Energy sharing strategies in a Citizen Energy Community including vulnerable consumers

Mariana Jiménez Martínez
Energy Systems Analytics
Catalonia Institute of Energy Research (IREC)
Barcelona, Spain
mcjimenez@irec.cat

Albert Farriol
Energy Systems Analytics
Catalonia Institute of Energy Research (IREC)
Barcelona, Spain
afarriol@irec.cat

Lucía Igualada
Energy Systems Analytics
Catalonia Institute of Energy Research (IREC)
Barcelona, Spain
ligualada@irec.cat

Cristina Corchero
Energy Systems Analytics
Catalonia Institute of Energy Research (IREC)
Barcelona, Spain
ccorchero@irec.cat

***Abstract*—This article presents an optimization model to allocate the energy produced by a PV-coupled battery system in an energy community using the compensation mechanism available to self-consumption renewable systems up to 100 kW in Spain. The considered community incorporates public buildings, an EV charging station, and a group of households in situation of energy poverty. The evaluated scenarios considered three strategies to fairly distribute the energy among the group of vulnerable households, while minimizing costs for all members' involved. The scenarios also incorporate the use of sharing coefficients with different temporalities (annual, monthly, hourly). Our results indicate that providing vulnerable households with the same energy volume annually, but with the flexibility to allocate it differently throughout the year is the most efficient. We also found that using temporarily variable coefficients – monthly, hourly – instead of fixed annual coefficients maximizes the energy community's benefits. These results highlight the importance of the regulation introduced by the end of 2021 in Spain, which allowed the use of sharing coefficients up to an hourly level.**

Keywords— Distributed generation, Energy communities, Energy consumption, Optimization methods, Renewable Energy Sources.

I. Introduction

Together with the Renewable Energy Communities (REC) and Citizen Energy Communities (CEC) concepts, Collective Self-Consumption (CSC) is gaining traction in Europe as a way to empower citizens, making them active participants in the energy transition. All these figures have been introduced in the European legislation as part of the recasts of the renewable energy directive (REDII) and the electricity market directive (EMDII). CSC can be considered equivalent to the "jointly acting renewables self-consumers" concept defined in the REDII [1]. Although the specific rules vary per Member State, in several markets the energy produced by the generator is distributed among two or more consumers through the establishment of sharing coefficients that are used to compensate consumption in the users' electrical bills. This is, for instance, the case in France, Portugal, and Spain [2].

Energy communities' main purpose is to provide environmental, economic or social community benefits rather than generating financial profits. However, RECs are limited to projects related to renewable energy generation, whereas CEC can engage in all types of energy activities [1]. CSC is an energy activity in which both energy communities can engage. Some examples are already found in the European landscape such as the Agra do Amial, Sonae Campus and POCITYF RECs in Portugal [3] or the ManzaEnergía and Alginet CECs in Spain [4].

A. CSC rules in Spain

In Spain, the regulation applicable to CSC is established in the Royal Decree 244/2019 [5], which contains all the rules applicable to self-consumption activities. The regulation considers two possible modalities for self-consumption:

1) Self-consumption without energy surpluses: Energy is consumed or stored behind the meter. A protection device must be installed to avoid energy injections to the grid.

2) Self-consumption with energy surpluses: Energy is consumed, stored or injected to the grid. The energy injected to the grid is valued following one of these alternatives:

a) Without compensation: Energy injected is sold at the market price. The user(s)' energy consumption is metered and billed independently.

b) With compensation (≤100 kW): Energy injected can be used to compensate the user(s)' energy costs within a billing period. Only available to generators based on renewable energy sources.

For self-consumption projects with energy surpluses and more than one consumer, independent metering for the total net generation (E_t) is required. Additionally, in a CSC scheme, all users must agree on the modality the project will follow (2-a or 2-b) and establish a set of sharing coefficients ($\beta_{i,t}$) indicating the fraction of the generated energy that will be assigned to each associated consumer in each time step. This fraction is known as individualized generation ($E_t * \beta_{i,t}$).

The $\beta_{i,t}$ assigned to each user is decided freely by the associated users, but in all cases the sum of all $\beta_{i,t}$ must be equal to 1 at all hours. The sharing coefficients can be fixed per user (β_i), meaning equal for all hours in a billing period, or variable for each hour and user ($\beta_{i,t}$). The latter became possible at the end of 2021, following the publication of Order

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 953020.

TED/1247/2021 [6]. Up to now, the sharing coefficients have to be notified *ex ante* to the distribution company. Nonetheless, the Spanish government is still considering the introduction of dynamic sharing coefficients with *ex post* application. In the absence of notification, the distributor applies a default value calculated based on the users' contracted power.

