Sharing-Cost Factors for a Community of PV Prosumers with Battery Storage

Jorge Barba
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
100346237@alumnos.uc3m.es

Sebastian Martin
Dept. of Electrical Engineering
Universidad de Málaga
Málaga, Spain
smartin@uma.es

***Abstract*—The aggregation of prosumers into energy communities brings multiple benefits in terms of use of the PV and reducing costs. However, it is also a challenge to determine the sharing cost (installation and operation) for each user. The main contribution of this work is a cost-sharing rule based on the influence that each prosumer has on the total cost of the community. In addition, the proposed sharing factors allow to determine in which equipment of the installation (PV, Battery, Grid connection) is more beneficial for the user to participate. The proposed sharing factors are illustrated on an energy community with ten users under different market energy prices and PV, battery costs. As a main conclusion, it is confirmed that taking part in an energy community is beneficial in terms of total (amortization + operation) savings for each participant.**

***Index Terms*—Smart Grid, Photovoltaic Power System, Energy Management, Prosumers, Power Profile**

NOMENCLATURE

Indices and Sets

t, T	Periods of time, $t \in T$.
w, Ω	Scenarios for PV and demand, $w \in \Omega$.
u, k, U	Users in the community, $u, k \in U$, $\|U\| = N$.

Parameters (common to all models)

α_c/α_d	Battery charge/discharge power rate, (kW/kWh).
α_I	For grid connection, (Injection capacity) = $\alpha_I \cdot$ (Consumption capacity), (p.u.).
Δ_t	Duration of time period t, (hours).
η_c/η_d	Battery charging/discharging efficiency, (p.u.).
CAB	Battery amortization cost, (€/(kWh·day)).
$CAPV$	PV installation amortization cost, (€/(kWp·day)).
CTP	Cost of network connection capacity, (€/(kW·day)).
$D_{u,t}^{w}$	Demand of user u in period t and scenario w, (kW).
PEC_t^w/PEV_t^w	Price of energy purchased from / sold to the grid at period t and scenario w, (€/kWh).
Pr^w	Probability of the scenario w, (p.u.).
PVA_t^w	Available PV gen. at period t scen. w, (kW/kWp).

Variables (base model)

$b/pv/cc$	Capacity of: battery (kWh) / pv (kWp) / grid connection (kW).
bd_t^w/br_t^w	Power from battery to demand / network at period t scenario w, (kW).
rb_t^w/rd_t^w	Power from network to: battery / demand at period t scenario w, (kW).
$soc_t^w/socini_u^w$	Energy in the battery: at the end of period t / before starting operation ($t = 0$) in scen. w, (kWh).
$vb_t^w/vd_t^w/vr_t^w/vs_t^w$	Power from PV to: battery / demand / main grid / not used at period t scenario w, (kW).

Results

$cb_u/cpv_u/cz_u$	Battery amortization / PV amortization / total cost z (installation + operation) shared cost for user u, (€/day).

I. INTRODUCTION

In the last few years, due to the advance of climate change, decarbonizing the electricity sector has become one of the key policy objectives worldwide (in Europe, the Clean Energy Package for all Europeans [1]). This has promoted, among many other measures, the fast deployment of energy communities, where users became "prosumeers", they can produce energy (mainly from PV generation) for self-consumption, to sell it the grid or to other users in the community. Thus the energy community allows to reduce the investment cost, to increase self-consumption and self-sufficiency, and also to get some revenues by selling the surplus to other users in the community.

The operation of energy communities arises several challenges, as how the costs and benefits should be shared among the community members. The impact of each participant in the community is not the same as a result of different consumption habits. Here an answer for that question is proposed, based on the quantification of the effect of each user on the whole community, by comparing the community performance with and without that user.

