Modelling and techno-economic analysis of Peer-to-Peer electricity trading systems in the context of Energy Communities

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***Abstract*—The increasing penetration of Renewable Energy Resources (RES) is an opportunity to empower citizens to actively participate in energy markets through energy communities. At the local level, the Peer-to-Peer (P2P) trade and exchange of renewable energy represents a valid solution to fulfil the energy demand of the members, increase self-consumption and obtain economic benefits. However, a proper evaluation of the benefits for the community would require new considerations in designing typologies, composition, sharing and pricing mechanisms. Based on these premises, this paper explores the possible influences of different community-based P2P trading systems by examining several categories, ranging from aggregation structures, market mechanisms, sharing policies and pricing mechanisms internal to the local market. Furthermore, a flexible Mixed Integer Linear Programming model was formulated to optimise the day-ahead scheduling of community members participating in the P2P energy market. In this way, different community types, sharing policies, and pricing mechanisms were tested. Finally, the optimisation results were evaluated based on several key parameters.**

***Index Terms*—Peer-to-Peer trading system, Optimisation, Energy Community**

I. Introduction

The increasing number of small scale power generation sources located at the household premises are able to generate a significant amount of power from solar, wind and geothermal sources. Harnessing of these resources would mitigate the congestion and enhance the utilisation of the main grid. Consequently, the role of prosumers, i.e., producers and consumers at the same time, is becoming increasingly important.

Potentially, prosumers could participate in the trading market as sellers, either individually or at the community level. Community-based trading markets have gained attention in recent years [1], and several Peer-to-Peer (P2P) market platforms have been established and tested, for example, in Germany (sonnenCommunity), the United States (Brooklyn Microgrid) and the Netherlands (Vandebron) [2]. Local P2P markets are characterised by active management of individuals, where direct communication and negotiation are feasible between end-users and with trades settled at an agreed price.

There are several studies on this topic in the literature. For example, [3] provides a comprehensive summary of Energy Communities (ECs), comparing different typologies, opportunities and related challenges. In [4], an overview of the P2P market is provided, examining challenges, motivations, and market designs of the P2P market. Moreover, [3] also provides a realistic test case for simulating P2P market designs. In [5], [6] mathematical models are established in terms of distributed and decentralised scenarios. Several solutions have been put forward in both collective way [7], [8] and separate ways [9]. However, when analysing the characteristics of the P2P market, the focus is usually on the economic aspect, while community welfare is often neglected. Indeed, to evaluate the performance of a community-based P2P market in a comprehensive way, it is necessary to couple the modelling of the P2P electricity market system design based on optimal sharing, and pricing mechanisms aim to maximise economic benefits, with the modelling of the energy choices of the community members.

As highlighted in [10], the price mechanism plays a crucial role in energy communities. Namely, the pricing mechanism determines how prosumers can sell their surplus energy to other participants in a competitive P2P market (P2P LEM). In this context, an effective pricing mechanism has yet to be found. Instead, the sharing policy expresses how the community energy resources, which can be in-common or distributed, consisting of PV generators, Electric Vehicles, or Energy Storage Systems, are shared among the participants. This topic was originally addressed in [11]. However, it is not comprehensively covered.

This papers investigates various pricing mechanisms and sharing policies in different energy community setups. In particular, this study extends the work done in [12] and [11] as described in the following. The Mixed-Integer Linear Programming (MILP) introduced in [12] was extended to include both a Non-Shared Resources Energy Community (NSR-EC) and a Shared Resources one (SR-EC), therefore adapting the formulation on the basis of the input configuration. For the sake of clarity, we defined SR-EC as a community consisting of simple consumers who decide to share their batteries and the solar energy generated by their PV plants in a sort of centralised RES and supportive community. Instead, we define NSR-EC as community based on the idea that several prosumers and consumers join together to form a community-based local energy market. In this arrangement, prosumers can sell their surplus energy to the other members of a community in a competitive P2P market. In this way, prosumers can earn more revenue by selling to the community than by selling to the grid, and at the same time, consumers pay less for that energy than they would in the stand-alone case, where each consumer and prosumer trades individually.