For projects under the 2-a modality, the income from selling the individualized generation is assigned to each corresponding user, while their consumption is billed independently as usual. In the compensation scheme, the individualized generation ($E_t * \beta_{i,t}$) and consumption ($p_{i,t}^{demand}$) are used at each hour to calculate the individualized self-consumed energy ($p_{i,t}^{self}$) as indicated in (1).

$$p_{i,t}^{self} = \begin{cases} \beta_{i,t} * E_t & \text{if } \beta_{i,t} * E_t < p_{i,t}^{demand} \\ p_{i,t}^{demand} & \text{if } \beta_{i,t} * E_t \geq p_{i,t}^{demand} \end{cases} \quad (1)$$

The individualized self-consumption is then used to calculate the individualized energy grid consumption ($p_{i,t}^{buy}$) and the individualized energy surplus ($p_{i,t}^{surplus}$) as shown in (2) and (3). The $p_{i,t}^{buy}$ is charged at the purchase cost applicable to each hour ($C_{i,t}^{buy}$) whereas the surpluses are valued at the respective selling price ($C_{i,t}^{sell}$). The selling price must be always lower than the applicable purchase cost. Finally, all the value generated from surpluses can be used at the end of the billing period to compensate for the costs associated to grid consumption. The regulation indicates that the users cannot receive payments for the excess surpluses that are not compensated at the end of the billing period. In practice, this means that all energy assigned to a user resulting in higher surplus values than energy purchase costs, is actually injected to the grid at zero cost.

$$p_{i,t}^{buy} = \begin{cases} 0 & \text{if } p_{i,t}^{demand} - p_{i,t}^{self} \leq 0 \\ p_{i,t}^{demand} - p_{i,t}^{self} & \text{if } p_{i,t}^{demand} - p_{i,t}^{self} > 0 \end{cases} \quad (2)$$

$$p_{i,t}^{surplus} = \begin{cases} p_{i,t}^{self} - p_{i,t}^{demand} & \text{if } p_{i,t}^{demand} - p_{i,t}^{self} \leq 0 \\ 0 & \text{if } p_{i,t}^{demand} - p_{i,t}^{self} > 0 \end{cases} \quad (3)$$

Using the compensation scheme results economically advantageous for self-consumers. This is particularly true for small-scale projects below the maximum capacity allowed to access this scheme. However, it also requires establishing the proper coefficients to maximize benefits to all users' involved. Deciding the best energy distribution strategy becomes complex with the adoption of temporarily variable coefficients, the incorporation of different consumer's profiles and the willingness to serve other benefits rather than maximizing profits, for instance, benefitting vulnerable consumers in an energy community context.

B. *CSC as a tool to fight energy poverty*

Some recent publications [7][8] highlight energy communities' role as key agents in the mitigation of energy poverty in Europe. In the actions suggested by [7], one of the strategies recommended to share the benefits of CSC projects with vulnerable families is to reserve part of the generated energy and assigned it to households suffering from energy poverty. This is already being tested in existing energy communities such as the Agra do Amial REC in Portugal [3] and ManzaEnergía CEC in Spain [4].

Although some studies analysing the optimal allocation of energy in Spanish CSC schemes are identified in the literature [2] [9] [10], to the authors' knowledge, there is none that considers the allocation of part of the generated energy to vulnerable consumers in energy communities. Thus, this paper presents and analyses different sharing strategies in a real CEC involving vulnerable consumers, a group of public buildings and an EV charging station that share energy from a PV-coupled battery system. For this, we built an optimization model that looks for the optimal $\beta_{i,t}$ values resulting in the least global energy's costs, considering a series of restrictions to ensure a fair benefits' distribution and the optimal management of the installed battery. As a sensibility analysis, we considered a set of scenarios using three different $\beta_{i,t}$ temporalities as well as two alternatives for the distribution of energy among vulnerable consumers.

II. CASE STUDY

The selected case study is based in ManzaEnergía, one of the pilots from the LIGHTNESS project, which supports the formation of CEC in five European countries, including Spain [4]. This pilot is located in the municipality of Manzanares el Real in Madrid, Spain, and involves the installation and management of a CSC scheme. The pilot has the support of the local government and is led by Traza and R2M Solutions Spain, the latter being in charge of the system's technical operation.

The shared energy system consists of a 100 kW PV system and a battery of 46 kWh capacity (2.3 C-rate) installed in the rooftop of a public sports centre. The produced energy will be shared among the sports centre, four public buildings, an EV station (22 kW) and 10 households through the previously described compensation scheme (Figure 1). The associated households are families in situation of energy poverty, which will receive a share of the system's produced energy as a community-led support mechanism. In a first project stage, the community is evaluating the option to provide the EV charging service at zero cost.

