

# Provision of the Energy Community Flexibility Services while Ensuring Optimal Social Welfare

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**Abstract**—As global awareness of environmental preservation grows, more previously passive consumers are integrating renewable energy sources (RES), thus becoming prosumers. To overcome the problems faced by prosumers, consumers, and prosumers can be grouped into energy communities (ECs). This paper proposes an enhanced two-stage stochastic optimization model based on mixed integer nonlinear programming (MINLP) to address the challenges of achieving optimal electricity management of the EC that provides flexibility services while ensuring the maximization of the community's social welfare. Also, the proposed model supports peer-to-peer (P2P) electricity trading, vehicle-to-grid (V2G) service, and flexibility services to third parties, e.g. balance responsible party (BRP), distribution system operator (DSO) or aggregator (AGG). An analysis of the obtained results shows the benefits that a high level of flexibility in the operation of the EC can be ensured with a small number of EVs within the EC.

**Index Terms**—electric vehicles, electricity markets, energy communities, flexibility services, prosumers

## I. INTRODUCTION

Climate change, the gradual depletion of conventional energy sources, and the increasing electricity demand have led to greater integration of RES into the power system. The European Union has also recognized the importance of RES electricity generation, and short- and long-term objectives have been set to limit  $CO_2$  emissions in the future [1], [2]. New concepts such as ECs and collective self-consumption (CSC) have shown great potential to support the clean energy transition and ensure overall social welfare [3], [4].

The primary flexibility platforms utilized across Europe, while providing information on the pros and cons of each platform, were described in [5]. The authors in [6] identified the advantages and disadvantages of various balance responsibility models.

In [7], the economic impacts of three pricing mechanisms - the supply-demand ratio mechanism, the consensus alternating direction of multipliers method, and the equilibrium approach, on different customer types in the local electricity market (LEM) are presented. Furthermore, the authors in [8] introduced three Renewable Energy Communities (REC) models - P2P energy trading, shared RES installation, and demand-side response, to point out the pros and cons of each.

In [9], the authors developed a stochastic two-stage mixed integer nonlinear programming (MINLP) optimization model

of the EC to ensure the efficient operation of the grid while simultaneously increasing overall social welfare, excluding the provision of flexibility services. A mathematical model based on mixed-integer linear programming (MILP) to estimate the energy and flexibility bidding strategy for a distribution system operator (DSO) within the wholesale market was developed in [10]. Furthermore, in [4], a two-stage linear optimization model was developed to estimate the flexibility bidding curve for an aggregator (AGG) in a local flexibility market (LFM) to manage unpredictability in market pricing while considering CSC regulation rules.

In [3], two allocation coefficient (AC) methods (fixed AC before delivery and dynamic AC after delivery) were compared to estimate how fixed and dynamic ACs affect the behavior of members and the operation of battery energy storage systems (BESS). Furthermore, the authors conducted a survey among electric vehicle (EV) owners in Croatia and carried out the results regarding the use of EVs as assets in [11]. The results showed a conservative attitude of users towards changing habits, as it may reduce their comfort level. Furthermore, the authors in [12] introduced the bidding model for EVs that operate in the LEM. In [13], a Battery-as-a-Service (BaaS) model was presented to address its advantages and effects on members within EC.

The authors in [14] developed a deterministic three-stage optimization model to independently address congestion caused by the high integration of distributed energy resources (DERs) within an EC using a local P2P and flexibility market framework.

In [15], an optimal planning model of community integrated energy station (CIES) considering frequency regulation (FR) service was proposed. The authors presented the flexible electricity pricing model to lessen the power fluctuation problem of tie-line. Furthermore, the optimal operation of a local energy community (LEC) participating in the provision of manual frequency restoration reserves (mFRR) services, including two stages - the day-ahead and real-time stage, was analyzed in [16]. A two-step Fast-PJ-ADMM algorithm that improves computational efficiency and stability, enabling AGGs and large-scale ECs to provide flexibility services, was proposed in [17].

The authors in [18] carried out a study on ECs in agricultural

environments. The authors in [19] categorized and analyzed eight business models (BMs) in agricultural environments, including flexibility management. Seven BMs to estimate the optimal sizing and operation of the assets in REC were developed in [20].

