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COUPLING OPTIMAL ENERGY MANAGEMENT AND ALLOCATION THROUGH KEYS OF REPARTITION IN ENERGY COMMUNITIES

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ABSTRACT

This paper presents the management of an energy community where distributed energy resources (DER) located 'behind the meter' are controlled collectively and the overall community energy is contractually dispatched among the members through the so-called 'keys of repartition'. An 'all-in-one' optimization method is proposed where the operational phase – energy management strategy (EMS) – is coupled with the cost allocation problem. This approach allows integrating 1) the control strategy of DER assets in the community to 2) the cost settlement that ultimately impacts the end-users' bill. This study is based on the organization and regulation of EC in the French context. For our test case of a real EC of seven households in the south of France, the proposed method shows a total bill reduction of 10.7% compared to an individual optimization-based EMS at the level of every end-users.

I. INTRODUCTION

Energy communities (EC) are emerging actors enhancing the integration of distributed generation at the end-users level, with people that can play an active role in the sustainable energy transition. EC are defined as the federation of electricity consumers/producers that come together to share energy collectively. Concerning the European Union's target of 45 % renewable energy by 2030, the EC concept has emerged to promote local renewable energy for end-users. The report on the State of Energy Union 2021 mentioned that at least 2.2 million people have been engaged in more than 7,700 EC [1]. In France, EC has been regulated since 2016 [2] and at least 240 projects of EC have been identified in 2019 [3].

One reason for this wide adoption is the idea to be more independent from the main grid. To measure the degree of autonomy, two metrics are typically considered: 1) self-sufficiency ratio (SSR) – i.e., the portion of consumption that is supplied by local generation and 2) self-consumption ratio (SCR) – i.e., the portion of local production that is consumed locally [4]. Conventionally, these metrics are measured for each individual. However, the growth of EC brings out a new scheme and both metrics can be considered collectively at the community level.

End-users within near geographical areas can then exchange and trade energy with each other inside EC. This leads to the concept of collective self-consumption (CSC), meaning that more local energy can be absorbed thanks to heterogeneous usages among community members. Individuals without any energy asset (as traditional consumers) can also have access to local, clean and green energy thanks to the energy surplus that is produced by the DER owned by other community members (as prosumers). Hence, the development of EC offers new possibilities for

residential consumers to manage their energy locally. In the literature, the operational aspect of energy systems is oftentimes addressed using EMS with the most common objective being the minimization of the total energy cost of the community [5]. Typically, the management takes the form of an optimization problem to find the best schedule for the flexible DER assets. More specifically, those degrees of freedom can include the charging/discharging power of batteries, the curtailment of energy sources, and/or shiftable loads [6]. The demand response capability from the consumers' load profile aggregation is also oftentimes integrated into the energy management optimization model [7].

Another important concern in EC with many participants is the energy/cost allocation problem – i.e., how to properly share the collective energy to each individual member? This allocation rule can be represented by some coefficients called 'keys of repartition' (KOR). As an example, the French regulation proposes a default scheme for the KOR based on the prorate of consumption [8], meaning that a consumer who consumes more will receive more energy from the community. In other words, one must increase his electricity usage to get more local energy. This idea does not align with the sustainable spirit to conserve and save energy. Therefore, an alternative strategy of KOR is required. This repartition of community energy to each individual member is important because it constitutes the deficit/surplus one must buy/sell from the main grid, which leads to billing calculation – i.e., more energy allocated to a member usually means lower bill (when the energy purchased from the community is cheaper than typical retail prices).

Various contributions address this issue by using internal local markets [9] and peer-to-peer trading [5]. Another method to fairly share the community cost is the game theory with cooperative interaction [10]. Optimal allocation and billing strategies are proposed by considering a penalty cost due to individual mismatch between commitment and realization, as well as a reward for the contribution to local voltage regulation [11]. Meanwhile, [12] sets the objective to minimize the variance of annual energy allocated by the community.

