Quantifying, Activating and Rewarding Flexibility in Renewable Energy Communities

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***Abstract*—Demand-side flexibility from renewable energy community members increases the benefits of local production and exchanges. To effectively harness this flexibility, end-users must be rewarded for their efforts regarding the shifted energy volumes and the associated discomfort. This work quantifies these last two quantities for three types of loads (electric vehicles, thermal loads and wet appliances). Then, a two-step model is proposed which first optimally activates the offered flexibility and then shares the benefits of this activation among the renewable energy community members through a rule-based or an optimization-based approach. Results show that the community framework can further increase the benefits brought by flexible demand.**

***Index Terms*—Renewable energy communities, Demand-side management, Distribution keys, Optimal power flow, Settlement methods**

I. INTRODUCTION

Renewable Energy Communities (RECs) can provide different benefits (economic, energy-related, societal) to end-users [1]. To extract as much value as possible from the local energy exchanges, end-users must consent to make their consumption more flexible. This necessitates adequate and explicit reward/incentive mechanisms along the energy communities' operation and settlement which consider end-users' (dis)comfort related to members' behavioral shift.

The potential of home appliance flexibility was studied in [2] where a mixed integer linear programming optimization problem is proposed to coordinate home appliances for demand response provision (load control and time-shifting of the appliances), with focus on efficient reformulation to solve problems involving up to 200 appliances.

RECs flexibility provision through load shifting, demand response and energy storage was reviewed in [3]. The identified outcomes from the provision include peak shaving and shifting, energy cost minimization, being a part of demand-side management, and self-sufficiency in islanded mode of operation. Load flexibilization within RECs was also considered in [4], [5]. The later revealed the potential for RECs to provide demand-side solutions by creating new business models.

End-users' discomfort modeling issues were addressed in [4], [6]. The thermal end-user comfort was modeled in [4] by the deviation of the indoor temperature from the setpoints. In [6] this was considered through a discomfort index of the consumer. This index was defined by a linear penalization for shifted time slots compared to ideal end-user preference.

An incentive-based and a price-based mechanisms (based on the financial compensation of the participants) for optimization-based demand response were considered in [7]. They calculated the load change for the incentive and the best times to realize the demand response while accounting for the comfort level. Authors in [8] propose a sharing mechanism based on keys of repartition (KoRs) for the benefits linked to the frequency reserve provision by REC storage systems. The benefits for the local arbitrage are shared using another standard KoR.

The work's particularity lies in proposing and comparing innovative explicit flexibility reward mechanisms for unlocking/mobilizing end-users flexibility in a renewable energy community framework for local arbitrage purposes only. To this end, we distinguish the benefits arising from the natural complementarity of REC members' behaviors from the additional benefits created by the activation of flexibility. Furthermore, the flexibility potential and associated end-users' discomfort regarding flexible load usage are quantified.

The paper will first present the centralized energy dispatch problem, which plans flexible load consumption and energy exchanges (section II II). Then, two distinct flexibility reward approaches are defined in section III: rule-based and optimization-based. The results for a domestic REC will be presented in section IV.

II. LOCAL FLEXIBILITY DISPATCH PROBLEM

The first step of the proposed procedure aims to optimally schedule (i.e., day-ahead) the use of flexible devices, battery storage systems and economic exchanges in the REC. The

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problem is a Mixed-Integer Second-Order Cone Programming (MISOCP) problem and can be written in general terms as:

$$\min_{\Omega} \quad \text{Objective function (2)} \tag{1}$$

subject to *Cost constraints* (3),
Energy exchange constraints (4) – (6),
Battery storage constraints (7) – (11),
Flexible devices constraints (12) – (22),
Power flow equations (23) – (29),
Discomfort constraints (30) – (31).