In order to fill the research gap, this paper proposes an enhanced two-stage stochastic optimization model to provide flexibility services, which can be used by third parties, such as balance responsible party (BRP), DSO, or AGG. The objective function of the proposed optimization model is to maximize social welfare while ensuring flexibility in service. Social welfare represents the overall economic benefit achieved by all involved parties (EC, AGG, BRP, DSO). Furthermore, for the BRP and AGG, it is defined as the net profit, the difference between the revenues obtained from energy trading and the associated operational costs. For the EC, it is expressed as the cost savings by accessing electricity at a price lower than their maximum willingness to pay. DSOs can potentially procure services at a reduced cost. In addition to the objective function, the proposed optimization model includes constraints on power balance, indoor temperature balance, hot water temperature balance, state of energy (SOE) of the battery of the EV, and technical constraints.

The rest of the paper is organized as follows. In section II, the proposed optimization model of EC is presented. In section III, case studies are described. Section IV analyses the results, and section V provides a conclusion.

## II. OPTIMIZATION MODEL

In general, any optimization model consists of an objective function and constraints.

The two-stage stochastic approach implies that the decision is made in the first stage without knowing the value of the realization of the random variable. On the other hand, in the second stage, the decision is made with knowledge of the value of the realization of the random variable. The value of the objective function is the mean value of the solutions of the first and second stages, according to [21]. The proposed optimization model is developed as a stochastic two-stage MINLP [9].

### A. Objective function

The objective function is defined according to expression (1):

$$\min(C_{el} + C_{CBDev}) \quad (1)$$

where:  $C_{el}$  are incurred electricity costs of EC and  $C_{CBDev}$  is the virtual cyclic and calendar degradation cost of the battery of the EV.

The first member of the objective function is defined according to (2):

$$C_{el} = \sum_{p=1}^{N_p} \sum_{t=1}^{N_t} (P_{grid(p,t)}^{imp} \cdot C_{grid(p,t)}^{imp} - P_{grid(p,t)}^{exp} \cdot C_{grid(p,t)}^{exp} + P_{lem(p,t)}^{imp} \cdot C_{lem(p,t)}^{imp} - P_{lem(p,t)}^{exp} \cdot C_{lem(p,t)}^{exp}) \quad (2)$$

where:  $P_{grid(p,t)}^{imp}$  and  $P_{grid(p,t)}^{exp}$  are the amounts of power when exchanging electricity with the grid;  $C_{grid(p,t)}^{imp}$  and  $C_{grid(p,t)}^{exp}$  are their corresponding prices;  $P_{lem(p,t)}^{imp}$  and  $P_{lem(p,t)}^{exp}$  are the amounts of power when exchanging electricity with the LEM;  $C_{lem(p,t)}^{imp}$  and  $C_{lem(p,t)}^{exp}$  are the corresponding prices.

### B. Constraints

The balance of power is defined according to expression (3):

$$P_{cons(p,t)} - P_{gen(p,t)} + P_{ev(p,t)} + P_{hvac(p,t)} + P_{wh(p,t)} = P_{grid(p,t)}^{imp} - P_{grid(p,t)}^{exp} + P_{lem(p,t)}^{imp} - P_{lem(p,t)}^{exp} \quad (3)$$

where:  $P_{cons(p,t)}$  is the power of consumption;  $P_{gen(p,t)}$  is the power of PV generation;  $P_{ev(p,t)}$  is the total power of the charging station of EV;  $P_{hvac(p,t)}$  and  $P_{wh(p,t)}$  are the total power of appliances that are controllable (HVAC - heating, ventilation, and air conditioning system; WH - water heater).

Electricity generation from PV is calculated based on solar irradiance, taking into account the functional dependence of the converter efficiency on the power, and a detailed model can be found in [9].

Constraints related to electricity exchange with the grid are expressed according to expressions (4) and (5):

$$P_{grid(p,t)}^{imp} \leq P_{grid(p,max)}^{imp} \cdot P_{bin(p,t)}^{imp} \quad (4)$$

$$P_{grid(p,t)}^{exp} \leq P_{grid(p,max)}^{exp} \cdot P_{bin(p,t)}^{exp} \quad (5)$$

where:  $P_{grid(p,max)}^{exp}$  and  $P_{grid(p,max)}^{imp}$  are the maximum amounts of contracted power that can be exported to/imported from the grid;  $P_{bin(p,t)}^{exp}$  and  $P_{bin(p,t)}^{imp}$  are binary decision variables for energy exchange.