Several works in the literature combine the EMS and the sharing/allocation rules for EC in two different stages, where the operational dispatch is optimized first before the collective energy is allocated to each household [13]. Similarly, using the cooperative model, [14] controls the storage output to minimize collective energy cost, then allocate the financial rewards to all participants in a way that prevents them to leave the coalition.

In light of these facts, this paper aims at developing a tool that couples the EMS for DER operation with the allocation of collective energy to each member through KOR. The novelty we propose is an optimization model of EC to control the residential storage within the EC that also indirectly define the allocation rules. More precisely, we use a real case study of an EC in France and follow the

framework and regulation of CSC based on the French distribution system operator (DSO). In addition, the individual benefit of forming a community in terms of bill reduction will be discussed.

The paper is structured as follows: Section 2 presents the proposed model of EC as well as the optimization method, Section 3 presents the case study and analyses the results, and Section 4 summarizes the study.

II. ENERGY COMMUNITY MODEL

In the context of CSC, a community manager plays a role as an ‘*organizing legal entity*’ (English translation of *personne morale organisatrice* (PMO) in French) that is responsible for the EC arrangement such as internal coordination and dealing with external parties such as the DSO. More precisely, the PMO is the one who defines the KOR. The design of KOR is then submitted to DSO for the computation of each energy exchange with the community and the main grid. Eventually, DSO sends these data to energy retailers for billing purposes.

We differentiate the power flows into *physical flows* that refer to the actual power measured at the house level and *contractual flows* that occur due to the internal energy sharing and trading within the community. Figure 1 illustrates the physical and contractual power flows in the EC: the household demand ($P_{n,t}^{load}$), the DER power output ($P_{n,t}^{PV}$ for solar PVs, $P_{n,t}^{bat+}$, $P_{n,t}^{bat-}$ for battery charge and discharge, and $P_{n,t}^{EV+}$, $P_{n,t}^{EV-}$ for electric vehicles – EV) as well as the contractual import and export power with the community ($P_{n,t}^{com+}$, $P_{n,t}^{com-}$) and the main grid ($P_{n,t}^{gd+}$, $P_{n,t}^{gd-}$). Note that the only measurable physical flow from DSO’s perspective is at the level of the home meter ($P_{n,t}^{met+}$, $P_{n,t}^{met-}$).

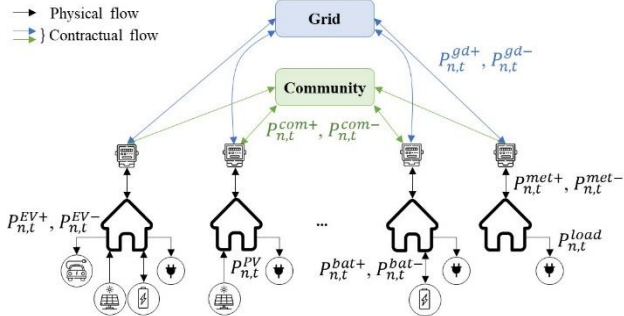


Figure 1 Typical energy community architecture.

The KOR ($\lambda_{n,t}$) is imposed on the collective net production at the meter and returns the allocated power from the community ($P_{n,t}^{alloc}$), as shown in (1). In the case where the portion of collective energy allocated to a member is higher than needed (i.e., consumption at the meter level), the imported power from the community is the minimum value between the allocated power and his consumption, as expressed in (2). However, if the collective energy given to a member is not sufficient compared to his consumption, the rest is supplied by the main grid as described in (3).

$$P_{n,t}^{alloc} = \lambda_{n,t} \cdot \sum_{n \in N} P_{n,t}^{met-} \quad (1)$$

$$P_{n,t}^{com+} = \min(P_{n,t}^{alloc}, P_{n,t}^{met+}) \quad (2)$$

$$P_{n,t}^{gd+} = P_{n,t}^{met+} - P_{n,t}^{com+} \quad (3)$$

Improper value of KOR could cause less absorption of collective energy because the remaining of allocated energy will be counted as surplus sent to the main grid. The overall surplus in the community ($P_{coll,t}^{sur}$) is equal to collective production minus the total exchanged energy inside the EC, as shown in (4). The potential collective surplus is then sold to the grid and assigned to each producer based on the prorate of their production, as in (5). Then, the exported power for the local community can be computed with (6).

