Optimal Sizing of PV-Battery Systems in Buildings Considering Carbon Pricing

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***Abstract*—Carbon pricing instruments have been used to provide economic signals to greenhouse gas emitters and allow them to adjust or transform their business activities. The application of carbon pricing instruments to buildings has not received a lot of attention, despite buildings being big greenhouse gas emitters. This paper addresses this gap by investigating how carbon pricing can be used to encourage building owners to install photovoltaic (PV) and battery energy storage systems (BESS), which can contribute to the reduction of greenhouse gas emissions. To achieve this goal, we propose a new planning optimization model to select the most cost-effective electricity tariff and PV-battery solution, considering investment, operating, and environmental costs. Our experiments show that carbon pricing is an effective instrument to reduce the carbon footprint of buildings by incentivizing the adoption of BESS and PV systems.**

Keywords—buildings, battery energy storage systems, photovoltaic systems, planning, sizing, carbon pricing.

I. Introduction

A. Motivation

The Paris climate agreement signed in 2016 establishes a long-term temperature goal to keep the rise of the global temperature below 2 °C, recognizing that this would reduce the impacts of climate change. The measures adopted by the signing countries to achieve this goal are mainly focused on increasing the integration of renewable energy sources and implementing energy efficiency programs to reduce greenhouse gas emissions. Some countries developed carbon pricing instruments, such as carbon markets [1] or carbon taxes, to provide an economic signal to emitters, and allow them to decide to either transform their activities or continue emitting and paying for their emissions. Most of these carbon pricing instruments have been applied to the supply-side, i.e., to the electricity generators responsible for emitting greenhouse gases. On the other hand, the application of carbon pricing instruments to the demand-side has not received a lot of attention from researchers and policymakers, despite buildings being responsible for a large amount of greenhouse gas emissions (e.g., more than 36% of the total emissions in the European Union [2]). To fill this gap, this paper investigates how carbon pricing can be used by policymakers to incentivize building owners to install PV-battery systems, which can contribute to the reduction of greenhouse gas emissions.

B. Related work

The sizing of PV-battery systems in buildings has been the focus of recent studies. The related work on this topic can be categorized into two groups.

The first group covers optimization algorithms used to size BESS and PV systems individually or jointly, considering only economic criteria. The individual sizing of BESS is addressed in works [3]–[5]. These works use heuristics based on battery simulation [3], [4] and optimization models [5]. More specifically, paper [3] simulates the operation of BESS to identify a cost-effective battery size, while paper [5] formulates a linear programming model to optimally compute the size of a BESS. The works [6]–[11] extend the sizing problem of papers [3]–[5] to PV systems. The first two works [6] and [7] use metaheuristic algorithms to size PV-battery systems. The other four works [8]–[11] use mixed-integer linear programs to compute the optimal sizes of PV and BESS considering both investment and operating costs. More precisely, they consider the costs of buying new BESS and PV systems and the net-costs of operating these devices during their lifetime.

The second group of works covers optimization algorithms that consider the costs of sizing PV-battery systems, as well as the impacts of these technologies in the environment during their life cycle. In the literature, we can find these three works [12]–[14] about this topic. The first work [12] uses an optimization approach to compute and benchmark different PV-battery solutions in terms of cost and environmental impact. The last two works [13] and [14] use mixed-integer linear programs to size PV-battery systems in the context of net-zero energy buildings. Both works include the environmental impacts of the sized technologies in the mathematical formulation of the problem through constraints or additional terms in the objective function. The environmental impacts include several aspects, such as carbon footprint, water scarcity, ozone depletion, and land use, among others. All these aspects are normalized and aggregated into a single indicator expressed in points.

In summary, works about the sizing of PV-battery systems considering economic and environmental criteria can be found in the literature. Nonetheless, none of these works investigates the impact of carbon pricing in the sizing of the PV-battery systems. Therefore, they do not investigate how carbon pricing can impact the sizing of PV-battery solutions, and how can be used to foster the adoption of these systems.

