Transactive Community Microgrids to Share Energy Storage Resources in Portugal

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Abstract—The contribution of renewable energy sources to Portugal’s energy generation portfolio is significant and on the path to achieving 100% renewable generation by 2050. Most of the new renewable generation capacity will be procured from distributed photovoltaic (PV) generation installed at buildings. The inherent intermittence of PV output combined with a mismatch with demand profile are challenging the operation and resiliency of the electrical grid. Addressing these issues requires leveraging spatio-temporal flexibility of controllable energy resources such as batteries and Electric Vehicles (EV). This need is recognized by regulators in Portugal and the recent renewable generation self-consumption legislation enables generation-surplus trading in communities. Implementing intracomunity trading and utilizing the potentials of renewable generation requires oversight and coordination at the community level in the context of transactive energy systems. This paper focuses on addressing energy sharing through a transactive energy market in community microgrids. The proposed framework considers public and commercial buildings with on-site battery storage and numerous EV charging stations as the main source of flexibility. The formulation is tested using real data from a community of buildings on a Portuguese University campus. The results showcase the achieved increase in renewable self-consumption at building and community levels, as well as the reduction in electricity costs.

Index Terms—Community Microgrid, Transactive Energy Market, Distributed Energy, Battery Storage, Electric Vehicles.

NOMENCLATURE

Inputs

| Symbol | Description |
|--------|-------------|
| $\Delta h$ | Time step (hour) |
| $C_P$ | Baseline parking tariff for EVs (€/h) |
| $C_C(h)$ | Tariff for the charging/discharging of EVs at time step $h$ (€/kWh) |
| $C_D(h)$ | Reward for EV charging flexibility (€/h) |
| $C_EG(h)$, $C_F$ | Tariff for power exported/imported to/from grid at time step $h$ (€/kWh) |
| $C_{TG}(h)$ | the grid at time step $h$ (€/kWh) |
| $C_G(h)$ | Tariff for grid use between buildings (€/kWh) |
| $T^{B+}_{R,n}$ | Charging/discharging period requested by EV owner $n$ in building $b$ (hour) |
| $t^{B+}_{P,n}$ | Total parking period of EV $n$ in building $b$ (h) |
| $L^{B+}(h)$ | Positive/negative net electricity load in building $b$ at time step $h$ (kW) |

Variables

| Symbol | Description |
|--------|-------------|
| $\eta^{EV}_{n}$ | Efficiency of the charging/discharging of EVs/batteries in building $b$ (%) |
| $S^{BS}_{c}$ | Minimum/maximum state of charge of the batteries in building $b$ (%) |
| $E^{BS}_{n}$ | Total capacity of batteries in building $b$ (kWh) |

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I. INTRODUCTION

A. Motivation

The decarbonization and expansion of distributed energy resources are clear drivers of change in the electric power system, which is increasingly based on distributed, intermittent, and non-dispatchable renewable sources. Portugal already has 55% of the electricity generation ensured by renewables and aims at achieving 100% renewable electricity generation by 2050 [1]. This will impact the future of an integrated grid at all scales, but mainly in buildings and communities, since 25% of the capacity will be ensured by decentralized photovoltaic (PV) generation. However, in most buildings, there is a high mismatch between the local PV generation
and demand profiles, leading to the need to export to the grid a significant part of the locally generated energy, even though the same amount is later imported back for local consumption [2]. This creates challenges for the electrical grid management and leads to economic losses to the end-user [3].

In this context, it will be fundamental to have a resilient transactive grid, being crucial the integration and management of new technologies to provide flexibility. At building and community levels, distributed energy storage with Battery Storage (BS) systems has emerged as an attractive solution for this new paradigm due to its decreasing costs and increasing efficiency and reliability. Simultaneously, the transport sector with Electric Vehicles (EV) is increasingly an important consumer of electricity and Portugal aims at achieving 70% electrification of transports by 2050 [1]. Therefore, EVs parked in buildings can also be used as flexible resources in transactive energy systems, adjusting the charging period with the Building-to-Vehicle (B2V) system, or used as energy storage resources by injecting into the building part of the stored energy with the Vehicle-to-Building (V2B) system [3].