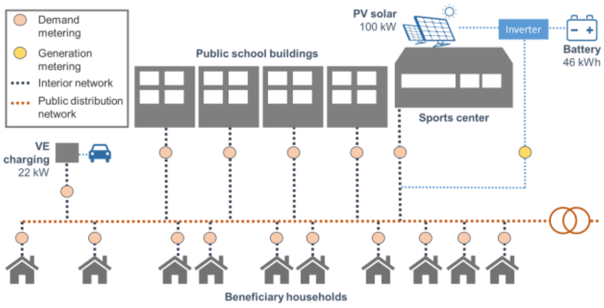

Fig. 1. Simplified scheme of the CEC in Manzanares el Real

A. *Users' load modelling*

For all the consumption points, except the EV charging station, we use the real demand curves from the users associated to the CSC scheme. For this purpose, hourly consumption data from 2021 was shared by R2M Solutions Spain in an anonymized format. For modelling the demand curve from the EV station we used the Electric Vehicle Charging Infrastructure Simulator (ELVIS) [11], considering a mean EV battery capacity of 60 kWh. We set the start charging time distribution based on the relative frequencies reported in [12] for street charging stations, and an average of three charging events per day.

B. PV-coupled battery system

The hourly solar generation from the PV system is calculated in the optimization model considering standard equations based on the local temperature, global solar irradiation and the panels' technical characteristics. The meteorological data used corresponds to that of a typical meteorological year for Manzanares el Real as provided by the PVGIS-SARAH2 database [13].

C. Energy prices

The tariffs from an electrical service provider in Spain [14] are used as reference for this study. For households, the selected tariff (2.0TD SOM) has differentiated purchase costs in three pricing periods. For public buildings (3.0TD SOM) and the EV station (3.0TD SOM), tariffs with six pricing periods are used. In general terms, the electricity prices available to the EV station are the most expensive, while public buildings have access to the cheapest energy. The offered compensation value (0.158 €/kWh) is fixed for all hours and users. In all cases, we considered the 21% VAT.

D. Enery sharing scenarios

The allocation of the energy injected to the grid by the PV-coupled battery system is evaluated considering different energy allocation strategies. For not vulnerable customers, it is stated that the total energy allocated to this group must not be larger than 70%. In all cases, we set as a restriction that the EV station must be assigned enough energy so that its energy-based costs are always zero by the end of the month. The latter considering the assumption that the community offers the charging service to its members for free. For vulnerable consumers, the rest of the available energy is allocated considering the following three strategies:

1) Equal beta: All vulnerable consumers are assigned the same $\beta_{i,t}$ value at any given timestep.

2) Equal savings: The $\beta_{i,t}$ assigned to each vulnerable customer must result in the same monthly savings for all.

3) Equal energy: All vulnerable consumers are assigned $\beta_{i,t}$ values so that the total energy assigned to them is the same at the end of the year.

In addition, three different strategies are considered regarding the $\beta_{i,t}$ temporality, with fixed values applicable to all hours all the year (annual), fixed values applicable to all hours in a month (monthly), and variable values per hour (hourly). As stated before, these are all possible with the current regulation as Order TED 1247/2021 allows setting variable $\beta_{i,t}$ values up to an hourly level. The resulting scenarios from combining these cases are summarized in Table I.

The calculations for each scenario are based on the actual users' consumption registered in the base case year. Thus, energy allocation is done based on a perfect forecast. In future work, the uncertainty from providing *ex ante* values will be considered, assessing its impact on the results obtained from this first analysis, which is equivalent to an *ex post* approach.

TABLE I. ENERGY SHARING SCENARIOS SUMMARY

ID	β temporality	Allocation strategy
EB_Y	Yearly	Equal Beta
ES_Y		Equal Savings
EE_Y		Equal Energy
EB_M	Monthly	Equal Beta
ES_M		Equal Savings
EE_M		Equal Energy
EE_H	Hourly	Equal Beta
EB_H		Equal Savings
EE_H		Equal Energy

E. Key Performance Indicators

To evaluate the scenarios, we considered as Key Performance Indicators (KPI) the following parameters:

TABLE II. KEY PERFORMANCE INDICATORS

KPI	Units
Total community savings achieved.	€/year
Savings per customer category (vulnerable consumers, sport centre, school buildings, EV station).	€/year
Energy allocation per customer category.	%
Share of energy self-consumed by the community.	%
Share of energy compensated at surplus value.	%
Share of energy not compensated (zero value).	%

III. OPTIMIZATION MODEL

To define the applicable $\beta_{i,t}$ values for each case, we built three optimization models, one for each temporal horizon, considering the rules applicable to the Spanish simplified energy compensation scheme explained in Section I. The models are designed using the GAMS optimization solver, following a bi-level program approach [15]. In this case, the leader or upper-level problem is the definition of the sharing coefficients, while the follower or lower-level problem is the battery's optimization.