Furthermore, constraints related to electricity exchange with LEM are expressed according to expressions (6) and (7):

$$P_{lem(p,t)}^{imp} \leq P_{lem(p,max)}^{imp} \cdot P_{bin(p,t)}^{imp} \quad (6)$$

$$P_{lem(p,t)}^{exp} \leq P_{lem(p,max)}^{exp} \cdot P_{bin(p,t)}^{exp} \quad (7)$$

where:  $P_{lem(p,max)}^{exp}$  and  $P_{lem(p,max)}^{imp}$  are the maximum amounts of power that can be exported to/imported from LEM.

The proposed model was developed so that at a certain point in time, it can either buy or sell electricity, i.e. it can either import electricity from the grid and/or LEM or export electricity to the grid and/or LEM, which is defined according to expression (8):

$$P_{bin(p,t)}^{exp} + P_{bin(p,t)}^{imp} \leq 1 \quad (8)$$

When modeling the battery of an EV, the SOE of the EV battery is considered according to expressions (9) for the first period and (10) for each following period:

$$SOE_{p,ev,t} = SOE_{p,ev}^{start} + P_{p,ev,t}^{ch} - P_{p,ev,t}^{dch} \quad (9)$$

$$SOE_{p,ev,t} = SOE_{p,ev,t-1} + P_{p,ev,t}^{ch} - P_{p,ev,t}^{dch} \quad (10)$$

where:  $SOE_{p,ev,t}$  is SOE of the EV battery,  $SOE_{p,ev}^{start}$  is the initial value of SOE of the EV battery,  $P_{p,ev,t}^{ch}$  and  $P_{p,ev,t}^{dch}$  are the amounts of power used to charge or discharge EV battery, respectively.

According to expressions (11) and (12), when modeling the charging and discharging battery of an EV, the functional dependence of the converter and battery efficiency on power is taken into account:

$$P_{p,ev,t}^{ch,batt} = P_{p,ev,t}^{ch,AC} \cdot \eta_{ev}^{ch,inv}(P_{p,ev,t}^{ch,AC}) \cdot \eta_{ev}^{ch,batt}(P_{p,ev,t}^{ch,AC}) \quad (11)$$

$$P_{p,ev,t}^{dch,AC} = P_{p,ev,t}^{dch,batt} \cdot \eta_{ev}^{dch,inv}(P_{p,ev,t}^{dch,AC}) \cdot \eta_{ev}^{dch,batt}(P_{p,ev,t}^{dch,AC}) \quad (12)$$

where:  $P_{p,ev,t}^{ch,batt}$  and  $P_{p,ev,t}^{dch,AC}$  are the amounts of power used to charge or discharge the EV battery;  $\eta_{ev}^{ch,inv}(P_{p,ev,t}^{ch,AC})$  and  $\eta_{ev}^{dch,inv}(P_{p,ev,t}^{dch,AC})$  are functional dependencies of the converter efficiency on power;  $\eta_{ev}^{ch,batt}(P_{p,ev,t}^{ch,AC})$  and  $\eta_{ev}^{dch,batt}(P_{p,ev,t}^{dch,AC})$  are functional dependencies of the battery efficiency on power.

The energy charging battery model is applied to the battery of the EV and is taken from [22]. According to the energy charging battery model, the charging power depends on the charging station power and the battery SOE, while the discharging power is a continuous variable limited by the charging station power.

The model of cyclic and calendar aging of the battery, which applied to the battery of the EV, and the models of dynamically and statically controllable consumers, i.e. HVAC and WH, were taken from [9].

In the presented Figures, it is assumed that electric power is constant within the observed hour.

### III. CASE STUDIES

The proposed model is applied to the EC, which consists of three business buildings (prosumers P1, P2, and P3), each with EVs, 10 HVACs and 3 WHs. The prosumers marked P1 and P2 have installed a photovoltaic (PV) power plant. The installed PV power for P1 is 90 kW, and P2 is 45 kW. While the third business building has no integrated PV power plant, it supports V2G service, and thus, it is marked as a prosumer. It is assumed that the highest electricity demands (peak loads) are in the morning and evening, between 8 a.m. and 10 a.m., and 5 p.m. and 7 p.m., and the condition is that during those hours  $P_{grid(p,t)}^{imp}$  is zero.

Fig. 1 shows profiles of electricity consumption of business buildings measurement (P1De, P2De, P3De, respectively), as well as direct (Gbeam) and diffuse (Gdifusse) irradiance on a flat surface. The electricity consumption profiles were measured with the smart meter while the solar irradiance profiles were taken from PVGIS [23].