A. Objective function

The energy community objective may be of different nature (economic, ecological, societal,...). In this work, we consider that the energy community aims to minimize its costs (i.e., maximize its benefits) while considering the REC members' discomfort function related to the flexible loads usage and the REC power loss costs. The global objective therefore writes as:

$$F(\Omega) = \Pi^{REC} + \sum_{u \in \mathcal{U}} J_u^{tot} + \pi^{loss} \sum_{t \in \mathcal{T}} P_t^{loss} \tag{2}$$

with $\mathcal{U}$ the set of REC users, $\mathcal{T}$ the set of optimization periods of length Δ_T, Π^{REC} the collective electricity bill in the community framework (3), J_u^{tot} the total discomfort function of member u (31) and P_t^{loss} the total power losses in the REC distribution network (29) compensated at price π^{loss}.

B. Constraints

1) Cost structure: The total community bill is defined by:

$$\Pi^{REC} = \sum_{t \in \mathcal{T}} \sum_{u \in \mathcal{U}} [\pi^{i,ret} i_{u,t}^{ret} - \pi^{e,ret} e_{u,t}^{ret} + \gamma^{com}(i_{u,t}^{\text{com}} + e_{u,t}^{\text{com}})] \Delta_T \tag{3}$$

where $i_{u,t}^{ret}$ and $i_{u,t}^{\text{com}}$ (resp. $e_{u,t}^{ret}$ and $e_{u,t}^{\text{com}}$) represent the power imported from (resp. exported to) the retailer and the REC by user u at time t. $\pi^{i,ret}$ and $\pi^{e,ret}$ are equivalent retailer import and export prices accounting for commodity and upstream grid usage charges. At this point, the commodity costs for the local energy exchanges are considered zero, the distribution of the benefits is done in the second step. However, a fee is charged for the intra-community exchanges, γ^{com}, accounting for the internal grid usage costs and the community operator remuneration.

2) Energy exchanges: The power injected by member u at time t, $P_{u,t}^{\text{inj}}$, can be expressed as a function of physical (4) or virtual (5) flows:

$$P_{u,t}^{\text{inj}} = P_{u,t}^{\text{PV}} + P_{u,t}^{\text{dis}} - P_{u,t}^{\text{fix}} - P_{u,t}^{\text{flex}} - P_{u,t}^{\text{cha}} \quad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \tag{4}$$

$$P_{u,t}^{\text{inj}} = e_{u,t}^{ret} + e_{u,t}^{\text{com}} - i_{u,t}^{ret} - i_{u,t}^{\text{com}} \quad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \tag{5}$$

with $P_{u,t}^{\text{PV}}$ the photovoltaic power injection, $P_{u,t}^{\text{dis}}$ and $P_{u,t}^{\text{cha}}$ the active powers going in and out of the battery storage system (BSS), $P_{u,t}^{\text{fix}}$ the non-flexible consumption and $P_{u,t}^{\text{flex}}$ the total flexible load consumption. Constraint (6) also ensures the export/import power balance within the REC.

$$\textstyle\sum_{u \in \mathcal{U}} e_{u,t}^{\text{com}} = \sum_{u \in \mathcal{U}} i_{u,t}^{\text{com}} \quad \forall t \in \mathcal{T}. \tag{6}$$

3) Battery storage system: All community members may use an individual battery storage system modeled with state-of-the-art constraints.

$$s_{u,1}^{BSS} = s_{u,0}^{BSS} + \Delta_T(\eta_u^{cha} P_{u,1}^{cha} - P_{u,1}^{dis}/\eta_u^{dis}) \quad \forall u \in \mathcal{U}, \tag{7}$$

$$s_{u,t}^{BSS} = s_{u,t-1}^{BSS} + \Delta_T(\eta_u^{cha} P_{u,t}^{cha} - P_{u,t}^{dis}/\eta_u^{dis}) \quad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}_{\setminus\{1\}}, \tag{8}$$

$$s_{u,T}^{BSS} = s_{u,0}^{BSS} \quad \forall u \in \mathcal{U}, \tag{9}$$

$$0 \leq P_{u,t}^{cha}, P_{u,t}^{dis} \leq \overline{P}_u^{BSS} \quad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \tag{10}$$

$$\underline{s}_u^{BSS} \leq s_{u,t}^{BSS} \leq \overline{s}_u^{BSS} \quad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}. \tag{11}$$

with $s_{u,t}^{BSS}$ the state of charge of the battery storage system affected by its efficiencies $\eta_u^{cha}, \eta_u^{dis}$ and $s_{u,0}^{BSS}$ the initial state of charge which is imposed to be recovered at the end of the period through constraint (9). Notations $\overline{[.]}$ and $\underline{[.]}$ are used to represent respectively upper and lower bounds of decision variables.