Several aspects have been further deepened. For example, w.r.t. [12], this work analyses not only the benefits for the whole community but also the effects on the different users. Indeed, an overall benefit for the community does not necessarily imply a benefit to certain types of users. Moreover, the market-clearing price was compared with post-clearing price mechanisms, such as Bill Sharing, Mid-Market Rate (MMR) and Supply and Demand Ratio [13]–[15]. Regarding the power grid, a dynamic retail price has been added to the previous Time-of-Use one. In previous studies, the way the community is composed was not deeply addressed. To this end, this work explores the composition of NSR-EC. On the other hand, in the SR-EC, the main focus has been the sharing policy. Several sharing policies introduced by [11] were further investigated, and new ones were analysed.

The results attained in this work were evaluated from both economic and technical viewpoints. Several assessment criteria were used in the form of Key Performance Indicators (KPIs). The principal ones are Net Costs, Self-Consumption Ratio, and Self Sufficiency Ratio. Both types of communities were found to be cost-effective for their members. In the NSR-EC, the best results are achieved with the clearing price and the MMR. Both prices lead to similar results from the aggregate point of view, but differences were found at the individual level. The rest of the paper is divided into three sections. Section II introduces the methodology, highlighting the flexibility of the framework. Section III presents results for the proposed scenarios comparing the obtained KPIs. Finally, Section IV draws conclusions.

II. Methodology

In this section, we present the framework for analysing different scenarios, ranging from shared self-consumption to local peer-to-peer energy markets (LEMs). An overview of the steps necessary to perform the simulations is depicted in Fig. 1, where the diverse macro-sections constituting the methodology are shown. This section deepens into every single block describing i) input configuration, ii) the flexible optimisation problem, with the pricing mechanism or sharing policy and iii) the performance assessment.

A. Input configuration

To analyse different energy community scenarios, the model requires different configurable inputs. The number of individuals within the community, i.e., the community size, is specified in a configuration file. Moreover, following the distinction made by [12], we divided the users into four different categories (i.e., $\mathcal{A}$, $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$). These groups represent, respectively: $\mathcal{A}$) simple consumers, $\mathcal{B}$) prosumers, i.e., households with photovoltaic (PV) panels; $\mathcal{C}$) consumers who own only a battery; and $\mathcal{D}$) households with PV panels and a battery. In the future, the group $\mathcal{C}$ could represent electric vehicle owners. The percentage of each type of user can be set

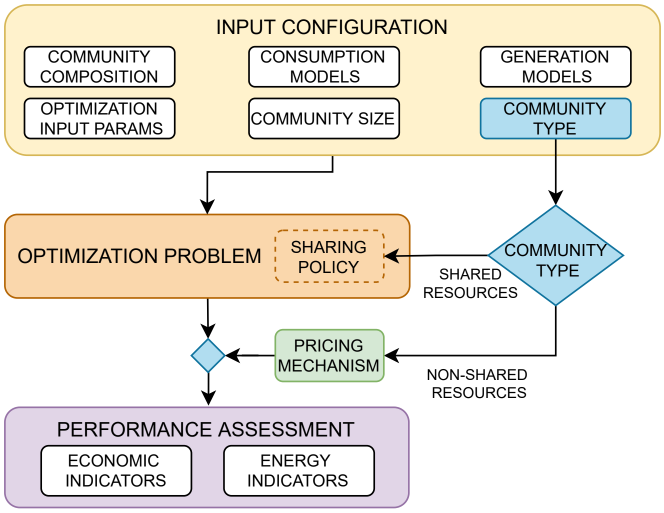

Fig. 1: Structure of the proposed framework

at the beginning of the simulation to analyse how different community compositions affect the results.

