Integrating Cross-Sector Flexible Assets in Flexibility Bidding Curves for Energy Communities

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***Abstract* —Distributed energy resources (DERs) offer untapped potential to meet the flexibility needs of power systems with a high share of non-dispatchable renewable generation, and local flexibility markets (LFMs) can be effective mechanisms for procuring it. In LFMs, energy communities (ECs) can aggregate and offer flexibility from their members' DERs to other parties. However, since flexibility prices are only known after markets clear, flexibility bidding curves can be used to deal with this price uncertainty. Building on previous work by the authors, this paper employs a two-stage methodology to calculate flexibility bids for an EC participating in an LFM, including not only batteries and photovoltaic panels, but also cross-sector (CS) flexible assets like thermal loads and electric vehicles (EVs) to assess their impact. In Stage 1, the EC manager minimizes the energy bill without flexibility to define its baseline. In Stage 2, it computes the optimal flexibility to be offered for each flexibility price to build the flexibility bidding curve. Case examples allow to assess the impact of CS flexible assets on the final flexibility offered.**

***Index Terms*— energy communities, local flexibility markets, bidding curves, cross-sector flexibility, electric vehicles**

I. INTRODUCTION

Following EU directives, local flexibility markets (LFMs) are expected to provide services for grid operators. As natural aggregators, ECs can offer their flexibility in LFMs to flexibility requesting parties (FRPs), such as distribution system operators (DSOs) or transmission system operators (TSOs). Local energy markets (LEMs) and LFMs can help both TSOs and DSOs to shape aggregators and final customers behaviours with market signals encouraging the proper adjustments in their energy behaviours [1].

Since there are different flexibility products that FRPs can request through LFMs [2], ECs entering these markets ought to be able to decide the optimal markets and bidding products types according to their flexibility availability. Thus, to remain competitive, ECs should efficiently leverage their assets and members' flexibility.

In this context, this work builds upon the methodology introduced in [3], which proposes a framework for computing flexibility bidding curves for an EC. While [3] merely focuses on distributed energy resources (DERs) such as photovoltaic (PV) panels and battery energy storage systems (BESS), this paper extends and enhances that approach by combining a broader range of flexible assets. Specifically, it integrates cross-sector (CS) assets, such as thermal loads like smart electric water heaters (EWHs), and electric vehicles (EVs) with bidirectional charging. These additions intend to address the critical interaction between energy and non-energy sectors, ultimately unlocking a significant share of consumer-side flexibility. Thus, by expanding the scope of the original methodology, this work provides a more profitable framework for ECs to participate in LFMs. Its main contributions include:

- A two-stage linear optimization model (Linear programming model) to calculate flexibility bidding curves for an EC equipped with energy and CS flexible assets, including BESS, PVs, EVs, and EWHs.
- A methodology to address price uncertainty in LFMs, by calculating the optimal amount of flexibility to be offered for a range of projected prices, tackling price uncertainty challenges.
- The combination, in the same framework, of the benefits of aggregation and collective self-consumption (CSC), by leveraging on internal local energy market (LEM) trades enabled by CSC regulation to support flexibility provision.
- The assessment of CS assets impact, to highlight their potential contribution to the overall consumer-side flexibility.

The rest of this paper is organized as follows. Section II describes the two-stage optimisation problem and the process to create the bidding curves, section III presents a case study for an EC with multiple energy and CS flexible assets, and analyses the results, and section IV presents the main conclusions drawn from this work.

II. OPTIMISATION MODEL

Based on [3], the optimisation model to compute the flexibility bidding curve has two stages, as shown in Figure 1.

In Stage 1, the EC manager optimizes the operation of the EC. It considers assets' details, consumption and generation forecasts, and the members opportunity costs (their energy buying price from their retailers, and their energy selling prices to their aggregators). This stage is used to define the baseline of the EC, defined as its aggregated metered net consumption without the provision of flexibility, to be provided for the flexibility verification process. In addition, the baseline is used

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in Stage 2 to compute the amount of flexibility to be offered by comparing the new EC energy schedule of Stage 2 with the baseline.