4) Flexible devices: REC members may consider shifting the consumption of certain appliances. This represents their flexibility potential. This work considers three types of flexible devices: white goods, electric vehicle chargers, and thermal loads.

White goods are loads with a fixed consumption cycle but whose starting time can be modified (e.g., dishwasher). They are modeled through the definition of a binary variable, $z_{w_u,t}$, representing the starting time of the device.

$$z_{w_u,t} = 0 \quad \forall w_u \in \mathcal{W}_u, \forall t \in \mathcal{T} \setminus \mathcal{T}_{w_u}^{flex}, \tag{12}$$

$$\textstyle\sum_{t \in \mathcal{T}_{w_u}^{flex}} z_{w_u,t} = 1 \quad \forall w_u \in \mathcal{W}_u, \tag{13}$$

$$P_{w_u,t}^{WG} = \textstyle\sum_{\tau} z_{w_u,\tau} P_{w_u,t-\tau+1} \quad \forall w_u \in \mathcal{W}_u, \forall t \in \mathcal{T}, \tau \in [t-D+1, t]. \tag{14}$$

Constraints (12) and (13) respectively impose that only one cycle is performed during the day and that the starting time falls within the flexible window, $\mathcal{T}_{w_u}^{flex}$, granted by user u for his device w_u. D represents the cycle duration in number of periods, P is the power consumption profile during a cycle and $P_{u,t}^{WG}$ is the actual white goods consumption.

Electric vehicles are modeled as one-way batteries for which we can adjust the charging power. The charging operation is characterized by the arrival and departure time to/from the charging station, $t_{e_u}^{arr}$ and $t_{e_u}^{dep}$, and the arrival and departure state of charge, $s_{e_u}^{arr,EV}$ and $s_{e_u}^{dep,EV}$.

$$s_{e_u,t_{e_u}^{arr}}^{EV} = s_{e_u}^{arr,EV} + \Delta_T P_{e_u,t_{e_u}^{arr}}^{EV} \quad \forall e_u \in \mathcal{E}_u, \tag{15}$$

$$s_{e_u,t}^{EV} = s_{e_u,t-1}^{EV} + \Delta_T P_{e_u,t}^{EV} \quad \forall e_u \in \mathcal{E}_u, \forall t \in [t_{e_u}^{arr}, t_{e_u}^{dep}], \tag{16}$$

$$s_{e_u,t_{e_u}^{dep}-1}^{EV} = s_{e_u}^{dep,EV} \quad \forall e_u \in \mathcal{E}_u, \tag{17}$$

$$0 \leq P_{e_u,t}^{EV} \leq \overline{P}_{e_u}^{EV} \quad \forall e_u \in \mathcal{E}_u, \forall t \in \mathcal{T}, \tag{18}$$

$$\underline{s}_{e_u}^{EV} \leq s_{e_u,t}^{EV} \leq \overline{s}_{e_u}^{EV} \quad \forall e_u \in \mathcal{E}_u, \forall t \in \mathcal{T}. \tag{19}$$

with $s^{EV}_{u,t}$ the electric vehicle state-of-charge and P^{EV} the charging power of the electric vehicle.

Thermal loads (e.g., electrical water heater) are considered to be fully power-flexible loads, represented by the following two constraints:

$$0 \leq P^{H}_{h_u,t} \leq \overline{P}^{H}_{h_u} \qquad \forall h_u \in \mathcal{H}_u, \forall t \in \mathcal{T}, \quad (20)$$

$$\textstyle\sum_{t\in\mathcal{T}} P^{H}_{h_u,t} = \sum_{t\in\mathcal{T}} P^{ref,H}_{h_u,t} \qquad \forall h_u \in \mathcal{H}_u, \quad (21)$$

with $P^{H}_{h_u,t}$ the power consumption of thermal loads and $P^{ref,H}_{h_u,t}$ the base consumption profile of those loads.

