Building Flexibility Bidding Curves for Energy Communities

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***Abstract* — The integration of renewable generation requires new sources of flexibility, including the flexibility from distributed resources that can be unlocked via local flexibility markets (LFMs). In these markets, aggregators (AGGs) offer the flexibility from their portfolios to the flexibility requesting parties (FRP), i.e. system operators or other balancing requesting parties. To bid in LFMs and manage market uncertainty, AGGs must compute the flexibility they are willing to offer at each possible flexibility market price, by optimizing their portfolios. This paper proposes a 2-stage methodology to compute the flexibility bidding curve that an energy community can send to a LFM when behaving as an AGG of its members resources. At stage 1, the energy community (EC) manager computes the optimal EC operation without flexibility provision, minimizing the EC energy bill, and serving as the baseline to verify the flexibility provision. Then, at stage 2, for each possible flexibility price, the EC manager computes the optimal flexibility to be offered, minimizing the EC energy bill but including the flexibility provision incomes, to build the flexibility bidding curve.**

***Index Terms*— energy communities, flexibility provision, bidding curves, flexibility markets, baseline**

I. INTRODUCTION

Renewable and distributed generation are expected to increase significantly in the European Union (EU), following the ambitious measures to reduce emissions and fossil fuel dependency [1]. Some of the measures are the new regulations regarding self-generation and self-consumption (SC) allowing individual self-consumption (ISC) and collective self-consumption (CSC) of any scale to generate energy for own consumption and for sharing with other CSC members or injecting back to the grid [2].

In CSC, the allocation of energy between the members of an energy community (EC) is often responsibility of the distribution system operator (DSO). The DSO informs the retailers of the CSC members on the energy self-consumed, so that they are only billed for the supply that results from their consumption minus their self-consumption. As explained in [3], CSC regulations allow to set up local energy markets (LEM) among CSC members and integrate them with wholesale markets, as long as the energy allocations respects local transactions, including peer-to-peer (P2P) trades. This requires the existence of what is often called dynamic allocation, which is performed after the energy measurements become available. This integration can be extended to local flexibility markets (LFM), where aggregated consumers provide flexibility to wholesale agents, since the delivered flexibility can be compensated by LEM transactions with CSC allocations done by the DSO [4]. LEM and LFM proposals can benefit from CSC regulation by using rules that, for instance, are already in practice in several EU members, such as Spain, Portugal, France, Austria, or Belgium [2], [5]. CSC allocation rules define the scope at which P2P trades are possible and may even allow retailers to compete for other CSC member's supply within the EC [6].

LFM are also expected to provide services increasingly needed by the grid [7], where AGGs, by managing their portfolio's assets, can provide flexibility to flexibility requesting parties (FRP) such as local DSO [8]. Since there are several possible flexibility needs from FRPs [9], the AGG must be able to bid for different products in advance of or in response to the request.

This paper addresses the provision of flexibility from an EC behaving as an AGG of its CSC members, and results from the work being developed in the BeFlexible project [10], where the digital platform GDBN to support all activities in the flexibility value chain is being developed [11]. One of the services that will be integrated into the GDBN is the EC management service with flexibility provision to the local DSO. Since DSO usually only publish their flexibility needs for a selected period, AGGs should build appropriate bidding curves to manage the market price uncertainty and compete in the LFM. These bidding curves provide, for each possible market price, the optimal flexibility to be provided, according to the DSO flexibility needs. To build those curves, AGGs must optimize their aggregated assets operation considering the LFM products requested, i.e., price and delivery periods, and, as will be described, other relevant parameters such as the baseline tolerance for the periods where no flexibility is being requested.

This work is based on the EC operation linear programming models in [6] and [11] where communities assets are optimized considering CSC rules and different pricing schemes. No many works deal with the provision of flexibility from EC. For example, using a similar linear programming, the work in [13] computes the price to provide the flexibility corresponding to a flexibility request from the FRPs, but no bidding curve is provided, which limits the possibility of being selected. AGG's bidding curves are computed in [14] using stochastic programming to evaluate flexibility in multi market levels. However, it's nor simulated for small scale final consumers neither considers CSC rules. The main contributions and findings of this work are:

- A linear programming model to compute the AGG's bidding curve with the optimal flexibility quantity to be provided for each possible market price, by scheduling the flexible EC assets.
- Use of CSC regulation to deliver flexibility using internal LEM trades.
- Assessment of impact of the internal EC pricing mechanisms on the flexibility bidding curves produced, showing that *ad-hoc* pricing rules reduce the available flexibility.
- Baseline computation proposal, and the proposal of a tolerance to relax the baseline on the periods where no flexibility is needed to increase the flexibility that can be provided on those periods where it is being requested.
- Assessment of the impact of this baseline tolerance on the final flexibility offered.