In Stage 2, the EC manager optimizes the operation of the EC with flexibility provision. It considers a) the baselines determined in Stage 1, b) the hours when flexibility is requested and the tolerance for the hours when it is not, and c) a range of flexibility prices λ^{flex} (from $\lambda^{flex_{init}}$ to $\lambda^{flex_{final}}$). For each expected flexibility price λ^{flex}, an optimisation problem computes the optimal flexibility to offer. In the following, we define upwards flexibility (UpFlex) as a reduction in consumption and/or an increase in generation, and downwards flexibility (DwFlex) as an increase in consumption and/or a reduction in generation.

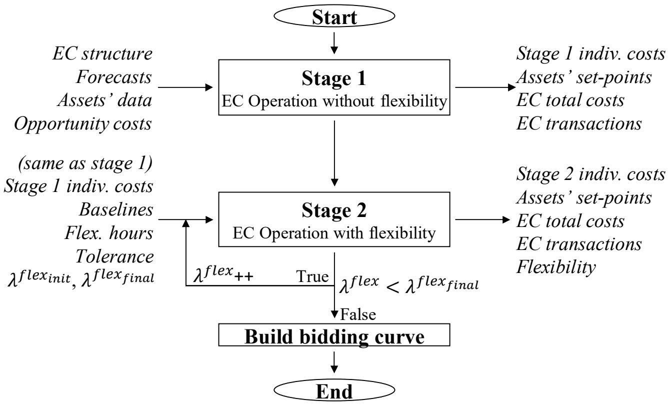

Figure 1. Steps for computing EC's bidding curve

A. *Stage 1: EC optimisation without flexibility*

In Stage 1 the objective function (1) is used to minimize the costs of operating the EC:

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

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 aggregator at feed-in price $\hat{\lambda}_{n,t}^{sell}$ and $E_{n,t}^{SLC}$ is the self-consumed energy which pays a grid access tariff $\hat{\lambda}_{t}^{grid}$. To avoid unprofitable BESS cycles, each BESS $s \in S$ has a degradation cost $\hat{\lambda}_{n,s}^{deg}$ applied to each discharge $E_{n,s,t}^{B,D}$. Finally, for each EWH $e \in E$, a comfort parameter $\hat{\lambda}_{n,e,t}^{comf}$ is applied to $cost_{n,e,t}^{use}$, a penalty incurred when water temperature falls below a user-defined comfort level.

Energy is traded internally in the EC LEM in a pool-like market, as in (2):

$$\sum_{n}\big(E_{n,t}^{PUR}\big) - \sum_{n}\big(E_{n,t}^{SALE}\big) = 0 \tag{2}$$

where $E_{n,t}^{PUR}$ and $E_{n,t}^{SALE}$ are the energy bought and sold in the LEM. The energy traded balance is given by (3):

$$E_{n,t}^{CMET_1} = E_{n,t}^{SUP} - E_{n,t}^{SUR} + E_{n,t}^{PUR} - E_{n,t}^{SALE} \tag{3}$$

where $E_{n,t}^{CMET\_1}$ is the metered net consumption of member *n* in Stage 1, where negative values mean injections to the grid.

Equation (4) is energy balance considering all member assets:

$$E_{n,t}^{CMET_1} = \hat{E}_{n,t}^{C} - \hat{E}_{n,t}^{G} + \sum_{s\in S}\big(E_{n,s,t}^{B,C} - E_{n,s,t}^{B,D}\big) + \sum_{ev\,\in\,EV}\big(E_{n,ev,t}^{EV,C} - E_{n,ev,t}^{EV,D}\big) + \sum_{e\in E}\big(E_{n,e,t}^{EWH}\big) \tag{4}$$

where the load and generation profiles $\hat{E}_{n,t}^{C}$ and $\hat{E}_{n,t}^{G}$ are input parameters, $E_{n,s,t}^{B,C}$ is the energy charged by member *n* BESS, $E_{n,ev,t}^{EV,C}$ and $E_{n,ev,t}^{EV,D}$ are, respectively, the energy charged and discharged by the EV, and $E_{n,e,t}^{EWH}$ is the energy consumed by the EWH. Equation (5) limits the members energy exchanges with the grid to their contracted power $\hat{P}_{n}^{max}$:

$$-\hat{P}_{n}^{max} \le \frac{E_{n,t}^{CMET}}{\Delta t} \le \hat{P}_{n}^{max} \tag{5}$$

The energy of each BESS is tracked with (6):