C. Contributions

This paper proposes a new planning optimization model to select the most cost-effective electricity tariff and PV-battery solution by minimizing the investment, operating, and environmental costs. The novel feature of this optimization model is the inclusion of a carbon pricing instrument to tax the environmental impacts of buying electricity from the network and manufacturing PV and BESS technologies. In short, the new planning optimization model supports the building owner to make the following decisions, considering economic and environmental aspects:

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1. Selecting the electricity tariff;
2. Installing and sizing a PV system;
3. Installing a BESS.

Carbon pricing is the novel feature introduced in this paper. The aim is to investigate how carbon pricing can affect the sizing of PV-battery solutions, and how can be used to incentivize the installation of these systems. The impact of carbon pricing is investigated in this paper using a portfolio of 100 real buildings from Portugal.

D. *Paper organization*

The remaining paper is organized as follows. Section II describes the planning optimization model. Sections III and IV discuss the case study and results. The conclusions are described in section V.

II. Planning optimization model

The planning optimization problem (1)-(16) selects the most cost-effective electricity tariff and PV-battery solution, considering investment, operating, and environmental (carbon) costs.

A. *Planning horizon*

The optimization horizon $t \in T$ covers one year. The horizon is divided into 8760 time-steps t of one hour $\Delta t\ (h)$. The investment and environmental costs are annualized by the expected lifetime of the technologies. More details of this approach can be found in [15].

B. *Objective function*

The objective function (1) minimizes the annual investment, operating, and environmental costs. The objective function is divided into the following three terms:

1. **Operating net-cost terms:** the first two terms model the annual operating net-cost of the building. The first term $\sum_{i\in I}\left(\theta_i\lambda_i^{CP} + \sum_{t\in T} X_{i,t}\right)$ includes the contracted power cost $\theta_i\lambda_i^{CP}$ and the cost of buying energy $X_{i,t}$. The second term $\sum_{t\in T}(E_t^S\lambda_t^S)$ is the revenue of selling energy. The binary variable θ_i selects the electricity tariff from a portfolio $i \in I$. The variable E_t^S is the energy injected into the network. The parameters λ_i^{CP} and λ_t^S are prices. More detailed information about the structure of the electricity tariffs will be provided in subsections II D and III A.
2. **Investment cost terms:** the next three terms model the annualized investment costs of PV and BESS. The two terms $\pi^{PV}\dot{\lambda}^{PV} + \delta^{PV}\ddot{\lambda}^{PV}$ model the investment cost in PV, while the term $\pi^{BESS}\lambda^{BESS}$ models the investment cost in BESS. The binary variables π^{PV} and π^{BESS} define the installation of PV and BESS, respectively. The integer variable δ^{V} defines the number of panels (size) of the PV system. The annualized prices of PV and BESS are given by $\dot{\lambda}^{PV}$, $\ddot{\lambda}^{PV}$, and λ^{BESS}.
3. **Environmental cost term:** the last term $\lambda^{CO2}C$ models the environmental cost of buying energy from the network, and manufacturing PV and BESS technologies. The carbon footprint C is taxed at λ^{CO2}.

$$Min \sum_{i\in I}\left(\theta_i\lambda_i^{CP} + \sum_{t\in T} X_{i,t}\right) - \sum_{t\in T}(E_t^S\lambda_t^S) + \pi^{PV}\dot{\lambda}^{PV} + \delta^{PV}\ddot{\lambda}^{PV} + \pi^{BESS}\lambda^{BESS} + \lambda^{CO2}C \quad (1)$$

Equation (2) details the carbon footprint of PV φ^{PV} and BESS φ^{BESS} technologies, and the carbon footprint of the energy bought from the network φ^{E}. The variable E_t^B defines the energy bought from the network.

$$C = \varphi^{PV}\delta^{PV} + \varphi^{BESS}\pi^{BESS} + \sum_{t\in T}\varphi^E E_t^B \quad (2)$$

The maintenance costs of PV and BESS are not considered in this problem because they are minimal, or even inexistent in the case of PV systems for small buildings. Interest rates are also not considered since we assume that the building owner does not need to borrow money to invest in small PV-battery systems.