$$P_{coll,t}^{sur} = \sum_{n \in N} P_{n,t}^{met-} - \sum_{n \in N} P_{n,t}^{com+} \quad (4)$$

$$P_{n,t}^{gd-} = \frac{P_{n,t}^{met-}}{\sum_{n \in N} P_{n,t}^{met-}} \cdot P_{coll,t}^{sur} \quad (5)$$

$$P_{n,t}^{com-} = P_{n,t}^{met-} - P_{n,t}^{gd-} \quad (6)$$

The deficit and surplus energy are exchanged with the main grid and conventional energy suppliers – i.e., any load not supplied by the community generation or any excess of community generation. Those exchanges are subject to different prices for buying (π^{gd+}) and selling (π^{gd-}), as expressed in (7) where Δt is the optimization time step compared to hourly prices. In this paper, we define a business model for EC using internal community prices (π^{com+} , π^{com-}) as shown in (8) so that it is always more interesting for the users to purchase and sell from/to the community rather than the grid – i.e., ($\pi^{com+} < \pi^{gd+}$) and ($\pi^{com-} > \pi^{gd-}$). Ultimately, every user has a bill (typically every month) from its conventional retailer and the community that allows computing its final cost/revenue in (9).

$$B_n^{gd} = \left(\pi^{gd+} \cdot \sum_{t \in T} P_{n,t}^{gd+} - \pi^{gd-} \cdot \sum_{t \in T} P_{n,t}^{gd-} \right) \cdot \Delta t \quad (7)$$

$$B_n^{com} = \left(\pi^{com+} \cdot \sum_{t \in T} P_{n,t}^{com+} - \pi^{com-} \cdot \sum_{t \in T} P_{n,t}^{com-} \right) \cdot \Delta t \quad (8)$$

$$B_n = B_n^{gd} + B_n^{com} \quad (9)$$

A. Proposed Optimization Method

The proposed method to manage the EC is formulated as an optimization problem where the operational control through EMS is simultaneously solved with the energy allocation problem. Note that in this paper, the management is somewhat simulated in an offline mode with deterministic profiles for the load and generation.

The considered decision variables are all positive semi-definite for every household n and at every time step t . It consists of:

- 1) storage charge $P_{n,t}^{st+}$ and discharge $P_{n,t}^{st-}$ as well as its state of charge $SOC_{n,t}^{st}$, refers to battery and EV;
- 2) the arbitrage with the grid and the community – import $P_{n,t}^{gd+}$, $P_{n,t}^{com+}$ and export $P_{n,t}^{gd-}$, $P_{n,t}^{com-}$ power flows; and
- 3) individual self-consumption power $P_{n,t}^{indsc}$ which refers to the amount of individual DER assets that can be consumed directly in-house, not for exports or imports.

Note that we do not include binary variables for the pairs $(P_{n,t}^{gd+}, P_{n,t}^{gd-})$, $(P_{n,t}^{com+}, P_{n,t}^{com-})$, and $(P_{n,t}^{st+}, P_{n,t}^{st-})$ as commonly done in the literature. However, we always check and ensure at the end of the simulation that there is only one positive value for each pair.

The first constraint is related to the limitation of the individual meter by the subscription power, as shown in (10) and (11).

$$P_{n,t}^{gd+} + P_{n,t}^{com+} \leq P_n^{subs} \quad (10)$$

$$P_{n,t}^{gd-} + P_{n,t}^{com-} \leq P_n^{subs} \quad (11)$$

Typical storage constraints (12) and (13) bound the power output and energy. For energy conservation purposes, the SOC value at the beginning and end of the horizon must be set at a certain value (in %), as expressed in (14).

