Energy Storage Management System for Smart Home: an Economic Analysis

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***Abstract*—The relationships between the environment and the energy sector are particularly relevant. The production and consumption of electricity are directly and indirectly responsible for some of the major negative impacts of human activity on the environment. Residential buildings have a strong impact on the electricity sector, and energy resource management models may be explored to minimize costs. This paper proposes the optimization of an energy storage system (ESS) capacity for residential use, in a single-family household, with the integration of photovoltaic (PV) generation and the use of electric vehicles (EVs) aiming to minimize electricity consumption costs. An economic viability study of the obtained solutions is also reported. The obtained results point that the optimal ESS capacity was 5.6 kWh. Furthermore, economic results show that the incentive householders' investment should be for environmental reasons.**

***Index Terms*—Battery Energy Storage System, Economic Analysis, Energy Optimization, Energy Storage Management, Renewable Sources, Smart Homes.**

I. INTRODUCTION

Residential buildings, in general, and single-family houses, in particular, represent a great potential for contributing to the optimization of energy resources, thus contributing to energy efficiency in this sector. Indeed, smart grids are facing great challenges, and one of the main goals of smart grid deployment is to reduce the impact of rising household energy demand on the current power grid. To attain this goal, Demand Response (DR) programs, with financial incentives, have been implemented [1].

Electricity customers (residential consumers) can play an active and important role by rescheduling their energy usage patterns in response to electricity price signs (peak-hours) or system contingencies [2], [3].

The bet on using Electric Vehicles (EVs) is already a certainty in most developed countries around the World. However, soon, it will be necessary to prevent the reuse of used batteries from electric vehicles [4]. This concern can open new opportunities to continue exploring the second usage-life of EV batteries mainly to support energy efficiency and to contribute to smooth the electricity peak demand [5], and also avoid overvoltage problems caused by the Photovoltaic (PV) injection into the distribution power grid [6]. In this regard, residential buildings are crucial to encourage the reuse of batteries' energy storage systems and promote actions to manage renewable energy resources.

Energy management based on the use of energy storage batteries in the residential sector, namely in single-family houses, has drawn the attention of researchers [7]. The energy storage system can store energy during off-peak periods and supply electricity to residential customers during peak periods, such that the stress on the main power system can be relieved [8]. However, in the residential building domain, the use of energy resources can be explored [9], and [10] by integrating PV generation, battery energy storage, demand-side management, and EVs usage to mitigate electricity costs.

This paper proposes a Home Energy Storage Management System (HESMS) that aims to size the optimal battery energy storage system (BESS) capacity for a single-family household considering the existence of a PV array, EV usage, and power grid interface to minimize consumer electricity costs. The economic viability of the several solutions is also analyzed and reported.

The main contribution of this work can be summarized as follows:

- The proposed HESMS can deal with any pricing policies used by electrical energy traders available in the electricity market;
- Ensure that the economic cost reduction is achieved taking into consideration the typical load consumption profile, and the energy resources (PV, EV, and BESS);
- Proposes the optimal value of the BESS capacity, for the particular case of the residence configuration;
- The proposed HESMS is built to be able to adapt to changes in energy resources, namely in the type of battery. Second-life EV batteries can be easily incorporated into the proposed model.

The remainder of this paper is organized as follows. In Section II, a brief review of energy storage systems optimization is presented. Section III and IV present the implemented methodology for the smart home. The case study and simulation results are described in Section V. And finally, the last Section VI provides the concluding remarks.

II. ENERGY SYSTEM OPTIMIZATION: A SHORT REVIEW

This work investigates the optimal energy storage system capacity to be deployed in residential housing with PV generation (prosumer), EV usage, load profile characterization

[11], and a power grid interface to minimize the electricity consumption from the external power network (minimizing electricity costs), and also optimizing the schedule of the EV charging/discharging operation, accordingly with the proposed mathematical formulation.

A. Energy storage management in smart homes

In recent years, energy storage management in residential housing has emerged as one of the main driving forces to stimulate future smart grid development. Some models regarding this topic could be found in the literature, for instance, in [12] a framework that considers the physical properties of batteries was developed, enabling to model the nonlinear behavior of the batteries, as well as to tests their feasibility, aiming to find the best battery types and configurations for a particular residential configuration. The results pointed that up to $43\%$of savings are obtained using the lithium-iron-phosphate, even though they are more expensive compared to lead-acid batteries.