Additionally, the recent legislation for the self-consumption of renewable generation in Portugal enables the establishment of communities, in order to trade the renewable generation surplus. Therefore, an aggregated optimization at the community level will be needed to coordinate the matching between renewable generation and demand in a transactive energy context.

B. Related Works

There is a vast body of works proposing methodologies to implement the participation of buildings in transactive energy markets, and the management of flexibility resources.

The implementation of transactive mechanisms for the management of EVs and energy storage is mainly considered in residential buildings. In [5] a transactive energy control for residential prosumers with BS and EVs is proposed. In [6] the case of EVs participating in a retail double auction electricity regulation market is considered, and in [7] a two-stage optimal charging scheme based on transactive control is proposed. However, in residential buildings, the flexibility resources belong to the building and there are no economic transactions between entities in order to use such resources.

Some works have also considered commercial buildings in transactive energy markets. In [8] the characteristics of commercial buildings and end uses are explored to determine factors supporting the feasibility of participation in transactive energy systems. In [9] a transactive control market structure for commercial building HVAC systems is presented and in [10] a passive transactive control strategy was applied to estimate the peak demand reduction potential and energy savings of a building. However, such works only consider demand flexibility, without the use of energy storage resources. The economic relationship between EV users and buildings is explored by some researchers. Reference [11] considers an office building with PV and EVs with the objective of minimizing energy costs and [12] presents a building with renewable generation and storage and EVs charging directly with the generated energy with the objectives of minimizing costs and greenhouse gas emissions. In [13] several commercial buildings and EV charging stations are considered with the objective of minimizing the costs of energy in the building and the charging costs. However, such works assume that buildings and EVs can trade electricity which does not comply with existing legislation in most countries. In [14], a first approach based on the parking costs to regulate the economic relationship between building and EV user is proposed, but without considering aggregation at the community level. In [15] a transactive real-time EV charging management scheme is proposed for the building energy management system of commercial buildings with PV on-site generation and EV charging services. However, such an approach requires complex information from the EV users that is not easily obtained in real scenarios and does not consider the optimization at the community level. In [16], a community is considered, using EVs as flexibility resources, but without considering energy storage and without implementing transactive energy market mechanisms in the aggregation.

C. Contribution

The main contribution of his work is the design of a transactive energy market for community microgrids constituted by large public and commercial buildings, using BS and EVs as flexibility resources. Therefore, a formulation is proposed to establish a transactive energy market for community microgrids, using price signals for the energy injected or consumed from the community, in order to give incentives for the aggregated matching between demand and PV generation while ensuring the minimization of electricity costs. Such management is not only ensured with transactions between buildings, but also with flexibility resources in buildings, such as BS and V2B/B2V systems. Therefore, the formulation implements the management of such flexibility resources at the building level. Since the formulation considers the case of large public and commercial buildings with parking lots, where EVs and buildings do not belong to the same entity, a transactive market between buildings and EV users is also established. The economic relationship between EV users and buildings is based on the parking time and added value services for the charging in order to minimize the monitoring requirements and comply with Portuguese legislation that does not allow electricity trading between buildings and EVs.

D. Paper Organization

The remainder of the paper is structured as follows. Section II presents the problem formulation. Section III presents the data and scenarios and Section IV presents the simulation results. Finally, Section V presents the main conclusions.

II. PROBLEM FORMULATION

A. Objective Function

The proposed problem aims at minimizing the total costs from the community perspective, considering $B$ buildings with
PV generation, BS and EVs, during all time steps (i.e., \( H \)). The objective function (\( 11 \)) accounts for the electricity costs in each building, as well as the profit associated with the parking, charging and discharging of \( N \) EVs at each building \( b \).

\[
\min_{b=1} B \left( \sum_{h=1}^{H} C_E^b(h) - \sum_{n=1}^{N} C_{EV}^n(n) \right) \tag{1}
\]