The load profiles of each household are derived from four typical standard profiles that are adjusted according to the number of members in each house. For the groups $\mathcal{B}$) and $\mathcal{D}$), the PV profiles were calculated from PVGIS [16] and scaled based on the PV power installed by each member. A Levelized Cost Of Energy (LCOE) is associated with each PV-generated quantity. Both the consumption and generation models are input data for the optimisation problem and can be easily changed with real data. A simple battery model was formulated for the groups $\mathcal{C}$) and $\mathcal{D}$). The cost associated with the battery is the Levelized Cost of Storage (LCOS), which is derived from the capital costs. The value of LCOS, LCOE and other input parameters are specified in a configuration file.

Finally, the choice of the ”community type” parameter gives the possibility to study the SR-EC and the NSR-EC typologies. The choice of this parameter affects the rest of the framework. If SR-EC is chosen, new constraints are added to the optimisation problem to determine how the jointly generated energy is shared among the members, while for NSR-EC the pricing mechanism is computed (see Section II-B).

B. The optimisation model

In this work, the MILP optimisation model was based on [12] that analysed only the NSR-EC type. The developed model is designed to be flexible enough that can also used for the SR-EC with a small variation in the constraints. Moreover, several aspects were extended from the original work, e.g., novel sharing policies were studied and new considerations were made. The parameters and decision variables used in the formulation are introduced in the following, together with the formulation.

Input parameters

α_t	Final electricity purchasing price from Grid at time t
β_t	Grid electricity selling price at time t
$\eta_{i,t}$	Reservation purchasing price at time t of prosumer $i \in \mathcal{P}$
$\gamma_{i,t}$	Reservation selling price at time t of prosumer $i \in \mathcal{B} \cup \mathcal{C} \cup \mathcal{D}$
λ_i	Battery charging/discharging rate of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
μ_i	LCOE of prosumer $i \in \mathcal{B} \cup \mathcal{D}$
ω_i	LCOS of battery-equipped prosumer $i \in \mathcal{C} \cup \mathcal{D}$
θ	P2P trader margin (%) on the total P2P trading amount
$D_{i,t}$	Load electricity demand at time t of prosumer $i \in \mathcal{P}$
M	Very high number used to build a big M constraint
$BINIT_i$	Initial battery level of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$CMAX_i$	Maximum battery level of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$CMIN_i$	Minimum battery level of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
NSR-EC	
O_t	PV Output production at time t of prosumer $i \in \mathcal{B} \cup \mathcal{D}$
SR-EC	
O_t^{tot}	Community single PV plant output production at time t

Decision variables

$EBG_{i,t}$	Energy discharged from Battery to be sold to Grid at time t by prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$EGB_{i,t}$	Energy purchased from Grid to charge Battery at time t by prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$EPU_{i,t}$	Energy purchased from P2P LEM to be used at time t by prosumer $i \in \mathcal{P}$
$EPB_{i,t}$	Energy purchased from P2P LEM to charge Battery at time t by prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$ESP_{i,t}$	Energy generated by PV panel to be sold to P2P LEM at time t by prosumer $i \in \mathcal{B} \cup \mathcal{D}$
$EBP_{i,t}$	Energy discharged from Battery to be sold to P2P LEM at time t by prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$EBU_{i,t}$	Energy discharged from Battery to be Used at time t by prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$EGU_{i,t}$	Energy purchased from Grid to be Used at time t by prosumer $i \in \mathcal{P}$
$ESB_{i,t}$	Energy generated by PV panel to charge Battery at time t by prosumer $i \in \mathcal{D}$
$ESG_{i,t}$	Energy generated by PV panel to be sold to Grid at time t by prosumer $i \in \mathcal{B} \cup \mathcal{D}$
$ESU_{i,t}$	Energy generated by PV panel to be Used at time t by prosumer $i \in \mathcal{B} \cup \mathcal{D}$
$NP_{i,t}$	Net Power of prosumer $i \in \mathcal{P}$
P_t	P2P market clearing price at time t
$I_{i,t}$	P2P purchasing decision variable at time t of prosumer $i \in \mathcal{P}$
$U_{i,t}$	P2P selling decision variable at time t of prosumer $i \in \mathcal{B} \cup \mathcal{C} \cup \mathcal{D}$
$Y_{i,t}$	Charging decision variable at time t of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
$Z_{i,t}$	Discharging decision variable at time t of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
NSR-EC	
$B_{i,t}$	Battery energy level at time t of prosumer $i \in \mathcal{C} \cup \mathcal{D}$
SR-EC	
B_t	Community shared single battery level at time t
$O_{i,t}$	PV Output production at time t of prosumer $i \in \mathcal{S}$