In Reference [13] an energy management system for smart homes is proposed to minimize the total costs. A dynamic pricing scheme is considered to evaluate the energy exchanges. The authors achieved promising cost-saving for a case study based on 24h time horizon. In [14] an energy management system is proposed for a smart home to support the management of domestic appliances, renewable generation, energy storage systems, and EV usage. A holist model is built to schedule the several equipment's. Jointly with the holistic model, mixed-integer linear programming is also proposed to obtain the lowest cost and assure the users' comfort. Obtained results show that by properly scheduling the energy storage and EV operation, the total costs are reduced by 28%.

In [15] a home energy management system (HEMS) is proposed to reduce energy costs. An optimization-based rolling horizon technique, which is executed every two minutes, is used to define and update the optimal settings of the energy management system. Results show that is obtained a reduction of nearly 32% in the daily household electricity costs. Also, it was verified a smooth electricity consumption during peak hours, providing benefit for both utility operator and householder.

In [16] the impact of using an EV on the cost and dissatisfaction of a householder is explored. An energy management system is proposed to reduce energy costs and the highest level of consumer comfort. Thus, the proposed optimization problem takes into consideration the definition of the priority of cost reduction and comfort made by the householders.

The economic issue regarding home energy management is as well a topic with special interest. In [17] a novel hybrid interval-stochastic optimization method is proposed to achieve an optimal bidding strategy for an autonomous HEMS, enabling both the management of the domestic energy resources (production and consumption), and the trade energy with the local market.

With the advent of widespread use of EVs, the reuse of second-life batteries tends to be a promising area. In [18] the reuse of EV batteries (lithium-ion nickel manganese cobalt/carbon battery) is explored and evaluated for two different applications: residential demand management and power smoothing renewable integration. Furthermore, the performance and degradation of second-life batteries were evaluated, taking into account the impact of first-life use. The results obtained, the history of aging of the first-life battery strongly influences the performance and degradation of the second-life battery, so they propose adequate battery selection and monitoring to certify the technical feasibility of the second-life battery.

III. INVESTIGATED HOME SYSTEM

In this work, we consider a residential home that is equipped with a PhotoVoltaic (PV) and Electrical Vehicle (EV), and the home includes a battery energy storage system (BESS) as well. Here, a bidirectional embedded battery of EV is considered that its battery can charge and discharge. Moreover, It is assumed that the EV only exits and enters once a day and is plugged in as soon as it gets home. Moreover, the generated power from PV is used for self-consumption, charging the battery of BESS and EV, and the extra power is injected into an external grid. Also, the BESS has been used to saves power in low-demand time and use it for charging the EV and home demand in high-demand time. Since a wrong or unsuitable BESS will impose an unnecessary charge on the electricity bill. So, finding the desired parameters of the BESS, such as its capacity, is an important task in this work.

The main aim is to find the optimal charging/discharging EV and BESS schedule to minimize the electricity bill, such that the suitable and optimal capacity of BESS will be determined.

The required parameters and decision variables in the mathematical formulation are all declared. The considered time period is supposed to contain D day(s) of duration tau time-step and let I represent all time-steps in the considered time period. The required parameters and variables are defined in Table I, which also includes their descriptions.

Note that $d \in \mathbb{D}$ denotes the day index in table I, and $d = 0$ and $d = D + 1$ appear as indexes in certain variables and parameters. In fact, these indexes define the start and end times of the time period under consideration. Moreover, the arrival time-step of EV is defined by $T^{\text{in}}_{\text{EV}}(d)$ and, $T^{\text{in}}_{\text{EV}}(0)$ and $T^{\text{in}}_{\text{EV}}(D+1)$ denote the first and last time-steps. It is notable that, the value of $S_{\text{EV}}(i)$ is not considered in formulation, when the EV is outside. But, for simplicity, the index $i \in \{1, \cdots, I\}$ is taken into account for S_{EV} in table I.

IV. MATHEMATICAL FORMULATION FOR OPTIMIZING THE BESS CAPACITY

In this section, the system of the stated problem in Section III is mathematically formulated.