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

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):

$$SOC_{n,s,t}^{B} = \frac{E_{n,s,t}^{B}}{\hat{E}_{n,s}^{B,N}}\cdot 100 \tag{7}$$

$$\widehat{SOC}_{n,s}^{B,min} \le SOC_{n,s,t}^{B} \le \widehat{SOC}_{n,s}^{B,max} \tag{8}$$

where $SOC_{n,s,t}^{B}$ is the SOC of the BESS, $\hat{E}_{n,s}^{B,N}$ is its nominal capacity, and $\widehat{SOC}_{n,s}^{B,min}$ and $\widehat{SOC}_{n,s}^{B,max}$ the minimum and maximum SOC. BESS charging and discharging rates are limited by (9) and (10), which also ensure it is not possible to charge and discharge simultaneously (for instance if inefficiencies are neglected):

$$\frac{E_{n,s,t}^{B,C}}{\Delta t} \le \hat{P}_{n,s}^{B,max}\cdot\big(\delta_{n,s,t}^{B,C}\big) \tag{9}$$

$$\frac{E_{n,s,t}^{B,D}}{\Delta t} \le \hat{P}_{n,s}^{B,max}\cdot\big(1-\delta_{n,s,t}^{B,C}\big) \tag{10}$$

where $\hat{P}_{n,s}^{B,max}$ is the maximum input and output power of the BESS and $\delta_{n,s,t}^{B,C}$ is binary and equal to 1 when charging, and 0 otherwise. The energy of each EV is tracked with (11):

$$E_{n,ev,t}^{EV,Stored} = E_{n,ev,t-1}^{EV,Stored} + \hat{\eta}_{n,ev}^{EV,C}\cdot E_{n,ev,t}^{EV,C} - \frac{E_{n,ev,t}^{EV,D}}{\hat{\eta}_{n,ev}^{EV,D}} - \hat{E}_{n,ev,t}^{Trip} \tag{11}$$

where $E_{n,ev,t}^{EV,Stored}$ is the energy stored by the EV, $\hat{\eta}_{n,ev}^{EV,C}$ and $\hat{\eta}_{n,ev}^{EV,D}$ are its charging and discharging efficiencies, and $\hat{E}_{n,ev,t}^{Trip}$ is the energy consumed for mobility. Charging and discharging rates are limited by (12) and (13):

$$\frac{1}{\hat{\eta}_{n,ev}^{EV,D}}\cdot E_{n,ev,t}^{EV,D} \le \hat{P}_{n,ev}^{EV,D\ Limit}\cdot\hat{X}_{n,ev,t}^{EV} \tag{12}$$

$$\hat{\eta}_{n,ev}^{EV,C}\cdot E_{n,ev,t}^{EV,C} \le \hat{P}_{n,ev}^{EV,C\ Limit}\cdot\hat{X}_{n,ev,t}^{EV} \tag{13}$$

where $\hat{P}_{n,ev}^{EV,D\ Limit}$ and $\hat{P}_{n,ev}^{EV,C\ Limit}$ are the maximum discharge and charge power of the EV, and $\hat{X}_{n,ev,t}^{EV}$ is a binary parameter equal to 1 when it is plugged-in, and 0 otherwise. Equation (14) limits the minimum and maximum energy stored in the EVs:

$$\hat{E}_{n,ev}^{EV,MinCharge} \le E_{n,ev,t}^{EV,Stored} \le \hat{E}_{n,ev}^{EV,BatCap} \tag{14}$$

where $\hat{E}_{n,ev}^{EV,MinCharge}$ is the minimum energy level of the EV battery and $\hat{E}_{n,ev}^{EV,BatCap}$ its total capacity.

EWH constraints are summarized next. For a more comprehensive description, including thermodynamic considerations, readers are referred to [4]. Equation (15) represents the thermal energy dynamics in the EWH over time, accounting for energy usage, input, and losses:

$$W_{n,e,t}^{tot} = W_{n,e,t-1}^{water} + W_{n,e,t-1}^{in} + W_{n,e,t-1}^{loss} \tag{15}$$

where $W_{n,e,t}^{tot}$ is the total thermal energy stored in the EWH, $W_{n,e,t-1}^{water}$ is the remaining energy after accounting for water usage and mixing with the inlet water, $W_{n,e,t-1}^{in}$ is the energy input from the heating element, and $W^{loss}_{n,e,t-1}$ are the thermal losses due to heat dissipation. Next, (16) describes energy input by the EWH's heating element:

$$W^{in}_{n,e,t} = \widehat{EWH}^{power}_{n,e} \cdot \delta^{in}_{n,e,t} \tag{16}$$

where $\widehat{EWH}^{power}_{n,e}$ is the rated power of the EWH and $\delta^{in}_{n,e,t}$ is a binary variable equal to 1 when the EWH is on, and 0 otherwise. Next, (17) wields the electrical energy consumed by the EWH.