C. *Energy balance constraint*

Constraint (3) defines the load or generation E_t^N of the building, where $\overline{P_t^I}$ is the inflexible load, $\overline{P_t^{PV}}\delta^{PV}$ is the PV generation, P_t^+ and P_t^- are the charging and discharging power rates of the BESS. The parameter $\overline{P_t^{PV}}$ is the generation of 1 PV panel.

$$E_t^N = \left(\overline{P_t^I} - \overline{P_t^{PV}}\delta^{PV} + P_t^+ - P_t^-\right)\Delta t,\ \ \forall\, t\in T \quad (3)$$

D. *Electricity tariff decision constraints*

Constraint (4) selects the electricity tariff of the building. The electricity tariffs in Portugal have two terms. The first term is the retail tariff and defines the price of electricity. The second term is the contracted power β_i, and defines the maximum power that a building can buy (5) and sell (6) to the electricity network. The contracted power represents the cost of using the electricity network infrastructure.

$$\sum_{i\in I}\theta_i = 1 \quad (4)$$

$$\sum_{i\in i}\theta_i\beta_i\Delta t \geq E_t^B,\ \ \forall\, t\in T \quad (5)$$

$$\sum_{i\in i}\theta_i\beta_i\Delta t \geq E_t^S,\ \ \forall\, t\in T \quad (6)$$

Constraints (7) and (8) define the cost of buying energy from the network $X_{i,t}$. The two constraints are used to exactly linearize the non-linear relationship $E_t^B\theta_i\lambda_{i,t}^B$. The energy bought from the network E_t^B is remunerated at retail price $\lambda_{i,t}^B$. The parameter M is a bid number.

$$0 \leq E_t^B\lambda_{i,t}^B - X_{i,t} \leq (1-\theta_i)M,\ \ \forall\, i\in I,\ \ t\in T \quad (7)$$

$$0 \leq X_{i,t} \leq \theta_i M,\ \ \forall\, i\in I,\ \ t\in T \quad (8)$$

Constraint (9) defines if the user buys E_t^B or sells E_t^S energy to the network.

$$E_t^N = E_t^B - E_t^S,\ \ \forall\, t\in T \quad (9)$$

$$E_t^B, E_t^S \geq 0,\ \ \forall\, t\in T \quad (10)$$

E. Photovoltaic system constraint

Constraint (11) installs and sizes the PV system, i.e. it defines the number of PV panels δ^{PV} in case of the system being installed. The parameter N^{PV} is the maximum number of panels that can be installed on the rooftop of the building.

$$\delta^{PV} \leq \pi^{PV} N^{PV} \tag{11}$$

F. Battery energy storage system constraints

Constraint (12) installs the BESS. Constraints (13)-(16) define the operation of the BESS. Constraints (13) and (14) define if the BESS charges or discharges, according to the value of the binary variable α_t. Constraints (15)-(16) set and bound the state-of-charge SOC_{t+1} by $\underline{SOC}$ and $\overline{SOC}$. Let η denote the efficiency of the BESS, and $\overline{P^{BESS}}$ be the maximum charging and discharging power rates of the BESS.

$$P_t^+ + P_t^- \leq \pi^{HEMS} \overline{P^{BESS}}, \ \forall t \in T \tag{12}$$

$$0 \leq P_t^+ \leq \alpha_t \overline{P^{BESS}}, \ \forall t \in T \tag{13}$$

$$0 \leq P_t^- \leq (1 - \alpha_t) \overline{P^{BESS}}, \ \forall t \in T \tag{14}$$

$$SOC_{t+1} = SOC_t + \left(P_t^+ \eta - \frac{P_t^-}{\eta}\right) \Delta t, \ \forall t \in T \tag{15}$$

$$\underline{SOC} \leq SOC_{t+1} \leq \overline{SOC}, \ \forall t \in T \tag{16}$$

III. Case Study

The case study addresses the planning of 100 real buildings in Portugal. The input parameters of the planning optimization problem are described in the next subsections.