A. Objective Function

The goal of the objective function in this paper is to reduce the total cost of the residential Smart home over the considered

TABLE I: The List of Sets, Parameters and variable of the model

Param	Index	Description
D		Number of Days per Time-Study
I		Number of time-steps per Time-Study
τ		time-step duration (hour)
i		Index of time-steps
d		Index of days
$P_{\text{A}}(i)$	$i \in \{1, \cdots, I\}$	Total power demand of home at period i
$P_{\text{PV}}(i)$	$i \in \{1, \cdots, I\}$	Total generated power by (PV) at period i
$T_{\text{EV}}^{\text{in}}(d)$	$d \in \{0, \cdots, D\}$	For $d = 0$, $T_{\text{EV}}^{\text{in}}(d) = 1$ and for $d \in \{1, \cdots, D\}$, $T_{\text{EV}}^{\text{in}}(d)$ is the number of period-time that EV enters to parking in day d
$T_{\text{EV}}^{\text{out}}(d)$	$d \in \{1, \cdots, D+1\}$	For $d \in \{1, \cdots, D\}$, $T_{\text{EV}}^{\text{out}}(D+1)$ is the number of period-time that the EV leaves in day d and for $d = D+1$, $T_{\text{EV}}^{\text{out}}(d) = I+1$
$S_{\text{EV}}^{\text{max}}$		Maximum allowable SoC of EV
$S_{\text{EV}}^{\text{initial}}(d)$	$d \in \{0, \cdots, D\}$	The initial SoC of EV at the beginning departure in time $T_{\text{EV}}^{\text{in}}(d)$
$S_{\text{EV}}^{\text{min\_out}}(d)$	$d \in \{1, \cdots, D\}$	The minimum allowable SoC for EV at exit time of each day d
$P_{\text{EV}}^{\text{ch}}$		Active power related to the charging process of EV
$P_{\text{EV}}^{\text{diss}}$		Active power related to the discharging process of EV
$E_{\text{EV}}^{\text{ch}}$		The charge efficiency of EV
$E_{\text{EV}}^{\text{diss}}$		The discharge efficiency of EV
$S_{\text{BE}}^{\text{max}}$		Maximum State of Charge(SoC) for BESS
$S_{\text{BE}}^{\text{initial}}$		Initial State of Charge(SoC) for BESS at the beginning of time-period
$S_{\text{BE}}^{\text{min}}$		Minimum State of Charge(SoC) for BESS
$P_{\text{BE}}^{\text{ch}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to the charging process of the BESS in period$i$
$P_{\text{BE}}^{\text{diss}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to the discharging process of BESS in period i
$C_{\text{G}}^{\text{buy}}(i)$	$i \in \{1, \cdots, I\}$	Purchased electricity cost from the grid in i-th time-step
$C_{\text{G}}^{\text{sell}}(i)$	$i \in \{1, \cdots, I\}$	Selling electricity cost to the grid in i-th time-step
c_B		Capital cost of the BESS system
CP		Contract Power Capacity
D_{BESS}		Depth of discharge of the battery system
Variable	**Index**	**Description**
$\alpha_{\text{EV}}(i)$	$i \in \{1, \cdots, I\}$	Binary variable that represents EV charging in i
$\beta_{\text{EV}}(i)$	$i \in \{1, \cdots, I\}$	Binary variable that represents EV discharging in i
$\alpha_{\text{BE}}(i)$	$i \in \{1, \cdots, I\}$	Binary variable that represents BESS charging process in period i
$\beta_{\text{BE}}(i)$	$i \in \{1, \cdots, I\}$	Binary variable that represents BESS discharging process in period i
$S_{\text{EV}}(i)$	$i \in \{1, \cdots, I\}$	SoC of the EV at the start of period $[T_{\text{EV}}^{\text{in}}, T_{\text{EV}}^{\text{out}}]$
$S_{\text{BE}}(i)$	$i \in \{1, \cdots, I\}$	SoC of the BESS at the start of period i
C_{BESS}		BESS Capacity
$P_{\text{G}}(i)$	$i \in \{1, \cdots, I\}$	Active power extracted from the grid in i
$P_{\text{G}\to\text{EV}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to charging the EV by grid in i
$P_{\text{EV}\to\text{B}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to discharging of EV to home in i.
$P_{\text{PV}\to\text{B}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to cover the home demand by PV in period i
$P_{\text{PV}\to\text{BE}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to charging the BESS by PV in i
$P_{\text{PV}\to\text{G}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to inject PV to grid in i
$P_{\text{BE}\to\text{G}}(i)$	$i \in \{1, \cdots, I\}$	Active power related to inject of BESS to grid in i