$$P_{n,t}^{st+}, P_{n,t}^{st-} \leq P_{max,n}^{st} \quad (12)$$

$$SOC_{min}^{st} \leq SOC_{n,t}^{st} \leq SOC_{max}^{st} \quad (13)$$

$$SOC_{n,1}^{st} = SOC_{n,end}^{st} = SOC_{initial}^{st} \quad (14)$$

Lastly, the battery efficiency (η_n^{st}) and energy capacity ($E_{max,n}^{st}$) is considered in the SOC computation for the next time step, as in (15).

$$SOC_{n,t+1}^{st} = SOC_{n,t}^{st} + \left(P_{n,t}^{st+} \cdot \eta_n^{st} - \frac{P_{n,t}^{st-}}{\eta_n^{st}} \right) \cdot \Delta t \cdot \frac{100}{E_{max,n}^{st}} \quad (15)$$

The next set of constraints is related to the individual power balance – from the generation and demand perspective, as described in (16) and (17).

$$P_{n,t}^{PV} + P_{n,t}^{st-} = P_{n,t}^{indsc} + P_{n,t}^{gd-} + P_{n,t}^{com-} \quad (16)$$

$$P_{n,t}^{load} + P_{n,t}^{st+} = P_{n,t}^{indsc} + P_{n,t}^{gd+} + P_{n,t}^{com+} \quad (17)$$

Moreover, the power balance between import and export at the community level is constrained by (18), assuming there are no losses in the local network of EC.

$$\sum_{n \in N} P_{n,t}^{com+} = \sum_{n \in N} P_{n,t}^{com-} \quad (18)$$

The objective is to minimize the total collective bill (19) which includes bills from the main grid (7) and bills from local exchanges (8).

$$f = \min \left(\sum_{n \in N} B_n \right) \quad (19)$$

s.t. (10)-(18)

After solving the optimization problem presented above, the next step would be to compute KOR from the resulting community exchanged power. For each individual and at a 30-minute resolution, KOR is defined as the ratio of a member's community import per total community generation as in (20). Note that these community exchanges are just mathematical variables modeled in the optimization formulation, not real and measurable flows.

$$\lambda_{n,t} = \frac{P_{n,t}^{com+}}{\sum_{n \in N} P_{n,t}^{com-}} \quad (20)$$

Figure 2 illustrates a flowchart to determine the actual amount of power that has to be contractually exchanged

with retailers $(P_{n,t}^{gd+*}, P_{n,t}^{gd-*})$ and with the community $(P_{n,t}^{com+*}, P_{n,t}^{com-*})$ based on the real power measured at the meter ($P_{n,t}^{met}$). These new flows (symbolized with *) will override the values obtained from the optimization results as the grid and community powers modeled in the optimization do not include the repartition procedure explained in Section 2 – i.e., equation (1), (2), and (5) because of its nonlinearity.

The optimization result gives the power measured at the house energy meter at each time step that discriminates the net consumers and the net producers. For consumers (i.e., members with positive $P_{n,t}^{met+}$), at every time step, the KOR shall be calculated first with (20) to obtain the ratio of community generation that they contractually allocated. Any deficit (i.e., remaining load) constitutes the import from the grid. To compute the producers' revenue (i.e. users with positive $P_{n,t}^{met-}$), at every time step, we define first the overall collective surplus (if any) at the community level (i.e., to be exported to the main grid), then distribute it to each producer based on prorate of their production. The results of grid and community power flow computed here are used to establish the energy bill invoiced to each member.

