IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 30, 2022, accepted February 14, 2022, date of publication February 22, 2022, date of current version March 10, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3153341

Goal Programming Approach for Energy Management of Smart Building

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This work was supported in part by the Fundo Europeu de Desenvolvimento Regional (FEDER) Funds through Programa Operacional para a Competitividade e Internacionalizaçã (COMPETE) Program, and in part by the National Funds through Fundação para a Ciência e a Tecnologia (FCT) under Project BENEFICE–PTDC/EEI-EEE/29070/2017, Project UIDB/00760/2020, and Grant CEECIND/02814/2017.

ABSTRACT In this paper, a collective residential building is considered in which the following points are taken into consideration: (i) a flexibility value of Contract Power (CP) is considered for each consumer; (ii) it is assumed a single CP for the entire building; (iii) an energy resource manager entity is considered to manage the energy resources in the residential building, such as Electric Vehicles (EVs), Photovoltaic (PV) generation system, and the Battery Energy Storage System (BESS). Taking into consideration the previous assumptions, the major goal of this work is to minimize the electricity consumption costs of the residential building by using a Multi-Objective Mixed-Binary Linear Programming (MOMBLP) formulation. The objective function of the MOMBLP model minimizes the electricity cost consumption of each apartment. Then, a Goal Programming (GP) strategy is applied to find the most appropriate solutions for the proposed MOMBLP model. Finally, the performance of the suggested model is evaluated by comparing the obtained results from a Single-Objective Mixed-Binary Linear Programming (SOMBLP) approach in which the whole building consumption cost is minimized. The results show that using the GP strategy a reduction of 7.5% in the total annual energy consumption is verified in comparison with SOMBLP. Moreover, the GP approach leads to fair benefit among building consumers, by finding a solution with less distance from the desired level.

INDEX TERMS Energy management, goal-programming methodology, multi-objective optimization problem, renewable energy, smart building.

I. INTRODUCTION

A significant part of global greenhouse gas emissions is related to energy consumption which is expected to rise around 40% in the following decades [1]. In the meantime, research studies show that energy demand will rise 50% in 2040 in comparison with 2010 [2]. Renewable energy sources are under consideration as a possible option for meeting the energy demand in a sustainable way. In particular, solar photovoltaic (PV) panels and wind power generation are attractive sources due to their broad accessibility and lower cost [3] despite the direct impact of the weather on their energy output [4]. Buildings' rooftop can provide vast areas to accommodate large amounts of PV generation. Energy Management System (EMS) in Smart Buildings (SB) may benefit from the penetration of renewable sources (PV generation) in an integrated and complementary way with the use of Battery Energy Storage Systems (BESS) and Electric Vehicles (EV) [5]–[7].

In this research work we consider the concept of a residential SB with PV, EV and BESS. The main goal of the optimization model we develop is to reduce the total electricity consumption cost by minimizing the cost of each consumer in which each apartment has EV and PV generation and equipped by BESS and EMS. Some assumptions have been considered in this work. In Portugal each apartment has to subscribe a given Contract Power (CP) value (e.g. 3.45 kVA, 5.75 kVA, 6.9 kVA and so on) according to their individual demand profile. Therefore, we propose a flexible Contract Power (CP) for each apartment and a single CP to supply the entire SB. Moreover, we assume that an energy manager entity is contracted by the SB to manage the power among

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Wang.

the local grid (for example the PV, EVs, and the BESS), consumers (apartments and common service) and external power grid.

In order to achieve our goals, we depart to employ a Multi-Objective Mixed-Binary Linear Programming (MOMBLP) formulation to reduce the overall consumption cost by minimizing the electricity cost of each consumer. MOMBLP is used to determine the optimal process charging/discharging of EVs batteries and BESS while minimizing the cost of every single apartment at the same time.

The challenge of the MOMBLP model is that produces unfeasible solutions if even one single constraint is not satisfied [8]. In fact, scalarization approaches are popular methods to determine the Pareto solution Multi-Objective Optimization Problems (MOOP) [9], [10]. A MOOP is converted to a set of parameter-dependent single-objective optimization problems (SOOP) by using these techniques [11]. The solution of each SOOP (corresponding to a varied set of parameters' values) is a solution of the multi-objective problem that is known as Pareto point [12], [13]. Goal programming (GP) is a useful method for dealing with MOOP that enables finding a balance among all of the Pareto points. This method establishes a distinct function and searches for a solution among the Pareto points that are closest to the desired levels [14]. Therefore, in this paper, GP is used to obtain the most appropriate solutions for the presented MOMBLP, a sub-category of a MOOP.

The main contribution of this work is to apply the GP approach to find the most appropriate solutions for the proposed MOMBLP model. The results suggest that the GP approach is very promising since it can reduce the total annual energy consumption when comparing with the counteurpart Single-Objective Mixed-Binary Linear Programming (SOMBLP) model, and by identifying a solution that is closer to the ideal point (main goal), leading to a fair benefit among the building users.