time period to find the optimal size of Battery Energy Storage System (BESS) as follows:

$$\mathcal{J}(\mathbf{z}) = c_B \text{C}_{\text{BESS}} + \text{C}_{Electricity}(\mathbf{z}). \tag{1}$$

where, $\text{C}_{Electricity}(\mathbf{z})$ denotes the total electricity cost of home that are related to transferred energy between the external grid and home system is given as:

$$\begin{aligned} \text{C}_{Electricity}(\mathbf{z}) = \sum_{i=1}^{I} \left(P_{\text{G}\to\text{B}}(i) + P_{\text{G}\to\text{EV}}(i) \right) C_{\text{G}}^{\text{buy}} - \\ \sum_{i=1}^{I} \left(P_{\text{PV}\to\text{G}} + P_{\text{BE}\to\text{G}} + P_{\text{EV}\to\text{G}}(i) \right) C_{\text{G}}^{\text{sell}}. \end{aligned} \tag{2}$$

Moreover, $c_B \text{C}_{BESS}$ is the capital cost that the home incurs for BESS during the time horizon.

B. Constraints

In this section, the constraints that should be considered in the model are presented to guarantee that the resources do not violate their physical limits.

1) Load Grid Constraints: In the developed model, it is ensured that the demand for smart home is fully satisfied. Therefore, the following power balance equation is considered in each time $i \in \{1, \cdots, I\}$ by the following equation:

$$\begin{aligned} P_{\text{G}}(i) + P_{\text{PV}}(i) + P_{\text{EV}\to\text{B}}(i) + P_{\text{EV}\to\text{G}}(i) + P_{\text{BE}\to\text{B}}(i) + P_{\text{BE}\to\text{G}}(i) = \\ P_{\text{A}}(i) + P_{\text{G}\to\text{EV}}(i) + P_{\text{PV}\to\text{BE}}(i) + P_{\text{C}}(i). \end{aligned} \tag{3}$$

Moreover, the purchasing power from the external grid and selling power to the grid is indicated by following bound constraints:

$$0 \leq P_{\text{G}}(i) \leq \text{ CP}, \qquad i \in \{1, \cdots, I\}, \tag{4}$$

$$0 \leq P_{\text{PV}\to\text{G}} \leq P_{PV}^{\text{Max}}, \qquad i \in \{1, \cdots, I\}. \tag{5}$$

in which $P_{\text{G}}(i)$ is defined as

$$P_{\text{G}}(i) = P_{\text{G}\to\text{B}}(i) + P_{\text{G}\to\text{EV}}(i), \quad i \in \{1, \cdots, I\}. \tag{6}$$

2) BESS System: The power for charging and discharging of BESS are limited by the equipment constraints, as are modeled by (7) and (8).

$$P_{\text{PV}\to\text{BE}}(i) \leq \alpha_{\text{BE}}(i).P_{\text{BE}}^{\text{ch}}\tau, \quad i \in \{1, \cdots, I\}, \tag{7}$$

$$P_{\text{BE}\to\text{G}}(i) + P_{\text{BE}\to\text{B}}(i) \leq \beta_{\text{BE}}(i) P_{\text{BE}}^{\text{diss}}\tau, \quad i \in \{1, \cdots, I\}. \tag{8}$$

that, the $\alpha_{\text{BE}}(i)$ and $\beta_{\text{BE}}(i)$ are binary variable that for $i \in \{1, \cdots, I\}$, if $\alpha_{\text{BE}}(i) = 1$, then the BESS is charged at most $P_{\text{BE}}^{\text{ch}}\tau$. Otherwise, if $\alpha_{\text{BE}}(i) = 0$, then BESS is not charged and $P_{\text{PV}\to\text{BE}}(i) = 0$. And also, if $\beta_{\text{BE}}(i) = 1$, then the BESS is discharged at most $P_{\text{BE}}^{\text{diss}}\tau$. Otherwise, if $\beta_{\text{BE}}(i) = 0$, then BESS is not discharged and $P_{\text{BE}\to\text{G}}(i) + P_{\text{BE}\to\text{B}}(i) = 0$.

