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Peer-reviewed version available at *Energies* **2020**, *13*, 1719; doi:10.3390/en13071719

Type of the Paper (Article)

A Mixed-Binary Linear Programming Model for Optimal Energy Management of Smart Buildings

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Abstract: Efficient alternatives in energy production and consumption are constantly investigated by increasingly strict policies. In this way, the pollutant emissions that contribute to the greenhouse effect reduce and sustainability of the electricity sector increase. With more than a third of the world's energy consumption, buildings have great potential to contribute these sustainability goals. Additionally, with growing incentives in the Distributed Generation (DG) and Electric Vehicle (EV) industry, it is believed that Smart Buildings (SBs) can be a key in the field of residential energy sustainability in the future. In this work, an energy management system in SBs are developed to reduce the power demanded of a residential building. In order to balance the demand and power provided by the grid, microgrids such as Battery Energy Storage System (BESS), EVs and Photovoltaic Generation panels (PV) are used. Here, a Mixed Binary Linear Programming formulation (MBLP) is proposed to optimize the charge and discharge scheduling of EVs and also BESS. In order to show the efficiency of the model, a case study involving three scenarios and an economic analysis is considered. The results point a 65% reduction in peak load consumption supplied by grid and a 28.4% reduction in electricity consumption costs.

Keywords: Distributed Generation; Energy Resource Management; Optimization; Mixed-Binary Linear Programming; Smart Buildings

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1. Introduction

Due to its great potential to be exploited, there has been a significant increase in investments in DG ventures worldwide. This is noticeable due to the increase in programs that aims the popularization of renewable energy sources implementation, in addition to investments in Research and Development (R&D) and publications of works in this field. To contextualize, in 1994, the Japanese government subsidized 50% of the investment for implantation of photovoltaic generation in about 70,000 roofs [1]. In Europe, the German government in 1999 launched the 100,000 Roofs Solar Program aiming the installation of photovoltaic generation on 100,000 roofs with 10-year financing at 0% interest rate [2]. According to [3], in 2017, China had the largest power capacity of wind turbines in the world with 164 GW installed. The United States and Germany had 89 GW and 56.1 GW, respectively.

In a consequence of the popularization of sustainable policies and the advancement in the DG field, SG is strengthened as techniques to control operation, generation and consumption of electric energy. Thus, by exploiting the evolution of information technology, this technique tends to replace manual generation and consumption measurement methods for computerized systems, allowing to obtain real-time data, to create a database with historical information, in order to operate the system remotely and also monitor failures and the quality of energy.

European Union (EU) intends that new buildings should be nearly Zero Energy Buildings (nZEB). It means that these buildings should be able to produce the amount of electrical energy they

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consume. Therefore, the EU strongly incentive to develop renewable energy sources and adequate strategies for their operation.

EVs and have great potential to dominate the automotive sector in a few years, and therefore, this market is on great expansion. In this way, policies aiming at the implementation of recharge points in residential buildings are beginning to emerge, mainly intending to reduce environmental and noise pollution, besides the consumption of fossil fuels. As EVs reach significant numbers in the automotive market, power distributors need to adapt to a new type of load that can be a significant impact on the power network.

New approaches are exploring the advantages of using the electrical energy stored in EVs to inject into the power grid at appropriate times, which is called Vehicle-to-Grid (V2G).

Therefore, charging and discharging preferences must comply with certain standards and protocols. The available energy that is injected into the power grid is defined by the driver to protect their needs. Charging and discharging periods must occur at different times, which can open doors to conciliation strategies, such as charging the batteries during the period of low consumption and discharging the energy during the period of high consumption [4].

The proposed paper aims to model an optimization problem considering the energy resources of a residential building, such as PV, EVs and BESS, and also considering the contracted power flexibility of each apartment, in order to reduce the building power demand.

During the mathematical formulation of the problem, it is assumed that the generated power data of the photovoltaic system, the load profile of the building and the trips of the EVs are known, from forecasting methods.

The energy resources scheduling problem is formulated as a MBLP problem, where the decision variables represent the charging and discharging process in each period of EVs and the BESS. Therefore, these variables must be binary, and it is used MBLP algorithms to obtain optimal solutions.