A. Electricity tariffs

The electricity tariffs in Portugal include the retail tariff λ^B and the contracted power β and price λ^{CP} values. TABLE I presents regulated electricity tariffs for low-voltage consumers. Three types of retail tariffs were considered: simple; time-of-use with two periods; and time-of-use with three periods. The time of peak, off-peak, and super off-peak periods can be found in [11]. The contracted power in the optimization model was converted to kW using a power factor of 0.98.

TABLE I. Regulated electricity tariffs for low-voltage consumers in Portugal (2019).

β (kVA)	λ^{CP} (€/year)	Retail tariff	λ^B (€/kWh)
1.15	29.64	Simple	0.1447
2.3	51.96		
3.45	60.0	Simple	0.1557
4.6	78.0	Time-of-use with two periods	Peak: 0.1875 Super off-peak: 0.1024
4.6	95.90	Time-of-use with three periods	Peak: 0.2246 Off-peak: 0.1682 Super off-peak: 0.1024
6.9	113.8		
10.35	167.5	Simple	0.1559
13.8	221.2	Time-of-use with two periods	Peak: 0.1890 Super off-peak: 0.1025
17.25	274.9	Time-of-use with three periods	Peak: 0.2287 Off-peak: 0.1704 Super off-peak: 0.1025
20.7	328.56		

The price of selling energy λ^S is 80% of the Iberian wholesale price. The remaining percentage is used by aggregators [16] or retailers to cover administrative and transaction costs. The Iberian wholesale prices were sourced from the ENTSO-E transparency platform [17]. The average wholesale price was 47.9 €/MWh in 2019.

A. Battery energy storage systems

TABLE II describes the parameters of a BESS. The parameters include the price λ^{BESS}, efficiency η^{BESS}, capacity $\overline{SOC}$,and maximum charging and discharging power $\overline{P^{BESS}}$. The price of the BESS in the optimization model is annualized by its expected lifetime.

TABLE II. Parameters of the BESS.

λ^{BESS} (€)	$\overline{SOC}$ (kWh)	$\overline{P^{BESS}}$ (kW)	η	Lifetime (years)
6000	13.5	5	0.95	10

B. Photovoltaic systems

TABLE III describes the parameters of the PV technology. In the optimization problem, the fixed $\dot{\lambda}^{PV}$ and variable $\ddot{\lambda}^{PV}$ prices are annualized by its expected lifetime. The peak power of one PV panel is 345 W.

TABLE III. Parameters of the PV technology.

$W/panel$	$\dot{\lambda}^{PV}$ (€)	$\ddot{\lambda}^{PV}$ (€/$panel$)	Lifetime (years)
345	100	700	25

TABLE IV describes the space available on the rooftop of the buildings to install PV panels.

TABLE IV. Number of slots available for PV panels.

Max. number of PV panels (N^{PV})	6	16	40
Number of buildings	22	50	28

C. Electricity metering data

The electricity metering data is divided into inflexible load $\overline{P^I}$ and PV generation $\overline{P^{PV}}$. In the optimization problem, we use the real inflexible load of the 100 buildings and a normalized profile of PV generation. The metering data covers one year in time-steps of one hour. The metering data can be provided upon request.

D. Environmental impacts

TABLE V presents the carbon footprint of buying energy from the network [18], and manufacturing PV and BESS technologies [19]. The carbon footprint of PV and BESS in the optimization problem is annualized by the expected lifetime of the technologies. The carbon tax λ^{CO2} is 0.1 €/kgCO_2eq.

TABLE V. Carbon footprint.

φ^{PV} ($kgCO_2eq/panel$)	φ^{BESS} ($kgCO_2eq$)	φ^{E} ($kgCO_2eq/kWh$)
346	857	0.4

E. Implementation of the planning optimization problem

The planning optimization model (1)-(16) is a mixed-integer linear program. The problem was implemented in Pyomo [20] and solved by the CPLEX 12.9 optimizer. We used a server with 126 GB RAM and an AMD Ryzen Threadripper 3990X 64-Core processor clocked at 2.9 GHz to run the experiments.