The question of cost sharing in energy communities has been addressed in the literature, most of the methods are based on: fixed sharing factors, energy consumption, P2P, or game theory. P2P models is the main working trend in energy communities nowadays [2], they allow to include particular sharing rules in the smart contracts. Cost sharing based on

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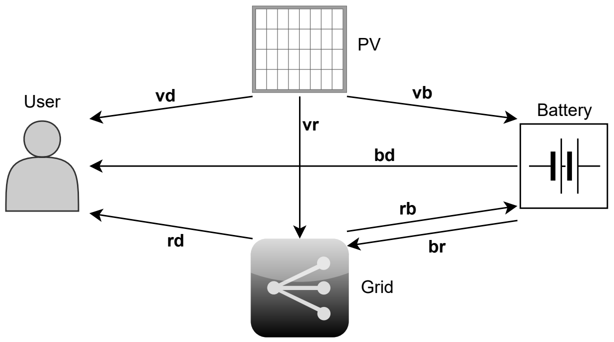


Fig. 1. Flow chart for the energy community considered.

energy consumption usually uses Time Of Use (TOU) tariffs, and they have been studied in several publications as in [3] where a multi-agent model with residential and non-residential users is used. Other approaches based on energy consumption that also consider sales to grid have been studied, as for instance in [4]. These methods only allocate operating costs (OPEX) and not investment (amortization) costs (CAPEX) which is highly conditioned by the demand curve of each user and represents a great share of the total cost, so it must also be distributed among the participants.

Methods based on game theory allow to efficiently allocate costs among the participants. The main difficulty with these methods is their high computational cost and that they are difficult to understand by the users in the community. Among the methods using game theory those based on nucleolus or Shapley value are quite common in the literature. For instance, the nucleolus method is studied in [5] where the cost of a common battery is distributed among the user by a coalition game. On the other hand, Shapley's values is used on other studies, as [6]. Both methods, nucleolus and Shapley, provide quite similar results [7]. However, these methods are too complex to be quickly and easily interpreted (to be accepted by the users in the community) and its computational cost is high.

The main contribution of this work is a cost-sharing rule that is easy to apply (linear computational cost with the number of users in the community) and understand, thus allowing it to be easily accepted by the participants in the community. The solution is based on the influence that each user has on the total cost of the community. The rule allows to assign the amortization cost and the operation (both separately) for each user in the community.

In addition, the proposed models provide the optimal size of the community equipment (PV, battery, grid connection).

In the rest of the paper, methodology is presented in Section II, the case study and the results are discussed on Section III, and conclusions in Section IV close the paper.

II. METHODOLOGY

Users with PV generation, battery, and grid connection are considered here, as illustrated on Fig. 1. When operating as a community it is assumed there is a single PV installation and a single battery that are shared for the whole community, this is illustrated in Fig. 2.

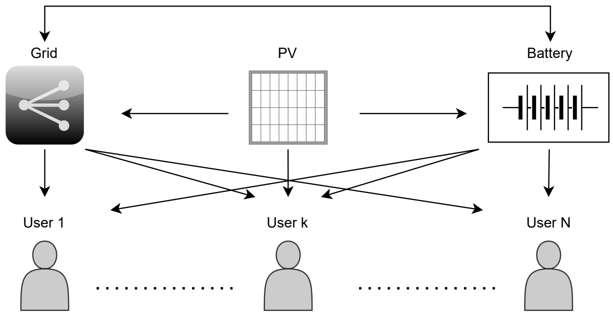


Fig. 2. Flow chart for the energy community considered.

The sharing-cost factor for each user in the community is computed based on the influence of that user in the community cost. That influence is computed by comparing the community cost, N users, with the cost of the community without that user u, $N-1$ users. $N+1$ problems are solved, one for the whole community (N users), and N problems with $N-1$ users each one (one for each user u that is removed from the community). The mathematical expression for these sharing factors are (2)-(4), where pv^N / b^N / z^N are the optimal values of PV / battery / total cost z (objective function = investment cost + operation cost) for the whole community, pv_k^{N-1} / b_k^{N-1} / z_k^{N-1} are the optimal values of PV / battery / total cost z for the whole community without user k, ($N-1$ users). Those values come from linear optimization problems described in Section II-A. Factors (2)-(4) can be computed using historical data and the computational cost is linear with the number of users in the community. Using this rule for each user u have been computed the shared factor for: total cost cz_u (1), PV amortization cost cpv_u (2), battery amortization cost cb_u (3), and grid connection cost ccc_u (4).