The equation (9) is forced the complementary of charging and discharging processes of BESS in time period i:

$$\alpha_{\text{BE}}(i) + \beta_{\text{BE}}(i) \leq 1, \quad i \in \{1, \cdots, I\}. \tag{9}$$

The equation (10) represents the dynamic of BESS that determined the updated State of Charge (SoC) of BESS in each time-slot.

$$S_{\text{BE}}(i+1) = S_{\text{BE}}(i) + \Big[(P_{\text{PV}\to\text{BE}}(i))E_{\text{BE}}^{\text{ch}} - (P_{\text{BE}\to\text{G}}(i) + P_{\text{BE}\to\text{B}}(i))/E_{\text{BE}}^{\text{diss}}\Big], \quad i \in \{1, \cdots, I\}. \tag{10}$$

Moreover, the upper and lower-bounds of battery SoC are shown by constraints (11), iin which the upper-bounded is its capacity, and the lower-bounded is considered by the battery depth of discharge.

$$\text{C}_{\text{BESS}}.(1-\text{D}_{\text{BESS}}) \leq S_{\text{BE}}(i) \leq \text{C}_{\text{BESS}}, \quad i \in \{1, \cdots, I\}. \tag{11}$$

Finally, the initial value of SoC $S_{\text{BE}}(0)$ and the final value $S_{\text{BE}}(I)$ of the BESS system are denoted by the following equations:

$$S_{\text{BE}}(0) = \text{C}_{\text{BESS}}^{0}, \quad S_{\text{BE}}(I) = \text{C}_{\text{BESS}}^{I} \tag{12}$$

3) Electrical Vehicles System: Likewise, the dynamic of electrical vehicles are depicted by:

$$S_{\text{EV}}(T_{\text{EV}}^{\text{in}}(d)-1) = S_{\text{EV}}^{\text{initial}}(d), d \in \{0\} \cup \mathbb{D}, \tag{13}$$

$$S_{\text{EV}}(i+1) = S_{\text{EV}}(i) + \tag{14}$$

$$\Big[P_{\text{G}\to\text{EV}}(i)E_{\text{EV}}^{\text{ch}} - (P_{\text{EV}\to\text{G}}(i) + P_{\text{EV}\to\text{B}}(i)) \cdot E_{\text{EV}}^{\text{diss}}\Big]\tau,$$

$$d \in \{0\} \cup \mathbb{D}, \; i = T_{\text{EV}}^{\text{in}}(d)-1, \ldots, T_{\text{EV}}^{\text{out}}(d+1)-2, \tag{15}$$

$$\alpha_{\text{EV}}(i) + \beta_{\text{EV}}(i) \leq 1, \quad i \in \{1, \cdots, I\}, \tag{16}$$

$$S_{\text{EV}}(i) = 0, \; d \in \mathbb{D}, \; i = T_{\text{EV}}^{\text{out}}(d), \ldots, T_{\text{EV}}^{\text{in}}((d+1)-2, \tag{17}$$

$$0 \leq S_{\text{EV}}(i) \leq S_{\text{EV}}^{\max}, \quad i \in \{1, \cdots, I\}, \tag{18}$$

$$S_{\text{EV}}(T_{\text{EV}}^{\text{out}}(d)-1) \geq S_{\text{EV}}^{\text{min\_out}}, \quad d \in \mathbb{D}, \tag{19}$$

$$P_{\text{G}\to\text{EV}}(i) \leq \alpha_{\text{EV}}(i).P_{\text{EV}}^{\text{ch}}, \quad i \in \{1, \cdots, I\}, \tag{20}$$

$$P_{\text{EV}\to\text{G}}(i) + P_{\text{EV}\to\text{B}}(i) \leq \beta_{\text{EV}}(i)P_{\text{EV}}^{\text{diss}}, \quad i \in \{1, \cdots, I\}, \tag{21}$$

$$\alpha_{\text{EV}}(i) \in \{0{,}1\}, \quad i \in \{1, \cdots, I\}, \tag{22}$$

$$\beta_{\text{EV}}(i) \in \{0{,}1\}, \quad i \in \{1, \cdots, I\}. \tag{23}$$

V. RESULTS AND DISCUSSION

This section presents an application of the proposed mathematical formulation in section IV on a prosumer to find the optimal value of BESS capacity. The following table II lists the important parameters of the smart home under consideration and the Li-ion battery technologies were investigated for this work. The considered home has 13.8 kVA as contract power and the PV generation (P_{PV}^{Max}) has a capacity of 3.6 kWp. The value of power demanded P_{A}, the arrival/departure time of EV $T_{\text{EV}}^{\text{in}}/T_{\text{EV}}^{\text{out}}$ and the PV generated power P_{PV} are reported for every 15 minutes in which some data was not recorded. In this regard, a regression model and adjacent interpolation method are used to fill the missing data. In this case, the considered time-slot is one year with $\tau = 15$ minutes. So, the time period contains $I = 96*365 = 35040$ time-steps. In addition, random sets are considered for the initial value of SoC of EVs at the arrival time $S_{\text{EV}}^{\text{initial}}$.