$$E^{EWH}_{n,e,t} = \widehat{EWH}^{power}_{n,e} \cdot \delta^{in}_{n,e,t} \tag{17}$$

Equation (18) determines the EWH's water temperature, which depends on the energy balance from (15):

$$\begin{cases} temp^{EWH}_{n,e,t} = \widehat{EWH}^{StartTemp}_{n,e}, & t = 0 \\ temp^{EWH}_{n,e,t} = \frac{W^{tot}_{n,e,t}}{\widehat{EWH}^{cap}_{n,e} \cdot \hat{c}}, & t > 0 \end{cases} \tag{18}$$

where $temp^{EWH}_{n,e,t}$ is the water temperature at the EWH's outlet, $\widehat{EWH}^{StartTemp}_{n,e}$ is its initial water temperature, $\widehat{EWH}^{cap}_{n,e}$ is its volume, $\hat{c}$ is the specific heat capacity of water. Equation (19) quantifies the thermal losses through the EWH's surface:

$$W^{loss}_{n,e,t} = \widehat{HC}_{n,e} \cdot \widehat{EWH}^{area}_{n,e} \cdot \left(temp^{EWH}_{n,e,t} - \widehat{temp}^{amb}_{n,e}\right) \tag{19}$$

where HC is the overall heat transfer coefficient of the EWH, $\widehat{EWH}^{area}$ is its surface area, and $\widehat{temp}^{amb}_{n,e}$ is the ambient temperature of the room where the EWH is placed. Next, (20) and (21) enforce upper and lower bounds on the energy and water temperature of the EWH:

$$\widehat{W}^{min}_{n,e,t} \le W^{tot}_{n,e,t} \le \widehat{W}^{max}_{n,e,t} \tag{20}$$

$$\widehat{EWH}^{min}_{n,e,t} \le temp^{EWH}_{t} \le \widehat{EWH}^{max}_{n,e,t} \tag{21}$$

where $W^{min}_{n,e,t}$ and $W^{max}_{n,e,t}$ are the minimum and maximum energy balance limits, and $\widehat{EWH}^{min}$ and $\widehat{EWH}^{\max}$ are the minimum and maximum temperature limits. Equation (22) ensures that the water temperature after use meets or exceeds the user-defined comfort level. A penalty cost is applied when the temperature falls below that level, which in turn is added to (1) as a positive term:

$$W^{tot}_{n,e,t} \ge \widehat{temp}^{set}_{n,e} \cdot \widehat{EWH}^{cap}_{n,e} \cdot \hat{c} - cost^{use}_{n,e,t} \tag{22}$$

where $\widehat{temp}^{set}_{n,e}$ is a user-defined comfort temperature for water.

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

In Stage 2 the objective function (23) minimizes the cost of operating the EC, while accounting for the income from flexibility provision:

$$min \sum_{t \in T} \Big(\sum_{n \in N} \Big[E^{SUP}_{n,t} \cdot \hat{\lambda}^{buy}_{n,t} - E^{SUR}_{n,t} \cdot \hat{\lambda}^{sell}_{n,t} - E^{FLEX}_{n,t} \cdot \hat{\lambda}^{flex}_{t} + E^{SLC}_{n,t} \cdot \hat{\lambda}^{grid}_{t} + \sum_{s \in S} \big(E^{B,D}_{n,s,t} \cdot \hat{\lambda}^{deg}_{n,s} \big) + \sum_{e \in E} \big(cost^{use}_{n,e,t} \cdot \hat{\lambda}^{comf}_{n,e,t} \big) \Big] \Big) \tag{23}$$

where $E^{FLEX}_{n,t}$ is the offered flexibility (output of this stage) for each input flexibility price $\hat{\lambda}^{flex}_{t}$. All constraints of Stage 1 hold, expect (4), which is replaced by (24):