Section II describes the 2-stage optimization problem and the process to create the bidding curves, section III presents a case study for an EC with battery energy storage systems (BESS) and PV generation, and analyses the results, and section IV concludes.

II. OPTIMIZATION MODEL

The model runs two stages to build the flexibility curve, as shown in Figure 1.

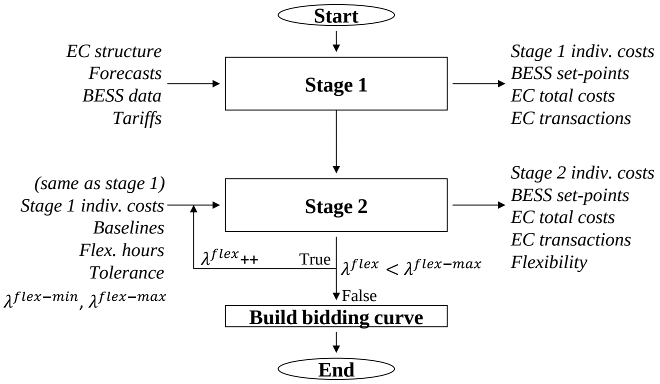

Figure 1. Steps for computing EC's bidding curve

In stage 1, the AGG computes the optimal operation of the EC considering its assets, consumption and generation forecasts, and price signals, but without providing flexibility. This stage is necessary for two reasons. First, it defines the EC baseline, i.e., its aggregated optimal energy behaviour when no flexibility is requested. It also computes the members energy cost, to guarantee that in stage 2 the provision of flexibility always keeps or reduces their individual cost.

Stage 2 computes the optimal operation of the EC with flexibility delivery, considering a) the flexibility required by the FRP and the periods where it is needed, and the baseline tolerance for the periods when it is not needed, b) the set-points of the flexible assets from Stage 1, and c) a range of flexibility prices λ^{flex} to build the flexibility curve. For each λ^{flex} an optimization problem computes the optimal flexibility to be provided, either up (UpFlex) or downward (DwFlex). Note that, since this model uses the members metered consumption as reference, DwFlex refers to decreasing net consumption and UpFlex refers to increasing net consumption.

A. *Stage 1: EC optimization without flexibility*

In stage 1 the objective function (1) minimizes EC's costs.

$$min \sum_{t\in T}\Big(\sum_{n\in N}\big(E_{n,t}^{SUP}\cdot\hat{\lambda}_{n,t}^{buy} - E_{n,t}^{SUR}\cdot\hat{\lambda}_{n,t}^{sell} + E_{n,t}^{SLC}\cdot\hat{\lambda}_{t}^{grid} + \sum_{s\in S} E_{n,s,t}^{B,D}\cdot\hat{\lambda}_{n,s}^{deg}\big)\Big) \quad (1)$$

where, for each member $n \in N$, $E_{n,t}^{SUP}$ is the energy supplied by its retailer at price $\hat{\lambda}_{n,t}^{buy}$, $E_{n,t}^{SUR}$ is the surplus sold to its retailer at feed-in price $\hat{\lambda}_{n,t}^{sell}$, $E_{n,t}^{SLC}$ is the self-consumed energy which pays a grid access tariff $\hat{\lambda}_{t}^{grid}$, and for each BESS $s \in S$, a degradation cost $\hat{\lambda}_{n,s}^{deg}$ is applied to each discharge $E_{n,s,t}^{B,D}$ to minimize unprofitable BESS cycles. Energy is traded internally in a pool-like market, as in (2).

$$\sum_{n}\left(E_{n,t}^{PUR}\right) - \sum_{n}\left(E_{n,t}^{SALE}\right) = 0,\ \forall\, t \in T \quad (2)$$

where $E_{n,t}^{PUR}$ is the energy bought locally and $E_{n,t}^{SALE}$ is the energy sold locally. Equation (3) is the energy trade equilibrium constraint:

$$E_{n,t}^{CMET} = E_{n,t}^{SUP} - E_{n,t}^{SUR} + E_{n,t}^{PUR} - E_{n,t}^{SALE},\ \forall\, t \in T, n \in N \quad (3)$$

where $E_{n,t}^{CMET}$ is the metered net consumption of member *n*, where negative values mean injections to the grid. Equation (4) is the energy equilibrium constraint:

$$E_{n,t}^{CMET} = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + \sum_{s\in S}\left(E_{n,s,t}^{B,C} - E_{n,s,t}^{B,D}\right),\ \forall\, t \in T \quad (4)$$

where both the load profile $\hat{E}_{n,t}^{C}$ and the generation profile $\hat{E}_{n,t}^{G}$ are fixed input parameters, $E_{n,s,t}^{B,C}$ is the energy charged by the *s* BESS of member *n*. Equation (5) limits the members exchanges to their contracted power:

$$-\hat{P}_{n}^{CPE,max} \leq \frac{E_{n,t}^{CMET}}{\Delta t} \leq \hat{P}_{n}^{CPE,max},\ \forall\, t \in T \quad (5)$$

where $\hat{P}_{n}^{CPE,max}$ is the contracted power of member *n*. The energy of each BESS is tracked with (6):

$$E_{n,s,t}^{B} = E_{n,s,t-1}^{B} + \left(E_{n,s,t}^{B,C}\cdot\hat{\eta}_{n,s}^{B,C} - \frac{E_{n,s,t}^{B,D}}{\hat{\eta}_{n,s}^{B,D}}\right),\ \forall\, t \in T, s \in S \quad (6)$$

where $E_{n,s,t}^{B}$ is the energy stored by the BESS, and $\hat{\eta}_{n,s}^{B,C}$ and $\hat{\eta}_{n,s}^{B,D}$ are the charging and discharging efficiencies. Their state of charge (SOC) is given by (7) and limited by (8), while (9) ensures the SOC is at 50% at the end of the last period.

$$SOC_{n,s,t}^{B} = \frac{E_{n,s,t}^{B}}{\hat{E}_{n,s}^{B,N}}\cdot 100,\ \forall\, t \in T, s \in S \quad (7)$$

$$\widehat{SOC}_{n,s}^{B,min} \leq SOC_{n,s,t}^{B} \leq \widehat{SOC}_{n,s}^{B,max},\ \forall\, t \in T, s \in S \quad (8)$$

$$SOC_{n,s,t}^{B} \geq 50,\ t = T_{last} \quad (9)$$

where $SOC_{n,s,t}^{B}$ is the SOC of the BESS, $\hat{E}_{n,s}^{B,N}$ is its nominal capacity, $\widehat{SOC}_{n,s}^{B,min}$ and $\widehat{SOC}_{n,s}^{B,max}$ the minimum and maximum SOC, and T_{last} is the last period of the optimization horizon set to one day. Charging and discharging rates are limited by (10) and (11), which also ensure the BESS cannot charge and discharge simultaneously (for example if efficiencies are neglected):

$$\frac{E^{B,C}_{n,s,t}}{\Delta t} \leq \hat{P}^{B,max}_{n,s} \cdot (\delta^{B,C}_{n,s,t}),\ \forall 1\ t \in T, s \in S \tag{10}$$

$$\frac{E^{B,D}_{n,s,t}}{\Delta t} \leq \hat{P}^{B,max}_{n,s} \cdot (1 - \delta^{B,C}_{n,s,t}),\ \forall\ t \in T, s \in S \tag{11}$$

where $\hat{P}^{B,max}_{n,s}$ is the maximum input and output power of the BESS and $\delta^{B,C}_{n,s,t}$ is binary and equal to 1 when charging. Finally, (12) calculates the individual member's energy costs $C^{ind\_1}_{n}$:

$$C^{ind\_1}_{n} = \sum_{t\in T}\big(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \big(E^{PUR}_{n,t} - E^{SALE}_{n,t}\big) \cdot \hat{\lambda}^{p2p}_{t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\big) \tag{12}$$

B. *Stage 2: EC optimization with flexibility provision*

In stage 2 the objective function (13) minimizes the total cost of the EC including the incomes from providing flexibility:

$$min \sum_{t\in T}\Big(\sum_{n\in N}\big(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{\mathrm{SUR}}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} - E^{FLEX}_{n,t} \cdot \hat{\lambda}^{flex}_{t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\big)\Big) \tag{13}$$

where $E^{FLEX}_{n,t}$ is the flexibility to be offered, output of this stage, given an input flexibility price $\hat{\lambda}^{flex}_{t}$. All the other stage 1 constrains apply, expect (4) which is replaced by (14):

$$E^{CMET\_2}_{n,t} = \hat{E}^{C}_{n,t} - E^{G}_{n,t} + \sum_{s\in S}\big(E^{B,C}_{n,s,t} - E^{B,D}_{n,s,t}\big),\ \forall\ t \in T, n \in N \tag{14}$$

where $E^{G}_{n,t}$ is the behind-the meter generation given by (15):

$$E^{G}_{n,t} = \hat{E}^{G}_{n,t} - E^{CURT}_{n,t},\ \forall\ t \in T, n \in N \tag{15}$$

where $E^{CURT}_{n,t}$ is the generation of member *n* curtailed to provide flexibility. Equation (16) computes flexibility provided by each member for the periods $t \in T_{wf}$ where it is requested:

$$E^{FLEX}_{n,t} = E^{CMET\_2}_{n,t} - \hat{E}^{CMET\_1}_{n,t},\ \forall\ t \in T_{wf} \tag{16}$$

