the simulation does not cover an entire P2P energy trading. From the communication perspective, comparing centralised and decentralised setups would have required implementing blockchain. Concerning the trading aspects, it has to be implemented to notice an evolution in the consumption profile. The current implementation of genetic algorithms to optimise the energy transfer and the battery state of charge does not improve the self-sufficiency and global cost compared to expectations. Implementing trading aspects implies modifying the actual agents to communicating agents. From comparing the scenarios, additional indicators have to be explored for better comparability, such as the Overall Performance Index [25].

B. Concluding Remarks

The initial approach was adopted to make the simulation algorithms be model-based software design. This approach was not as fruitful as expected. A lot of time was spent debugging. An iterative approach enabled the creation of simple simulations that were iteratively improved with new features. Each iteration was then used to check the progress between the different scenarios.

The implementation of the P2P energy trading scenario was much more time consuming than expected. It is not realistic that the decision-maker spends days implementing one approach from scratch. Therefore, efforts have to be made to ease and simplify the implementation and the comparability. Another aspect is the data used to compare; it was time-intensive and required negotiation with economic actors to have enough detailed data to do the simulation. In order to create a kind of benchmark to compare the different alternatives, it would require a freely accessible dataset with the features required for P2P energy trading. Once again, this dataset has to integrate variations related to climate and geographical position with the decision-making perspective. An alternative to this dataset is creating various predictive models for production and consumption according to, at least, the location and the weather. The main aspect remains the accessibility of the simulations to any actors who want to engage in this kind of comparative approach. For this reason, the source code of our extermination has been released. It could accelerate the process for anyone in the community who wants to simulate the energy system and P2P energy trading.

C. Future Work

In the perspective to assist decision-makers, the authors think additional work has to be done to create a framework that would allow modelling a P2P energy trading system and compare the advantages and drawbacks of the different trading mechanisms and coordination mechanisms. It is even more important that policy encourages auto consumption and P2P energy sharing, but no tools permit to compare modalities of this new economic model with transparency. The next step can be split into four axes:

- Identify or create a dataset that can be used as a reference to compare results of P2P energy trading.
- Explore the possibility of creating predictive models for consumption and prediction to bypass dataset needs.

- Extend the actual experimentation with centralised and decentralised trading aspects.
- Create a framework that allows modelling a P2P scenario and simulate it in order to generate indicators.

This work is a first step based on open innovation, open technology, and open engineering for P2P energy trading supporting environmental and economic resilience.

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