1) Objective Function: The objective function (1) minimises the net total cost of the households participating to the community. This cost is defined as the sum over the time of the costs of buying energy from the grid and from the P2P LEM, the costs of producing and storing energy, and the revenue from selling it to the community or to the grid. In particular, when the community shares the resources (SR-EC), the terms listed in Equation (2) are set to zero in the objective function.

$$\begin{aligned}
&\textit{min} \quad \text{Net Total Cost} = \\
&\alpha_{i,t}\left(\sum_{i\in\mathcal{P}}\sum_{t=1}^{T} EGU_{i,t} + \sum_{i\in\mathcal{C}\cup\mathcal{D}}\sum_{t=1}^{T} EGB_{i,t}\right) \\
&+ \eta_{i,t}(1+\theta)\left(\sum_{i\in\mathcal{P}}\sum_{t=1}^{T} EPU_{i,t} + \sum_{i\in\mathcal{C}\cup\mathcal{D}}\sum_{t=1}^{T} EPB_{i,t}\right) \\
&+ \mu_i\left(\sum_{i\in\mathcal{D}}\sum_{t=1}^{T} ESB_{i,t} + \sum_{i\in\mathcal{B}\cup\mathcal{D}}\sum_{t=1}^{T}(ESU_{i,t} + ESP_{i,t} + ESG_{i,t})\right) \\
&+ \omega_i\Bigg(\sum_{i\in\mathcal{D}}\sum_{t=1}^{T} ESB_{i,t} + \sum_{i\in\mathcal{C}\cup\mathcal{D}}\sum_{t=1}^{T}(EPB_{i,t} + EGB_{i,t} \\
&+ EBU_{i,t} + EBP_{i,t} + EBG_{i,t})\Bigg) \\
&- \beta_{i,t}\left(\sum_{i\in\mathcal{B}\cup\mathcal{D}}\sum_{t=1}^{T} ESG_{i,t} + \sum_{i\in\mathcal{C}\cup\mathcal{D}}\sum_{t=1}^{T} EBG_{i,t}\right) \\
&- \gamma_{i,t}(1-\theta)\left(\sum_{i\in\mathcal{B}\cup\mathcal{D}}\sum_{t=1}^{T} ESP_{i,t} + \sum_{i\in\mathcal{C}\cup\mathcal{D}}\sum_{t=1}^{T} EBP_{i,t}\right)
\end{aligned} \tag{1}$$

where

$$EGB_{i,t}, EPU_{i,t}, EPB_{i,t}, ESP_{i,t}, EBP_{i,t} = \begin{cases} 0, & \text{if SR-EC} \\ \text{unknowns}, & \text{if NSR-EC} \end{cases} \tag{2}$$

For the sake of readiness, for each of the following constraints it was omitted the notation of the belonging of member i and time t. However, it was reported the generalized constraint formulation that is valid for all the groups of members and community types, since some of the terms will be null.

2) Demand constraint:

$$D_{i,t} = EGU_{i,t} + EPU_{i,t} + ESU_{i,t} + EBU_{i,t} \tag{3}$$

The constraint (3) ensures that the demand of the members belonging to different groups will be satisfied by using their PV panels and batteries, if present, or through the community and the grid.