In this section, we describe the hourly $\beta_{i,t}$ model equations, as the monthly and yearly versions are simplified versions of it. The model's overall objective is to minimize the community's energy costs as shown in the objective function below. Consider that the term $z_{i,t}^{sell}$ represents only the share of energy surpluses that can be compensated.

$$\min \sum_T \sum_I C_{i,t}^{buy} \cdot p_{i,t}^{buy} - C_{i,t}^{sell} \cdot z_{i,t}^{sell} \tag{4}$$

To represent the community's energy balance among all consumption, storage and generation flows, we use (5), $\forall t \in T$. The PV panel's hourly production – here, equivalent to the total net generation (E_t) – is represented by PV_t, while the battery's charged and discharged power are defined as $p^{ch}_{es,t}$ and $p^{dch}_{es,t}$, respectively. Similarly, we set (6), $\forall t \in T$ and $\forall i \in I$, to represent the energy balance for each individual member.

$$PV_t+p^{dch}_{es,t}-p^{ch}_{es,t}=\sum_{n\in I}\beta_{i,t}\left(PV_t+p^{dch}_{es,t}-p^{ch}_{es,t}\right) \quad (5)$$

$$\beta_{i,t}\left(PV_t+p^{dch}_{es,t}-p^{ch}_{es,t}\right)+p^{buy}_{i,t}=p^{demand}_{i,t}+z^{sell}_{i,t}+z^{zero}_{i,t} \quad (6)$$

As explained before, the maximum economic benefit that users can obtain under the simplified compensation mechanism is the offset of their total energy-based costs generated in the hours in which their consumption was larger than their assigned energy share. In case that further economic surpluses are generated, these are lost after each billing period. The energy share that will result in non-compensable surpluses, and, thus, in zero economic benefits is represented in (6) as $z^{zero}_{i,t}$. To ensure this rule is followed by the model, we set the restriction indicated in (7), $\forall i \in I$:

$$\sum_{t\in T} C^{buy}_{i,t}\cdot p^{buy}_{i,t}-C^{sell}_{i,t}\cdot z^{sell}_{i,t}\geq 0 \quad (7)$$

In the case study, it is defined that the EV station must cover all its energy costs through the compensation mechanism so it can offer the service for free to the community's member. To ensure this, we set (8), $\forall m \in M$, as a restriction, identifying the charging station with the individual index *ev*. Similarly, we define (9), $\forall t \in T$, to avoid that more of the maximum energy volume allowed (λ_p = 70%) is allocated to non-residential buildings.

$$\sum_{t\in T} C^{buy}_{ev,t}\cdot p^{buy}_{ev,t}-C^{sell}_{ev,t}\cdot z^{sell}_{ev,t}=0 \quad (8)$$

$$\sum_{n\in I_{nonresidential}}\beta_{i,t}\leq\lambda_p \quad (9)$$

Finally, to represent each of the energy sharing scenarios defined in Section II, we include a set of additional restrictions that differentiate one case from another. Equation (10), $\forall i \in I_{households}$, is used in the *Equal Beta* scenario so all households are assigned the same $\beta_{i,t}$ values at all times.

$$\beta_{i,t}=\beta_{i+1,t} \quad (10)$$

In the *Equal Savings* scenario, we use (11), $\forall i \in I_{households}$, to ensure all households achieve the same annual savings regardless of the $\beta_{i,t}$ values assigned to them. Finally, (12), $\forall i \in I_{households}$, is set for the *Equal Energy* strategy, in which all households receive the same amount of kilowatt-hours at the end of the year, although not necessarily in all time steps as happens in the *Equal Beta* strategy.

$$C^{buy}_{I,t}\cdot p^{demand}_{I,t}-\left(C^{buy}_{I,t}\cdot p^{buy}_{I,t}-C^{sell}_{I,t}\cdot z^{sell}_{I,t}\right)= C^{buy}_{i+1,t}\cdot p^{demand}_{i+1,t}\left(C^{buy}_{i+1,t}\cdot p^{buy}_{i+1,t}-C^{sell}_{i+1,t}\cdot z^{sell}_{i+1,t}\right) \quad (11)$$

$$\sum_{t\in T}\beta_{N_{households}}\cdot\left(PV_t+p^{dch}_{es,t}-p^{ch}_{es,t}\right)= \sum_{t\in T}\beta_{N_{households}+1}\cdot\left(PV_t+p^{dch}_{es,t}-p^{ch}_{es,t}\right) \quad (12)$$

Finally, the battery's optimal energy management is modelled as done in [16]. Considered that under this arrangement, the battery is only allowed to charge directly from the PV solar system and not from the grid.

IV. RESULTS

As observed in Figure 2, the demand from the public buildings (sport centre, school buildings) show a high seasonality with considerably larger consumptions in winter than in summer. Nonetheless, winter peaks are particularly pronounced in the sport centre. The EV charging station also presents a seasonal pattern, but with an opposite trend as the higher demands are observed in the summer months. In all non-residential users, the higher consumption hours concentrate in business times. For the sport centre and EV station, busy hours extend up to late evening whereas the school's consumption decreases earlier in the afternoon.