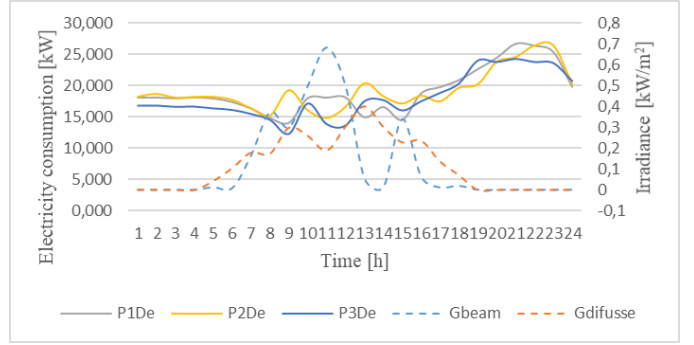


Figure 1. Profiles of electricity consumption of business buildings, and direct and diffuse irradiance on a flat surface

According to the two-tariff model currently present in Croatia, the high tariff (ht) is active from 8 a.m. to 10 p.m., and the low tariff (lt) is active from 10 p.m. to 8 a.m., during daylight saving time [24]. During winter time calculation, the time goes back one hour. Therefore, the prices for electricity purchased from the grid are 0.203 € in the ht and 0.124 € in the lt, including fees and taxes. The price of electricity sold to the grid is 0.035 €, according to the current market model in Croatia [25]. Furthermore, the cost of electricity purchased from LEM is 0.125 €, including the electricity and grid fee. In comparison, the electricity sold to the LEM is 0.110 €, including just the electricity price. The  $CO_2$  emission for imported electricity from the grid is 0.205 kg/kWh according to [26].

Furthermore, the rated power of the EV charging station is 11 kW, and the battery's SOE must be maintained between 20 % and 80 %. It is assumed that battery's SOE is the same value at the beginning and the end of the period. Also, the indoor temperature is maintained between 18 °C and 24 °C, and the hot water temperature is maintained between 60 °C and 80 °C to user requests according to [11].

A combination of scenarios is selected to demonstrate the benefits of providing flexibility services. The number of EVs is set accordingly to meet the specific requirements of each case and compared with base cases. The case studies are:

- S1 - base case study - without integration of EVs and without flexibility services;
- S2 - a case study with the integration of seven EVs, without flexibility services;
- S3 - a case study with the integration of seven EVs, without flexibility services, taking into consideration battery degradation;
- S4 - a case study with the integration of two EVs, with one flexibility service (one peak load reduction);
- S5 - a case study with the integration of seven EVs, with two flexibility services (two peak load reductions);
- S6 - a case study with the integration of seven EVs, with two flexibility services, considering battery degradation;
- S7 - a case study with the integration of seven EVs, with two flexibility services and evening export request;
- S8 - a case study with the integration of seven EVs, with two flexibility services and noon export request.

The time step is 1 hour with a scheduling horizon of 24 hours. Functional dependencies are integrated using Special Ordered Sets of type 2 (SOS2) variables while the realization of the random variable, i.e., solar radiation, ranges from 90 % to 105 % of the forecasted values. SOS2 variables are defined as a set of variables, such that at most two variables within the set may have nonzero values and these variables have to be adjacent [27].

#### IV. RESULTS

In this section, results are presented. The average electricity costs for EC and the average amounts of  $CO_2$  by case studies are given in Tables I and II. The benefits of the provided flexibility services are not included in the costs.

In S1, the electricity cost is 179 €. With the integration of seven EVs within the EC, the cost decreases to 149 € in S2. On the other hand, in S3, when battery degradation is considered, the cost increases to 162 € because the system puts less strain on EV batteries. In S4, with one peak load reduction and integration of two EVs within the EC, the cost amounts to 167 €.

TABLE I  
THE RESULTS OF CASE STUDIES S1-S4

Case study	S1	S2	S3	S4
Electricity cost [€]	179	149	162	167
$CO_2$ [kg]	76	70	70	73

In S5, with two peak load reductions, the cost is 155 €, and it increases if battery degradation is considered in S6 to 177 €. Furthermore, in S7, the electricity cost is 151 €, and in S8, it is 176 € with evening and noon export requests. Also, in S2, the lowest of  $CO_2$  (70 kg) is achieved, while in S8, the highest one (82 kg).