$$E^{CMET_2}_{n,t} = \hat{E}^{C}_{n,t} - E^{G}_{n,t} + \sum_{s \in S} \big(E^{B,C}_{n,s,t} - E^{B,D}_{n,s,t} \big) + \sum_{\mathrm{ev} \in \mathrm{EV}} \big(E^{EV,C}_{n,ev,t} - E^{EV,D}_{n,ev,t} \big) + \sum_{e \in E} \big(E^{EWH}_{n,e,t} \big) \tag{24}$$

where $E^{CMET_2}_{n,t}$ is the metered net consumption in Stage 2, and $E^{G}_{n,t}$ is the behind-the meter generation given by (25):

$$E^{G}_{n,t} = \hat{E}^{G}_{n,t} - E^{CURT}_{n,t} \tag{25}$$

where $E^{CURT}_{n,t}$ is the generation curtailment. The flexibility provided by each member for the periods when it is requested ($t \in T_{wf}$) is given by (27):

$$E^{FLEX}_{n,t} = E^{CMET_2}_{n,t} - \hat{E}^{CMET_1}_{n,t} \tag{26}$$

Alternatively, in the periods when flexibility is not requested ($t \in T_{nf}$), (27) applies a tolerance that allows members to deviate from their baseline calculated in Stage 1 as $\hat{E}^{CMET_1}_{n,t}$, increasing their flexibility potential when it is needed:

$$\sum_{N} \hat{E}^{CMET_1}_{n,t} - \rho_t \le \sum_{N} E^{CMET_2}_{n,t} \le \sum_{N} \hat{E}^{CMET_1}_{n,t} + \rho_t \tag{27}$$

where ρ_t is an hourly tolerance pre-defined by the DSO.

III. CASE STUDY

A. *Case description*

An EC with four members is simulated. Their supply capacity and assets characteristics are given in TABLE I. The attributes of these assets are derived from data corresponding to commercially available EVs and devices. At last, load and PV forecasts are based on data from [5].

TABLE I. CHARACTERIZATION OF EC MEMBERS AND SPECIFICATION OF ASSETS

ID	**Contracted Power**	**PV Power**	**BESS**				**EV**				**EWH**		
			Capacity	**Max. power**	**SOC^{min}**	**SOC^{max}**	**Capacity**	**Charger power**	**SOC^{min}**	**SOC^{max}**	**Capacity**	**Power**	**Temp. setpoint**
M1	4.6 kVA	—	—	—	—	—	—	—	—	—	70 L	1200 W	50 ºC
M2	6.9 kVA	2.2 kWp	—	—	—	—	40 kWh	3.7 kW	20%[1]	80%[1]	—	—	—
M3	6.9 kVA	—	6.4 kWh	2.0 kW	5%	95%	—	—	—	—	—	—	—
M4	13.8 kVA	4.4 kWp	13.5 kWh	5.0 kW	5%	95%	75 kWh	7.4 kW	20%[1]	80%[1]	100 L	1500 W	60 ºC

[1] maintained within the specified range to decrease EV battery degradation [6]

The prices at which EC members buy [7] and sell [8] energy from the retailer (opportunity costs), local P2P transactions prices (computed based on [9] as a function of λ^{buy} and λ^{sell}), and the grid access tariffs for self-consumption [10] are provided in TABLE II.

TABLE II. EC ENERGY PRICES AND TARIFFS

λ^{buy}	λ^{sell}	λ^{P2P}	λ^{grid}
0.16 €/kWh	0.05 €/kWh	0.105 €/kWh	0.0106 €/kWh

This case study involves one base case (BC) and two scenarios, summarized in TABLE III. The main differences between the two scenarios are in the hours during which flexibility is required by the DSO and in the direction of the needs (DwFlex or UpFlex). These are divided into noon flexibility (NF) needs, where consumers are incentivized to increase consumption or reduce generation (DwFlex), and evening flexibility (EF) needs, where consumers are incentivized to reduce consumption or increase generation (UpFlex). Each scenario is further divided into multiple sub-scenarios based on the assets capable of providing flexibility. So, in addition to the BC where the EC operates without flexibility (as described in Section II, Stage 1 formulation), two sets of sub-scenarios are defined. The first set assumes that flexibility is provided solely by BESS and PV panels, while EVs and EWHs, though present, are not used for flexibility provision. The second set of sub-scenarios assumes that all assets can provide flexibility, thus presenting a complete overview of the dynamics of using energy and CS assets in an EC to provide flexibility. The goal is to analyse the impact of CS assets on EC's flexibility.