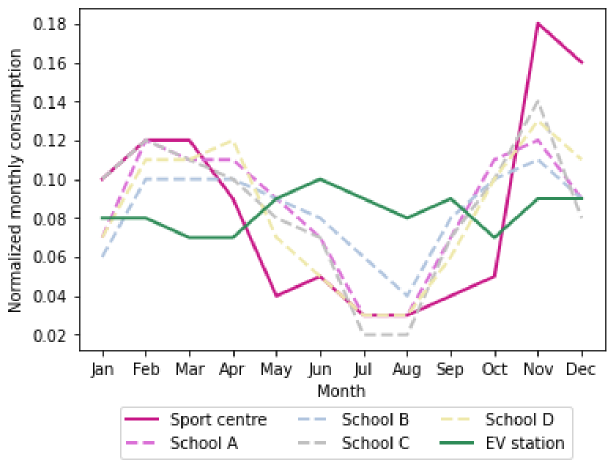

Fig. 2. Normalized monthly demand from non-residential members.

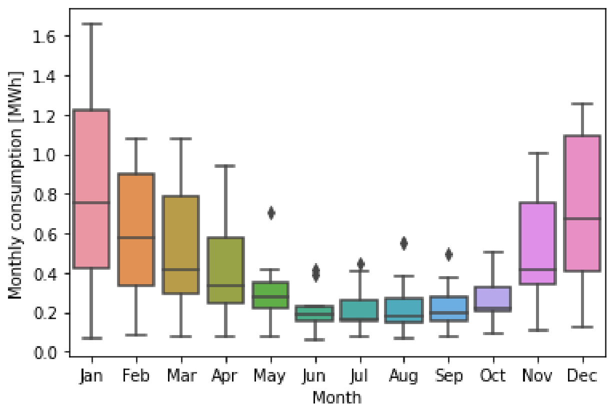

Fig. 3. Boxplots showing household's electricity consumption per month. Description of the box plot parameters: median by horizontal line; 25–75% percentile by box; 10% and 90% by whiskers.

Households (Figure 3) also show higher electrical consumption in winter, probably due to the usage of electrical heating devices and the fact that people tend to stay indoors more often than in summers. In warmer months, most households have a much lower consumption although some outliers are observed; probably families that make use of electrical cooling devices. Contrary to the non-residential users, the hourly consumption curves from households vary considerably from user to user. Individual curves are not shown due to privacy reasons.

A. *Community and customer groups' savings*

The total community savings estimated for the scenarios described in Table I and presented in Figure 4 show that the *Equal Energy* option results in the largest global community savings, while the least are found in the *Equal Savings* case. The latter independently of the temporal horizon used for setting the $\beta_{i,t}$ values. The *Equal Beta* tends to result in 2% less global savings than the *Equal Energy* scenario, except when fixed yearly values are used as the total savings are the same in this case.

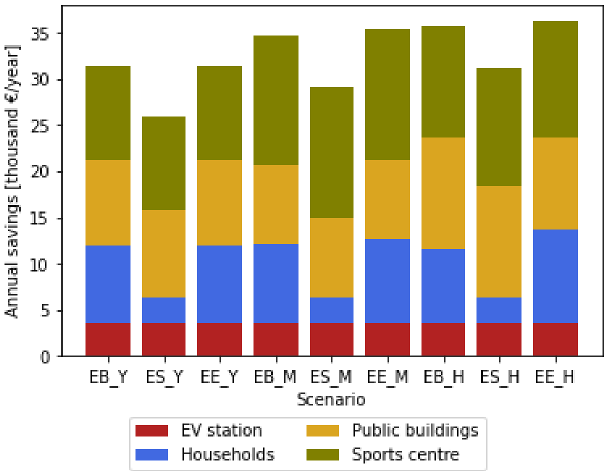

Fig. 4. Annual savings registered per user group

Moreover, it is observed that using a higher level of temporal disaggregation when setting the $\beta_{i,t}$ values results in higher total cost savings at the community level, regardless of the strategy used. This highlights the importance of allowing users in CSC schemes to set temporarily variable sharing coefficients instead of fixed per year, as done with the enactment of Order TED/1247/2021 [6]. Nonetheless, it is also observed that using monthly $\beta_{i,t}$ instead of fixed values for the entire year results in larger improvements in terms of total community cost savings than when using hourly values instead of monthly ones.

When looking at the vulnerable consumers' results, the cost savings achieved by this group are in average 289.6 €/year-household under the *Equal Savings* approach, with little variations depending on the temporal horizon used for setting the applicable $\beta_{i,t}$ values. This is much lower than the mean cost savings reported per household when using the *Equal Beta* (837.1 €/year-household) or the *Equal Energy* (926 €/year-household) strategies.

Regarding the $\beta_{i,t}$ temporality, the most significant impact is observed in the *Equal Energy* option, which results in larger average benefits per household when using hourly (1,020 €/year-household) instead of monthly (855 €/year-household) or yearly values (941 €/year-household). However, it is relevant to observe that the households' group obtains better global results when using fixed yearly $\beta_{i,t}$ rather than monthly under the *Equal Energy* strategy.

