A Framework to Integrate Flexibility Bids into Energy Communities to Improve Self-Consumption

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***Abstract*—Hastened by the emergence of new technologies, a revolution of the electricity retailing business has put forward new ways of electricity trading. One such new concept is the renewable energy communities (RECs), composed of consumers, prosumers, and generation assets, and managed by an energy community manager. This paper introduces a framework in which demand response in the form of flexibility bids is integrated into RECs to improve their welfare. By using an optimization framework, we have designed a day-ahead activation strategy for such bids where the manager of the REC plans the provisioning of the community in the day-ahead market. Results show that creating a community where flexibility bids are integrated reduces the total system costs by making use of flexibility bids to enhance the matching of supply and demand.**

***Index Terms*—energy communities, multi-agent simulation, demand response, flexibility bids**

I. INTRODUCTION

Electricity retailing is rapidly evolving in response to the emergence of new technologies such as smart meters or energy management systems (EMSs). These new technologies enable new forms of decentralized electricity trading [1]. In this regard, the European Parliament in its 2018/2001 directive has introduced the concept of **R**enewable **E**nergy **C**ommunities (RECs) [2]. RECs are usually composed of consumers and local renewable generators which are connected to the same low voltage feeder. When an REC is established, their users benefit from lower electricity bills owing to: i) a greater synchronization between renewable electricity production and consumption; and ii) a discount on the distribution fee offered by the distribution system operator for all locally consumed electricity. RECs are managed by an **E**nergy **C**ommunity **M**anager (ECM), in charge of billing the users and ensuring the adequate functioning of the REC. The role of the ECM then, includes managing the generation assets within the REC in order to maximize the global self-consumption of the REC, and creating an adequate business model where the financial balance is positive.

To maximize the REC's self-consumption, the ECM needs to synchronize supply and demand. However, when relying on renewable resources such as solar photovoltaic (PV), the generation output cannot be controlled. A solution might involve the deployment of storage devices such as batteries, yet their limited capacity as well as their price make them an impractical solution for large scale implementations. Hence, another potential way of boosting the supply and demand synchronization is the use of demand response (DR) or other flexibility services provided by the users. In this regard, this paper focuses on the development of a novel method to deal with DR in the context of an REC with generation assets in the form of solar PV, owned by an investor (for instance the ECM). This REC is composed of non-flexible consumers who simply consume electricity, flexible consumers who consume electricity and offer DR, and generation assets that can sell the electricity either to the REC or to the main network.

In this set-up, flexibility bids can be offered by the REC's flexible consumers one day before physical delivery. Every day at noon, the flexible consumers can post their flexibility bids for every quarter of the following day. The ECM must then select the bids according to the best interest of the system (e.g. self-consumption maximization). To that end, the ECM makes use of forecasts of consumption, production, and day-ahead market prices. It is important to note that network constraints of the REC are not considered during this process.

Several works in the existing literature have tackled the issue of flexibility. In [3], the authors present an optimization model to study the participation of a DR aggregator with a portfolio of DR resources in the wholesale market, highlighting the cost opportunity offered to the aggregator, and the possibility of transferring such a gain to promote the participation of end-users in DR programs. In [4], several "smart" buildings are modeled to provide flexible consumption as fast regulation reserve to the grid, reporting a reduction in operating costs. The authors in [5] study the provision of reserve with DR and stress the importance of accounting for the rebound effect when using flexibility bids. In [6], the authors create a framework in which flexible consumers can provide flexibility bids while an aggregator supervises the flexibility transactions, suggesting the need for interaction between the different agents. In [7], three different market designs are proposed for the activation of flexibility services within distribution networks. This paper focuses on the coordination between retailer, transmission system operation, and distribution system operation (DSO). Another work, [8], proposes the use of hierarchical agent-based modeling for the study of the impact of DR on the day-ahead market, showcasing a cost reduction on the user end while profits are maximized for the retailer.