where $\hat{E}^{CMET\_1}_{n,t}$ is the metered consumption in stage 1. In the periods $t \in T_{nf}$ where no flexibility is requested, (17) and (18) apply a tolerance ρ_t so that the members can deviate from their baseline from stage 1, $E^{CMET\_1}_{n,t}$, to increase its flexibility potential of stage 2 resulting from $E^{CMET\_2}_{n,t}$:

$$\sum_{N} E^{CMET\_2}_{n,t} \leq \sum_{N} \hat{E}^{CMET\_1}_{n,t} + \rho_t,\ \forall\ t \in T_{nf} \tag{17}$$

$$\sum_{N} E^{CMET\_2}_{n,t} \geq \sum_{N} \hat{E}^{CMET\_1}_{n,t} - \rho_t,\ \forall\ t \in T_{nf} \tag{18}$$

Finally, (19) calculates the new individual costs $C^{ind\_2}_{n}$ of stage 2, and (20) guarantees they are lower than in stage 1:

$$C^{ind\_2}_{n} = \sum_{t\in T}\big(E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} - E^{FLEX}_{n,t} \cdot \hat{\lambda}^{flex}_{t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \big(E^{PUR}_{n,t} - E^{SALE}_{n,t}\big) \cdot \hat{\lambda}^{p2p}_{t} + \sum_{s\in S} E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s}\big) \tag{19}$$

$$C^{ind\_2}_{n} \leq \hat{C}^{ind\_1}_{n},\ \forall\ n \in N \tag{20}$$

Note that constrain (20) enforces that stage 2 does not increase the member's cost of stage 1, guaranteeing that all members benefit from the flexibility provision. Since the LEM price is defined from an *ad-hoc* mechanism, local trades do not necessarily reflect the true opportunity costs of the energy on the second stage, and this may limit the members ability the share their flexibility through local trades, impacting the EC available flexibility and the bidding curve. This effect is illustrated in the case study.

III. CASE STUDY

A. *Case description*

An EC with 4 members is simulated. Their supply capacity, BESS and PV characteristics are provided in TABLE I. Load and PV forecasts are based on data from [15].

TABLE I. EC MEMBERS CHARACTERIZATION

ID	Contracted Power	BESS				PV power
		Capacity	Max. power	SOC^{min}	SOC^{max}	
M1	3.45 kVA	------	------	------	------	------
M2	6.9 kVA	------	------	------	------	2.2 kWp
M3	6.9 kVA	6.4 kWh	2.0 kW	15%	95%	------
M4	10.35 kVA	13.5 kWh	5.0 kW	15%	95%	4.4 kWp

The prices at which EC members buy [16] and sell [17] energy, local P2P transactions prices (computed based on [18] as a function of λ^{buy} and λ^{sell}), and the grid access tariffs for self-consumption [19] are all given in TABLE II.

TABLE II. EC ENERGY PRICES AND TARIFFS

λ^{buy}	λ^{sell}	λ^{P2P}	λ^{grid}
0.1625 €/kWh	0.06 €/kWh	0.08 €/kWh	0.0106 €/kWh

This case study involves 4 main scenarios (TABLE III. each with a different tolerance. Scenarios are divided in 2 sub-scenarios: for noon (NF) and for evening flexibility (EF).

TABLE III. SCENARIOS AND FLEXIBILITY REQUIREMENTS

Scenario	Tolerance	Sub-scenario ID	Time period
S1	1kWh	NF1	11:00h – 13:00h
		EF1	19:00h – 21:00h
S2	4kWh	NF4	11:00h – 13:00h
		EF4	19:00h – 21:00h
S3	0.4kWh	NF04	11:00h – 13:00h
		EF04	19:00h – 21:00h
S4	0kWh	NF0	11:00h – 13:00h
		EF0	19:00h – 21:00h

B. *Results*

This section analyses the main results of the scenarios. The outcomes of S1 are presented first and thoroughly analysed. Then, S2, S3 and S4 are studied with the focus on how tolerance changes the results by comparing with S1.

1) *Scenario 1*

The bidding curves for NF1 (noon flexibility with 1kWh tolerance) and EF1 (evening flexibility) are given in Figure 2. They relate the amount of flexibility EC^{FLEX} that minimizes the EC cost when the flexibility price is λ^{flex}.

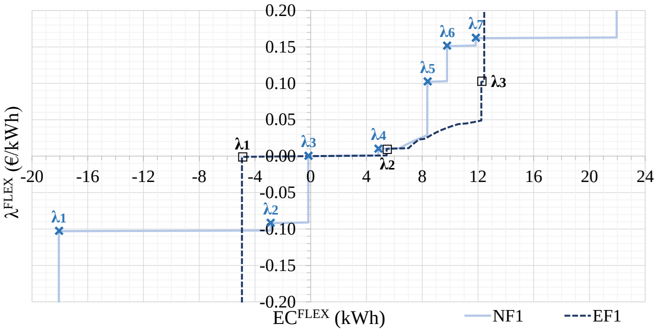

Figure 2. EC bidding curves for NF1 and EF1

From the analysis of NF1 bidding curve:

- For $\lambda^{flex} < \lambda_1$, EC^{FLEX} is −18.1kWh, which is the maximum DwFlex in NF1. It is offered by the BESS of M3 and M4.