By analysing the individual results' distribution (Figure 5), it is observed that using hourly $\beta_{i,t}$ leads to higher savings for practically all households when compared to monthly or yearly values under the *Equal Energy* strategy. However, when monthly $\beta_{i,t}$ are applied, some households significantly increase their savings when compared to the fixed annual case, but others actually end up with less, which result in overall lower savings. Notably, when using the *Equal Beta* strategy, the monthly values report the highest savings for the group while the hourly $\beta_{i,t}$ report the least. However, the difference between these cases are not as relevant as for the *Equal Energy* case.

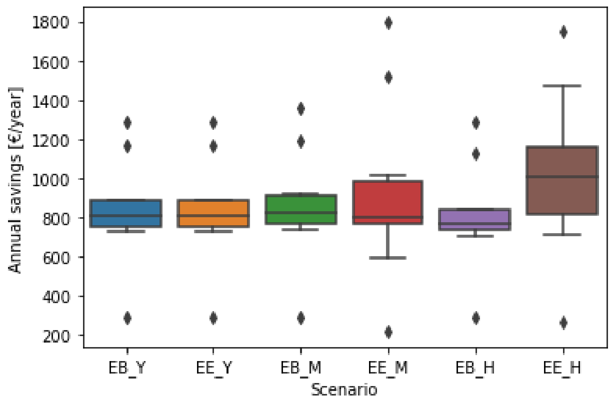

Fig. 5. Boxplots showing household's annual savings. Description of the box plot parameters: median by horizontal line; 25–75% percentile by box; 10% and 90% by whiskers.

The estimated savings reported for the sport centre remains practically the same in all sharing strategies as long as the same $\beta_{i,t}$ temporality is used. For this particular building, using the monthly $\beta_{i,t}$ values result in the largest annual economic benefits (14,032 €/year) while the lowest are registered when using the fixed yearly values (10,154 €/year). The hourly $\beta_{i,t}$ result in total savings in between (12,472 €/year). This is probably explained by this building's consumption patterns, which present significant differences between summer and winter months (Figure 2).

The largest annual cost savings for the School buildings are registered when using hourly disaggregation, being largest for the *Equal Savings* strategy (12,025 €/year) and lowest for the *Equal Energy* (10,043 €/year), while the *Equal Beta* offers a result in between (11,996 €/year). When using yearly or monthly $\beta_{i,t}$ values, little differences between sharing strategies are observed in this group. The average annual savings registered by the school buildings are 9,413 €/year when using the fixed values and 8,554 €/year for the monthly ones. These buildings benefit from the hourly distribution as they have shorter business hours so their consumption is concentrated in a shorter time span of the day.

For the EV station, all scenarios lead to the same cost savings (3,512 €/year) due to the restriction that the station's total costs must be compensated through the CSC scheme.

B. *Energy allocation per customer group*

When using the fixed yearly $\beta_{i,t}$, the amount of energy allocated to each group remains equal for all scenarios (Figure 6), which indicates that the lower savings obtained under the *Equal Savings* scenario the result of a suboptimal allocation strategy. In this case, the optimization model allocates energy in hours that are not beneficial to some households so that the equal savings restriction is met.

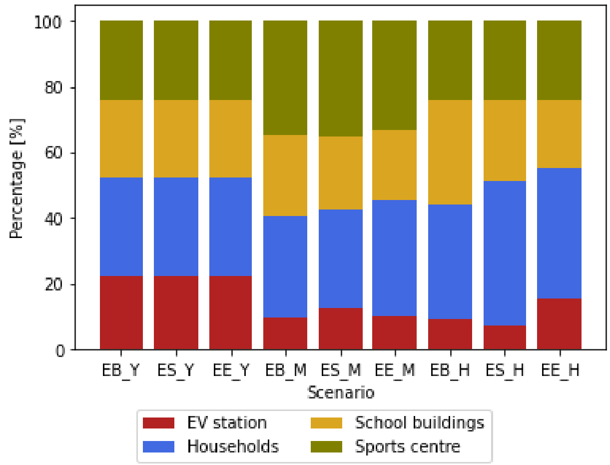

Fig. 6. Percentage of generated energy allocated per user group

Using more temporarily disaggregated $\beta_{i,t}$ reduces the amount of energy that needs to be allocated to the EV station to ensure its total costs are compensated. This is a positive outcome as it frees energy to be allocated to other groups, further minimizing community's energy costs. This reduction, however, is much significant when passing from yearly to monthly values than when using hourly instead of monthly $\beta_{i,t}$.