IV. RESULTS

The results discuss how carbon pricing impacts the configuration of the buildings, which is defined by the electricity tariff and energy building technologies (PV and BESS). To discuss the impacts of carbon pricing, we use three building configurations:

1. Original configuration (O-C): original configuration of the building;
2. Economic configuration (E-C): new building configuration computed by the planning optimization model considering only economic aspects;
3. Economic and ecologic configuration (EE-C): new building configuration computed by the planning optimization model considering economic and environmental aspects.

The building configurations are compared and discussed in the next three subsections. The first subsection discusses the characteristics of the building configurations. The second subsection analyses the economic performance of the building configurations. The last subsection discusses the carbon footprint of the building configurations.

A. *Comparison of the building configurations*

The planning optimization model installed and sized PV-battery systems under the E-C and EE-C. In this case study, the optimization model installed PV systems on the rooftop of all buildings. This result demonstrates that installing PV systems on the rooftop of the buildings is cost-effective without any type of incentive in Portugal.

The inclusion of the carbon pricing affected slightly the sizing of the PV systems, as illustrated in Fig. 1. The average size of the PV systems was increased from 3.8 kW (E-C) to 3.9 kW (EE-C). This small increase suggests that the carbon pricing instrument used in this paper fits the purpose of increasing the integration of renewable energy resources at the demand-side level. In addition, the carbon pricing instrument also incentivized the installation of 17 BESS. The installation of the BESS was accompanied by the increase of the size of the PV systems, in order to improve self-consumption. The remuneration mechanism used by aggregators incentivizes self-consumption instead of PV injection. It is in line with the Portuguese regulation [21], which encourages sizing PV-battery systems to enhance self-consumption.

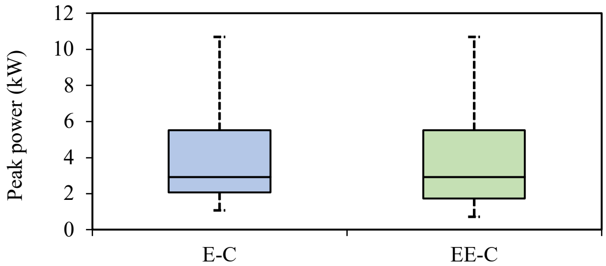

Fig. 1. PV systems installed on the rooftop of buildings.

The other two components of the building configuration are the contracted power and retail tariff. The contracted power values of the three building configurations are compared in TABLE VI. The optimization model reduced the original contracted power of 94 buildings under E-C and EE-C. The installation of PV systems in the E-C and EE-C helped to reduce the peak power of some buildings. However, we observed that most building owners overestimate the contracted power that they need in their installations. The installation of BESS in the EE-C contributed to further reduce the contracted power of 16 buildings since BESS were used to perform peak shaving.

TABLE VI. Number of buildings per contracted power.

	Contracted power (kVA)									
	1.15	**2.3**	**3.45**	**4.6**	**5.75**	**6.9**	**10.35**	**13.8**	**17.25**	**20.7**
O-C	0	0	6	11	0	34	16	9	8	16
E-C	2	13	28	22	9	13	12	1	0	0
EE-C	2	13	33	27	9	11	4	1	0	0

The retail tariffs of the three building configurations are compared in TABLE VII. The optimization model changed the original retail tariffs of 63 buildings. Under the E-C, we observed that most building owners were not aware of their load profile. The installation of the BESS in the EE-C increased the number of buildings with time-of-use tariffs with three periods since BESS were used to perform energy arbitrage. In fact, all the buildings with time-of-use tariffs with three periods have BESS.

TABLE VII. Number of buildings per retail tariff.