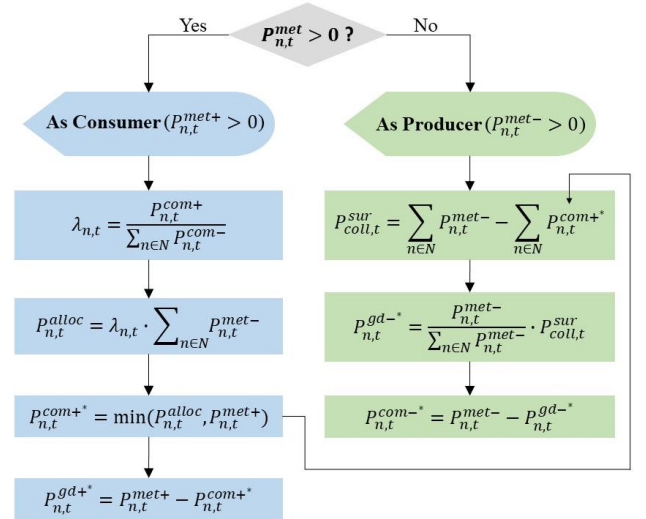


Figure 2 Computation of KOR, grid and community power flow as consumers or producers at each time step.

III. RESULTS

A. Case Study

A pilot project of EC located in Le Cailar, south of France that consists of seven households with different combinations of DER assets is used as our test case. Characteristics of the installed DER and typical parameters are given in Table 1. The EV is available only at certain time slots: 6 pm-8 am on weekdays, 3 pm-11 am on Saturdays, and all-time on Sundays. We perform a one-month offline simulation with the deterministic load and PV profiles from March 2021 at a half-hourly time step. The optimization problem is written in YALMIP [15] and solved with Gurobi.

Table 1 Test case parameters.

| House | PV (kW) | Battery EV (kW/kWh) | Subs Power (kVA) |
|--------------------------|---------|-----------------------|------------------|
| 1 | 3.2 | 5/9.8 11/40 | 6 |
| 2 | 6.12 | 5/9.8 - | 36 |
| 3 | - | 5/9.8 - | 6 |
| 4 | 3.2 | - | 9 |
| 5 | 3.2 | - | 9 |
| 6 | 3.2 | - | 6 |
| 7 | - | - | 9 |
| Arbitrage price (c€/kWh) | | | |
| π^{gd+} | 13.31 | π^{com+} | 7.5 |
| π^{gd-} | 6.5 | π^{com-} | 7 |
| Storage's operation (%) | | | |
| SOC_{min}^{st} | 10 | $SOC_{initial}^{st}$ | 50 |
| SOC_{max}^{st} | 100 | η_n^{st} | 97.5 |

B. Optimal Community Energy Management

From the optimization results, we can compute the degree of energy independency based on two metrics: SSR and SCR. The first metric SSR is the ratio of demand that can be fulfilled locally and computed by excluding the portion of energy import taken from the main grid (21). On the contrary, SCR is seen from the generation perspective by excluding the grid export energy (22).

$$SSR = 1 - \frac{\sum_{n \in N} \sum_{t \in T} P_{n,t}^{gd+}}{\sum_{n \in N} \sum_{t \in T} P_{n,t}^{load}} \quad (21)$$

$$SCR = 1 - \frac{\sum_{n \in N} \sum_{t \in T} P_{n,t}^{gd-}}{\sum_{n \in N} \sum_{t \in T} P_{n,t}^{PV}} \quad (22)$$

Table 2 describes the comparison between the results of the proposed method (Community EMS) and a case in which the DER assets are controlled individually at the level of every user (Individual EMS) – i.e., by setting $P_{n,t}^{com+}$ and $P_{n,t}^{com-}$ to zero. Obviously, the overall SSR and SCR increase significantly (i.e., more than one and a half the values of the Individual EMS) when the households form an EC, such that the individual energy surplus is shared with other members and the community takes advantage of heterogeneous profiles. Moreover, the collective energy bill (i.e., the summation of the individual bill) is also improved by 10.7 % thanks to the more affordable tariff when buying electricity from the community and the higher price for selling energy locally.

Table 2 SSR, SCR, and energy bill for the overall households.

| | SSR (%) | SCR (%) | Bill (€) |
|----------------|---------|---------|----------|
| Individual EMS | 27 | 64 | 375 |
| Community EMS | 42 | 99 | 335 |

C. Allocation and Settlement Among Members

Using the contractual power flow within the community from the optimization results and the methodology described in Figure 2, we can compute the coefficients of energy allocation (i.e., KOR) for every user. Figure 3a displays the KOR values over a given day. Those KOR directly impact the energy that every user trade with the

community – i.e., local energy import (positive value) or export (negative value) as illustrated in Figure 3b. Note that there is somewhat of complementarity between users with house 2, 4, and 6 playing roles as net producers or local energy exporters for the particular sample day. During the daytime when the total community production is high, a large allocation is given to house 3, 5, and 7.