Compared to stage 1, M3 and M4 reschedule their BEES to charge before T_{wf} so they get closer to SOC^{max} at the start of T_{wf}. This adjustment allows them to offer the requested DwFlex by discharging during T_{wf}, consequently reducing the net load of the EC in that period.

- λ^{flex} reaches $\lambda_1 = -(\lambda^{buy} - \lambda^{sell}) = -0.1025€/kWh$.
- For $\lambda_1 < \lambda^{flex} < \lambda_2$, EC^{FLEX} is −2.87kWh. The main change compared to the previous price range is that BESS do not charge as much before T_{wf} and do not discharge as much during T_{wf}, being closer to the schedule of stage 1, as flexibility is now less profitable.
- λ^{flex} reaches $\lambda_2 = \lambda_1 - \lambda^{grid} = -0.0919€/kWh$.
- For $\lambda_2 < \lambda^{flex} < \lambda_3$, EC^{FLEX} decreases further, with the EC offering even less flexibility, only −0.175kWh.
- λ^{flex} reaches $\lambda_3 = 0€/kWh$, resulting in an inversion from DwFlex to UpFlex.
- For $\lambda_3 < \lambda^{flex} < \lambda_4$, EC^{FLEX} is 4.86kWh, being provided by the BESS of M3, which charges during T_{wf}. The operation of M4's BESS when compared to stage 1 is still the same and used to store generation surpluses.
- λ^{flex} reaches $\lambda_4 = \lambda^{grid} = 0.0106€/kWh$.
- For $\lambda_4 < \lambda^{flex} < \lambda_5$, the BESS of M3 offers its maximum flexibility, going from SOC^{min} to SOC^{max} during T_{wf}, and the M4 BESS starts to offer flexibility by charging during T_{wf}. The maximum value of EC^{FLEX} for this price range is 8.37kWh, but, up to a certain value of λ^{flex}, EC^{FLEX} is actually lower than that. Graphically, this issue matches the curved portion of the bidding curve between λ_4 to λ_5. The reason why EC^{FLEX} does not go directly to 8.37kWh when λ^{flex} reaches λ_4 is due to (20). This constraint ensures that no member loses out compared to stage 1, but when λ_4 is reached, the values of C^{ind_2} and C^{ind_1} for M4 are equal, meaning M4 would lose out if it were to provide more flexibility. Thus, EC^{FLEX} increases with λ^{flex} until λ^{flex} is high enough to allow M4 to offer its maximum flexibility for this price range.
- λ^{flex} reaches $\lambda_5 = \lambda^{buy} - \lambda^{sell} = 0.1025€/kWh$.
- For $\lambda_5 < \lambda^{flex} < \lambda_6$, EC^{FLEX} is 9.78kWh. Because M3 is already offering its maximum flexibility, only M4 can provide more flexibility by charging its BESS during T_{wf}.
- λ^{flex} reaches $\lambda_6 = \lambda^{buy} - \lambda^{grid} = 0.1519€/kWh$.
- For $\lambda_6 < \lambda^{flex} < \lambda_7$, EC^{FLEX} rises to 11.8kWh. Flexibility is provided by both BESS and M2 starts now to curtail its PV generation during T_{wf}.
- λ^{flex} reaches $\lambda_7 = \lambda^{buy} = 0.1625€/kWh$.
- Finally, for $\lambda^{flex} > \lambda_7$, the EC offers its maximum UpFlex, 22.0kWh. During T_{wf} both BESS are charged from SOC^{min} to SOC^{max}, and all generation is curtailed, there are no P2P trades, and all energy is supplied by the retailers.

Regarding EF1, it has a simpler curve than NF1. Since there is no PV generation during T_{wf}, and flexibility cannot be provided by curtailing generation. This bidding curve progresses as follows:

- For $\lambda^{flex} < \lambda_1$, EC^{FLEX} is −4.93kWh, which is the maximum DwFlex in EF1. Flexibility results from reducing the net consumption by discharging the BESS during T_{wf}.
- λ^{flex} reaches $\lambda_1 = 0€/kWh$.
- For $\lambda_1 < \lambda^{flex} < \lambda_2$, EC^{FLEX} is 5.45kWh, provided by both BESS which are incentivized to charge during T_{wf}.
- λ^{flex} reaches $\lambda_2 = \lambda^{grid}$ 0.0106€/kWh.
- For $\lambda_2 < \lambda^{flex} < \lambda_3$, like described in NF1, due to (20) the value of EC^{FLEX} starts at 7.02kWh and increases with λ^{flex} until 12.2kWh, the maximum for this price range.
- λ^{flex} reaches $\lambda_3 = \lambda^{buy} - \lambda^{sell}$ 0.1025€/kWh.
- Finally, for $\lambda^{flex} > \lambda_3$, it reaches the maximum UpFlex in EF1, 12.5kWh. This value is lower than in NF1, explained by the impossibility to offer flexibility via PV curtailment.