The remaining of this paper is organized as follows. In Section 2, a brief literature review related to SBs optimization is presented. In section 3, it is presented the methodology used in this work, as well as the mathematical formulation. Section 4 presents the results obtained to validate the developed method, considering 3 different scenarios and an economic analysis. In section 5, a brief discussion of the results and further works are suggested. Finally, the last section summarizes the concluding remarks.

2. Literature Review

The 21th century can already be characterized by the implementation of policies aiming the sustainability, having as one of the great challenges to reduce the Ecological Footprint [1]. In the electricity sector, there are large investments for the development of renewable energy sources within the DG, mainly due to the increasing number of works related to SBs [5].

It is known that combustion vehicles represent 18% of the world's carbon dioxide (CO2) emissions. The EU has committed itself to reduce emissions by up to 25% by the present year of 2020. As a result, the highlight of EVs on the world stage is increasing, which gives rise to works related to this technology. Thus, many studies take advantage of the large penetration amount of DGs ventures to reduce electricity costs, peak load demand, and even reduction in CO2 emissions, and also optimize the scheduling of charging and discharging EVs process as well as BESS [5,6].

With the objective to mitigate the problem caused by uncertainties in the generation of renewable sources, the work presented in [7,8], proposes a day-ahead optimization problem for managing energy resources, considering forecast errors, dispatching of EVs and energy markets. The problem is formulated through Mixed Integer Linear Programming (MILP) formulation due to the large presence of continuous, discrete and binary variables, in order to minimize operating costs and maximize the profit. The problem constraints involved active power balance, distributed generation,

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[1] Ecological footprint is an ecological indicator for the amount of land and water, measured in hectares, needed to sustain current generations.

energy supply in each period, rate and efficiency of EVs' charging and discharging process, capacity and requisition of EVs trips.

In [9], a consumer-dependent system to manage energy and find a balance between cost and CO2 emissions is developed. In this way, a model is proposed, where it is intended to involve the manager of the building in the decisions of the renewable energy use acceptability, even though it is more expensive than energy from non-renewable sources. The formulation of the problem is done by Linear Programming (LP), where it is planned to minimize the energy cost by assigning weights to each type of source, in which their price, the consumer acceptability and initially provided are considered by the building manager. The constraints of the proposed model are the system energy balance, the limits related to energy from renewable and non-renewable sources, the minimum and maximum limits of BESS energy storage capacity and the limit of energy supplied by a diesel generator.

The work developed by [10] presents an approach to find the optimal scheduling for EVs charging and discharging processes in SB context. Artificial Neural Networks are used to predict the power load demand of the building and photovoltaic energy generation, where the problem is formulated as LP. The objective function is formulated in order to minimize the total energy costs, while its constraints cover the limits for the EVs' batteries State of Charge (SOC), charging and discharging limit rate, besides considering that the EV must be with the battery fully charged at end of the period and the system cannot inject power into the power network.

The references [11] and [12] present works involving the operation of SBs considering local generation and the use of EVs as an energy resource. In [11] optimize the charging and discharging process of Plug-In Hybrid Electric Vehicles (PHEVs), in order to reduce the power demand of the building and its electricity costs. The objective function is formulated intending to minimize the costs of the energy supplied by the grid, while its constraints present the update and limits for the PHEV battery SOC, the system energy balance and ensure that the system should not sell and buy energy from the power grid at the same time. In [12], a MILP model is presented to minimize the total daily cost with electric energy consumption and also the stochastic model is considered to forecast PV generation and building load demand.

In [13] the effect of a PHEV fleet on a building demand profile in Belgium is analyzed. The main goal is to develop a MILP formulation to minimize energy demand and electricity costs. The objective function presents the same approach as in [11], where its restrictions use binary variables to ensure that the PHEV is not charging and discharging at the same time, while the available energy in the batteries must respect its minimum and maximum limits and guarantee the system energy balance.

The work presented by [14] proposes a study through MILP formulation to schedule EVs charging and discharging processes and an energy storage system. The method defines an ideal charging time for a day, considering the arrival and departure periods of the EVs and their initial SOC. In [15], optimal scheduling for a BESS on a Microgrid (MG) application is proposed. For this, a MILP formulation is developed to minimize the operating cost of the MG and is solved through the CPLEX tool. The constraints of the problem involve the system energy balance, electrical energy and power limits for the EVs and the BESS. Besides, binary variables are used to ensure that resources cannot be charged and discharged at the same time.