The subsequent sections are organized as follows: A short related work is presented in section II. A brief overview of MOOP and the GP approach is discussed in section III. The problem configuration and mathematical formulation, such as the proposed MOMBLP model and obtained GP, are presented in Section IV. In Section V, the simulation results are reported, and at the end of Section VI, the conclusion is provided.

II. RELATED WORK

The majority of current literature on energy management focuses on formulating Smart Building (SB) problems using Mixed-Integer Linear Programming (MILP). The MILP formulation is often applied to reduce the SB's overall energy consumption cost.

For example, in [15], an optimal charge and discharge process for a BESS on Micro-grid (MG) is presented to reduce the MG's operational costs. In [16], a MILP model for EV charging is proposed, taking into account the use of PV generation. The main goal is to reduce the cost from the external grid while keeping in mind the limited capacity of the power grid. Furthermore, constraints include vehicle-to-grid (V2G) and a dynamic pricing scheme.

In [17], a home energy management system is proposed to reduce electricity cost, peak to average ratio, and maximize consumer comfort. To achieve these goals, the authors have proposed a scheduling technique based on a bacteria foraging algorithm and a harmony search algorithm. The concept of coordination among appliances was also proposed and implemented. The results showed that when compared to the 'without coordination' scenario, the cost of electricity use is reduced. The developed scheme proved to efficiently manage the load in order to reduce electricity consumption cost, peak to average ratio, and also increase the user comfort. In [18], a residential demand-side management strategy is implemented to make energy usage more efficient. For that purpose, 3 heuristics were used to schedule residential electrical equipment. Three performance indicators were used to evaluate those proposed algorithms: peak to average ratio, electricity consumption cost, and consumer comfort. Despite the best values for all 3 performance parameters cannot being achieved simultaneously, the implemented heuristic algorithm (hybrid elephant adaptive cuckoo) revealed efficiency in managing the load consumption. The authors of papers [19] and [20] investigate the possibility of decreasing the energy costs by moving loads from high-demand to low-demand periods time by charging and discharging EVs and BESS.

In [20], the peak load is minimized in the SB by using an energy management system. It is assumed that the CP of each client is flexible and a single CP is applied for the whole building. The problem is formulated by a Mixed Binary Linear Programming formulation (MBLP) in which a binary variable is defined to show the state of charging and discharging of EVs and BESS. In [19], a Multi-Objective Mixed-Binary Linear Programming (MOMBLP) approach is designed to minimize both total consumption and peak load at the same time. The SB takes into account the installation of PV generation panels, EV, and BESS in each consumer. Furthermore, flexible contract power value is assumed for each apartment, with a single CP to provide the building demand. The major goal of this research study was to use MOMBLP to find the optimized process for charging and discharging EV batteries and BESS with the two aforementioned objectives. In [21], an MBLP formulation is proposed to minimize the total electricity cost, in which the the whole residential building is powered by a single contract power and an energy management system is considered for managing the flow of power among the resources. In the proposed problem, the optimal contract power value is determined where in [20] the contract power was fixed. Moreover, the best charging and discharging schedule for EVs and BESS id obtained. Authors improved the electricity bill in [21] by finding the optimal value of contract power and optimal size of BESS in [22].

The main difference of this work with previous work [19], [20], and [21] is proposing a MOMBLP model in which the energy consumption cost of each consumer is considered as objective functions. In addition, the GP approach is used for solving the proposed model to find the more appropriate solution with fair benefit among the building users.

III. MULTI-OBJECTIVE OPTIMIZATION AND GOAL-PROGRAMMING METHODOLOGY

Most of the real-world problems are formulated with the Multi-Objective Optimization Problem (MOOP) [23]. Formally, a standard formulation of the MOOP with r objective function can be presented as follows:

$$\text{MOOP}: \begin{cases} \text{Min} \quad \mathcal{J}(\boldsymbol{y}) = [J_1(\boldsymbol{y}), \cdots, J_r(\boldsymbol{y})], \\ S.t. \quad \boldsymbol{y} \in \Omega. \end{cases} \tag{1}$$

where Ω is known as *feasible set* and is denoted by $\Omega = \{\boldsymbol{y} \in \mathbb{R}^n \mid \boldsymbol{g}(\boldsymbol{y}) \leq 0,\ \boldsymbol{h}(\boldsymbol{y}) = \boldsymbol{0},\ \boldsymbol{g} \in \mathbb{R}^m,\ \boldsymbol{h} \in \mathbb{R}^k\}$. This problem is different from the SOOP with a single solution. There are several solutions called Pareto front [19].