TABLE II  
THE RESULTS OF CASE STUDIES S5-S8

Case study	S5	S6	S7	S8
Electricity cost [€]	155	158	151	176
$CO_2$ [kg]	72	71	71	82

It can be concluded that electricity costs have decreased for cases with integrated EVs as well as the amount of  $CO_2$ . On the other hand, due to the battery prices, electricity costs have increased in cases where battery degradation is considered.

The hourly power values when electricity is imported and exported to the grid in case studies are shown in Figs. 2-6. Furthermore, a two-stage stochastic approach sought to ensure that the power in the grid was equal regardless of the realization of the random variable, which was achieved by rescheduling the operation of other controllable loads. Due to

space limitations in the paper, only the more important results of the conducted case studies will be presented in detail.

Fig. 2 shows the power exchange with the grid for S1 without EVs and a request for flexibility service. The results of S4 with one flexibility request (one peak load reduction) are shown in Fig. 3. Based on the results, it can be concluded that the system met the requirement with only two EVs connected to the charging stations. Fig. 4 shows the power exchange with the grid for S5 with two flexibility services (two peak load reductions). In this case, it can also be concluded that the system met the requirement with only seven EVs connected to charging stations.

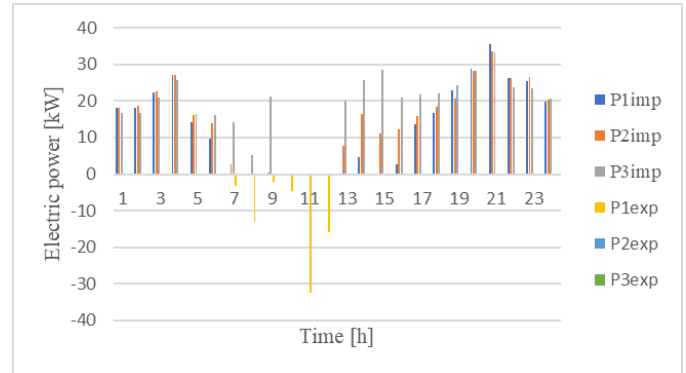


Figure 2. The hourly power values for case study S1

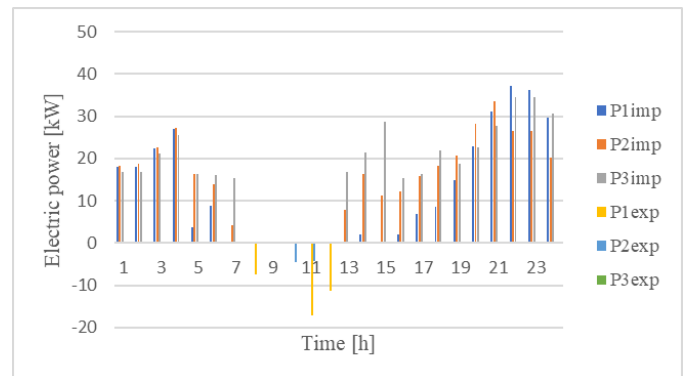


Figure 3. The hourly power values for case study S4

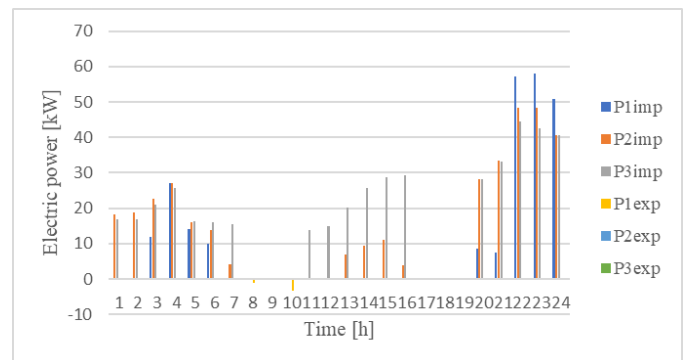


Figure 4. The hourly power values for case study S5

Fig. 5 and Fig. 6 show the results for case studies S7 and S8. In these case studies, an effort was made to examine the possibility, in addition to limiting the import power (two peak load reductions), to set the power requirements when exporting electricity to the grid.

Fig. 7 shows maintenance indoor temperature and engaged power HVAC for S8. User comfort is defined by minimum and maximum temperature thresholds set by the users as constraints.