For the rest, the results vary depending on the energy sharing scenario and temporality considered. In the vulnerable customer's group, the energy assigned to them when using the yearly $\beta_{i,t}$ is the minimum allowed (100% $-\lambda_p$) for all sharing scenarios. This trend is mostly maintained when using the monthly $\beta_{i,t}$ as only in the *Equal Energy* strategy, the assigned energy to this group goes slightly up (34%). The volume of energy allocated to this group increases for all scenarios when using the hourly $\beta_{i,t}$, being the largest (44 %) in the *Equal Savings* case despite being the scenario in which least savings are reported for this group. In the *Equal Energy*, which results in the largest savings for the vulnerable customer group, the energy allocated is 40% when using the hourly $\beta_{i,t}$.

As happens with the reported savings, the energy allocated to the sports centre is barely affected by the sharing scenario selected. However, the usage of monthly $\beta_{i,t}$ results in higher energy being allocated to this group, which leads to more savings as observed in Figure 4. Most of the energy is allocated in the winter months to satisfy increasing demand. It must be noted that the electricity prices also are higher in winter than in summer.

The school buildings are allocated the highest energy volume when using the *Equal Beta* sharing strategy and least when using the *Equal Energy* case. They also tend to receive more energy when the hourly $\beta_{i,t}$ are used, particularly under the *Equal Beta* case. This impacts on the savings, which are larger for this group under the scenarios with hourly $\beta_{i,t}$ as previously explained.

C. *Energy compensation per scenario*

The lower savings obtained for the *Equal Savings* strategy (Figure 4) is explained by the larger amount of non-compensated surpluses registered, which can be observed in Figure 7. This is mostly attributed to the vulnerable customers' group and the equal distribution restriction impose to it under this scenario.

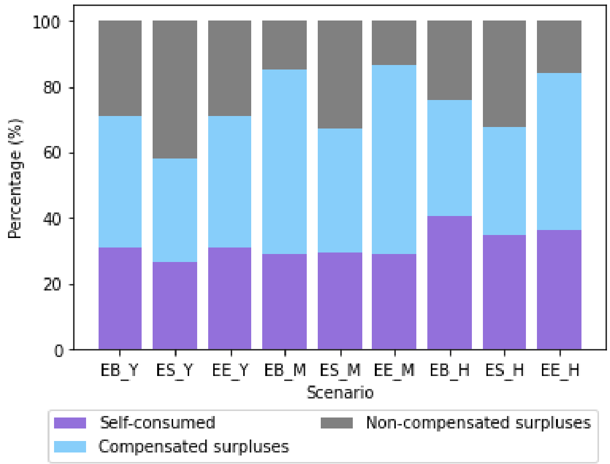

Fig. 7. Percentage of energy self-consumed and registered as compensated or non-compensated surpluses.

For the other two sharing strategies, it is relevant to observed that using the monthly $\beta_{i,t}$ allows to compensate a higher surpluses volume, but the level of self-consumption does not increase significantly. On the contrary, when using the hourly $\beta_{i,t}$, the amount of compensated surpluses is lower than in the monthly case – although still larger than when using fixed annual values – but the level of self-consumption improves. As the energy costs avoided through self-consumption are larger than the value given to surpluses, the higher self-consumption levels result in higher community savings for the hourly cases.

V. Conclusions

The results from this case study show that using the *Equal Energy* strategy results in overall higher savings for the vulnerable customer group; especially when paired with using hourly $\beta_{i,t}$ values. This is explained by the high variability in consumption habits present in this group. It also highlights the importance of having the possibility to use temporarily variable sharing coefficients as introduced recently in the Spanish regulation. However, under this strategy, the school buildings receive less energy and, thus, register less savings than when using the *Equal Beta* or *Equal Savings* strategies. Although they still present significant savings, the community should decide which group must be prioritized in the distribution strategy.

Furthermore, using the *Equal Energy Strategy* presents the highest potential to encourage users to consume more energy in hours in which they can benefit the most from the compensation scheme, maximizing their savings without the need to allocate more energy to them. This, however, must be further evaluated given the users' consumption habits and access to suitable appliances.

The *Equal Beta* strategy does not benefit significantly from using the temporarily variable coefficients (monthly, hourly), although some improvements can be obtained from considering seasonality by setting monthly $\beta_{i,t}$ values. This strategy results in lower savings than the *Equal energy* case, but its simplicity facilitates agreements as it is clear to households that energy is shared fairly among the group. Still, it might be worth considering using a more flexible strategy – such as the *Equal Energy* case – if temporarily variable $\beta_{i,t}$ are going to be used, even if it requires deeper communication efforts during the engagement process. Specially, if other initiatives, such as demand response programs are expected to be implemented as part of the energy community's services.

Using an *Equal savings* strategy with the characteristics considered in this article, results in suboptimal energy allocation to the vulnerable consumers' group, as some of the users that would otherwise present higher savings are penalized in order to fulfil the equality restriction. It might be worth to redesign this strategy setting a specific amount of savings that each household should receive and evaluate how much energy would need to be allocated to this group to comply with it. In [7], the authors suggest this approach given that the savings guaranteed to each family are aligned with their socioeconomic characteristics (number of family members, total income, age, etcetera). A first approximation to define this amount could be the criteria used for the bill discounts offered for vulnerable and extremely vulnerable consumer through the *Bono Social*, a social aid scheme offered by the Spanish government [17].