3) PV production constraints:

$$ESU_{i,t} + ESP_{i,t} + ESG_{i,t} + ESB_{i,t} \begin{cases} \le O_{i,t}, & \text{if NSR-EC} \\ = O_{i,t} & \text{if SR-EC} \end{cases} \tag{4}$$

$$\sum_{i\in\mathcal{P}} O_{i,t} = O_t^{tot} \tag{5}$$

Constraints (4)(5) ensures that the energy generated by PV systems will be used by the members to partially satisfy their loads, charging the battery or selling back to the grid or the P2P LEM. However, if the community shares resources (SR-EC), the energy generated $O_{i,t}$ will be allocated for each member, thus it is no more an input, but a decision variable for the optimization model.

4) Battery constraints:

$$EGB_{i,t} + EPB_{i,t} + ESB_{i,t} \le \lambda_i Y_{i,t} \tag{6}$$

$$EBG_{i,t} + EBP_{i,t} + EBU_{i,t} \le \lambda_i Z_{i,t} \tag{7}$$

$$Y_{i,t} + Z_{i,t} \le 1 \qquad B_{i,1} = BINIT_i \tag{8}$$

$$B_{i,t} \le CMAX_i \tag{9}$$

$$B_{i,t} \ge CMIN_i \tag{10}$$

if NSR-EC:

$B_{i,t+1} = B_{i,t} + (EGB_{i,t} + EPB_{i,t} + ESB_{i,t})$

else if SR-EC:

$$B_{t+1} = B_t + \sum_{i \in \mathcal{P}} ESB_{i,t} - \sum_{i \in \mathcal{P}} EBU_{i,t} - \sum_{i \in \mathcal{P}} EBG_{i,t} \quad (11)$$

Constraints (6)-(11) are used to describe a simple model of battery dynamics and states at each timestep based on the previous one by calculating the energy balance for charging and discharging phases through EC members or the grid. Moreover, they impose the technological characteristics of the battery, i.e., the capacity and charging/discharging operations. Specifically, Equation (11) ensures the dynamics of the battery for both types of ECs.

5) Pricing and trading constraints:

$$\eta_{i,t} + M\,(1 - I_{i,t}) \geq P_t \quad (12)$$

$$\gamma_{i,t} + M\,(1 - U_{i,t}) \leq P_t \quad (13)$$

$$EPU_{i,t} + EPB_{i,t} \leq D_{i,t} I_{i,t} \quad (14)$$

$$ESP_{i,t} + EBP_{i,t} \leq O_{i,t} U_{i,t} \quad (15)$$

$$I_{i,t} + U_{i,t} \leq 1 \quad (16)$$

$$\sum_{i \in \mathcal{P}} EPU_{i,t} + \sum_{i \in \mathcal{C} \cup \mathcal{D}} EPB_{i,t} = \sum_{i \in \mathcal{B} \cup \mathcal{D}} ESP_{i,t} + \sum_{i \in \mathcal{C} \cup \mathcal{D}} EBP_{i,t} \quad (17)$$

Constraints (12)-(16) regulate the pricing and trading mechanisms inside the P2P LEM of NSR-EC. Moreover, the constraint (17) guarantees the energy balance of the total quantities purchased and sold inside the community for each timestep. However, these constraints are automatically deactivated when SR-EC is considered.

6) SR-EC sharing policies: The sharing policies define how the common resources have been allocated inside the shared-resources community. As depicted in Figure 1, the sharing policies are directly evaluated inside the optimization problem as added constraints. The policies evaluated are the following:

- *Demand Dependent (DD).* In this policy, community participants are able to use energy generated by PV panels or stored in batteries whenever they needs. No constraints are added in this case. The complete mathematical definition can be found in [11];
- *Proportional Output Sharing (POS).* This method guarantees that the same energy amount is allocated to each member, whether it comes from shared PV panels or batteries. This work includes the evaluation of POS by considering also the energy allocation for the time horizon hourly, 12h and daily.

Finally, to solve the optimization problem all decision variables need to be equal or more than zero, exept for the binary variables that need to be zero or one, for all i and t.