$$cz_u = \frac{z^N - z_u^{N-1}}{\sum_{k \in U}(z^N - z_k^{N-1})} \cdot z^N \tag{1}$$

$$cpv_u = \frac{pv^N - pv_u^{N-1}}{\sum_{k \in U}(pv^N - pv_k^{N-1})} \cdot pv^N \cdot CAPV \tag{2}$$

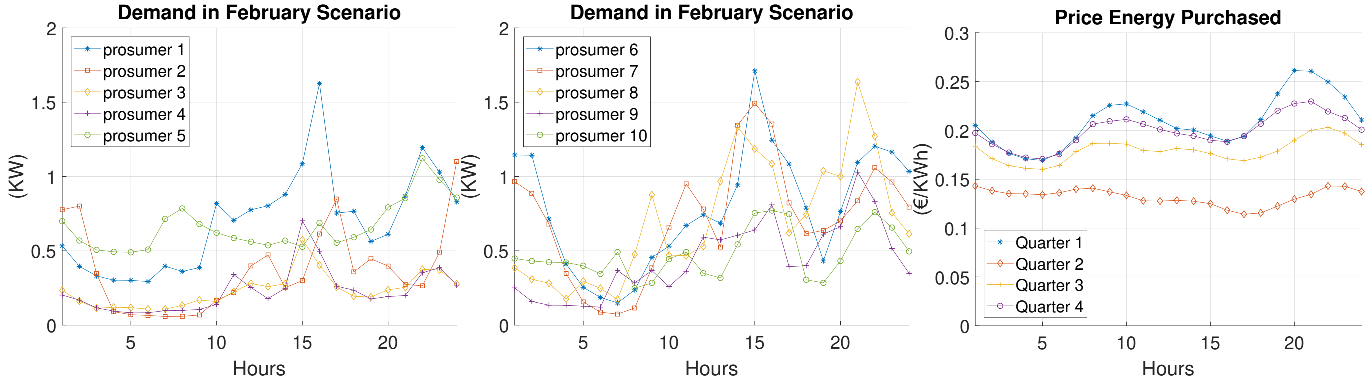
$$cb_u = \frac{b^N - b_u^{N-1}}{\sum_{k \in U}(b^N - b_k^{N-1})} \cdot b^N \cdot CAB \tag{3}$$

$$ccc_u = \frac{cc^N - cc_u^{N-1}}{\sum_{k \in U}(cc^N - cc_k^{N-1})} \cdot cc^N \cdot CTP \tag{4}$$

With the information provided by these factors it is quantified whether adding user u to the community is beneficial or not for the user and beneficial or not for the community.

A. Mathematical Model

A single optimization problem is used to size and operate the installations in three different configurations: i) independent operation of each particular user u, then N problems are solved, one problem for each user u, ii) the energy community as a whole, a single problem that includes at the same time all (N) users in the community, iii) the energy community with all the users except user u, $N-1$ users in each problem and N problems are solved. The base optimization problem (5)-(15) and the changes to represent each configuration are



(a) (b) (c)

Fig. 3. Sample of scenarios for: (a) Demand for users 1 to 5; (b) Demand for users 6 to 10; (c) Price of energy purchased from grid.

described in what follows. Each problem consists of a set of constraints and one objective function: minimizing total cost z = investment (amortization cost, first stage) + operation (expectation of net operation profit, second stage). Uncertainty is considered in demand, PV generation and market energy prices, and it is modelled through a scenario tree.

The first stage corresponds to the sizing decisions, capacity of: PV (pv), battery (b), and grid connection (cc). The second stage correspond to operation decisions, such as the power consumed from the network (rd_t^w) or the battery state of charge (soc_t^w). They can have a different value for each scenario w and period of time t (operation in real time).

$$\begin{aligned}\min\Big\{z = CAPV\cdot pv + CAB\cdot b + CTP\cdot cc+\\ +\sum_{t\in T}\sum_{w\in\Omega} Pr^w\cdot\Delta_t\cdot\big[PEC_t^w\cdot(rd_t^w+rb_t^w)-\\ -PEV_t^w\cdot(br_t^w+vr_t^w)\big]\Big\}\end{aligned}\tag{5}$$