Goal Programming (GP) is a practical method of dealing with MOOP [24], which can establish a balance between all solutions (Pareto front). Here, the following GP problems are considered:

$$\text{GP}: \begin{cases} \text{Min} \quad \boldsymbol{Z} = \sum_{i=1}^{r}(d_i^- + d_i^+), \\ S.t. \quad J_i(\boldsymbol{y}) + d_i^- - d_i^+ = z_i, \quad i = 1, \cdots, r, \\ \qquad \boldsymbol{y} \in \Omega, \\ \qquad d_i^- \geq 0, d_i^+ \geq 0 \quad i = 1, \cdots, r. \end{cases} \tag{2}$$

where, d_i^- and d_i^+ are the *negative deviation* and the *positive deviation* of i-th objective function J_i with respect to its goal z_i respectively. Moreover, the $\boldsymbol{z} = [z_1, \cdots, z_r]$ is the *desired level* or *main goal* of problem that specifies the maximum or minimum of each objective function that should be given as a solution to satisfy the decision maker's criteria. For each $i = 1, \cdots, r$, if $\boldsymbol{y}_i^* \in \Omega$ assume as an optimal solution for following SOOP.

$$\begin{cases} \text{Min} \quad J_i(\boldsymbol{y}), \\ s.t. \quad \boldsymbol{y} \in \Omega. \end{cases} \tag{3}$$

Then, the vector $\boldsymbol{z} = [z_1, \cdots, z_r] = [J_1(\boldsymbol{y}_1^*), \cdots, J_r(\boldsymbol{y}_r^*)]$ is the main goal of the MOOP (1). In other words, the GP approach defines a distinct function and finds a solution among the Pareto front that has less distance from the main goal.

IV. PROBLEM CONFIGURATION AND MATHEMATICAL FORMULATION

A. PROBLEM CONFIGURATION

The authors based their research on a collective residential building with J apartments and common service, such that each apartment has a solar PV panel and an EV, and the entire building may take advantage of a BESS and an Energy Management System (EMS), as shown in Figure 1. The EMS communicates with external grids, EVs, PVs, BESS, and apartment appliances, common services, and manages power flow among them to reduce the electricity building's expense, as shown in Figure 1. It should be noted that the EMS is connected to the power grid and can either buy or sell energy. Every EV's wallbox is developed as a bidirectional charger, allowing it to charge and discharge. Furthermore, each EV arrives and leaves the building exactly once during the day, and is plugged in as soon as the owner returns home. In this work, the EMS controls and shares the power generated by PVs and then uses it for the apartments' demand, charging the EVs, and, if required, injecting into the grid the electricity surplus. Moreover, as shown in Figure 1, a single CP is considered to provide electrical energy to the whole building, and the apartments have flexibility in their electricity consumption. The investigated problem is studied for a given long time-period time and formulated by a MOMBLP with J-th objective functions. The proposed MOMBLP provides the optimal schedule for the charge and discharge process of each EV and BESS to minimize the total costs of energy consumption of each apartment over the given period such that constraints are satisfied.

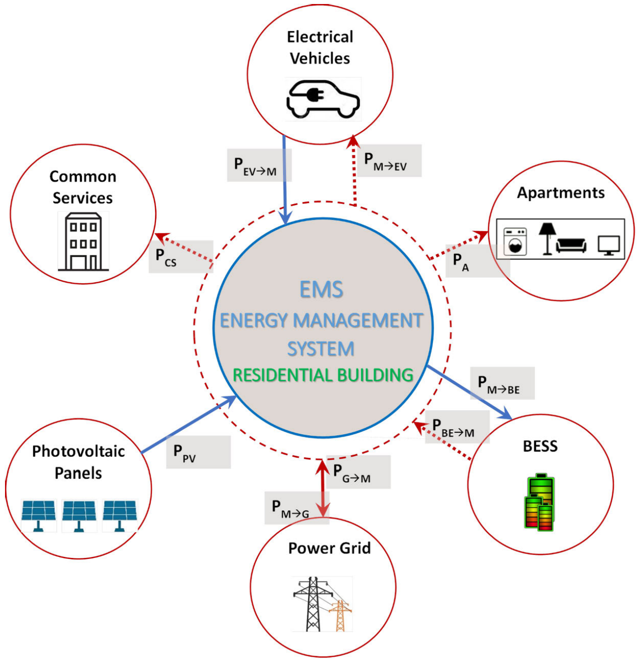

FIGURE 1. Proposed smart residential building approach.

B. REQUIRED PARAMETERS AND VARIABLES

This sub-section contains all of the required sets, parameters, and decision variables. The considered time is presumed to contain D day(s) of length *tau* time-step. Let T represent the total number of time-steps in the considered time, and J represents the number of apartments or EVs. Table 1 describes the necessary sets, parameters, and variables, which also include their explanations, based on the problem structure in Section IV-A. Figure 2 is drawn to help understand the role of parameters and variables.