TABLE II: Parameters Value of the Considering Smart Home.

Parameter	**Value**	**Unit**	**Parameter**	**Value**	**Unit**
D	365	day	$C_{\text{G}}^{\text{buy}}(i)$	1.24	EUR
τ	15	Minutes	$C_{\text{G}}^{\text{sell}}(i)$	0.93	EUR
c_B	300	EUR/kWh	$S_{\text{EV}}^{\max}$	27.2	kWh
$P_{\text{BE}}^{\text{ch}}$	3.0	kW	$P_{\text{EV}}^{\text{ch}}$	3.7	kW
$P_{\text{BE}}^{\text{diss}}$	3.0	kW	$P_{\text{EV}}^{\text{diss}}$	3.3	kW
D_{BESS}	0.6	p.u.	$E_{\text{EV}}^{\text{ch}}$	0.92	p.u.
$\text{C}_{\text{BESS}}^{\text{Max}}$	10	kWh	$E_{\text{EV}}^{\text{diss}}$	0.93	p.u.
Life time	16	Year	$\text{C}_{\text{BESS}}^{0}$	C_{BESS}	kWh
$\text{C}_{\text{BESS}}^{I}$	C_{BESS}	kWh			

A. Finding Optimal Capacity of BESS

This section reports the obtained results for two scenarios: with and without considering the energy management system. In the first scenario, the EV is charged as soon as it arrives home, but the discharging process of the EV and also BESS are not considered. In the second scenario, EV's charging/discharging process is considered, and a BESS is used as well. Note that the first scenario is a reference case study and no optimization is needed, and the total consumption costs are obtained by simple calculating. The obtained results are reported in Table III. Note that in Table III the positive sign refers to the electrical energy that is consumed, and the negative sign concerns the electrical energy that is produced.

TABLE III: Electricity Consumption And Cost In Scenario I

CP (kVA)	Building Con. (kWh)	EV Con. (kWh)	PV gen. (kWh)	Electricity Cost (EUR)
13.8	+65504.17	+ 5201.74	-15178.09	7973.4743

To improve the total cost of the smart home, the discharging process of EV and the BESS is used in the second scenario. Now, the proposed model in section IV is applied for various charge/discharge rates to find the optimal value of BESS capacity and shows their impacts on the total cost of the smart home. In Table IV, the electricity bill of homes for various sizes and charge/discharge rates $P_{\text{BE}}^{\text{ch}}$ and $P_{\text{BE}}^{\text{diss}}$ of BESS is plotted for one year.

TABLE IV: Optimal Capacity of BESS for Different Value of $P_{\text{BE}}^{\text{ch}}$ and $P_{\text{BE}}^{\text{diss}}$

Battery (kWh)	$P_{\text{BE}}^{\text{ch}}$ (kW)	$P_{\text{BE}}^{\text{diss}}$ (kW)	Cost of BESS (EUR)	Electricity Cost (EUR)	Total Cost (EUR)
5.60	6	5	105.00	7370.70	7475.70
5.33	6	3	99.93	7376.25	7476.18
4.55	3	3	85.31	7392.19	7477.50

Based on obtained results presented in Table IV, and if the charging and discharging rate of BESS are 6kW and 5kW, respectively, the BESS optimal capacity is 5.60 kWh.