The net cost of the electricity consumption and self-generation (\( 2 \)) in each building \( b \) considers the cost/financial compensation of energy drawn/injected from the community or from the grid.

\[
C_E^b(h) = \Delta h \cdot \left( P_{EH}^b(h) \cdot C_{IC} + P_{EH}^b(h) \cdot C_{EC} + \right)
\]

\[
\left( L_1(h) - P_1^b(h) - P_{BS}^b(h) - \sum_{n=1}^{N} P_{EV,n}^b(h) \right) C_{IC}(h) + \]

\[
\left( L_1(h) - P_2^b(h) - P_{BS}^b(h) - \sum_{n=1}^{N} P_{EV,n}^b(h) \right) C_{EC}(h) \tag{2}
\]

The total parking costs (\( 3 \)), for each EV \( n \) in building \( b \), depend on the parking period, used periods for charging and discharging in each time step, and the total charging and discharging periods over all time steps, as presented in detail in (14). Equations (\( 4 \)) and (\( 5 \)) derive the net used charging and discharging periods in each time step and calculate the total periods over all steps \( H \).

\[
C_{EV}^n(n) = t_{U,n}^+ \cdot C_P + (t_{T,n}^- - t_{U,n}^-) \cdot C_F + \]

\[
+ \sum_{h=1}^{H} \left( t_{U,n}^+(h) \cdot C_C(h) + \sum_{h=1}^{H} \left( t_{U,n}^-(h) \cdot C_D(h) \right) \right) \tag{3}
\]

\[
t_{U,n}^+(h) = \frac{P_{EV,n}^+(h)}{P_{EV,n}^<} \cdot \Delta h, \quad t_{T,n}^+ = \sum_{h=1}^{H} t_{U,n}^+(h) \tag{4}
\]

\[
t_{U,n}^-(h) = \frac{P_{EV,n}^-(h)}{P_{EV,n}^<} \cdot \Delta h, \quad t_{T,n}^- = \sum_{h=1}^{H} t_{U,n}^-(h) \tag{5}
\]

**B. Constraints**

The defined objective is subject to constraints related with the flexibility and limits associated with the use of BS and charging of EVs, as well as with the management of the community.

1) Battery Storage: The charging and discharging power is limited by the maximum (\( 6 \)) and minimum (\( 7 \)) State of Charge (SoC) of batteries (\( 3 \)).

\[
P_{BS}^{b+}(h) \cdot \Delta h \cdot \eta_{BS,n}^b \leq (-S_{BS}^b(h-1) + S_{BS}^b) E_{BS}^b \tag{6}
\]

\[
P_{BS}^{b-}(h) \cdot \Delta h \leq (S_{BS}^b(h-1) - S_{BS}^b) E_{BS}^b \tag{7}
\]

\[
S_{BS}^b(h) = S_{BS}^b(h-1) + (\eta_{BS} \cdot P_{BS}^{b+}(h) - P_{BS}^{b-}(h)) \Delta h \tag{8}
\]

2) Electric Vehicles: The charging period achieved until the end of the parking period (\( 9 \)) should be enough to ensure the satisfaction of the charging period requested by the user and to compensate for the used discharging period, including the losses. The requested charging and discharging periods were defined based on the maximum power, therefore such periods must be corrected by the ratio between the average and the maximum power. The total discharging period must be lower than the maximum period allowed by the user and the used discharging period, until the actual time step \( x \), must be lower than the used charging period (\( 10 \)), in order to ensure that a SoC lower than the initial value is never achieved.

\[
t_{T,n}^+ = \frac{t_{T,n}^+}{P_{EV,n}} P_{EV,n}^< + \frac{t_{T,n}^-}{P_{EV,n}} P_{EV,n}^> \tag{9}
\]

\[
t_{T,n}^- \leq \sum_{h=1}^{H} t_{U,n}^-(h) < \sum_{h=1}^{H} t_{U,n}^+(h) \tag{10}
\]

3) Community: The import (\( 11 \)) or export (\( 12 \)) power flow between each building and the community is limited to the net load of such building added by the impact of the flexibility resources. It is also only possible to export to the community if other building needs to import such energy (\( 13 \)).