Subject to:

$$rd_t^w + bd_t^w + vd_t^w = D_t^w;\ \ \forall t\in T;\ \forall w\in\Omega \tag{6}$$

$$vd_t^w + vr_t^w + vb_t^w + vs_t^w = pv\cdot PVA_t^w;\ \ \forall t\in T;\ \forall w\in\Omega \tag{7}$$

$$soc_t^w = soc_{t-1}^w + \eta_c\cdot\Delta_t\cdot(vb_t^w+rb_t^w)- -\frac{\Delta_t}{\eta_D}\cdot(br_t^w+bd_t^w);\ \ \forall t>1\in T;\ \ \forall w\in\Omega \tag{8}$$

$$soc_t^w = socini^w + \eta_c\cdot\Delta_t\cdot(vb_t^w+rb_t^w)- -\frac{\Delta_t}{\eta_D}\cdot(br_t^w+bd_t^w);\ \ t=1;\ \ \forall w\in\Omega \tag{9}$$

$$socini_u^w = soc_{|T|}^w;\ \ \forall w\in\Omega \tag{10}$$

$$soc_t^w \le b;\ \ \forall t\in T;\ \ \forall w\in\Omega \tag{11}$$

$$rb_t^w + vb_t^w \le \alpha_C\cdot b;\ \ \forall t\in T;\ \ \forall w\in\Omega \tag{12}$$

$$bd_t^w + br_t^w \le \alpha_D\cdot b;\ \ \forall t\in T;\ \ \forall w\in\Omega \tag{13}$$

$$rd_t^w + rb_t^w \le cc;\ \ \forall t\in T;\ \ \forall w\in\Omega \tag{14}$$

$$br_t^w + vr_t^w \le \alpha_I cc;\ \ \forall t\in T;\ \ \forall w\in\Omega \tag{15}$$

The objective function (5) is the total cost z, sum of the amortization cost plus the operation cost. Equations (6)-(15) stand for the constraints: (6) is the demand balance; (7) is the PV generation balance; (8) and (9) correspond to the battery energy balance, for $t>1$ and $t=1$ respectively; (10) avoids the use of free energy from the battery; (11) links the battery size to the upper bound of energy it can contain; (12) and (13) are the upper bound for battery charging / discharging, respectively; (14) and (15) are the upper bound for the grid connection capacity for consumption / injection respectively.

The problem for each single user is (5)-(15), in this case $D_t^w = D_{u,t}^w$ and the variables add the subscript u to indicate the user, for instance pv_u is the PV installed by user u for individual operation.