The constant total flexible load consumption is expressed as:

$$P^{flex}_{u,t} = \textstyle\sum_{w_u\in\mathcal{W}_u} P^{WG}_{w_u,t} + \sum_{e_u\in\mathcal{E}_u} P^{EV}_{e_u,t} + \sum_{th_u\in\mathcal{H}_u} P^{H}_{th_u,t} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}. \quad (22)$$

5) Power flow model: Power flow constraints are added to the problem to ensure a reliable operation of the distribution network. The radial configuration of the distribution grid allows usage of a relaxed DistFlow model [9].

Line u represents the electrical line reaching user u from the node upstream with impedance $Z_u = R_u + jX_u$ and $\mathcal{C}_u$ is the set of children of user u in the oriented graph of the electrical network:

$$P^{\text{inj}}_{u,t} + P^{\text{line}}_{u,t} - R_u I^{\text{sqr}}_{u,t} = \sum_{c\in\mathcal{C}_u} P^{\text{line}}_{c,t} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \quad (23)$$

$$Q^{\text{inj}}_{u,t} + Q^{\text{line}}_{u,t} - X_u I^{\text{sqr}}_{u,t} = \sum_{c\in\mathcal{C}_u} Q^{\text{line}}_{c,t} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \quad (24)$$

$$V^{\text{sqr}}_{u,t} = V^{\text{sqr}}_{a_u,t} - 2(R_u P^{\text{line}}_{u,t} + X_u Q^{\text{line}}_{u,t}) + (R_u^2 + X_u^2) I^{\text{sqr}}_{u,t} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \quad (25)$$

$$I^{\text{sqr}}_{u,t} V^{\text{sqr}}_{a_u,t} \geq P^{\text{line}^2}_{u,t} + Q^{\text{line}^2}_{u,t} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}. \quad (26)$$

Equations (23) and (24) represent power balance at each node u, with $P^{\text{line}}_{u,t}$ and $Q^{\text{line}}_{u,t}$ the active and reactive powers flowing in line u. Equations (25) and (26) determine respectively the voltage drop and the squared current in each line.

The maximum of $P^{\text{inj}}_{0,t}$ at the substation (slack bus) corresponds to the peak power of the community.

The physical network limits are bounding the squared line currents (I^{sqr}) and squared node voltages (V^{sqr}):

$$\underline{V}^{\text{sqr}} \leq V^{\text{sqr}}_{u,t} \leq \overline{V}^{\text{sqr}} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}, \quad (27)$$

$$I^{\text{sqr}}_{u,t} \leq \overline{I}^{\text{sqr}}_{u} \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}. \quad (28)$$

The total active power losses in the system (P^{loss}_t) for each time step are:

$$P^{\text{loss}}_t = \sum_{u\in\mathcal{U}} R_u I^{\text{sqr}}_{u,t} \qquad \forall t \in \mathcal{T}. \quad (29)$$

C. Discomfort functions

Flexible devices' usage is associated with a discomfort function which is defined for each type of flexible load by:

$$J^{K}_u = \sum_{k_u\in\mathcal{K}_u} \alpha_{k_u} \sum_{t\in\mathcal{T}} (P^{ref,K}_{k_u,t} - P^{K}_{k_u,t})^2 \qquad \forall u \in \mathcal{U}, \quad (30)$$

with $K := \{W, EV, H\}$, $\mathcal{K}_u := \{\mathcal{W}_u, \mathcal{E}_u, \mathcal{H}_u\}$ and α_{k_u} the discomfort price of each flexible load. $P^{ref,K}_{k_u,t}$, the reference consumption profile of flexible loads, represents the preferred behavior of member u which corresponds to a cycle starting at the preferred time for white goods, an electric vehicle charging at full rate upon arrival until full charge or departure, and a typical thermal load profile to meet the desired temperature. The discomfort functions of flexible loads are summed to form the total discomfort of member u.