To complement this study, the total E^{CMET} of the EC, and the SOC of M3's BESS in NF1 for 2 values of λ^{flex} (0.2€/kWh, −0.2€/kWh) are given in Figure 3 and Figure 4, and analysed next.

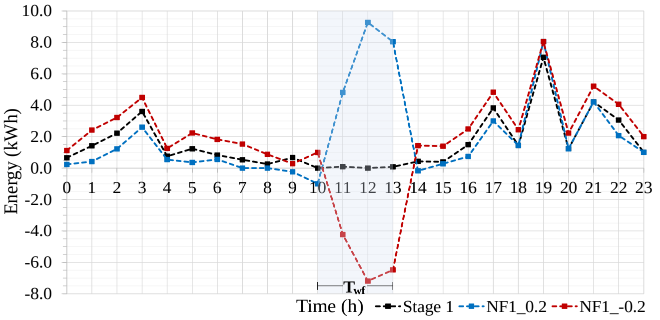

Figure 3. Sum of E^{CMET} for stage 1 and 2 (λ^{flex}: 0.2€/kWh; − 0.2€/kWh)

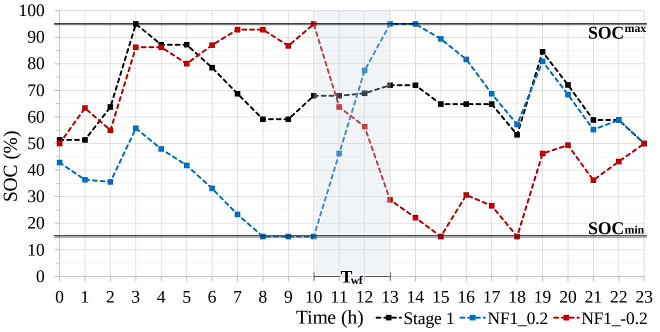

Figure 4. SOC of M3 in stage 1 and 2 (λ^{flex}: 0.2€/kWh; − 0.2€/kWh)

Compared to stage 1, when $\lambda^{flex} = 0.2€/kWh$ the EC increases its net E^{CMET} during T_{wf} and decreases it during T_{nf}. In contrast, when $\lambda^{flex} = -0.2€/kWh$ the net E^{CMET} decreases during T_{wf} and increases during T_{nf}. This highlight the benefit of applying the tolerance to the baseline for those hours where no flexibility is needed.

Regarding M3's BESS SOC, for $\lambda^{flex} = 0.2€/kWh$, the BESS's schedule changes when compared to stage 1 by discharging before T_{wf} so that it reaches SOC^{min} at the start of that period. Then, during T_{wf}, it charges to SOC^{max} to raise the EC's net consumption. For $\lambda^{flex} = -0.2€/kWh$, the opposite happens. The BESS stays at a high SOC before T_{wf}, reaching SOC^{max} at the beginning of that period. Then, it discharges during T_{wf} to supply the EC, lowering the net consumption.

2) *Scenario 2*

In S2, the tolerance is increased to 4kWh, and the resulting bidding curves are in Figure 6 (Appendix). The curves of NF4 and NF1 are similar in structure, with changes in the values of EC^{FLEX}. For instance, maximum DwFlex goes from −18.1kWh to −21.7kWh, an increase of 20%. Meanwhile, the maximum UpFlex is still 22.0kWh, as expected, because in NF1 the EC was already providing its maximum UpFlex by curtailing all generation and charging both BESS from SOC^{min} to SOC^{max} during T_{wf}. Regarding evening requirements, in EF4 the maximum DwFlex increases from −4.93kWh to −13.6kWh, about 176%, while the maximum UpFlex increases from 12.5kWh to 17.1kWh, around 37%.

3) *Scenario 3*

In S3 the tolerance is lowered to 0.4kWh, with the resulting bidding curves in Figure 7 (Appendix). In NF04 and EF04, as the tolerance is lower, EC^{FLEX} is smaller than in the previous scenarios. In NF04 the maximum DwFlex is −8.40kWh, a reduction of 54% compared to NF1. However, the EC offers the same maximum UpFlex observed before, 22.0kWh. In EF04 the maximum DwFlex is −4.93kWh, with a reduction of 57% compared to EF1, while the maximum UpFlex falls from to 11.3kWh, 11% lower than in EF1.