TABLE III. SCENARIOS AND SUB-SCENARIOS SUMMARY

Scenario	Period and direction	Sub-scenario ID	Flexible assets
0	No flexibility	BC	None
1	11:00h – 13:00 DwFlex	NF	BESS and PVs
		NF_CS	All assets
2	19:00h – 21:00h UpFlex	EF	BESS and PVs
		EF_CS	All assets

B. Results

This subsection presents the main results of the listed scenarios. The outcomes of each scenario are shown and analysed, with the respective sub-scenarios being evaluated and compared among themselves.

1) Scenario 1: Noon flexibility needs – DwFlex

The bidding curves for sub-scenarios NF and NF_CS are given in Figure 2.

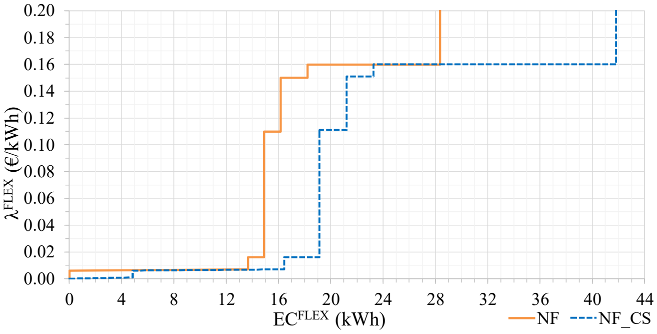

Figure 2. EC bidding curves for NF and NF_CS scenarios

These curves illustrate the correlation between the values of flexibility (EC^{FLEX}) to bid in an LFM, and the corresponding flexibility price (λ^{flex}). As λ^{flex} increases, the value of EC^{FLEX} also increases. However, this relationship is not linear, instead it follows a stepwise pattern: for a range of λ^{flex} values, the amount of EC^{FLEX} remains constant. Only when λ^{flex} reaches a critical threshold, does EC^{FLEX} move to a higher value. After that, the value of EC^{FLEX} stabilizes until another threshold of λ^{flex} is reached, repeating the process. These thresholds are associated with the EC's opportunity costs, such as λ^{buy} and λ^{sell}, and, in some cases, the thresholds can result from combinations between opportunity costs, such as the sum or difference between them. For instance, in Figure 2, when λ^{flex} reaches 0.16€/kWh (the value of λ^{buy}), EC^{FLEX} rises sharply in NF and NF_CS. This leap occurs because, at this point, offering flexibility becomes even more advantageous for the EC than the cost of providing it. Beyond this point, in both sub-scenarios, the EC bids the largest value of EC^{FLEX}, with no higher values being offered no matter how much λ^{flex} increases. An in-depth analysis of this stepwise behaviour is provided in [3], to which readers are referred for a more detailed description. Moreover, NF_CS clearly provides more flexibility than NF due to the addition of EVs and EWHs as flexibility providers.

The economic benefits of providing flexibility are assessed by comparing NF and NF_CS with BC. The daily operating costs, savings, and EC^{FLEX} for several values of λ^{flex} are given in TABLE IV.

TABLE IV. SCE. 1: DAILY COSTS, SAVINGS AND AVAILABLE FLEX.

Sub-scenario	λ^{flex}	EC^{cost}	EC^{save}	EC^{flex}
BC	-	9.73 €	-	-
NF	0.01	9.68 €	0.51 %	13.66 kWh
	0.05	9.09 €	6.58 %	14.90 kWh
	0.10	8.35 €	14.2 %	14.90 kWh
	0.15	7.56 €	22.3 %	18.23 kWh
	0.20	6.24 €	35.9 %	28.35 kWh
NF_CS	0.01	9.64 €	0.92 %	16.42 kWh
	0.05	8.89 €	8.63 %	19.13 kWh
	0.10	7.94 €	18.4 %	19.13 kWh
	0.15	6.90 €	29.1 %	21.22 kWh
	0.20	5.00 €	48.6 %	41.82 kWh

In both NF and NF_CS, costs drop and saving increase as λ^{flex} increases. This is expected as a higher λ^{flex} delivers greater incentives for an EC to provide flexibility, making it more beneficial to displace consumption to the hours where DwFlex is required. For instance, at λ^{flex} = 0.15 €/kWh, NF reduces the cost to 7.56 € (22.3% savings), while NF_CS further reduces it to 6.90 € (29.1% savings). Similarly, NF_CS provides more flexibility than NF. In addition, the value of EC^{FLEX} increases with λ^{flex} in a stepwise manner, as explained earlier, and, as a result, EC^{FLEX} stays constant for some values of λ^{flex}.