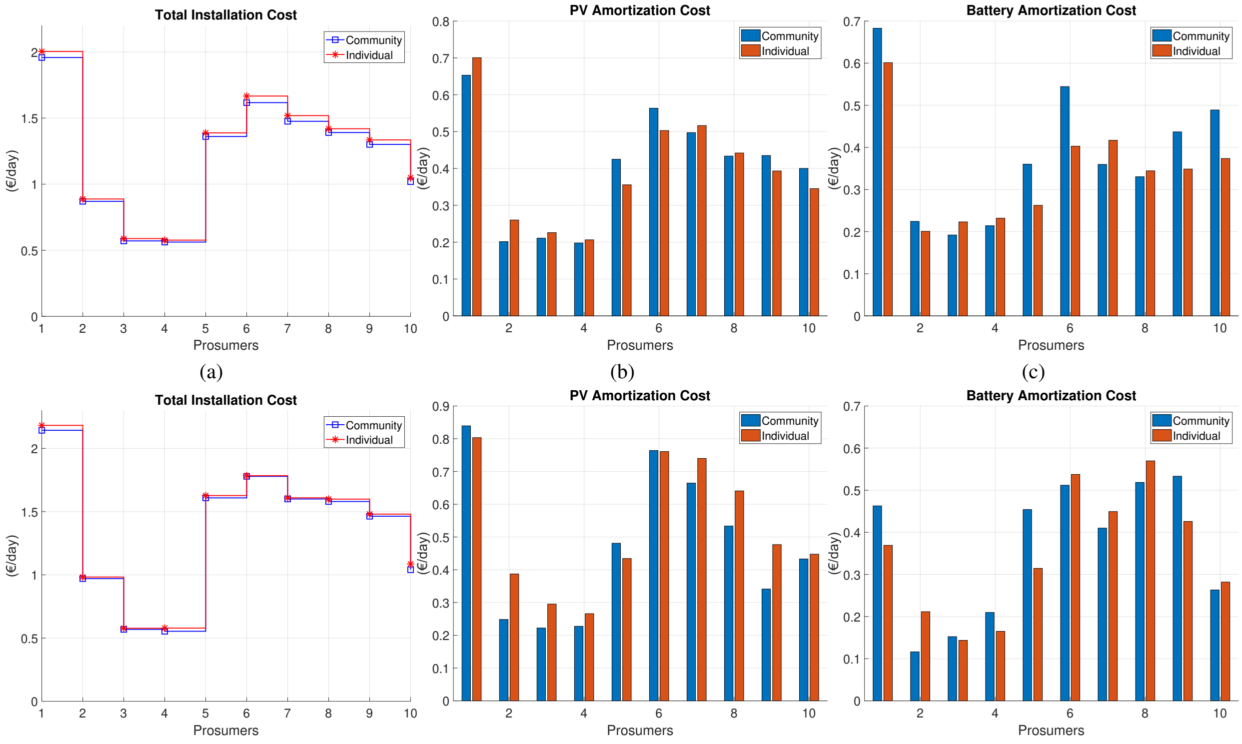
For the whole community (N users) it is assumed one single PV and one single battery are shared for all the users. In this case the optimization problem is (5)-(15) with $D_t^w = \sum_{u\in U} D_{u,t}^w$, and variables are named adding the superscript N, for instance pv^N and b^N are the PV and the battery installed for the whole community respectively.

Problem for the whole community but user u. This problem with $N-1$ users is solved N times, each time removing a different user u from the community. In this case the equations are again (5)-(15), but with $D_t^w = \sum_{k\in U} D_{k,t}^w - D_{u,t}^w$ (user u is removed). The variables add the superscript $N-1$ and the subscript u to indicate the user that is removed. For instance, pv_u^{N-1} is the optimal PV installed for the whole community without user u.

The optimization problems are solved using CPLEX under GAMS [8] in a laptop with Intel(R) Core(TM) i7-8550U CPU, 8GB RAM, and Windows 10 x64. The model size for all configurations considered is 2596 variables and 2317 equations, and the solving time is around 1.42 seconds.

III. CASE STUDY AND RESULTS

To illustrate the proposed methodology it is applied to a case study consisting of a community with ten users, a neighbourhood in the south of Spain (Málaga). The data for PV generation to calculate PVA_t^w correspond to Málaga and come from [9]. The values for demand $D_{u,t}^w$ come from the users smart meters. Regarding the market energy prices (PEC, PEV), five configurations are considered to study the effect of those prices. Those price configurations are got from the real market prices for domestic users in the Spanish market in 2022, [10], multiplying the profiles by a scale factor, and the values are listed on Table I. When a value of PEC or PEV is given without indices, that means the annual average, for instance $PEC = 0.18$ (€/kWh), is the annual average price.



(a) (b) (c)

(d) (e) (f)

Fig. 4. Summary of results community vs individual operation for: total cost z (investment + operation), investment in PV, investment in battery, for: 1) Price configuration 1: (a)-(c) PEC=0.18 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.11 (€/($kWh \cdot day$)); 2) Price configuration 2: (d)-(f) PEC=0.12 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.11 (€/($kWh \cdot day$)).

TABLE I
CONFIGURATIONS FOR MARKET ENERGY PRICES

Config.	PEC €/kWh	$CAPV$ €/($kWp \cdot day$)	CAB €/($kWh \cdot day$)	Scale (p.u.)
1	0.18	0.15	0.11	0.66
2	0.12	0.15	0.11	0.44
3	0.12	0.15	0.06	0.44
4	0.27	0.15	0.11	1.00
5	0.27	0.15	0.06	1.00

PEV and PEC are related, $PEV \approx \frac{(PEC-0.09)}{1.5}$. Those price values range from the post-pandemic (very high) prices to the pre-pandemic prices (around 44% of the high prices).