To date, no work has addressed the issue of introducing flexibility services in the context of an REC. Although there exists literature on peer-to-peer trading, this mechanism is based on a decentralized planner. In our paper, we take the standpoint of a centralized one, where the novelty lies on the introduction of flexibility trading where consumers can submit their willingness to offer flexibility services in the context of European RECs as they have been laid out by the European Commission. Furthermore, no comprehensive interaction model can be found in the literature where flexibility bids coming from consumers' EMSs can be offered in an REC managed by an ECM. Our work aims at filling this gap, introducing a novel multi-agent model capable of simulating the operation of an REC composed of different agents: flexible consumers, non-flexible consumers, generation assets, and ECM. In addition to the regular operation of the REC, a strategy for activating flexibility bids from flexible consumers, based on an optimization problem is proposed and tested.

After this introduction, in Section II, we detail the functioning of the proposed the multi-agent the simulator. Section III presents the mathematical formulation of the optimization problem written to select the flexibility bids. In Section IV, we introduce a test case showcasing and discussing the capabilities of the simulator. Finally, in Section V we provide the conclusion of this work.

II. SIMULATOR

In this section, we present an overview of the proposed simulator, establishing the interactions between the agents of the REC. Moreover, the flow of information in our multi-agent computational tool is explained in detail.

As explained in the introduction, the goal of the developed simulator is the detailed representation of the activities of an ECM and the REC it manages. The REC is composed of a portfolio of flexibility providers among its consumers, namely the flexible consumers. To maximize the self-consumption of the REC (or its welfare as we will see later on the document), the ECM can use the flexibility provided by flexible consumers when purchasing energy in the European day-ahead market.

In the developed simulator, the demand of the REC is introduced by means of several consumers (flexible and non-flexible) that are modeled through their demand profiles. The generation needed to supply such a demand comes from the generation assets of the REC or, if needed, from the main network (outside the REC).

In this work, the ECM produces forecasts of the day-ahead market prices and the demand of the non-flexible consumers. Then, the flexible consumers and the renewable generation assets provide their individual demand forecasts to ECM, who adds them to the forecast of the non-flexible consumers. With all the demand forecasts (flexible and non-flexible), an initial baseline is computed and the flexible consumers are scheduled.

In addition, the ECM receives flexibility bids from the flexible consumers, and activates these bids in order to increase or reduce the demand at certain periods. The ECM will choose the bids that maximize the welfare of the REC which, in the case presented, also maximizes the self-consumption of the system (i.e. the part of the demand met by local generation). A detailed explanation of the role of each agent is provided in this section. The selection process of the flexibility bids is presented in Section III.

A. Agents

In the following, the different agents of the multi-agent simulator are presented, highlighting the interactions between them and their impact on the simulation. The agents of the proposed model are the day-ahead market operator, the flexible consumers, the non-flexible consumers, the generation assets, and the ECM. They all have different roles and ways of interacting.

1) Day-ahead market operator: this agent is meant to provide the history of day-ahead market prices to the ECM so that the it can produce forecasts. In addition, once the day-ahead market has been cleared and the prices are fixed (not forecasts), this agent provides the actual prices that will be charged to the ECM for its day-ahead provisioning.

2) Flexible consumers: this group of agents is composed of electricity consumers that can offer demand response (flexibility). Upon request of the ECM, these agents will compute and offer a flexibility bid upward or downward. This flexibility offer states that, if activated, the flexible consumer is obliged to increase or decrease its consumption at a given point in time. This offer also states that, at a later moment in time, the same amount of energy will be returned to the flexible consumer, decreasing or increasing its demand accordingly (rebound). Each flexibility bid is offered at a fixed price. In principle, each flexible consumer should design this price according to their own utility function through a bidding process. In this paper, however, for the sake of simplicity we consider the same price per unit of energy for all flexibility bids.

Flexible consumers have a baseline and a schedule, and while the baseline represents their consumption without flexibility, the schedule can be adjusted depending on the flexibility bids accepted by the ECM. The EMS of each agent is responsible for the computation of the flexibility bids and for communicating them to the ECM.