$$J^{tot}_u = J^{WG}_u + J^{EV}_u + J^{H}_u \qquad \forall u \in \mathcal{U}. \quad (31)$$

D. Particular Cases

We can derive different variants (i.e., benchmark cases) from the original problem presented against which the collective framework with flexibility potential can be compared to evaluate performance. In this work, three particular cases can be created by constraining two major features: the flexibility potential and the community exchanges.
The first alternative is to not consider any flexibility potential by adding the following constraint for each type of flexible load which restricts the usage of flexible loads to their reference one:

$$P^{K}_{k_u,t} = P^{ref,K}_{k_u,t} \qquad \forall k_u \in \mathcal{K}_u. \quad (32)$$

The second alternative is to consider an individual framework in which the following constraint imposes no internal exchanges:

$$i^{\text{com}}_{u,t} = e^{\text{com}}_{u,t} = 0 \qquad \forall u \in \mathcal{U}, \forall t \in \mathcal{T}. \quad (33)$$

III. Flexibility Reward Methods

The daily total benefits to be shared among members are split between the direct benefits from the consumption and production profiles complementarity of REC members, which can be shared with standard techniques [8], and benefits that are related to flexibility expressed as follows:

$$B^{\text{flex}}_d = \Pi^{\text{REC,fixed}}_d - \Pi^{\text{REC,flexible}}_d \qquad \forall d \in \mathcal{D}, \quad (34)$$

with $\mathcal{D}$ the set of days in a month, $\Pi^{\text{REC,flexible}}_d$ and $\Pi^{\text{REC,fixed}}_d$ respectively the daily community bills with and without flexibility potential.

The second step of the model dispatches those economic benefits created by the activation of the flexibility potential of REC members. To dispatch the benefits fairly considering the activated and offered flexibility. We propose two mechanisms either based on keys of repartition or flexibility prices.

Before sharing the benefits, daily activated and offered flexibility volumes are computed for each member. The activated volume is directly related to the optimal usage of the flexible devices obtained through solving a local flexibility dispatch problem:

$$E^{\text{act,flex}}_{u,d} = \textstyle\sum_{t\in\mathcal{T}} |P^{\text{flex}}_{u,t} - P^{\text{ref,flex}}_{u,t}| \Delta_T/2 \;\; \forall u \in \mathcal{U}, \forall d \in \mathcal{D}. \quad (35)$$

On the other hand, the offered volume is computed by solving another problem which finds the maximum activated volume under the flexible device constraints as presented hereafter;

$$E^{\text{cap,flex}}_{u,d} = \text{argmax } E^{\text{act,flex}}_{u,d} \text{ s.t. (12)-(22).} \quad (36)$$

A. Rule-based Distribution of Flexibility Benefits

The first method proposed to distribute the benefits fairly among the flexibility providers is the application of the following KoR, $k_{u,d}$, based on the pro-rata of the weighted sum of activated and offered flexibility.

$$k_{u,d} = \frac{E^{\text{act,flex}}_{u,d} + \omega E^{\text{cap,flex}}_{u,d}}{\sum_{u\in\mathcal{U}} E^{\text{act,flex}}_{u} + \omega E^{\text{cap,flex}}_{u,d}} \quad \forall u \in \mathcal{U}, \forall d \in \mathcal{D}, \quad (37)$$

$$B^{\text{flex}}_{u,d} = k_{u,d} B^{\text{flex}}_{d} \quad \forall u \in \mathcal{U}, \forall d \in \mathcal{D}. \quad (38)$$

with $B^{\text{flex}}_{u,d}$ the daily individual share of benefits. Different values of parameter ω are compared in the results section.