\[
P_{EH}^b(h) \leq L_{EH}^+(h) - P_{BS}^b(h) - \sum_{n=1}^{N} P_{EV,n}^b(h) + \sum_{n=1}^{N} P_{EV,n}^b(h) \tag{11}
\]

\[
P_{EH}^b(h) \leq L_{EH}^-(h) - P_{BS}^b(h) - \sum_{n=1}^{N} P_{EV,n}^b(h) \tag{12}
\]

\[
\sum_{b=1}^{B} \left( P_{EH}^b(h) - P_{EH}^b(h) \right) = 0 \tag{13}
\]

In order to provide incentives to share the renewable generation surplus in the community, the tariff for exporting energy to the community must be lower than the tariffs of exporting and importing to the grid discounted by the grid use (\( 14 \)). The tariff of importing energy from the community should be between the tariff of exporting to the community added by the grid use and the tariff of importing from the grid (\( 15 \)).

\[
C_{EC}(h) \leq C_{EC}(h) + C_{IC}(h) \leq C_{IC}(h) - C_G(h) \tag{14}
\]

\[
C_{EC}(h) + C_G(h) \leq C_{IC}(h) \tag{15}
\]

The price signals are then adapted for the market conditions by linking the exporting (\( 16 \)) and importing (\( 17 \)) tariffs with the ratio between the power flow of buildings with generation surplus and the total of the buildings (\( 19 \)), therefore leading to lower/higher prices when the availability of renewable surplus in the community is high/low.

\[
C_{EC}(h) = \left( 1 - P_{EH}^+(h) \right) (C_G(h) - C_{IC}(h)) + P_{EH}^+(h) C_{EC}(h) \tag{16}
\]

\[
C_{IC}(h) = C_{IC}(h) + P_{EH}^+(h) (C_G(h) - C_{EC}(h) - C_{IC}(h)) \tag{17}
\]

\[
P_{EH}^+(h) = \frac{\sum_{b=1}^{B} L_{EH}^-(h) - \sum_{b=1}^{B} L_{EH}^+(h)}{L_{EH}^+(h)} \tag{18}
\]
III. DATA AND SCENARIOS

A. Buildings

The simulations use data from the Department of Electrical and Computer Engineering at the University of Coimbra (Portugal). The building has a total area of about 10,000 m² and an electricity consumption of about 500 MWh/year. The actual PV system has 79 kWp and covers about 16% of the existing electricity demand [17]. However, in order to have periods with renewable generation surplus and deficit, the PV generation was adjusted for a future scenario ensuring 50% of the demand.

It was selected data from March, in order to have a month of intermediate consumption and generation. Data from four days of different weeks in March from the same building was selected to represent four different buildings. Fig. 1 presents the net loads considered for the four buildings. It assumed that there are simultaneously buildings with surplus and others with a deficit of PV generation. Since the input is the net load, and not directly the PV generation, the generation surplus does not have a proportional variation in the different buildings.

B. Tariffs

It was considered a tariff for the electricity consumed from the grid with an average cost equal to the actual average cost in the reference building (122.8 €/MWh), but with a variation proportional to the wholesale market in March and a flat tariff with 90% of the monthly average of the wholesale market (-35.8 €/MWh) for the electricity exported to the grid, as defined by the actual legislation. It was also considered a flat tariff of 50 €/MWh for the grid use between buildings. For the EVs, the parking, flexibility and discharging considered flat tariffs of 0.5 €/h, -0.5 €/h and -3 €/h, respectively, being used for the charging a tariff with an average cost of 2 €/h and a variation proportional to the tariff for the electricity consumed from the grid.

C. Battery Storage

The reference building has a BS system with lithium-ion batteries, ensuring a total storage capacity of about 30 kWh and inverters with a charging/discharging power of 15 kW. It was considered the same adjustment factor used for the PV generation, being considered a storage capacity of 90 kWh and 45 kW of charging/discharging power.