4) *Scenario 4*

In S4, the tolerance is 0kWh, and the resulting bidding curves are in Figure 8 (Appendix). The main difference is that EC^{FLEX} is 0kWh until λ^{flex} reaches 0.1519€/kWh ($\lambda^{buy} - \lambda^{grid}$), meaning that the EC cannot offer DwFlex, explained in the next section. Regarding UpFlex, in NF0 the EC offers up to 22kWh, which is the same maximum of the other scenarios, and in EF0 it offers up to 10.5kWh, 16% less than in EF1.

C. *Tolerance*

In this section we assess the impact of the baseline deviation tolerance on the EC flexibility. Figure 5 shows the variation of EC^{FLEX} in relation to each deviation tolerance, for both NF and EF, and for two values of λ^{flex}: -0.2€/kWh and 0.2€/kWh.

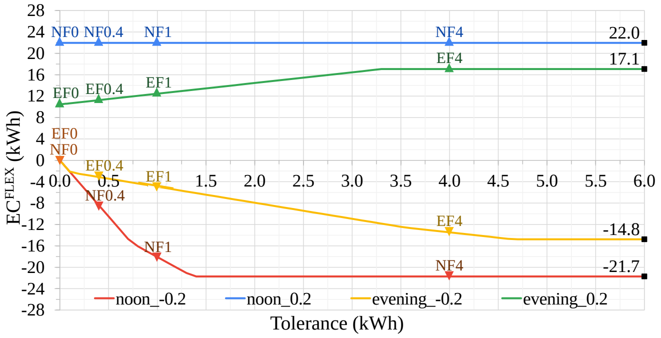

Figure 5. Variation of EC^{FLEX} with tolerance (λ^{flex}: 0.2€/kWh; −0.2€/kWh)

DwFlex is significantly impacted by low tolerances. $\hat{E}_{n,t}^{C}$ is fixed in both stages, so flexibility comes only from the curtailment $E_{n,t}^{CURT}$ or from storage $(E_{n,s,t}^{B,C} - E_{n,s,t}^{B,D})$. Energy curtailment adds to UpFlex and can be provided at any $t \in T$. BESS adds to both UpFlex and DwFlex, but its operation is intertemporal and delivering in $t \in T_{wf}$ also impacts $t \in T_{nf}$.

When ρ_t = 0kWh the EC net consumption ($\sum_N E_{n,t}^{CMET}$) in $t \in T_{nf}$ must be equal in both stages. To provide UpFlex, BESS must decrease its SOC in previous periods by curtailing generation, and to provide DwFlex, BESS must increase its SOC. However, this it is not possible without changing the delivery since there is no variable to compensate the BESS discharge, unless there were demand response, not modelled in this work. This effect is further detailed in the Appendix.

For ρ_t > 0kWh, the delivery increases as the tolerance increases, and DwFlex increases faster for noon than for evening requirements, settling at -21.7kWh and -14.8kWh, respectively. Regarding UpFlex, in what concerns noon requirements, it is observed that this EC is always able to offer its maximum UpFlex independently of the tolerance. Finally, for evening requirements, the EC already offers 10.5kWh when ρ_t = 0kWh, a value that grows until it settles at 17.1kWh.

IV. CONCLUSION

This paper introduces a 2-stage linear optimisation model to estimate the flexibility supply curves for an AGG bid in an LFM to manage market price uncertainty. The model considers the CSC regulation rules that establish how members in an EC can allocate energy among themselves. The computed bidding curves revealed well behaved patterns, where larger positive prices lead to larger upward flexibility, and larger negative prices to larger downward flexibility.

This work also assesses the effects of the tolerance to allow deviations from the baseline in the delivery periods where no flexibility is needed. It shows that less tolerance significantly hampers the downward flexibility. Also, since the tolerance is applied to the whole EC, the AGG can use LEM trades using CSC allocation to extrapolate individual tolerance limits by compensating with other member's schedules.

As stated in the introduction, CSC, LEM and LFM can be integrated to provide increasingly needed services to grid operators and BRP. This works moves one step forward by providing a practical tool to bid in these integrated markets. Further research will consider demand response such as load shifting, and other flexible assets such as thermal loads or electric vehicles and assess the impacts of different CSC allocation rules and pricing mechanisms on the bidding curve.