The flexibility bids are composed of three elements:

- Initial flexibility: this is the initial change in schedule offered by the flexible consumer, it can be positive or negative and is instantaneous (i.e. it will be activated at the appointed time for the appointed duration). The magnitude of the initial flexibility depends on the baseline of the flexible consumer (it cannot be greater than the baseline itself).
- Idle time: this is the time between the flexibility offered and the start of the rebound, during this time the flexibility bid follows the original schedule.
- Rebound: this is the amount of energy the flexible consumer must recover for the flexibility offered. It may span over several time-steps and its magnitude is equal to the initial flexibility offered, multiplied by a factor (typically greater than 1 in order to account for losses). We assume

that the energy is equally distributed over all rebound time-steps.

In Figure 1, an illustration of a possible flexibility bid is provided. Note that, in the simulation, all three parameters: magnitude of initial flexibility, duration of idle time, and duration of rebound, can be adjusted.

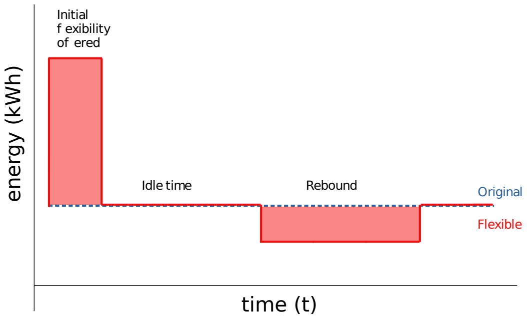

Figure 1: Flexibility bids' structure with three elements: the initial flexibility, an idle time, and the rebound.

3) Non-flexible consumers: this group of agents contains all electricity consumers with non-flexible baselines. These consumers do not offer flexibility bids to the ECM. In this case, the forecasts of these agents' consumption profiles are computed by the ECM and, therefore, deviations between forecast and actual consumption will not be charged to the agents.

4) Generation assets: in addition to the users, the REC contains generation assets, usually owned by an investor that can be the ECM, one of the consumers, or another entity. These generation assets locally produce electricity, which can be used to meet the demand of the REC, or be sold to the main network. In this work, we assume that solar PV is the only available generation technology within the REC and that the locally generated electricity will be sold primarily within the REC. However, this last assumption will depend on the optimization problem. The generation assets forecast their production and submit it to the ECM.

5) ECM: the last agent of the simulator is the energy community manager. The role of this agent is to receive i) price signals from DAM, ii) forecasts from flexible consumers, and iii) forecasts from generation assets. Additionally, it must forecast the consumption of the non-flexible consumers. With all this information, the ECM decides the demand provisioning of the REC, and the flexibility bids to accept. Regarding the demand provisioning, the ECM will act so as to maximize the self-consumption (or welfare as presented in section III) of the REC according to the optimization problem laid out in section III, taking into account the flexibility bids. The objective of the optimization is to maximize the matching of demand with PV production. Finally, the ECM will try to maximize the local electricity exchanges within the REC.

III. DAY-AHEAD FLEXIBILITY ACTIVATION

In this section, the optimization problem that defines the flexibility activation and the day-ahead schedule is formulated. The objective function of this problem aims at maximizing the welfare of the REC and, as a result, its self-consumption.

The proposed REC is composed of consumers (flexible or not), and generation assets. This means that the system will have generation and demand profiles and, as such, its consumption can be divided into:

1) Local consumption: corresponds to the self-consumption of the system, i.e. the part of the demand covered with the local PV generation;
2) Global consumption: corresponds to the imports from the main network (outside the REC), and typically covers the consumption not met by the local generation.

In an ideal REC, the total demand should be covered by the local production and, only if it is not sufficient, should the system resort to imports. The rationale behind this is that, when a high-enough percentage of the production of an REC is locally consumed and, under the new European directive, the distribution system operator serving the REC will offer certain discount on all exchanges taking place inside the community. Thus, the ECM can select flexibility bids to increase or decrease the instantaneous demand, taking into account the idle time and the rebound of each bid so as to maximize self-consumption (minimize imports from the main network). To account for the potential negative effect of activating bids due to their rebound effect, a comprehensive bid activation strategy must be developed. One that not only looks at the flexibility offered to match instantaneously demand and local supply, but also takes into account the adverse –or not– effects of the rebound taking place several time-steps later.