	Simple	Time-of-use with two periods	Time-of-use with three periods
O-C	66	24	10
E-C	23	77	0
EE-C	23	60	17

B. *Comparison of the building costs*

The annual total cost of all buildings is divided into economic and environmental costs, as illustrated in TABLE VIII. The economic cost results from the investment in PV and BESS technologies and the operation of the buildings. The environmental cost is associated with the carbon footprint of buying energy from the network and manufacturing PV and BESS technologies.

The EE-C presents the lowest total cost of 86 k€/year followed by E-C and O-C with total costs of 88 k€/year and 132 k€/year, respectively. The consideration of carbon pricing drove down the environmental cost from 23 k€/year (O-C) to 13 k€/year (EE-C) by incentivizing the installation of environmentally friendly energy building technologies, such as PV and BESS. Therefore, carbon pricing shows to be an effective mechanism to reduce the environmental costs of buildings.

TABLE VIII. Costs of all buildings.

	Economic cost (k€/year)	Environmental cost (k€/year)	Total cost (k€/year)
O-C	108	23	132
E-C	72	16	88
EE-C	73	13	86

The economic analysis performed above was based on the annual cost of all buildings. Now, we are going to discuss the individual results. Fig. 2 shows that all the buildings reduced their total cost with the adoption of the E-C and EE-C. The medium total cost was reduced from 853 €/year (O-C) to 568 €/year (E-C and EE-C). The EE-C reduced even further the total cost of 27 buildings compared to E-C. The average cost reduction was of 9 €/year. The consideration of carbon pricing in the EE-C reduced the original environmental costs of all buildings. The medium environmental cost was reduced from 145 €/year (O-C) to 91 €/year (EE-C). The EE-C reduced the environmental costs of 27 buildings compared to the E-C.

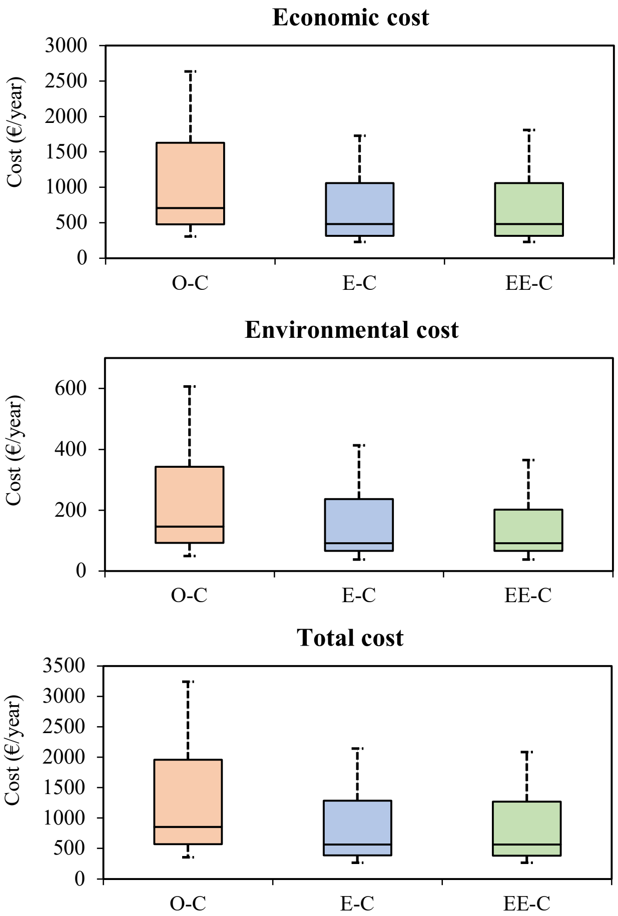

Fig. 2. Costs per building.

The capital invested by the building owners to buy BESS and PV systems is illustrated in Fig. 3. The E-C recommended only the installation of PV systems, corresponding to an investment of 7.9 k€ on average. On the other hand, the EE-C recommended the installation of 17 PV-battery systems and 83 PV systems, corresponding to an investment of 9.1 k€ on average. The average cost of the investment increased mainly due to the installation of BESS and larger PV system sizes. The largest investment was 27.8 k€ and was made to buy a PV-battery solution with a PV system of 10.7 kW.