7) NSR-EC post-clearing pricing mechanisms: In this work, different stat-of-the-art post-clearing pricing mechanisms were designed for P2P LEM to define the internal community price to be cost-effective for all members. The pricing mechanisms evaluated are the following:

- *Clearing Price (CP)*: It is based on the buying and selling offers submitted to the community market, the so-called reservation prices. It is the price at which all the internal market transactions are cleared;
- *Bill Sharing (BS).* This mechanism is in the form of a cost share of a single electricity bill of the overall energy community. The complete mathematical definition can be found in [13];
- *Mid-Market Rate (MMR)*: This method assumes that the exchange price internal to community is the middle of the buying and selling grid prices. The complete mathematical definition can be found in [13];
- *Supply Demand Ratio (SDR)*: Authors in [14] first proposed this type of pricing mechanism based on SDR (SDR 1) that formulates an internal price with the following characteristics: it has to be bounded between the feed-in-tariff and the utility grid buying price, and it has to be inversely proportional to the SDR as the basic principle of economics teaches. Another similar formulation (SDR 2) was evaluated based on [15].

C. Performance assessment

Several KPIs were used to compare different scenarios:

- *Net Total Savings (NTS)*: it represents the overall savings of the community by relating the net total cost with the standalone case.
- *Net Single Savings (NSS)*: Savings for each households are calculated a posteriori by replacing reservation prices with prices formulated through diverse pricing mechanisms and comparing them to standalone case costs.
- *Allocated import and export energy*: it is calculated by summing at every time instant the allocated energy quantities imported from and exported to the grid by all the community participants.
- *Self Consumption Ratio (SCR)*: As done in [17], SCR is defined as the ratio of total PV energy consumed in the community to total one.
- *Self Sufficiency Ratio (SSR).* As done in [17], it is defined as the ratio between the PV-generated energy and the energy consumed in a given period. For an SSR > 1, generation fully covers demand.
- *Peak-to-Average Ratio (PAR)*: it is the ratio between the maximum and the average grid power demand.

III. EXPERIMENTAL RESULTS

Different typologies of energy communities, member compositions, sharing and pricing mechanisms were simulated.

As a reference case study to compare the two main community types, the community size was set to 500 participants in both cases, with 20% belonging to group $\mathcal{A}$, 55% to $\mathcal{B}$, 5% to $\mathcal{C}$ and 20% to $\mathcal{D}$. These percentages represent a plausible scenario for the near future. Both community types, i.e., NSR-EC and SR-EC, were analysed and compared. To reflect heterogeneity in solar system size and time of installation, the levelised costs were set to random values in the range of 0.047-0.11 €$/kWh$ for the LCOE and in the range of 0.067-0.13 €$/kWh$ for the LCOS. α has been plausible set around 0.20 €$/kWh$. These costs were chosen based on the average trends of local prices in northern Italy. β and p2p margin have the same value of [12], i.e., 0.076 $€/kWh$ and 10%, respectively. Plausible values were chosen for the batteries. Daily optimisation was performed and simulations were run over a monthly time horizon. In order to obtain a meaningful result, the NTS were compared with the simulation of the standalone case and the sum of the costs of all individual users, amounting to 82480 €, was calculated. Moreover, the average of the sum of NSS for each group was calculated, which was given, for instance, as *avg* $\mathcal{A}$ for group $\mathcal{A}$. In this way, it is possible to appreciate the fairness among the members of the community. The same calculation was performed by grouping all members who receive positive savings ($\mathcal{P}^+$) and all who have incurred additional costs ($\mathcal{P}^-$).

A. NSR-EC results

Figure 2 shows the aggregate load profile obtained from the community members' profiles scheduled in the different uses. Around midday, the community uses the PV system and the energy purchased from the community market. During the night hours, the grid is largely involved, since no PV production is available. In the evening, the batteries are discharged to meet the community's energy needs. Although a major amount of PV generation is used for self-consumption, a consistent part of the PV produced energy is sold back to the grid.