For this reason, in this work we propose a framework to perform the flexibility bid activation according to the output of an optimization problem. The problem is defined as following. Let $\mathcal{T} = \{1, \ldots, T\}$ represent the time discretization of the horizon T, where $t \in \mathcal{T}$ represents the time-steps (the resolution will depend on the used data set). In addition, we can define a set $\mathcal{U} = \{1, \ldots, U\}$ of users. In the proposed framework, $D_{u,t}$ and $P_{u,t}$ denote the demand and the production forecasts of each user u respectively; Π_t^{l-} is the local energy price (without distribution, transmission, or taxes); Π^{dl} is the local distribution price (which contains also transmission and taxes); Π_t^{g-} is the global energy price (without distribution, transmission, or taxes), this is the price of the energy imported; and Π^{dg} is the global distribution costs (including transmission and taxes).

Additionally, we must define all the parameters related to the flexibility bids. Let $\mathcal{B} = \{1, \ldots, B\}$ denote the set of flexibility bids offered by the flexible consumers. Then, we can define the set $\mathcal{I}_b = \{1, \ldots, I_b\}$ representing the discretization of the flexibility bid duration in time-steps, where I_b is the length of the idle time plus the rebound effect of bid $b \in \mathcal{B}$. In this context, every bid $b \in \mathcal{B}$ can be defined as $b = (F_{i,b} \;\; \forall i \in \mathcal{I}_b)$, where $F_{i,b}$ denote the volume of flexibility offered at the i^{th} time-step by bid b. The activation time of a bid $b \in \mathcal{B}$ is given by τ_b. Finally, we can define the subset $\bar{\mathcal{B}}(t) \subseteq \mathcal{B}$ denoting the set of flexibility bids which are active at time-step t, thus $\bar{\mathcal{B}}(t) = \{b \in \mathcal{B} \mid t - I_b \leq \tau_b \leq t\}, \ \forall t \in \mathcal{T}$. Table I contains a detailed overview of the notation used.

$$\min \sum_{t \in \mathcal{T}} \begin{bmatrix} \rho_t^{g-} \cdot \left(\Pi_t^{g-} + \Pi^{dg} + \Pi^o\right) \\ + \rho_t^{l-} \cdot \left(\Pi_t^{l-} + \Pi^{dl} + \Pi^o\right) \\ + \sum_{b \in \mathcal{B}} x_b \cdot C_b \\ - \rho_t^{g+} \cdot \Pi_t^{g+} \\ - \rho_t^{l+} \cdot \Pi_t^{l+} \end{bmatrix} \quad , \tag{1}$$

Subject to, $\forall t \in \mathcal{T}$:

$$\sum_{u \in \mathcal{U}} D_{u,t} + \sum_{b \in \bar{\mathcal{B}}(t)} x_b \cdot F_{t,b} - \sum_{u \in \mathcal{U}} P_{u,t} = \rho_t^{g-} - \rho_t^{g+} \quad , \tag{2}$$

$$\rho_t^{l-} = \sum_{u \in \mathcal{U}} D_{u,t} - \rho_t^{g-} + \sum_{b \in \bar{\mathcal{B}}(t)} x_b \cdot F_{t,b} \quad , \tag{3}$$

$$\rho_t^{l+} = \sum_{u \in \mathcal{U}} P_{u,t} - \rho_t^{g+} \quad . \tag{4}$$

With:

$$\rho_t^{g-}, \rho_t^{g+}, \rho_t^{l-}, \rho_t^{l+} \in \mathbb{R}^+ \quad \forall t \in \mathcal{T} \quad , \tag{5}$$

$$x_b \in [0, 1] \quad \forall b \in \mathcal{B} \quad . \tag{6}$$

The goal of this problem is the selection of flexibility bids offered by the flexible consumers so as to maximize the self-consumption of the REC. The objective function (Equation (1)) minimizes the costs subtracting the revenues of the REC. Equation (2) ensures the energy balance at all time-steps. Equation (3) computes the local consumption ρ_t^{l-}. Equation (4) computes the share of locally generated energy that is sold locally ρ_t^{l+} (i.e. never leaves the REC). Finally, $x_b \in [0, 1]$ is a continuous variable used to activate each bid b if its effect (activation and rebound) contributes positively to the increase of the welfare.