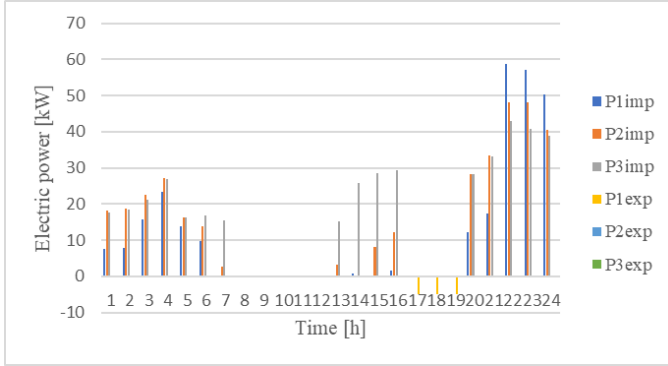


Figure 5. The hourly power values for case study S7

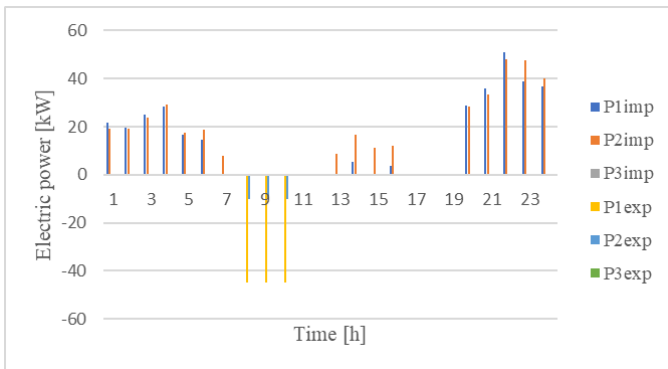


Figure 6. The hourly power values for case study S8

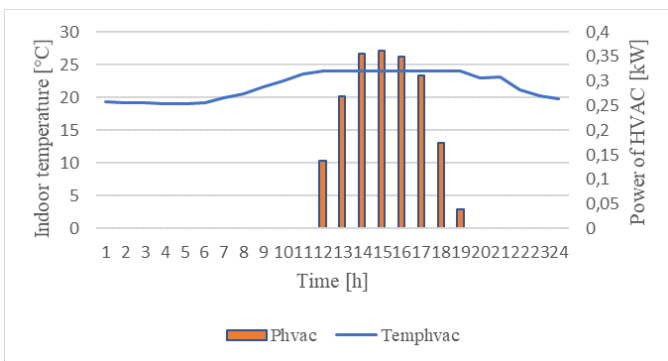


Figure 7. Indoor temperature and engaged power of HVAC

Based on the results shown in Fig. 5 and Fig. 6, it can be concluded that the system is able to provide electricity to

the grid at certain hours, as needed. Also, this is possible by rescheduling the operation of other controllable loads within the EC. Furthermore, HVAC systems are in the category of dynamically controllable loads and are more adaptable to changes in input data. On the other hand, WH systems are in the category of statically controllable loads and are less adaptable to changes in input data.

## V. CONCLUSION

This paper presents an enhanced two-stage stochastic optimization model to maximize social welfare while providing flexibility services.

The proposed EC model is applied to EC, which consists of three business buildings. Each of the buildings integrates EVs, WH, and HVAC, while two of the buildings have installed PV power plants. Case studies are conducted with and without incorporating flexibility services, EVs, and battery degradation of EVs. Results of conducted case studies show that integrating EVs can decrease EC's electricity costs as well as the amount of  $CO_2$ , but battery degradation increases it. Comparing case studies S2 and S5, it can be concluded that ensuring flexibility services increases the electricity costs of EC by 4.03 %, but that cost will be compensated by the income from the provision of flexibility services. On the other hand, while analyzing S2 and S7, as well as S8, the results show that, in addition to limiting the import power from the grid, the possibility of evening export request (S7) increases electricity costs by 1.34 %, while the noon export request (S8) increases electricity costs by 18.12 %. Finally, an important conclusion emerges from the paper that a high level of flexibility in the operation of the EC can be ensured with a small number of EVs within the EC, which provides economic benefits to EC, AGG, and BRP. Also, DSOs can acquire services at a lower cost than current procurement mechanisms.

Future research may explore mechanisms for pricing flexibility services as well as the possibility of extending the optimization model or objective function to directly determine third parties' benefits as well as overall social welfare.

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