In order to represent the different consumption patterns (for each user), PV production profile and grid energy prices, the simulation is carried out for a total duration of one year. Hourly values are considered and processed (monthly average) to get a representative day (24 hourly values) for each month of the year. Thus 12 scenarios w are considered, each one with a probability $Pr^w \approx \frac{1}{12}$. For illustrative purposes, demand scenarios for February for the ten users are provided in Figs. 3a and 3b and four scenarios for prices (out of 12) are represented in Fig. 3c. The rest of the parameters in the model are listed on Table II.

The optimal capacities (PV, battery, grid connection) and optimal operation cost for all the prices configurations and all the users operating individually and operating in community are calculated, and also the sharing-cost factors according to the proposed rules (2)-(4). A summary of the results for each price configuration is provided on Tables III-VII. Net cost correspond to the value of the objective function z (5) (amortization + operation). Two operation modes are considered:

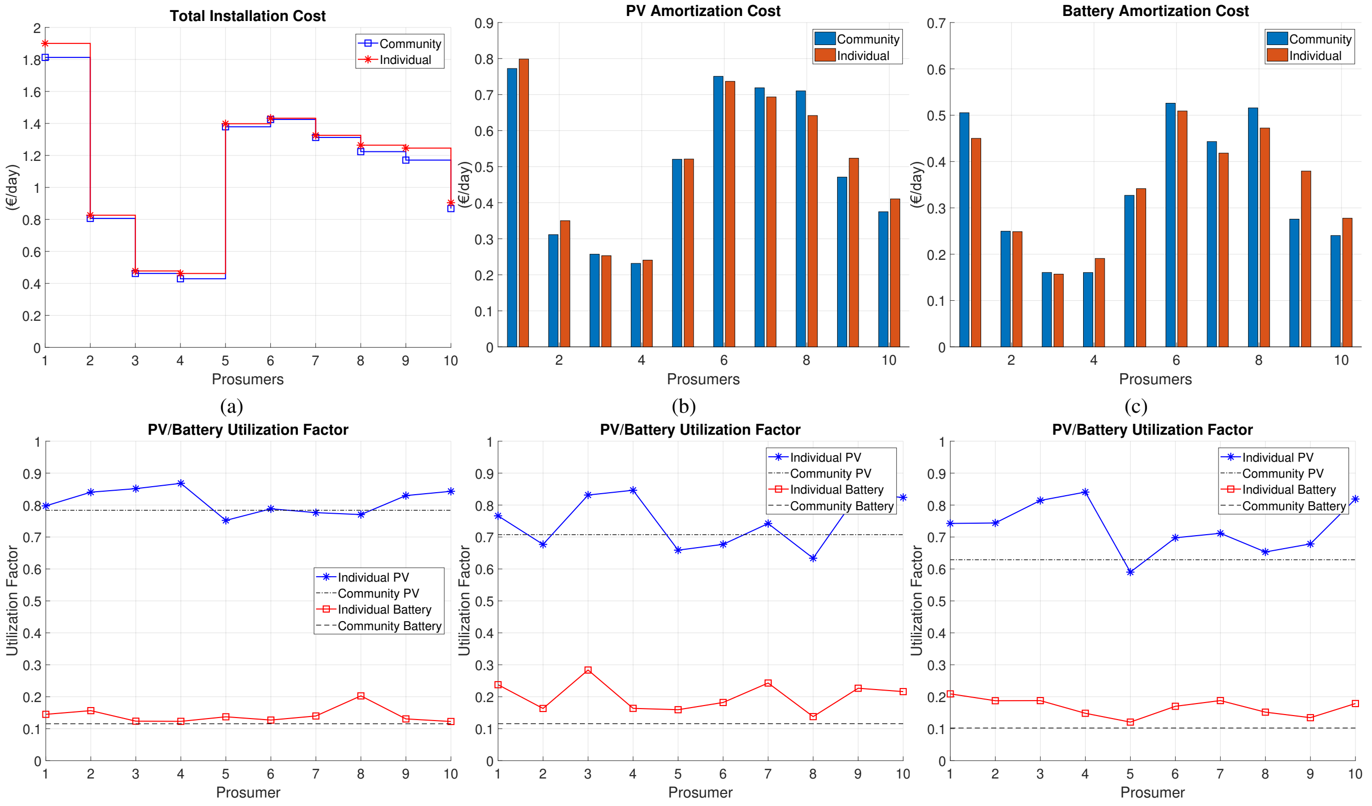
- Individual operation of each user. Each user solves an optimization problem for the sizing and operation of his/her installation without taking into account the other users. Values “Individual (sum)” on Tables III-VII correspond to the sum of that magnitude for all the users in the community.