B. Optimization-based Remuneration of Flexible Behavior

The second method is based on the definition of an optimal flexibility price by solving the following optimization problem: minimizing the variance of individual profits among members regarding their discomfort.

$$\min \sum_{d\in\mathcal{D}} \sum_{u\in\mathcal{U}} [(B^{\text{flex}}_{u,d} - J^{tot}_{u,d}) - (B^{\text{flex}}_{d} - \sum_{u\in\mathcal{U}} J^{tot}_{u,d})/|\mathcal{U}|]^2 \quad (39)$$

$$\text{s.t. } B^{\text{flex}}_{u,d} = \pi^{\text{act}}_{d} E^{\text{act,flex}}_{u,d} + \pi^{\text{cap}}_{d} E^{\text{cap,flex}}_{u,d} \quad \forall u \in \mathcal{U}, \forall d \in \mathcal{D}, \quad (40)$$

$$\pi^{\text{act}}_{d} E^{\text{act,flex}}_{u,d} \geq J^{\text{tot}}_{u,d} \quad \forall u \in \mathcal{U}, \forall d \in \mathcal{D}, \quad (41)$$

$$\sum_{u\in\mathcal{U}} B^{\text{flex}}_{u,d} = B^{\text{flex}}_{d} \quad \forall d \in \mathcal{D}, \quad (42)$$

with π^{act}_{d} and π^{cap}_{d} respectively the reward price for the activated and offered flexibility volumes (*i.e.*, decision variable of the problem). Equation (41) ensures the total discomfort of each member is at least compensated by the benefits of their flexibility activation.

IV. Case Study and Results

A. Case Study Parameters

The REC considered in this work is composed of 20 domestic end-users connected to a radial distribution grid [10] as depicted in Fig.1. Their non-flexible consumption as well as their flexible loads usage parameters are based on the Pecan Street project open data [11]. The first model is solved daily with a one-hour resolution for a complete year. The flexibility rewards settlement problems are run monthly. We assume perfect forecasts of the non-flexible and production profiles in day-ahead (i.e., no deviations between the first and second steps). A constant $\alpha_{k_u} = 0.05$ €/kWh^2 was chosen to represent a community where each participant's aversion to demand flexibilization is equivalent. In this case study, users are considered to have equal tariffs for retailer imports ($\pi^{\text{i,ret}} = 0.4$ €/kWh) and exports ($\pi^{\text{e,ret}} = 0.1$ €/kWh). The internal community fees are set to 0.01 €/kWh. All input data is available in [12].

B. Collective Economic Surplus

Figure 2 shows the monthly total cost of energy for the four variants of the problem where "Ind." states for *Individual* and relates to the case without local exchanges (33) and "fix" relate to the case without flexibility potential (32). Table I displays yearly financial and flexibility usage results. As expected from previous works [13], the community creation significantly reduces the total energy bill. Unlocking end-users' flexibility further improves the benefits of the community, especially during spring and summer when the solar potential is the highest (i.e., more local production). Those additional benefits related to flexibility are more important in the EC framework thanks to the internal exchange possibility but must also be put in perspective to the discomfort costs to be compensated which represent a higher share of the benefits in the EC framework, 14.2% vs 8.8%.

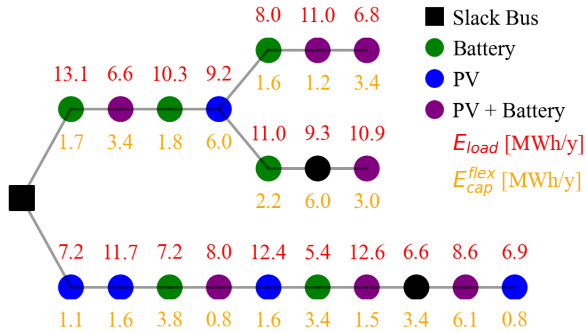

Fig. 1. Case study considered for the simulation.

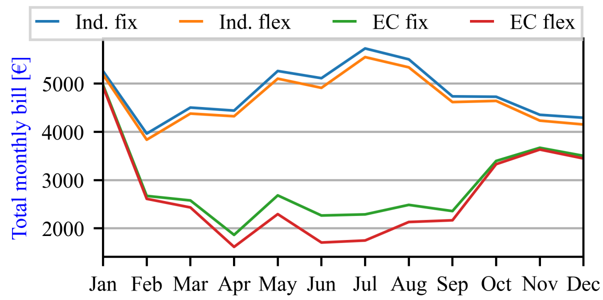

Fig. 2. Monthly bills of the whole community for the four problems.