TABLE I: Notation.

Symbol	Meaning	Units
Π_t^{g-}	Global energy price	€/MWh
Π_t^{l-}	Local energy price	€/MWh
Π^{dg}	Global distribution price	€/MWh
Π^{dl}	Local distribution price	€/MWh
Π_t^{g+}	Global selling price of energy	€/MWh
Π_t^{l+}	Local selling price of energy	€/MWh
Π^o	Cost of transmission and taxes	€/MWh
$D_{u,t}$	Demand of user u	MWh
$P_{u,t}$	Production of user u	MWh
ρ_t^{g-}	Total imports of the REC from the grid	MWh
ρ_t^{g+}	Total exports of the REC to the grid	MWh
ρ_t^{l-}	Total local consumption of the REC	MWh
ρ_t^{l+}	Total production locally consumed by the REC	MWh
$F_{t,b}$	Flexibility volume offered	MWh
x_b	Acceptance ratio of the bid	%
C_b	Cost of the bid	€

TABLE II: List of prices in the simulations (€/MWh).

Π_t^{g+}	Π_t^{g-}	Π_t^{l+}	Π_t^{l-}	Π_t^{dg}	Π_t^{dl}	Π^o
40	60	55	56	85	67.15	75

IV. TEST CASE

In this section, we illustrate the use of the proposed framework and its main features by providing an example for the case of an REC in Belgium with the following characteristics:

- the simulation's resolution is 15 minutes;
- 20 flexible consumers whose demand profiles come from data from real users in Belgium;
- 10 non-flexible consumers whose demand profiles come from data from real users Belgium;
- 1 solar PV installation of 48 MW whose production profile is computed using the python library PVLIB [9], calibrating the model for a location in Belgium;
- the idle time of the flexibility bids is 120 minutes;
- the payback duration of the flexibility bids is 60 minutes.

The values of the different price components used for the simulations are listed in Table II. Note that, in the proposed test case, the imports from the main grid are charged at retail price. Thus, the ECM has an incentive to reduce the overall consumption by matching PV generation with demand, using the flexibility bids from flexible consumers.

A. Cost analysis

The costs of the REC (C_{REC}) are given by equation (7). Results of the cost analysis are reported in Table III. Three different cases are considered for the computation of the costs:

1) no REC is established: consumers and producers simply buy and sell the electricity from the outside market;
2) the REC is established, but no flexibility is used: consumers and producers benefit from certain discount on the distribution tariff;
3) the REC is established and flexibility is used: consumers and producers benefit from certain discount on the distribution tariff and from flexibility bids.

Furthermore, we provide results for simulations corresponding to 1 day (January 2, 2017), 1 week (second week of 2017), 1 month (January 2017), and 1 year of operation (2017). Note that January is selected to showcase the results of the costs analysis under the worst possible case.

$$\begin{aligned} C = & \sum_{t \in \mathcal{T}} \rho_t^{g-} \cdot \left(\Pi_t^{g-} + \Pi^{dg} + \Pi^o\right) + \\ & \sum_{t \in \mathcal{T}} \rho_t^{l-} \cdot \left(\Pi_t^{l-} + \Pi^{dl} + \Pi^o\right) - \\ & \sum_{t \in \mathcal{T}} \left(\rho_t^{g+} \cdot \Pi_t^{g+} + \rho_t^{l+} \cdot \Pi_t^{l+}\right) \quad . \end{aligned} \tag{7}$$

TABLE III: Costs for the three different cases and percentage of difference with respect to the reference (first column).