TABLE II
VALUES OF PARAMETERS IN THE MODELS

Parameter	Value	Parameter	Value (p.u.)
$CAPV$	0.15 €/(kWp · day)	α_c	0.37
CAB	0.11 €/(kWh · day)	α_d	0.37
CTP	0.12 €/(kW · day)	η_d	0.90
PEV	0.12 €/(kWh)	η_c	0.90
PEC	0.27 €/(kWh)	α_I	0.50

TABLE III
SUMMARY OF RESULTS FOR CONF. 1: PEC=0.18 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.11 (€/($kWh \cdot day$)).

Indicator	Individual (sum)	Community
PV (kW)	26.32	26.78
Battery (kWh)	30.96	34.85
Connection (kW)	6.92	5.72
Amortization (€/day)	8.18	8.53
Energy consum. from grid (€/day)	5.57	4.65
Energy sold to grid (€/day)	1.32	1.07
Net Cost (€/day)	12.43	12.12



(a) (b) (c)

(d) (e) (f)

Fig. 5. Summary of results community vs individual operation for: total cost z (investment + operation), investment in PV, investment in battery, for price configuration 3, (a)-(c) PEC=0.27 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.06 (€/($kWh \cdot day$)). Utilization factor for price configuration (Table I): 1 (d), 2 (e), and 3 (f).

TABLE IV
SUMMARY OF RESULTS FOR CONF. 2: PEC=0.12 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.11 (€/($kWh \cdot day$)).

Indicator	Individual (sum)	Community
PV (kW)	17.79	16.46
Battery (kWh)	16.70	11.39
Connection (kW)	6.89	6.23
Amortization (€/day)	5.33	4.47
Energy consum. from grid (€/day)	5.84	6.42
Energy sold to grid (€/day)	0.25	0.22
Net Cost (€/day)	10.93	10.66

- Community operation. One single optimization problem is solved for the sizing and operation of the aggregate set of users in the community. The results are in the column “Community” in Tables III-VII.

To quantify the use of the installed capacity the usage factors (16) and (17) are defined. Those factors (16) and (17) are computed as a fraction with the current usage (computed on the optimization problem) in the numerator, and the maximum possible usage in the denominator:

$$fb_u = \frac{\sum_{t\in T}\sum_{w\in\Omega} \cdot Pr^w \cdot \Delta_t \cdot (br^w_{u,t} + bd^w_{u,t})}{b \cdot \alpha_c \cdot \eta_c} \tag{16}$$

$$fpv_u = \frac{\sum_{t\in T}\sum_{w\in\Omega} \cdot Pr^w \cdot \Delta_t \cdot (vd^w_{u,t} + vb^w_{u,t} + vr^w_{u,t})}{\sum_{t\in T}\sum_{w\in\Omega} \cdot Pr^w \cdot PVA^w_t \cdot \Delta_t \cdot pv_u} \tag{17}$$

Price configuration 1 (Table I) corresponds to moderate energy market prices and current prices for PV and battery. Results for this configuration are summarized on Table III, where we can see the values for the community and the single user operation are quite similar, in fact the difference in the aggregate net saving is around 3% (12.43 vs 12.12 €/day). All the users get a lower net cost z (amortization + operation) when operating as a community, Fig. 4a. But some users get

TABLE V
SUMMARY OF RESULTS FOR CONF. 3: PEC=0.12 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.06 (€/($kWh \cdot day$)).