In [16], mathematical models for different types of loads is presented, enabling their operation in real time. The objective function aims to minimize the peak load demand over a given day, while its constraints involve electrical energy and power limits for each type of load and the system energy balance. The proposed method is able to reduce the peak load demand, taking into account Demand Response (DR) schemes.

The work developed by [17], proposes an integrated model for the charging process of EVs using PV generation as a primary source. Therefore, it is considered a dynamic price scheme, V2G and the networks' capacity restriction to formulate a MILP problem. The objective function intends to minimize the total costs with electricity from the grid to charge the EVs.

The references [18] and [19] also consider PV generation to optimize the EVs charging process. Reference [18], has as main objective to minimize EVs charging cost, reduce the impact on the grid

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and to increase the energy consumption from the PV generation. The work considers a forecasting model for the PV generation and formulates the optimization problem through MILP. In [19] it is possible to find a collaborative assessment of dynamic prices and DR strategies based on the peak power limit with the possibility of bidirectional energy use for EVs and BESS. The paper proposes a model based on MILP formulation, considering a Home Energy Management (HEM) system. The HEM system considers small-scale renewable energy generation, V2G, BESS and DR strategies.

The work presented in [20], also develop an approach to find an optimal EV charging strategy, considering V2G, charging and discharging efficiency, and battery degradation. In this way, it is possible to analyze the viability of V2G and define limits for the model profitability. The problem formulation provides a linear objective function, with the objective to minimize energy cost, and it is solved by integer linear programming.

3. Methodology

In order to reduce the power demanded of a residential building, the scheduling of the charging and discharging process of EVs and a BESS are considered. The decision variables of the problem are binary. Therefore, the problem is formulated by a MBLP.

In the following subsection, the objective function and constraints of the proposed mathematical formulation are presented and the most important notation and parameters are shown in Table 1.

Table 1. Nomenclature of the Mathematical Formulation

Indices	
I	Index of time periods
J	Index of EVs
τ	The length of interval in each period "i"
Parameters	
P_g^i	Active power extracted from the grid in period "i" (kW)
c^i	penalty factor based on the available PV versus the consumption in period "i"
P_{sb}^i	Active power related to the smart building load expected in period "i" (kW)
P_{pv}^i	Active power related to the photovoltaic generation foreseen in period "i" (kW)
P_{ch_evj}	Active power related to the charging process of the EV "j" (kW)
P_{dis_evj}	Active power related to the discharging process of the EV "j" (kW)
σ_j^i	Binary parameter based on the forecasted EVs' trips, which represents the connection of the EV "j" in period "i"
P_{ch_B}	Active power related to the charging process of the BESS (kW)
P_{dis_B}	Active power related to the discharging process of BESS (kW)
SOC_j^{max}	Maximum SOC that EV "j" can assume in period "i"
SOC_j^{min}	Minimum SOC that EV "j" can assume in period "i"
$SOC_j^{min\_final}$	Minimum SOC that EV "j" can assume at the end of the period
SOC_B^{max}	Maximum SOC that BESS can assume in period "i"
SOC_B^{min}	Minimum SOC that BESS can assume in period "i"
P_g^{max}	Maximum power that the grid can feed the building (kW)
Variables	
α_j^i	Binary variable that represents the EV "j" charging process in period "i"
β_j^i	Binary variable that represents the EV "j" discharging process in period "i"
α_B^i	Binary variable that represents the BESS charging process in period "i"
β_B^i	Binary variable that represents the BESS discharging process in period "i"
SOC_j^i	SOC of the EV "j" at the start of period "i"
SOC_B^i	SOC of the BESS at the start of period "i"

3.1. Objective Function

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In the case under analysis, it is intended to minimize the peak load power demand by a residential building. For this goal, the building load forecasted, local photovoltaic generation, and the connection of "n" EVs, which are able to charge and discharge, and also a BESS for energy storage are considered, in "I" periods of time with one hour step ($\tau = 1$). In addition, the connection period of the EVs with the building is based on trip forecasts [7,8]. Therefore, the decision variables of the problem are binary and identified by α and β, which represent the charging and discharging EV "j", respectively, and the BESS in each time period "i". In this way, the objective function is presented by equation (1).