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V. APPENDIX

A. *Bidding curves*

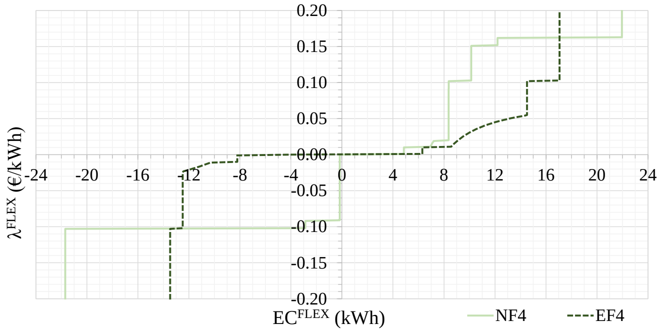

Figure 6. EC bidding curves for NF4 and EF4

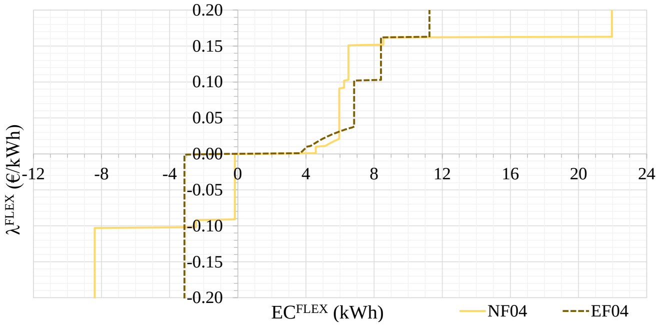

Figure 7. EC bidding curves for NF04 and EF04

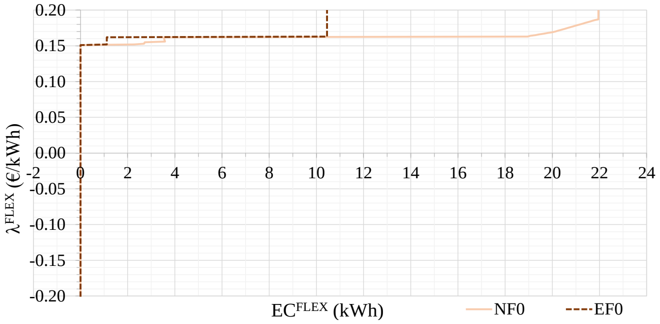

Figure 8. EC bidding curves for NF0 and EF0

B. *Impact of having no tolerance*

When ρ_t = 0kwh, (17) and (18) can be rewritten as:

$$\sum_N E_{n,t}^{CMET\_2} = \sum_N \hat{E}_{n,t}^{CMET\_1}, \ \forall t \in T_{nf} \tag{A1}$$

Replacing the left side of (A1) with (14) and the right side with (4):

$$\hat{E}_{n,t}^{C} - E_{n,t}^{G} + E_{n,s,t}^{B,C_2} - E_{n,s,t}^{B,D_2} = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + E_{n,s,t}^{B,C_1} - E_{n,s,t}^{B,D_1} \tag{A2}$$

Then, by replacing $E_{n,t}^{G}$ with (15):

$$\begin{aligned}\hat{E}_{n,t}^{C} - (\hat{E}_{n,t}^{G} - E_{n,t}^{CURT}) + E_{n,s,t}^{B,C\_2} - E_{n,s,t}^{B,D\_2} \\ = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + E_{n,s,t}^{B,C\_1} - E_{n,s,t}^{B,D\_1}\end{aligned} \tag{A3}$$

Which is equivalent to:

$$\begin{aligned}\hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + E_{n,t}^{CURT} + E_{n,s,t}^{B,C\_2} - E_{n,s,t}^{B,D\_2} \\ = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + E_{n,s,t}^{B,C\_1} - E_{n,s,t}^{B,D\_1}\end{aligned} \tag{A4}$$

As $\hat{E}_{n,t}^{C}$ and $\hat{E}_{n,t}^{G}$ are equal in both stages, (A4) is equivalent to:

$$E_{n,t}^{CURT} + E_{n,s,t}^{B,C\_2} - E_{n,s,t}^{B,D_2} = E_{n,s,t}^{B,C_1} - E_{n,s,t}^{B,D_1}, \qquad \forall t \in T_{nf} \tag{A5}$$

From (A5) it is concluded that, by curtailing generation ($E_{n,t}^{CURT}$) and discharging the BESS ($E_{n,s,t}^{B,D\_2}$) in the same amount during T_{nf}, the value of $\sum_N E_{n,t}^{CMET\_2}$ remains equal to $\sum_N \hat{E}_{n,t}^{CMET\_1}$. This way the EC can provide UpFlex even when ρ_t = 0kwh by curtailing generation and discharging the BESS (simultaneously and in the same amount) before T_{wf}, so that when T_{wf} arrives the BESS are at a low SOC and ready to charge and provide UpFlex by increasing the net load of the EC.

However, this same mathematical condition prevents the EC from providing DwFlex when ρ_t = 0kwh. For that to happen, the EC would have to charge the BESS ($E_{n,s,t}^{B,C\_2}$) before T_{wf}, but it is impossible to do so without changing $\sum_N E_{n,t}^{CMET\_2}$, because there is no variable in the left side of (A5) to counterbalance an increase in $E_{n,s,t}^{B,C\_2}$.