TABLE I
FINANCIAL AND FLEXIBILITY RESULTS FOR THE FOUR PROBLEMS

Framework	Indiv.		REC	
Demand	Fixed	Flex.	Fixed	Flex.
Total costs [€]	57,900	56,300	34,700	32,000
Total discomfort [€]	0	142	0	382
Activated flex. [MWh]	0	5.3	0	9.2

C. Flexible Loads Usage and Discomfort level

Table II displays flexible load capacity, usage and discomfort for each type of load. It shows that EVs represent the biggest share of available flexibility as they are more energy-intensive assets. They are also the most activated flexibility as the power level can be adjusted during each period. On the contrary, white goods usage is less modulated as it implies the shift of the full consumption window. Discomfort levels are directly linked to flexibility activation.

TABLE II
FLEXIBILITY USAGE AND ASSOCIATED DISCOMFORT

	Individual				REC			
	WG	EV	H	Tot.	WG	EV	H	Tot.
E^{cap}[MWh]	9.1	40.4	4.8	54.3	9.1	40.4	4.8	54.3
E^{act}[MWh]	0.7	2.5	2.0	5.3	1.0	5.1	3.1	9.2
J[€]	37	79	26	142	51	269	61	382

D. Individual Economic Surplus

The upper part of figure 3 shows the individual activated and offered flexibility volumes ordered by ascending activated flexibility and the lower part compares the individual benefits obtained from the different settlement methods. It clearly shows that for all methods, the individual discomforts are compensated. Compared to an equal distribution of the benefits (solid blue line), the different methods proposed (green, red and purple bars) follow the individual flexibility level. Green bars (i.e., activated flexibility only KoR) do not exactly follow the activated flexibility volume as the benefits are aggregated over one year with a daily settlement frequency.

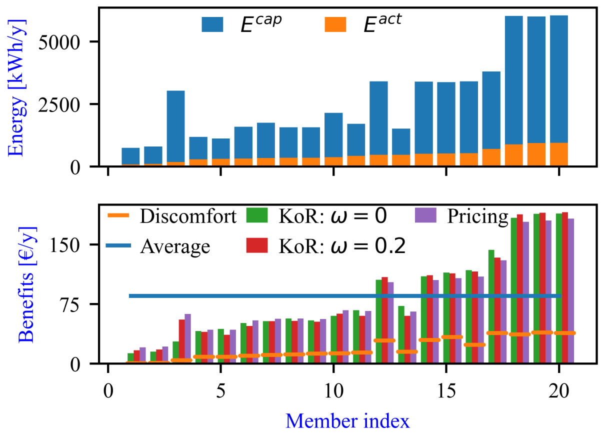

Fig. 3. Individual benefits for users depending on the settlement method

E. Grid Usage

Regarding the stress on the distribution network, Table III shows that if several benefits arise by aggregating end-users in a community, as already demonstrated in [14], the activation of flexibility has a relatively low impact. It mainly improves the losses and the self-consumption and self-sufficiency rate in both individual and EC frameworks.

V. CONCLUSION

By proposing realistic discomfort modeling and fair flexibility reward methods, this work shows the added value of incentivizing end-users to mobilize flexibility in a REC framework in terms of economic savings and network usage. Readers should also notice that despite the easiest implementation of the rule-based approach, it requires finding an adequate value for ω.

TABLE III
SUMMARY OF NETWORK USAGE FOR THE FOUR PROBLEMS

Framework	Individual		REC	
Demand	Fixed	Flex.	Fixed	Flex.
Total losses [MWh]	143.8	134.6	94.7	86.9
Max voltage [pu]	1.03	1.03	1.02	1.03
Max line loading [%]	74	74	69	70
Self-consumption [%]	51	52	84	87
Self-sufficiency [%]	40	42	67	69

A natural extension of this work will be to consider the flexibility capacity as a decision variable of the REC members in a bilevel approach with the community manager as leader with improved modeling of thermal loads and considering different tariff structures (e.g., time of use retailer pricing).

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