$$\min: \sum_{i=1}^{I} P_g^i \cdot c^i \quad (1)$$

In order to guarantee the system power balance, it is required to define the mathematical formulation of the electrical energy supplied by the power grid. As can be seen in equation (2), this is composed by the expected building load consumption, which is considered the power required to supply the demand of each apartment, as well as the common services. It is also considered the power generated by the photovoltaic panels and the EVs / BESS charging and discharging process.

$$P_g^i = P_{sb}^i - P_{pv}^i + \sum_{j=1}^{n} \left(P_{ch\_evj}^i \cdot \alpha_j^i - P_{dis\_evj}^i \cdot \beta_j^i\right) \cdot \sigma_j^i + P_{ch\_B}^i \cdot \alpha_B^i - P_{dis\_B}^i \cdot \beta_B^i \quad (2)$$

A cost power availability for EVs / BESS charging and discharging process, in period "i", is considered in equation (3). This parameter finds the most appropriate time to optimize the EVs / BESS charging and discharging process. Therefore, it is defined considering the power values related to the expected building loads and the generation of the PV panels.

$$c^i = \frac{\left(P_{sb}^i - P_{pv}^i\right)}{\min\left(P_{sb} - P_{pv}\right)} \quad (3)$$

It is worth noting that in this work it is assume that the consumption energy by SBs is higher than the PV production in each period.

3.2. Constrains

This subsection presents the constraints of the proposed MBLP problem. For the effectiveness of the model, it is necessary to ensure that the resources do not violate their physical limits and they are not charging and discharging at the same time. Also, there are restrictions for the minimum SOC of the batteries and the maximum value of the power to be consumed from the power grid.

3.2.1. Electric Vehicles Constraints

It is necessary to set the following restrictions to ensure that the physical limitations of the storage capacity of the EVs batteries are not violated. The updated formulation of SOC for each EV $i = 0, 1, \ldots, I-1$ is defined by constraint (4).

$$SOC_j^{i+1} = SOC_j^i + \sigma_j^i . \left(P_{ch\_evj} \cdot \alpha_j^i - P_{dis\_evj} \cdot \beta_j^i\right) \cdot \tau \quad (4)$$

Note that SOC_j^0 are the initial SOC value for each EVs when they connect with the building. Then, the constraint (5) is presented to guarantees the maximum value for the SOC that the battery of each EV can assume in each period "i".

$$SOC_j^i \le SOC_j^{max}, \quad i = 0, \ldots, I \quad (5)$$

In addition, the minimum SOC values of the EVs have to be defined. Although, they do not assume negative values. But, for the feasibility of the study, the minimum value for the SOC_j^i at $i = 1, 2, \ldots, I-1$ is set at 50% of their maximum capacity. Thus, the equations (6) and (7) represent the constraints for the minimum value of SOC_j^i at any period of time "i", $i = 1, 2, \ldots, I-1$ and in the last period ($i = I$).

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$$SOC_j^i \geq \sigma_j^i . SOC_j^{min}, (i = 1, 2, \dots, I-1), \tag{6}$$

$$SOC_j^I \geq SOC_j^{\min\_final}. \tag{7}$$

To avoid the charging and discharging of EVs at the same period, the constraint (8) is formulated.

$$\alpha_j^i + \beta_j^i \leq \sigma_j^i \tag{8}$$

Finally, the following constraints (9) and (10) are presented to ensure that the decision variables related to the EVs are binary.

$$\alpha_j^i \in \{0,1\}, \tag{9}$$

$$\beta_j^i \in \{0,1\}. \tag{10}$$

3.2.2. BESS Constraints

Here, with a similar approach that presented for the EVs in the last subsection, the necessary constraints for the SOC of BESS are defined. The constraint (11) presents the update formulation for the SOC of BESS in each period of time "i" with $i = 0, 2, \dots, I\text{-}1$.

$$SOC_B^{i+1} = SOC_B^i + \left(P_{ch\_B} \cdot \alpha_B^i - P_{dis\_B} \cdot \beta_B^i\right) \cdot \tau. \tag{11}$$

As proposed for the EVs' constraints, the constraint (12) guarantees the maximum SOC value that the BESS can assume in each period "i".