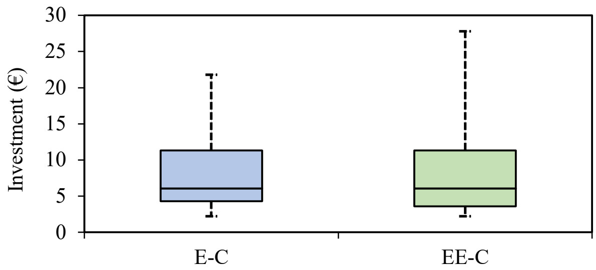

Fig. 3. Investment per building (PV+BESS).

C. *Comparison of the environmental impacts*

The carbon footprints of the three building configurations are compared in TABLE IX. The EE-C presents the lowest carbon footprint of 131 tCO2eq/year followed by E-C and O-C with carbon footprints of 155 tCO2eq/year and 234 tCO2eq/year, respectively.

The installation of PV systems reduced the carbon footprint from 234 tCO2eq/year (O-C) to 155 tCO2eq/year (E-C). The increase of PV system sizes together with the installation of BESS reduced even further the carbon footprint from 155 tCO2eq/year (E-C) to 131 tCO2eq/year (EE-C). In summary, the carbon pricing instrument used in this paper contributed to reducing by 44% the carbon footprint of the buildings with the O-C.

TABLE IX. Carbon footprint of all buildings.

	Carbon footprint ($tCO_2eq/year$)
O-C	234
E-C	155
EE-C	131

The distribution of the carbon footprint per building is presented in Fig. 4. All buildings reduced their carbon footprint with the adoption of the E-C and EE-C. The medium carbon footprint was reduced from 1.5 tCO2eq/year (O-C) to 0.9 tCO2eq/year (E-C and EE-C). The EE-C reduced further the carbon footprint of 27 buildings compared to E-C. The average reduction was 0.24 tCO2eq/year (15%).

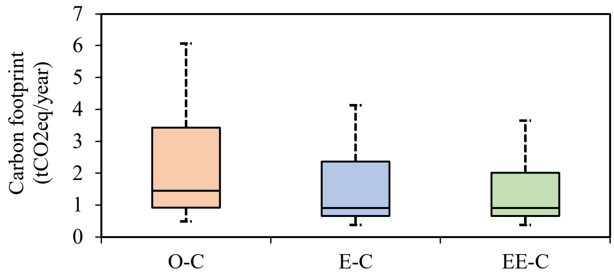

Fig. 4. Carbon footprint per building.

V. CONCLUSIONS

This paper presents a new planning optimization model to select the most cost-effective electricity tariff and PV-battery solution for a building, considering investment, operating, and environmental costs. The novel feature of this approach is the introduction of a carbon pricing instrument to tax the environmental impacts of buying electricity from the network and manufacturing PV and BESS technologies. The aim is to incentivize the adoption of energy building technologies, which can contribute to the reduction of greenhouse gas emissions.

The impact of the carbon pricing instrument was investigated using a portfolio of 100 real buildings from Portugal. The results of our studies allow us to draw the following conclusions:

1. The consideration of carbon pricing in the planning of energy building technologies contributes to significantly reducing the carbon footprint of buildings. The carbon footprint of the buildings was reduced by 44% in our case study;

2. Rooftop PV technologies are cost-effective and do not need any type of economic incentive in Portugal. However, carbon pricing can incentivize the adoption of larger PV systems, as demonstrated in our case study;

3. BESS technologies for building applications are not cost-effective at the current prices (2021). Incentives are required to make them cost-effective. Carbon-pricing instruments can be used to incentivize the adoption of PV-battery systems, as shown in our case study.

Future work consists of investigating the carbon pricing of other energy building technologies and studying other carbon pricing instruments to encourage the adoption of environmentally friendly technologies.

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