Finally, for the non-residential buildings, it is clear that using temporarily disaggregated $\beta_{i,t}$ instead of fixed annual values leads to higher savings. From some users, in which consumption presents significant peaks in particular months and remains high during most hours of the day, setting monthly $\beta_{i,t}$ might be enough to ensure an optimal usage of the energy compensation scheme. However, for users that have narrower consumption peaks due to shorter business hours, using the hourly $\beta_{i,t}$ maximizes its savings. In this sense, it is recommended to test mixed scenarios in which some users are assigned monthly $\beta_{i,t}$ while others used hourly $\beta_{i,t}$, evaluating its impact at the community and individual levels. In any case, using fixed yearly values is never the most efficient approach.

ACKNOWLEDGMENT

The authors thank R2M Solutions Spain for providing the necessary data to model the case study evaluated in this paper, and Lucas Porto for his feedback.

REFERENCES

[1] D. Frieden, A. Tuerk, C. Neumann, S. d'Herbemont and J. Roberts. Collective self-consumption and energy communities: Trends and challenges in the transposition of the EU framework (2020), 2021.

[2] J. T. Villalonga Palou, J. Serrano González, J. M. Riquelme Santos, C. Álvarez Alonso, and J. M. Roldán Fernández, "Sharing approaches in collective self-consumption systems: A techno-economic analysis of the Spanish Regulatory Framework," *Energy Strategy Reviews*, vol. 45, p. 101055, 2023.

[3] Entidade Reguladora Dos Serviços Energéticos. Pilot-projects approved under article 55 of the Self-Consumption code (Regulation 373/2021, of 5th May), 2022. https://www.erse.pt/media/12jdlvsw/lista_ppiloto_cer_en_14122022.pdf

[4] "Pilot sites - lightness project in five local contexts," *LIGHTNESS PROJECT*, 15-Feb-2022. [Online]. Available: https://www.lightness-project.eu/pilot-sites/. [Accessed: 03-Apr-2023].

[5] Spanish Official Gazette, Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, t´ecnicas y econ´omicas del autoconsumo de energía eléctrica, 2019.

[6] Spanish Official Gazzette, Orden TED/1247/2021, de 15 de noviembre, por la que se modifica, para la implementación de coeficientes de reparto variables en autoconsumo colectivo, el anexo I del Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica, 2021.

[7] Amigos de la Tierra. "Sin dejar a nadie atrás. Las comunidades energéticas como herramienta frente a la pobreza energética", 2023.

[8] F. Hanke, R. Guyet, and M. Feenstra, "Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases," *Energy Research & Social Science*, vol. 80, p. 102244, Oct. 2021, doi: https://doi.org/10.1016/j.erss.2021.102244.

[9] Á. Manso-Burgos, D. Ribó-Pérez, T. Gómez-Navarro, and M. Alcázar-Ortega, "Local energy communities modelling and optimisation considering storage, demand configuration and sharing strategies: A case study in Valencia (Spain)," *Energy Reports*, vol. 8, pp. 10395–10408, Nov. 2022, doi: https://doi.org/10.1016/j.egyr.2022.08.181.

[10] A. J. Gil Mena, V. F. Nasimba Medina, A. Bouakkaz, and S. Haddad, "Analysis and optimisation of collective self-consumption in residential buildings in Spain," *Energy and Buildings*, vol. 283, p. 112812, Mar. 2023, doi: https://doi.org/10.1016/j.enbuild.2023.112812.

[11] DAI-Laboratory, TU Berlin. 2022. *Electric Vehicle Charging Infrastructure Simulator (ELVIS).* Accessed: April 02, 2023. [Online]Available: https://github.com/dailab/elvis

[12] C. Corchero García. "European electric vehicle fleet: driving and charging behaviors". *X Congreso de la Asociación Española para la Economía Energética*, 2015.

[13] European Commission, 2023. "Typical Meteorological Year", Photovoltaic Geographical Information System [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/

[14] Som Energia. "Tarifas de electricidad". Apr. 1, 2023. [Online]. Available: https://www.somenergia.coop/es/tarifas-de-electricidad/

[15] McCarl, B. A. McCarl GAMS User Guide Version 24.6, Texas A&M University, USA, 2016.

[16] L. Igualada, C. Corchero, M. Cruz-Zambrano, and F.-J. Heredia, "Optimal Energy Management for a Residential Microgrid Including a Vehicle-to-Grid System," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 2163–2172, Jul. 2014, doi: https://doi.org/10.1109/tsg.2014.2318836.

[17] Gobierno de España. "Bono social de electricidad". Apr.19, 2023. [Online]. Available: https://www.bonosocial.gob.es/#inicio