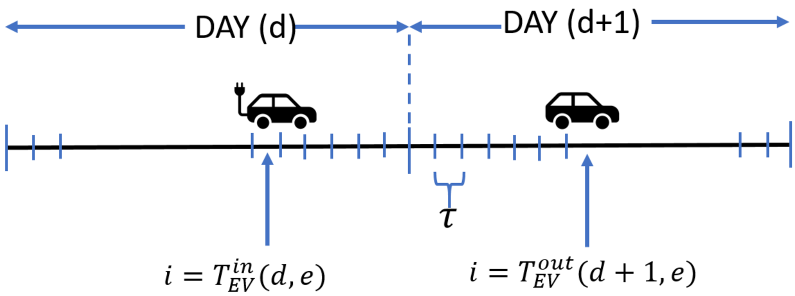

FIGURE 2. Visualizing the exit and arrival times for EV of *e*-th apartment in day *d*.

Notice that $d \in \mathbb{D}$ denotes the day index and $d = 0$, $d = D+1$ appear as indexes in certain variables and parameters in Table 1. These indexes describe the start and end times of the time-period under consideration. Here, $T^{\text{in}}_{\text{EV}}(d, e)$, $d \in \mathbb{D}$ denotes the arrival time-step in day d, and $T^{\text{in}}_{\text{EV}}(0, j)$ and $T^{\text{in}}_{\text{EV}}(D+1, e)$ denote the first and last time-steps, respectively. Furthermore, when EV e is outside in period t, so the value of $S_{\text{EV}}(t, e)$ must be ignored in the formulation.

For purpose of effortlessness, the list $t \in \mathbb{T}$ is considered for S_{EV} in table 1, But we care about it in the objective function and constraints.

C. MATHEMATICAL FORMULATION

Here, a multi-objective framework is used to formulate the problem described in Section IV-A. This research also aims to determine the best schedule for charging/discharging of the EVs and BESS during the study period to reduce the overall electricity costs of each apartment, at the same time. For this purpose, the detail of mathematical formulations is carried out in the following sections.

1) OBJECTIVE FUNCTION

The objective of the proposed Multi-Objective Mixed Binary linear problem (MOMBLP) is to minimize the total consumption cost of each apartment individually is given by Equation (4).

$$\text{Minimize } \mathcal{J} = \{J_1, \cdots, J_E\}. \tag{4}$$

that, each objective function J_e, $e \in \mathbb{E}$ is defined as:

$$J_j := \sum_{t\in\mathbb{T}} C^{\text{buy}}_{\text{G}}(t)[P_{\text{M}\to\text{EV}}(t, e) + P_{\text{A}}(t, e)] - \sum_{t\in\mathbb{T}} C^{\text{sell}}_{\text{G}}(t)[P_{\text{EV}\to\text{M}}(t, e) + P_{\text{PV}}(t, e)], \quad e \in \mathbb{E}. \tag{5}$$

2) CONSTRAINTS

In this sub-section, the physical boundaries of the energy resources and the assumptions about the problem in the proposed MOMBLP model are considered. In what follows, the required constraints that should be considered for Battery Energy Storage System (BESS) are briefly presented.

$$S^{\min}_{\text{BE}} \le S_{\text{BE}}(t) \le S^{\max}_{\text{BE}}, \quad t \in \mathbb{T}, \tag{6}$$

$$S_{\text{BE}}(0) = S^{\text{initial}}_{\text{BE}}, \tag{7}$$

$$P_{\text{M}\to\text{BE}}(t) \le \alpha_{\text{BE}}(t) P^{\text{ch}}_{\text{BE}} \tau, \quad t \in \mathbb{T}, \tag{8}$$

$$P_{\text{BE}\to\text{M}}(t, e) \le \beta_{\text{BE}}(t, e) P^{\text{diss}}_{\text{BE}} \tau, \quad t \in \mathbb{T}, \tag{9}$$

$$S_{\text{BE}}(t+1) = S_{\text{BE}}(t) + P_{\text{M}\to\text{BE}}(t) E^{\text{ch}}_{\text{BE}} - \frac{P_{\text{BE}\to\text{M}}(t)}{E^{\text{diss}}_{\text{BE}}}, \quad t \in \mathbb{T}, \tag{10}$$

$$\alpha_{\text{BE}}(t) + \beta_{\text{BE}}(t) \le 1, \quad t \in \mathbb{T}. \tag{11}$$

Here, Equation (6) presents the capacity constraints of State-of-Charge (SoC) of BESS battery. The initial charge value of BESS is shown in the constraints (7). Equations (8) and (9) illustrate the charging/discharging restrictions of BESS. The equations (10) computes the SoC of BESS in each period. Finally, the charging/discharging process of BESS does not occur concurrently which is guaranteed by constraints (11).