Indicator	Individual (sum)	Community
PV (kW)	24.00	24.97
Battery (kWh)	39.60	42.79
Connection (kW)	4.38	3.04
Amortization (€/day)	6.50	6.67
Energy consum. from grid (€/day)	3.13	2.66
Energy sold to grid (€/day)	0.17	0.13
Net Cost (€/day)	9.47	9.20

TABLE VI
SUMMARY OF RESULTS FOR CONF. 4: PEC=0.27 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.11 (€/($kWh \cdot day$)).

Indicator	Individual (sum)	Community
PV (kW)	35.02	31.70
Battery (kWh)	31.53	33.02
Connection (kW)	13.38	8.52
Amortization (€/day)	10.33	9.41
Energy consum. from grid (€/day)	9.02	7.42
Energy sold to grid (€/day)	5.84	3.52
Net Cost (€/day)	13.51	13.31

TABLE VII

SUMMARY OF RESULTS FOR CONF. 5: PEC=0.27 (€/kWh), $CAPV$=0.15 (€/($kWp \cdot day$)), CAB=0.06 (€/($kWh \cdot day$)).

Indicator	Individual (sum)	Community
PV (kW)	34.47	34.13
Battery (kWh)	57.42	56.73
Connection (kW)	4.28	3.65
Amortization (€/day)	9.13	8.96
Energy consum. from grid (€/day)	4.54	2.61
Energy sold to grid (€/day)	2.43	0.68
Net Cost (€/day)	11.23	10.89

higher amortization cost for PV, battery or both, Figs. 4b and 4c, than they get with individual operation. This depends on the user demand profile, those users with a profile that complement the other profiles in the community (higher direct self-consumption in the community) get lower amortization costs.

Price configuration 2 (Table I) corresponds to low energy market prices and current prices for PV and battery. Results for this configuration are summarized on Table IV, where again the values for the community and single operation are quite similar, less than 2.5% in net cost (z). The main difference is in the battery size, that is lower for the community because it allows a more efficient use of the battery.

Price configuration 3 (Table I) corresponds to low energy market prices, current price for PV and low battery cost (expected price in 10 years). Results for this configuration are summarized on Table V, where again the values for the community and single operation are quite similar, less than 2.9% in net cost (z). The main difference is in the battery size and the grid connection, more battery and less grid connection for the community, that allows a lower energy consumption from the grid.

Price configuration 4 (Table I) corresponds to high energy market prices (post-pandemic prices) and current prices for PV and battery. Results for this configuration are provided on Table VI (aggregated value) and Figs. 4d-4f (values for each user). The total savings of the community compared to individual operation are quite low, around 1.4%. The main differences are the community installs less PV, more battery, less grid connection capacity, than the individual operation. In this case community operation is oriented to self-consumption and individual operation is oriented to sales to the grid. Price configuration 5 (Table I) corresponds to high energy market prices (post-pandemic prices), current prices for PV, and low battery cost. Results for this config. are provided on Table VII (aggregated values) and Figs. 5a-5c (values for each user). The total savings of the community compared to individual operation are around 3%.

Also the utilization factor for price configurations 1, 4 and 5 are provided in Figs. 5d-5f. The utilization factor (PV or battery) for the community operation are not greater or only lightly greater in general than those of the individual operation. It depends on the heterogeneity of the demand profiles.

The main mechanisms for the community to get greater savings are to increase the efficiency in the use of PV and battery and increasing self-consumption, but this depends to grand extent on the demand profile of the users in the community. In the case study, with a small energy community (10 users), the difference in total cost are quite small, ranging from 1.4% to 3% for a wide range of energy market prices scenarios.

IV. CONCLUSIONS

For the case study tested, small energy community (10 users), the total cost (investment + operation) savings are quite small (1.4%-3%) for a wide range of energy market prices. Even some users could loss money by operating in the community respect to what they can get by individual operation.

In principle energy communities should allow for a greater self-consumption and higher utilization factor of the equipment (PV, battery), but this strongly depend on the user demand profiles. In a real case, with 10 users, the results show that there is a very low incentive (less than 3% of saving) to operate in community. The factors related with the community size (number of users) could have a significant impact on the savings when operating as a community. We left that study as a future work.

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