Simulations were also performed considering different community compositions. The results are reported in Table I. The highest total savings is achieved in the configuration "25-25-25-25". In this case, the values of SCR and SSR do not reach very high levels, i.e., 0.653 and 0.310, respectively. The highest SCR is obtained in the configuration with 70% simple consumers (group $\mathcal{A}$), and the other groups composed by 10% members each. In fact, as the number of simple consumers, i.e., consumption, increases, so does the self-consumption. The highest SSR is reached in the case of the highest concentration of group $\mathcal{D}$, i.e., in the configuration "10-10-10-70".

Table II reports the KPIs for NSR-EC evaluating several price mechanisms in the case of "20-55-5-20" composition. The corresponding savings' variance (*var*) for CP has the

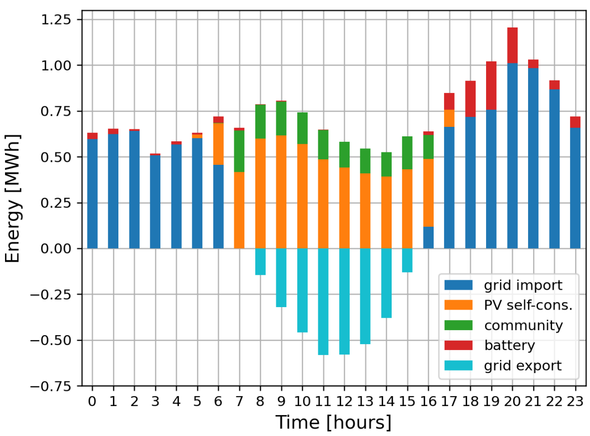

Fig. 2: NSR-EC aggregate load profile

TABLE I: KPIs in case of diverse NSR-EC compositions based on clearing price mechanism.

EC composition A-B-C-D [%]	Savings [%]	SCR	SSR	PAR
20-55-5-20 (ref)	7.50	0.610	0.336	2.600
25-25-25-25	**10.52**	0.653	0.310	2.675
49-17-17-17	10.24	0.805	0.265	2.420
17-49-17-17	8.47	0.528	0.329	2.700
17-17-49-17	10.03	0.778	0.265	2.770
17-17-17-49	9.89	0.544	0.355	3.101
70-10-10-10	6.90	**0.959**	0.186	2.062
10-70-10-10	7.20	0.465	0.364	2.787
10-10-70-10	7.85	0.925	0.188	2.520
10-10-10-70	8.46	0.468	**0.371**	**3.345**

TABLE II: KPIs of NSR-EC "20-55-5-20" with different pricing mechanisms

KPI		CP	BS	MMR	SDR 1	SDR 2
Savings [%]	*avg* $\mathcal{A}$	**13**	0.3	6.4	0.1	1.4
	avg $\mathcal{B}$	5.4	-1.1	5.6	7	**11.4**
	avg $\mathcal{C}$	**9**	-3	5.5	0.01	2.5
	avg $\mathcal{D}$	7.5	-13	21	24	**43**
	var $\mathcal{P}$	**0.9**	3.5	13.3	4.2	47.3
	avg $\mathcal{P}^+$ *(#)*	7.7 (493)	2.3 (236)	8.8 (500)	9.4 (485)	15.7 (495)
	avg $\mathcal{P}^-$ *(#)*	-5.6 (7)	-8.4 (264)	/ (0)	-1 (15)	-0.4 (5)
	NTS	**7.1**	-0.45	5	3.8	6.2
SCR	-	0.610	0.610	0.610	0.610	0.610
SSR	-	0.336	0.336	0.336	0.336	0.336
PAR	-	2.60	2.60	2.60	2.60	2.60

lowest value. Thus, with respect to the standalone case, the community participants save money uniformly. On the contrary, the savings achieved in the case of BS, MMR and SDR are much more diverse. BS is economically disadvantageous for members with PV systems, in line with the literature. Indeed, members from the groups $\mathcal{B}$ and $\mathcal{D}$ actually have higher costs compared to the standalone case. Both the two versions of the SDR are characterised by very high savings. However, the average savings from groups $\mathcal{A}$ and $\mathcal{C}$ are very poor. Finally, the MMR provides good results, both in terms of maximum and minimum savings and homogeneity. Moreover, the SCR, SSR and PAR have the same value regardless of the pricing mechanisms since they are cost independent.