Similar to BESS constraints, the following constraints are considered for EVs:

$$0 \le S_{\text{EV}}(t, e) \le S^{\max}_{\text{EV}}(e), \quad t \in \mathbb{T}, \ e \in \mathbb{E}, \tag{12}$$

$$S_{\text{EV}}(T^{\text{in}}_{\text{EV}}((d, e) - 1), e) = S^{\text{initial}}_{\text{EV}}(d, e), e \in \mathbb{E}, d \in \{0\} \cup \mathbb{D}, \tag{13}$$

$$P_{\text{M}\to\text{EV}}(t, e) \le \alpha_{\text{EV}}(t, e) P^{\text{ch}}_{\text{EV}}(e) \tau, \quad t \in \mathbb{T}, \ e \in \mathbb{E}, \tag{14}$$

$$P_{\text{EV}\to\text{M}}(t, e) \le \beta_{\text{EV}}(t, e) P^{\text{diss}}_{\text{EV}}(e) \tau, \quad t \in \mathbb{T}, \ e \in \mathbb{E}, \tag{15}$$

$$S_{\text{EV}}(t+1, e) = S_{\text{EV}}(t, e) + P_{\text{M}\to\text{EV}}(t, e) E^{\text{ch}}_{\text{EV}} - \frac{P_{\text{EV}\to\text{M}}(t,e)}{E^{\text{diss}}_{\text{EV}}}, \tag{16}$$

$$e \in \mathbb{E}, d \in \{0\} \cup \mathbb{D}, t = T^{\text{in}}_{\text{EV}}(d, e) - 1, \ldots, T^{\text{out}}_{\text{EV}}(d+1, e) - 2,$$

$$S_{\text{EV}}(T^{\text{out}}_{\text{EV}}(d, e) - 1, e) \ge S^{\text{min\_out}}_{\text{EV}}(e), \quad e \in \mathbb{E}, \ d \in \mathbb{D}, \tag{17}$$

$$S_{\text{EV}}(t, e) = 0, \ t = T^{\text{out}}_{\text{EV}}(d, e), \ldots, T^{\text{in}}_{\text{EV}}((d+1, e) - 2, \tag{18}$$

$$\alpha_{\text{EV}}(t, e) + \beta_{\text{EV}}(t, e) \le 1, t \in \mathbb{T}, \ e \in \mathbb{E}. \tag{19}$$

that the capacity of SoC of EV is presented by Equation (12). The Equation (13) shows the initial charge value of EV. Equations (14) and (15) illustrate the charging/discharging restrictions of EV. The SoC of EV in each period is updated

TABLE 1. The list of sets, parameters and variable.

Set	Index	Description
$\mathbb{T}=\{1,\ldots,T\}$	t	Set for numbers of time periods
$\mathbb{E}=\{1,\ldots,E\}$	e	Set for numbers of EVs
$\mathbb{D}=\{1,\ldots,D\}$	d	Set for numbers of day
Parameter	**Index**	**Description**
D		The days number
T		The time periods number
τ		Duration of time-slots
E		The apartments number
$P_{\text{A}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	Demand of e-th apartment in time t
$P_{\text{PV}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	The power Generated by e-th PV in time t
$T^{\text{in}}_{\text{EV}}(d,e)$	$e\in\mathbb{E}$, $d\in\{0\}\cup\mathbb{D}$	The time that EV e arrive to home in day d. If $d=0$, then $T^{\text{in}}_{\text{EV}}(d,e)=1$
$T^{\text{out}}_{\text{EV}}(d,e)$	$e\in\mathbb{E}$, $d\in\mathbb{D}\cup\{D+1\}$	The time that EV e exits home in day d. If $d=D+1$ then $T^{\text{out}}_{\text{EV}}(d,e)=T+1$
$S^{\text{max}}_{\text{EV}}(e)$	$e\in\mathbb{E}$	The maximum amount of SOC for EV e
$S^{\text{initial}}_{\text{EV}}(d,e)$	$e\in\mathbb{E}$, $d\in\{0\}\cup\mathbb{D}$	The value of SOC for EV e in departure time
$S^{\text{min\_out}}_{\text{EV}}(d,e)$	$e\in\mathbb{E}$, $d\in\mathbb{D}$	The minimum amount of SOC for EV e in the exit time
$P^{\text{ch}}_{\text{EV}}(e)$	$e\in\mathbb{E}$	Power for charging the e-th EV
$P^{\text{diss}}_{\text{EV}}(e)$	$e\in\mathbb{E}$	Power for discharging the e-th EV
$E^{\text{ch}}_{\text{EV}}(e)$	$e\in\mathbb{E}$	Efficiency charge for e-th EV
$E^{\text{diss}}_{\text{EV}}(e)$	$e\in\mathbb{E}$	Efficiency discharge for e-th EV
$S^{\text{max}}_{\text{BE}}$		Maximum value for SOC of BESS
$S^{\text{initial}}_{\text{BE}}$		Initial value of SOC of BESS in initial time
$S^{\text{min}}_{\text{BE}}$		Minimum value for SOC of BESS
$C^{\text{buy}}_{\text{G}}(t)$	$t\in\mathbb{T}$	The electricity consumption cost in time t
$C^{\text{sell}}_{\text{G}}(t)$	$t\in\mathbb{T}$	The revenue for selling electricity to external grid in time t
$P^{\text{ch}}_{\text{BE}}(t)$	$t\in\mathbb{T}$	Power for charging the BESS in time t
$P^{\text{diss}}_{\text{BE}}(t)$	$t\in\mathbb{T}$	Power for discharging the BESS in time t
CP		Contract Power value
Variable	**Index**	**Description**
$\alpha_{\text{EV}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	Binary variable for showing the charge state of EV e in period t
$\beta_{\text{EV}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	Binary variable for showing the discharge statues of EV e in period t
$\alpha_{\text{BE}}(t)$	$t\in\mathbb{T}$	Binary variable for showing the BESS charging process in period t
$\beta_{\text{BE}}(t)$	$t\in\mathbb{T}$	Binary variable for showing the BESS discharging process in period t
$S_{\text{EV}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	The value of SOC for e-th EV in interval $[T^{\text{in}}_{\text{EV}}, T^{\text{out}}_{\text{EV}}]$
$S_{\text{BE}}(t)$	$t\in\mathbb{T}$	The value of SOC for BESS in time t
$P_{\text{M}\to\text{G}}(t)$	$t\in\mathbb{T}$	Power from EMS to grid
$P_{\text{G}\to\text{M}}(t)$	$t\in\mathbb{T}$	Power from grid to EMS
$P_{\text{M}\to\text{EV}}(t,e)$	$t\in\mathbb{T}, e\in\mathbb{E}$	Power from EMS to e-th EV