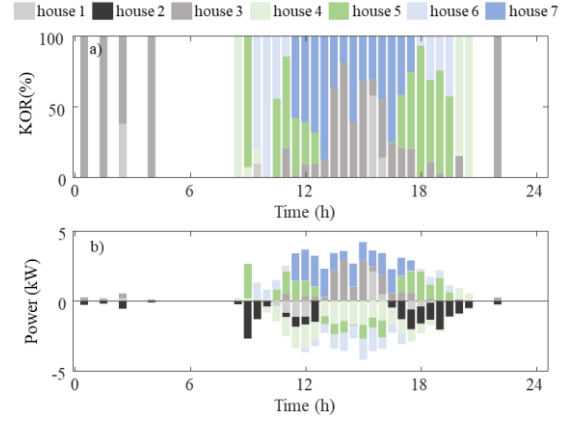


Figure 3 Time profiles for each household at a sample day of a) KOR values and b) its corresponding energy exchange in the community.

Compared to trading the energy only with the main grid through retailers (i.e., without community), internal community sharing can reduce the individual bills by 14.1 % on average, with a minimum of 5.3 % over all the members, as shown in Table 3.

Table 3 Individual bill reduction.

| House | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|------------|-----|------|------|------|-----|-----|------|
| Saving (%) | 8.4 | 12.5 | 26.3 | 27.2 | 6.9 | 5.3 | 12.0 |

D. Sensitivity of Internal Community Prices

A sensitivity study of the community price is conducted. Figure 4 illustrates the results of different community tariffs in the range of 5-15 c€/kWh and their impact on the overall community bill. Note that we exclude some cases where $\pi^{com+} < \pi^{com-}$ because it is not economically feasible (i.e., beneficial) for the community manager. These cases where the selling price to the community is higher than the purchase price correspond to the white area in Figure 4.

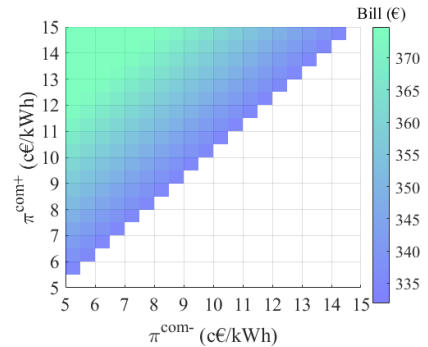


Figure 4 Collective bill for different values of internal community buying and selling prices.

The results show that the lowest bill occurs when the difference between the community buying and selling price is small. Moreover, the overall bill depends on the internal price difference rather than each value of buying and selling tariff taken independently – i.e., the same bill for the same $(\pi^{com+} - \pi^{com-})$.

IV. CONCLUSION

In this paper, we present the management of the energy community that simultaneously solves the operational aspect through EMS and the allocation of collective energy to each individual member through some coefficients called *keys of repartition*. It offers the community manager to utilize just one optimization tool to operate the EC properly. The coupling between the energy management and the allocation problem is based on the power flow division of the physical and measurable house meter to the contractual exchanges to other members inside EC and the rest (deficit/surplus) to the main grid. We adopt the EC framework and regulation in France and take a real test case of EC with seven households. Nevertheless, the coupled optimization between EMS and KOR is generic and can be widely applied to other similar forms of EC. Compared to the individual optimization, the proposed method returns an overall 10.7 % community bill reduction with a minimum of 5.3 % individually. The sensitivity of the internal community tariffs is presented where the lowest difference between buying and selling prices results in the lowest global community bill. Future work will address the real-time operation of EC participating in ancillary services and determine the appropriate size of prosumers in EC.

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