2) Scenario 2: Evening flexibility needs – UpFlex

The bidding curves for sub-scenarios EF and EF_CS, are given in Figure 3. Similarly to NF and NF_CS, these curves also follow a stepwise pattern, linked with the opportunity costs of the EC.

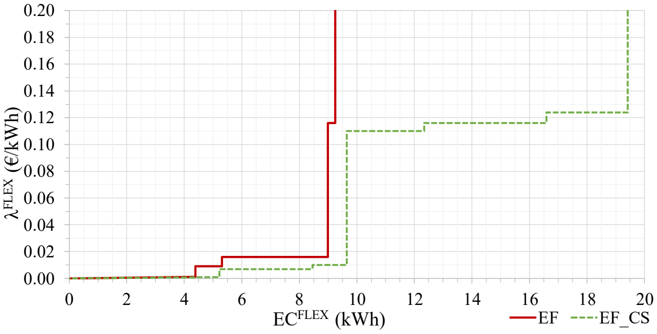

Figure 3. EC bidding curves for EF and EF_CS scenarios

Again, the costs and savings resulting from flexibility provision are compared. The daily operating costs, savings, and EC^{FLEX} for different values of λ^{flex} are given in TABLE V.

TABLE V. SCE. 2: DAILY COSTS, SAVINGS AND AVAILABLE FLEX.

Scenario	λ^{flex}	EC^{cost}	EC^{save}	EC^{flex}
BC	-	9.73 €	-	-
EF	0.01	9.68 €	0.51 %	5.31 kWh
	0.05	9.35 €	3.91 %	8.99 kWh
	0.10	8.89 €	8.63 %	8.99 kWh
	0.15	8.44 €	13.3 %	9.25 kWh
	0.20	7.98 €	17.9 %	9.25 kWh
EF_CS	0.01	9.66 €	0.72 %	8.45 kWh
	0.05	9.28 €	4.62 %	9.65 kWh
	0.10	8.79 €	9.66 %	9.65 kWh
	0.15	7.99 €	17.9 %	19.4 kWh
	0.20	7.02 €	27.9 %	19.4 kWh

In EF and EF_CS a higher λ^{flex} creates greater incentives for an EC to shift consumption away from the hours where UpFlex is needed. For λ^{flex} = 0.15 €/kWh, EF reduces the daily cost to

8.44 € (13.3% savings), while EF_CS reduces it to 7.99 € (17.9% savings).

3) *Assets performance in Scenario 1 and 2*

To complement this study, the behaviour of the EC and some of its assets is analysed. This comparison focuses on the results of BC, NF_CS and EF_CS (λ^{flex} = 0.15 €/kWh). First, Figure 4 depicts the total EC^{MET} of the EC. Compared to BC, in NF_CS the EC increases its net consumption during T_{wf} by decreasing it during the rest of the day. It also depicts how the EC increases its consumption throughout most of the day so that it can effectively reduce it during the evening in EF_CS.

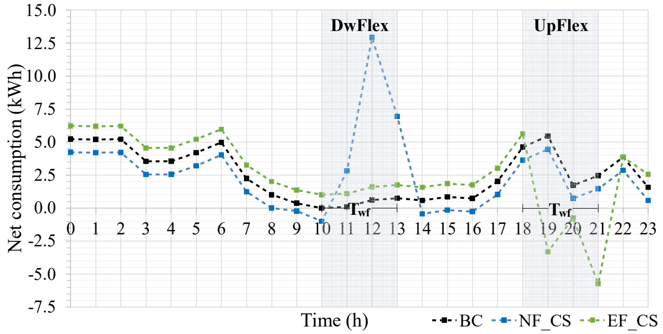

Figure 4. Sum of EC^{MET} in BC, NF_CS, and EF_CS (λ^{flex} = 0.15 €/kWh)

Next, Figure 5 provides the evolution of the SOC of M3's BESS. In NF_CS, the BESS discharges during the morning and charges intensively during T_{wf}. Meanwhile, in EF_CS the BESS charges throughout the day and discharges quickly during T_{wf}.