by equations (16). The constraint (17) describes the minimum value of SoC for the exit. And finally, the charging/discharging process of EVs does not occur concurrently which is guaranteed by constraints (19).

The following constraint represents the power balance in each period $t\in\mathbb{T}$:

$$P_{\text{G}\to\text{M}}(t)+\sum_{e\in\mathbb{E}}P_{\text{EV}\to\text{M}}(t,e)+\sum_{e\in\mathbb{E}}P_{\text{PV}}(t,e)+P_{\text{BE}\to\text{M}}$$
$$=P_{\text{M}\to\text{G}}(t)+\sum_{e\in\mathbb{E}}P_{\text{A}}(t,e)+\sum_{e\in\mathbb{E}}P_{\text{M}\to\text{EV}}(t,e)+P_{\text{M}\to\text{BE}}+P_{\text{C}}(t),$$
$$t\in\mathbb{T}. \tag{20}$$

The following constraints limit the electricity consumption from the external power grid and electricity injected into the external power network, namely:

$$P_{\text{G}\to\text{M}}(t)\le \text{CP},\quad t\in\mathbb{T}, \tag{21}$$
$$P_{\text{M}\to\text{G}}(t)\le \tfrac{1}{2}\text{CP},\quad t\in\mathbb{T}. \tag{22}$$

D. GOAL-PROGRAMMING MODEL

In the next step, the developed Multi-Objective Mixed Binary Linear Problem (MOMBLP) is transformed into a Goal Programming model (GP). In the GP problem, the desired level (or goals) of each objective function are defined. Additionally, upward deviations are superscripted with an d_e^+, $e\in\mathbb{E}$, while d_e^-, $e\in\mathbb{E}$ superscripts are utilized to address downward deviations. The purpose of the GP problem is to minimize the deviation of all objectives function J_e, $e\in\mathbb{E}$ from the set goals. Therefore, the corresponding GP of the proposed problem in Section IV-A is formulated as:

$$\text{Min } \mathbf{Z}=\sum_{e=1}^{\mathbb{E}}(d_e^-+d_e^+), \tag{23a}$$
$$\text{S.t. } d_e^- - d_e^+ + \sum_{t\in\mathbb{T}}C^{\text{sell}}_{\text{G}}(t)[P_{\text{M}\to\text{EV}}(t,e)+P_{\text{A}}(t,e)] \tag{23b}$$
$$-\sum_{t\in\mathbb{T}}C^{\text{buy}}_{\text{G}}(t)[P_{\text{EV}\to\text{M}}(t,e)+P_{\text{PV}}(t,e)]=z_e,\ e\in\mathbb{E},$$
$$\begin{cases}\text{BESS constraints (6)} - \text{(11)}\\ \text{EVs constraints (12)} - \text{(19)}\\ \text{Power Generation constraints (20)} - \text{(22)},\end{cases} \tag{23c}$$
$$d_e^-\ge 0,\ d_e^+\ge 0\quad e\in\mathbb{E}. \tag{23d}$$

Here, z_e, $e\in\mathbb{E}$ are desired level or goals of each objective function J_e and d_e^-, d_e^+ are the deviational variables.

V. RESULTS AND DISCUSSION

In this section, the proposed Goal Programming model in section IV-D is considered for a residential smart building containing 15 apartments to minimize the total consumption cost of each apartment.