Case	**NO REC (%)**	**REC NO FLEX (%)**	**REC FLEX (%)**
1 day	262 k€ (-)	260.6 k€ (-0.006)	260.6 k€ (-0.006)
1 week	1,785 k€(-)	1,730 k€ (-3.1)	1,726 k€ (-3.3)
1 month	7,054 k€ (-)	6,863 k€ (-2.7)	6,850 k€ (-2.9)
1 year	65,455 k€ (-)	61,303 k€ (-6.3)	61,019 k€ (-6.8)

TABLE IV: Results of the analysis of flexibility use.

Parameter	**With no flexibility**	**With flexibility**	Difference
SSR	33.80%	36.72%	+2.92%
SCR	57.22%	62.23%	+5.01%
Total demand	333,325 MWh	333,688 MWh	∼ same
Production	196,918 MWh	196,918 MWh	same
Local production	112,679 MWh	122,546 MWh	+8.1%
Global production	84,239 MWh	74,372 MWh	-13.27%

B. Performance analysis

To further evaluate the value of RECs and the use of flexibility, we compute the self-sufficiency rate (SSR) and the self-consumption rate (SCR):

$$\mathrm{SSR} = \frac{\sum_{t\in\mathcal{T}} \rho_t^{l+} + \sum_{b\in\bar{\mathcal{B}}(t)} x_b \cdot F_{t,b}}{\sum_{t,u\in\mathcal{T}\times\mathcal{U}} D_{u,t}} \quad , \tag{8}$$

$$\mathrm{SCR} = \frac{\sum_{t\in\mathcal{T}} \rho_t^{l+} + \sum_{b\in\bar{\mathcal{B}}(t)} x_b \cdot F_{t,b}}{\sum_{t,u\in\mathcal{T}\times\mathcal{U}} P_{u,t}} \quad . \tag{9}$$

The available flexibility can be used to improve the matching between supply and demand, as illustrated in Figure 2. The demand shift of the system (before and after flexibility) is shown by comparing the initial with the flexible demand. In Figure 2, we can observe that, in times of high local production, upward flexibility is activated in order to increase the self-consumption of the REC and vice-versa, when there is scarcity of production, the flexible demand decreases as a result of downward bid activation. In Table IV, these findings are summarized for the yearly operation of an REC. A substantial increase in the utilization of local production is achieved when flexibility is considered (+8.1%). Subsequently, the SCR is improved in the REC by 5.01%. A similar trend can be observed for the SSR, which increases by 2.92% when introducing flexibility. It is important to note that these results are sensitive to the amount of offered flexibility and to the REC configuration.

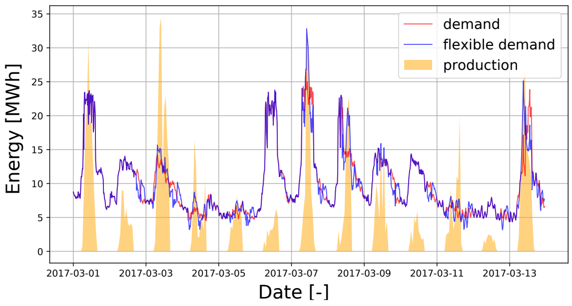

Figure 2: Initial demand (in red) vs demand after using flexibility (in blue). The PV production is displayed in yellow. Detail of 13 days in March 2017.

V. CONCLUSIONS

In this paper a modeling framework is proposed for analyzing the benefits of creating an REC with flexible and non-flexible consumers, and with PV generation assets. In this framework, an ECM is responsible for managing the REC and its participation in the European day-ahead market. Results show a 6.3% yearly reduction of total costs when an REC is created. A discount on the distribution tariff offered by the DSO when energy is produced and consumed locally has a key role on this cost reduction. Furthermore, we account for flexibility offered by the flexible consumers of the REC. We propose a bid acceptance algorithm according to which the ECM can optimize the amount of flexibility activated in the REC while accounting for the rebound effect. The incorporation of flexibility in the REC is shown to further reduce the total system cost by 6.8%. The importance of the instantaneous matching of supply and demand is showcased by an increase of the SSR and SCR of the REC when flexibility is introduced. Future work may consist in performing sensitivity analysis on the prices, considering an additional optimization step closer to real-time. Additionally, the variability of the consumption and the PV production could be better accommodated by means of probabilistic forecasts in the optimization process.

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