The obtain results corresponding to $\text{C}_{\text{BESS}} = 5.60(\text{kWh})$ are reported in Figure 1 for some days in summer. Figure 1 shows the impact of the BESS in reducing power consumption from the external grid. As seen, The BESS and EV stores the extra power at the low demand time periods and discharge it

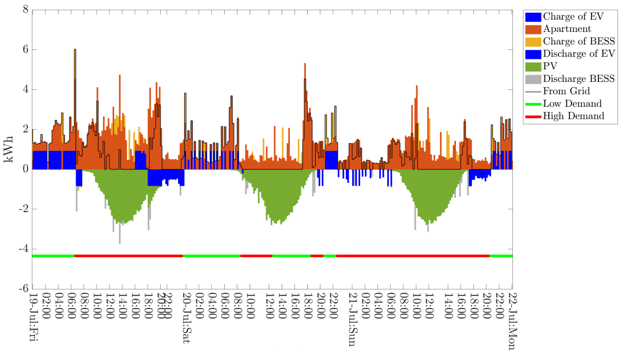

Fig. 1: Power among Grid, PV, EV and BESS in Home for $C_{\text{BESS}} = 5.60$(kWh)

at the high demand time. Based on this Figure, the total home demand is mostly covered by the PV generation during the central hours and is covered by discharging of EV, BESS, and grid at other times. Now, the proposed model is solved for three existing standard choices of Li-ion BESS. The obtained results, including total cost, BESS cost, and electricity cost of the home, are reported in Table V.

TABLE V: The Annual Cost for different value of BESS capacity .

Battery (kWh)	$P_{\text{BE}}^{\text{ch}}$ (kW)	$P_{\text{BE}}^{\text{diss}}$ (kW)	Cost of BESS (EUR)	Electricity Cost (EUR)	Total Cost (EUR)
3.3	3	3	61.87	7416.18	7478.05
6.3	6	3	118.12	7358.18	7476.30
6.5	6	5	121.87	7353.96	7475.83

B. Optimal BEES Capacity: Economic Analysis

In order to evaluate the economic analysis of the obtained results, for each achieved BESS capacity it was calculated several economic indices, namely Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. These indices are depicted in (24), (25), and (26), respectively.

$$\text{NTV} = \sum_{j=1}^{n} \frac{cf}{(1+a)^j} - \sum_{j=0}^{n-1} \frac{I_j}{(1+a)^j}, \tag{24}$$

$$\text{IRR} = \sum_{j=1}^{n} \frac{cf}{(1+IRR)^j} - Initial\ Inv, \tag{25}$$

$$\text{Payback} = \frac{ln(\frac{cf}{cf-a.I_t})}{ln(1+a)}, \tag{26}$$

Where j is the year in analysis, cf is the cash flows, a is the discount rate (it was considered for this case 4%), I_j and I_t represents the investment cost, and n is the time horizon of the investment. In this case, the considered time frame was 16 years (estimated service life of BESS by the manufacturer).

In Table VII, it is possible to see the investment value of each BESS, used from: https://ampere-energy.pt, as well as the expected income from the electricity bill that is saved from the deployment of BESS. The considered annual income results from the difference of the saving bill between Table III and Table V. Table VII presents the obtained economic results for each BESS capacity. The economic results are not promising, from the financial point of view. In fact, the payback is approximately 16 years. Thus, the incentive for this type of investment by householders should be seen as a green contribution to a cleaner planet (boosting self-consumption through the use of renewable resources) instead of the incentive being only and purely monetary.

TABLE VI: Investment and Annual incomes for BESS capacities.

Battery (kWh)	Investment (EUR)	Annual Income (EUR)
3.3	$5,800.00$	497.29
6.3	$6,900.00$	615.29
6.5	$7,300.00$	619.51

TABLE VII: Economic results for BESS capacities.

Battery (kWh)	NTV (EUR)	IRR (%)	Payback (Years)
3.3	-5.00	3.99	16.0
6.3	$+270.00$	3.88	15.2
6.5	-81.00	3.18	16.3

VI. CONCLUSION

The results of this paper show that the economic viability of the deployment of battery energy storage systems for dwellings is strongly dependent on the householders' awareness about the ecological path that they could give to society through the use of renewable resources. An optimal battery energy storage system optimization model was implemented aiming to minimize the electricity costs of the residential home, taking into consideration the load consumption, photovoltaic generation, and electric vehicle (EV) usage. The results pointed to a battery capacity of 5.6 kWh which can be found in the market for this kind of application. In the near future, the reuse of the EV batteries will be a promising resource, with the advantage of the huge energy capacity of this kind of battery (even though the reduction of nearly 80% of their maximum capacity). Thus, as future work, authors will study the viability of the reuse of second-life EV batteries in smart homes to become nearly zero electricity buildings.

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