The value of the main parameters is listed in Table 2. Each customer is equipped with one EV and one PV solar panel system with a capacity value of 0.5 kWp. The parameters, like the load demand of apartments P_{A}, the common services P_{C}, the PVs solar panels P_{PV} and arrival/departure time of EVs $T^{\text{in}}_{\text{EV}}/T^{\text{out}}_{\text{EV}}$ are recorded for every 15 minutes. Some recorded data was discovered to be missing. A regression approach and adjacent interpolation methods were used to obtain the value of missing data. The time slot in this work is one year and tau = 15 minutes, as previously mentioned. Each day split into $24\times4=96$ time-steps and then, the considered time has $T=96*365=35040$ time-steps. Furthermore, the initial SoC of EVs in the initial time $S^{\text{initial}}_{\text{EV}}(e)$ is determined randomly. Here, the energy tariff from the Portuguese energy regulator

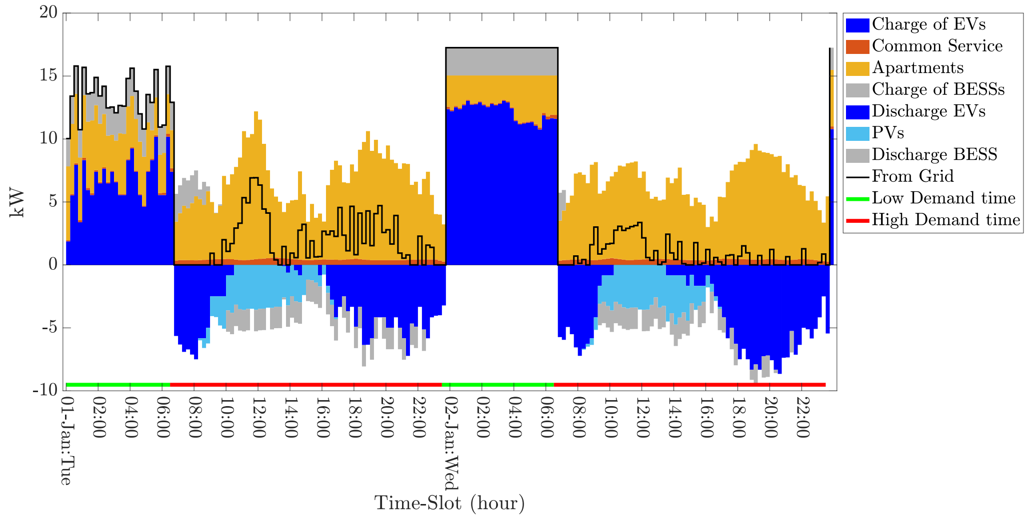

FIGURE 3. Power trace among apartments, external grid, EVs, PV, and BESS.

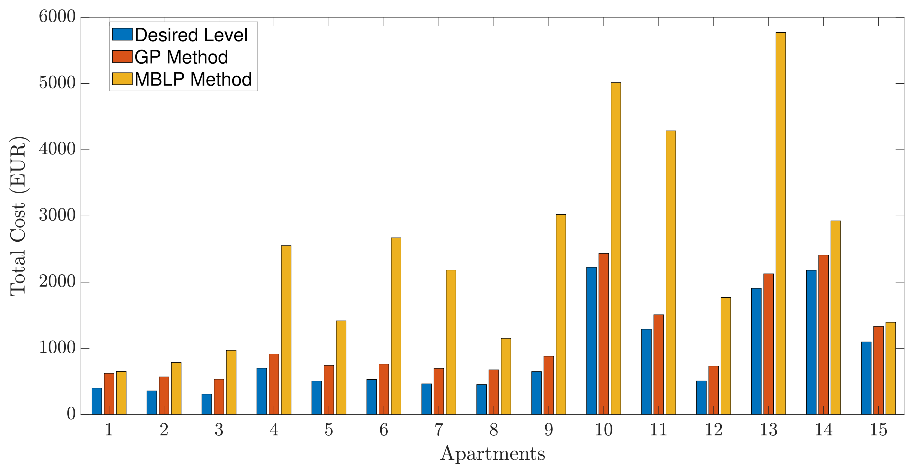

FIGURE 4. Comparison of the annual consumption cost of each apartment in GP with MBLP Methods ([20], [21]), and desired leve.

TABLE 2. Value of parameters in considering SB.

Parameter Symbol	Value	Unit
D	365	day
τ	15	Minutes
$S_{\text{EV}}^{\text{max}}$	27.2	kWh
$P_{\text{EV}}^{\text{ch}}$	3.7	kW
$P_{\text{EV}}^{\text{diss}}$	3.3	kW
$E_{\text{EV}}^{\text{ch}}$	0.92	-
$E_{\text{EV}}^{\text{diss}}$	0.93	-
$C_{\text{G}}^{\text{sell}}(t)$	0.04	€
$S_{\text{BE}}^{\text{initial}}$	0	kWh
CP	20.7	kVA

was obtained to simulate a realistic value for the grid energy price ($C_{\text{G}}^{\text{buy}}$) considered in the work.[1]

[1] Energy consumption price obtained in https://www.erse.pt

TABLE 3. Desired level value (goal) of each apartment.