B. SR-EC results

In Figure 3, the total load profile of the SR community is depicted in the case of a demand-dependent sharing policy. The term community energy no longer appears since the energy is no more exchanged in the community market. In this case, the community PV energy is shared between the participants according to the sharing policy.

The KPIs for SR-EC are shown in the Table III, which compares the different sharing policies. The lowest community costs are obtained with DD. Similarly, the best results for SCR and SSR are obtained with DD, while the worst situation is obtained with POS 1h. However, for PAR the situation is exactly the opposite. An egalitarian trend in savings can be

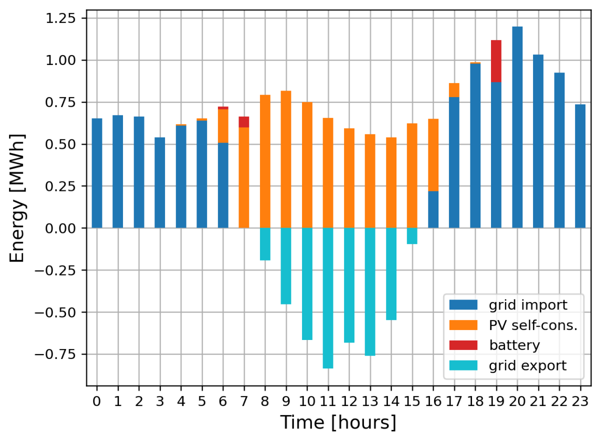

Fig. 3: SR EC aggregated load profile with DD sharing policy

observed for this policy, which is confirmed by the variance values that are almost zero. On the other hand, economic performance varies much more across members in the DD policy.

TABLE III: KPIs of SR-EC with different sharing policies

	KPI	**DD**	**POS 1h**	**POS 12h**	**POS 24h**
Savings [%]	*avg* $\mathcal{P}^+$ *(#)*	9.3 (200)	1.4 (403)	3.3 (421)	4.4 (412)
	avg $\mathcal{P}^-$ *(#)*	-24.8 (300)	-4.7 (97)	-8.3 (79)	-8 (88)
	var $\mathcal{P}$	0.08	0.001	0.003	0.004
	NTS	**5.4**	1.0	3.0	3.5
SCR	-	**0.68**	0.57	0.61	0.62
SSR	-	**0.31**	0.26	0.28	0.28
PAR	-	2.6	**2.4**	2.5	2.5

C. Energy Communities comparison

From the comparison of the NTS of the two EC typologies, it appears that the largest economic benefit comes from NSR-EC when using the CP mechanism, which is 7.1%. However, the two EC typologies lead to very different results for individual users. In fact, the cooperative nature of SR-EC leads to a supportive and fair sharing of energy resources and, in particular, economic benefits. Indeed, as can be seen in Table III, there are, generally, more members with losses in favour of members who would have been simple consumers in standalone configuration. On the other hand, the competitiveness of the NSR-EC LEM leads to higher total savings. However, as can be seen in Table II, prosumers receive larger benefits than consumers. The Bill Sharing mechanism is the only exception, as it aims to be fair and supportive as SR-EC, but the NTS results in losses.

IV. Conclusion and Future Works

The proposed work investigated the role of pricing mechanisms and sharing policy in the energy communities' context through a flexible optimisation formulation. Two main types of energy communities were compared in terms of different economic and energy KPIs. In both cases, EC members are able to reduce costs compared to the standalone case. In the NSR-EC, the best outcomes were obtained with the CP and the MMR. The presented work represents a good starting point for introducing more complex mechanisms, especially for NSR-EC. For example, the reservation prices of each prosumer could change dynamically over time as users interact in an agent-based framework.

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