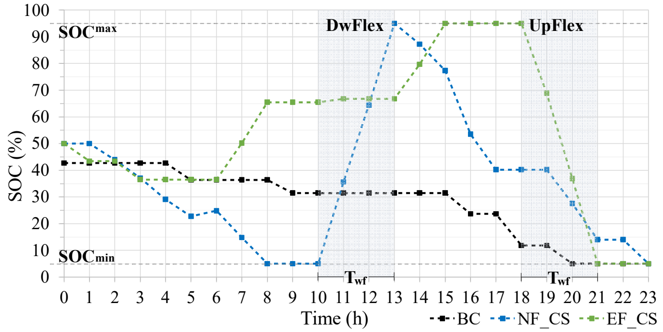

Figure 5. M3's BESS SOC in BC, NF_CS, EF_CS (with λ^{flex} = 0.15 €/kWh)

Additionally, Figure 6 shows the charging power of M4's EV. The difference between BC and NF_CS is clear, with the EV not charging so much overnight, and instead charging more intensively during T_{wf}. Meanwhile, the difference between BC and EF_CS is not very noticeable during T_{wf}, with the EV not charging during T_{wf}.

At last, Figure 7 illustrates the power input of M1's EWH. In this case, due to the times at which the EC members use hot water, the difference between BC and NF_CS is not as sharp as in the case of the BESS and EV. Still, it is visible a small increment in energy consumption during T_{wf} (at t = 13h). On the contrary, the difference between BC and EF_CS is sharper, with the EWH increasing its consumption before T_{wf}, and decreasing it during T_{wf}.

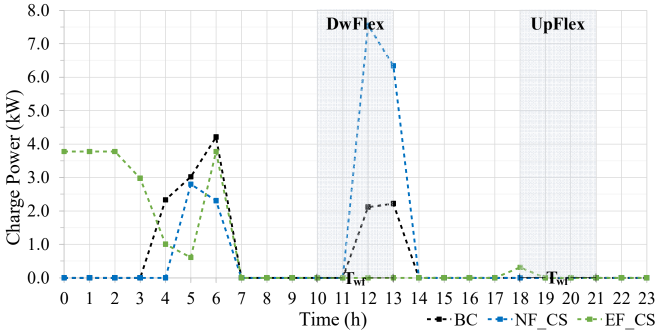

Figure 6. M4's EV charging in BC, NF_CS and EF_CS (λ^{flex} = 0.15 €/kWh)

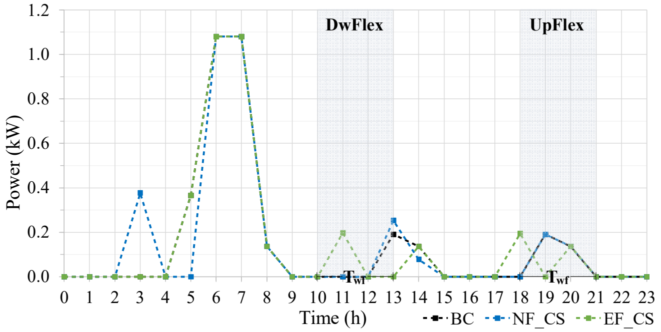

Figure 7. M1's EWH power in BC and NF_CS (λ^{flex} = 0.15 €/kWh)

IV. CONCLUSION

This paper proposes a two-stage linear optimisation model that incorporates energy and CS DERs to compute the flexibility bidding curves of an EC participating in an LFM. The resulting bidding curves show a stepwise pattern, where larger flexibility prices lead to larger amounts of flexibility being offered. This stepwise behaviour is linked with the EC's opportunity costs and reflects a strategic cost optimisation approach where flexibility is offered only when the associated revenues surpass the costs of its provision. For the EC, this ensures costs minimisation while maximizing the economic benefits of participating in an LFM.

These results further highlight the economic and operational benefits of introducing CS assets as flexibility providers within the EC, unlocking untaped potential. Moreover, these findings emphasise the broader advantages of electrifying traditionally fossil-fuel-dependent sectors, such as mobility and heating. Thus, electrification can not only reduce the dependence on fossil fuels, but also improve grid flexibility, contributing to a more efficient and sustainable energy system.

Future developments to this model could include the integration of additional flexible assets, such as heat pumps or hydrogen-based technologies, further expanding the benefits of CS flexibility.

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