$\mathbf{z}_1$	401.3 €	$\mathbf{z}_5$	507.5 €	$\mathbf{z}_9$	650.2 €	$\mathbf{z}_{13}$	1907.7 €
$\mathbf{z}_2$	358.3 €	$\mathbf{z}_6$	530.7 €	$\mathbf{z}_{10}$	2225.4 €	$\mathbf{z}_{14}$	2181.0 €
$\mathbf{z}_3$	310.5 €	$\mathbf{z}_7$	464.9 €	$\mathbf{z}_{11}$	1290.7 €	$\mathbf{z}_{15}$	1097.9 €
$\mathbf{z}_4$	701.9 €	$\mathbf{z}_8$	453.9 €	$\mathbf{z}_{12}$	508.6 €	**Total Cost**	**13591.2 €**

In order to evaluate the desired level z_e before using the proposed model (23), the CPLEX solver was applied for solving the corresponding SOOP (3) for the problem described in Section IV-A. The obtained desired level of the Multi-Objective Mixed Binary linear problem (MOMBLP) (4)-(22) is depicted in Table 3.

Then, the Goal Programming (GP) approach (23) is applied to the problem with the desired goals z_e, depicted in Table 3. The annual consumption cost of each apartment (as well as the total consumption cost of the building) are reported in Table 4.

TABLE 4. Annual consumption cost (EUR) of each apartment and building in GP and MBLP methods.

Apartment	Method		Apartment	Method	
	GP	MBLP		GP	MBLP
Ap1	624.2	470.2	**Ap9**	883.4	938.5
Ap2	569.8	519.9	**Ap10**	2434.4	3375.1
Ap3	535.4	439.6	**Ap11**	1508.3	1675.7
Ap4	915.7	1409.2	**Ap12**	733.8	745.8
Ap5	744.5	648.7	**Ap13**	2126.3	2008.7
Ap6	763.9	1200.8	**Ap14**	2409.7	1845.2
Ap7	699.1	885.2	**Ap15**	1332.7	1421.9
Ap8	676.4	754.8	**ToTal Cost**	**16,958.18**	**18,339.77**

Furthermore, the interactions among the resources, such as energy consumption from the external power grid, the power generation by solar PVs panel, the load consumption of the building, and the used energy for charging/discharging EVs during one day are plotted in Figure 3 with different colors.

As mentioned in Section IV-A, the Goal Programming approach is proposed aiming to minimize the total electricity cost of each apartment. To evaluate the performance of the proposed model (23), the obtained results were compared with the classic model [20]. In the classic model, the objective function is considered as a single-objective Mixed-Binary linear Problem (MBLP) that minimizes the total consumption cost of the whole building [21]. The results of both approaches (GP and MBLP) are compared in Table 4 and Figure 4.

Figure 4 shows that the GP approach finds a solution with less distance from the desired level than MBLP methods. As reported in Table 4, the total consumption cost of the building is improved by considering the GP model in comparison with the MBLP model.

VI. CONCLUSION

The main aim of this research was to minimize the overall consumption cost of a residential SB that included Electric Vehicles (EV), Battery Energy Storage Systems (BESS), and Photovoltaic (PV) generation system. In this regard, a flexible contract power was proposed for each apartment, as well as a single contract power for the entire SB. The Energy Manager System (EMS) was also considered for managing the power flow among resources (EVs, PVs, BESS), and apartments, common service, and external power grid.

The considered problem is formulated by a multi-objective mixed binary linear problem (MOMBLP) in which the objective functions are the total consumption cost of each apartment. The proposed MOMBLP is reformulated by a Goal Programming (GP) problem to obtain the most appropriate solution.

Finally, the results of the GP approach were compared with a classic model, namely the Single-Objective Mixed-Binary linear Problem (SOMBLP) to minimize the total electricity cost of the whole building. Simulation results have shown that the developed GP approach successfully optimizes the energy management system for finding the optimal charging/discharging process of EV and BESS. Furthermore, an optimal solution with the shortest distance from the desired level was discovered.

The results demonstrated that using the Goal Programming approach it was obtained about 7.5% reduction in electricity consumption costs when compared to SOMBLP. For future work, the authors intended to extend this concept to a set of residential buildings (private condominiums) and also consider the uncertainty for PV generation and load consumption.

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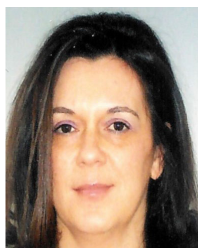

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