D. Electric Vehicles

The simulations considered EVs available in the buildings mainly between 8 a.m. and 8 p.m. with an average of 8:00 hours, 2:00 hours and 0:45 hours for the parking, charging and discharging periods, respectively. The requirements of 30 EVs were generated with a small standard deviation (1:00, 0.30 and 0.25 for the parking, charging and discharging, respectively) in order to ensure uniform requirements. Such periods are aligned with the typical use of parking in University campuses. For each building, six EVs were randomly selected from the 30 available EV profiles. The used chargers have a maximum charging/discharging power of 10 kW and 93% of efficiency.

IV. SIMULATION RESULTS

The formulation was implemented in Python using Gurobi Optimizer as a linear optimization solver. Fig. 2 presents the net load for building 2 for the baseline, and for scenarios with the use of EVs and BS as flexibility resources, with individual and community management of buildings. Fig. 3 presents the power flow between EVs, BS and building 2.

As can be seen, the BS and EVs preferentially charge in periods of negative net load (generation surplus) and discharge in periods of positive net load (generation deficit). Additionally, the BS also charges during the night taking advantage of the period with lower tariffs for the energy imported from the grid, being such energy partially used to ensure the charging of the first EVs in the morning. The presented net load is from the grid point-of-view, being therefore influenced by the availability of community management and respective power.
flow with the community. Therefore, using the capacity of community management, it was possible to compensate for all periods of negative net load which was not possible with the individual management during a short period. The availability of an additional flexibility resource (the power flow with the community) in the community scenario justifies the slightly different profiles for the use of BS and EVs.

Fig. 4 presents the power flow between each building and the community. As a result of the established market, the tariffs for the energy exported to and imported from the community were -68.99 €/MWh and 121.48 €/MWh, respectively.

![Power flow between each building and the community](image)

Tab. I presents the costs achieved in the simulated scenarios. In the individual and community scenarios, there is a demand increase of 29.5% due to the required charging of EVs and storage losses. However, due to the use of charging and discharging flexibility with EVs and BS, such higher demand was ensured with a lower cost. Additionally, by considering community management it was possible to reduce the electricity costs by 3%. The objective function takes into account not only the electricity costs, but also the costs paid by EV users, and due to the profit ensured by the designed charging scheme, the total costs relative to the baseline were reduced in 27%.

| TABLE I | COSTS BY BUILDING AND SCENARIO (€) |
|---------|-----------------------------------|
| Build. | Base. | Individual | Community |
| #      | $C_E$ | $C_E$ | $C_{EV}$ | Obj. | $C_E$ | $C_E$ | $C_{EV}$ | Obj. |
| 1      | 129.6 | 122.9 | -31.5 | 91.4 | 121.4 | -31.4 | 89.9   |
| 2      | 140.0 | 141.2 | -39.1 | 102.0 | 139.3 | -39.1 | 100.2  |
| 3      | 201.9 | 214.5 | -33.0 | 181.5 | 202.3 | -32.8 | 169.5  |
| 4      | 90.0  | 82.0  | -31.0 | 51.1  | 82.0  | -30.9 | 51.1   |
| Total  | 561.5 | 560.0 | -134.6| 426.0 | 545.0 | -134.3| 410.7  |

V. CONCLUSIONS

This paper proposes a novel method to establish a realistic transactive energy market for energy sharing in Portugal. The energy trade is envisioned at the community microgrid level and enables mostly by large public and commercial buildings with on-site batteries and EV charging stations. The proposed method establishes a transactive energy market between buildings and EV users in which parking time and added value services (stemming from charging) are the currency that facilitates economic relationships. The proposed method is aligned with the Portuguese legislation that does not allow direct electricity trading between buildings and EVs while blessing energy-surplus sharing between buildings in renewable energy communities.

The formulation was simulated for a building community located at the campus of the University of Coimbra. The results show the increased self-consumption of local generation and reduction of costs achieved with the management of flexibility resources. The results also showcase a higher impact achieved with the management at the community level when compared with the individual management of buildings, highlighting the effectiveness of the proposed formulation.

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