$$SOC_B^i \leq SOC_B^{max}, \qquad i = 0, \dots., I \tag{13}$$

In addition, the constraint (13) ensures that the SOC of the BESS system in each period "i" does not violate its minimum limit.

$$SOC_B^i \geq SOC_B^{min}, \qquad i = 1, \dots., I$$

In the same way, as proposed for the EVs, it is necessary to ensure that the BESS cannot charge and discharge at the same period "i", as formulated in (14).

$$\alpha_B^i + \beta_B^i \leq 1. \tag{14}$$

Finally, the decision binary variables related to the BESS are shown by equations (15) and (16).

$$\alpha_B^i \in \{0,1\}, \tag{15}$$

$$\beta_B^i \in \{0,1\}. \tag{16}$$

3.2.3. Load Grid Constraints

In this subsection, the constraint (17) is defined that represents the maximum power of grid that can feed the building during each period "i".

$$P_g^i \leq P_g^{max}, i = 1, \dots, I. \tag{17}$$

The presented model in this section was formulated as a MBLP problem. In order to solve this optimization problem, a mathematical programming language (AMPL) software is used. In this way, we use CPLEX solver to solve the MBLP in which the Branch and Bound (B&B) algorithm is used.

The results obtained from this application are presented and discussed in the next section.

4. Results

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In order to validate the proposed mathematical formulation in the previous section, a case study for a residential building with 12 apartments and various consumption profiles to reduce its peak power in the period of 6 hours is presented. Besides, it is assumed that the actual data of PV, total building electrical energy consumption, trips and initial value of SOC for the batteries of the EVs and BESS are known from forecasting methods [7,8].

4.1. Case Study

Here, the following three scenarios are considered as a case study in this work.

1. In the base scenario, the EVs start their charging process as soon as they are connected to the building and the process is stopped as soon as their SOC reaches 65% of its total capacity. Note that in this case, the discharge process does not occur as well as the BESS it is not considered.
2. In the second scenario, it is intended to optimize the schedule of the charging and discharging process for each EVs. Like the first scenario, the BESS is not considered.
3. The last scenario is similar to the second one but in this case, the BESS with a storage capacity of 500 kWh, is added to the model.

Finally, an economic analysis is performed for the scenarios considered in this work, where a contracted demand for the building is proposed, considering a penalty cost for each exceeded kWh and bonuses for users who choose to perform a DR when it is necessary.

In order to validate the developed model close to real situations, the characteristics of the EVs and the BESS are considered based on the market specifications.

In this respect, the characteristics of the EVs come from the BMW i3 94 Ah vehicle found on the manufacturer's website [20], while the BESS data come from the catalog of the company NARADA according to the model BESS-1000L [22]. Both data are presented in Table 2.

Table 1 – EVs and BESS specifications.

	Storage Capacity (kWh)	Charge Power (kW)	Discharge Power (kW)
BMW i3 94 Ah	27,2	3,7	3,33
BESS-1000L	500	6,3	5,67

Table 3 shows the value of some parameters regarding of the initial SOC of each 12 EVs that were considered.

Table 3 – EVs and BESS Parameters.

SOC_1^0	SOC_2^0	SOC_3^0	SOC_4^0	SOC_5^0
$38\%SOC_1^{max}$	$40\%SOC_1^{max}$	$37\%SOC_1^{max}$	$70\%SOC_1^{max}$	$40\%SOC_1^{max}$
SOC_6^0	SOC_7^0	SOC_8^0	SOC_9^0	SOC_{10}^0
$47\%SOC_1^{max}$	$80\%SOC_1^{max}$	$37\%SOC_1^{max}$	$40\%SOC_1^{max}$	$43\%SOC_1^{max}$
SOC_{11}^0	SOC_{12}^0	SOC_B^0	SOC_B^{max}	P_g^{max}
$78\%SOC_1^{max}$	$56\%SOC_1^{max}$	$80\%SOC_B^{max}$	100%Capacity	70

4.2. Base Scenario– EV charge up to 65% of its maximum SOC capacity

For validation of the developed MBLP optimization model, firstly, the base scenario is considered in which the EVs continue with their charging process until reaches 65% of their maximum capacity.

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Figure 1 shows the power curves of the building resource, as well as the electricity consumption from the power grid (Pg) in the analyzed period, which is the base value used for comparison with the other scenarios.

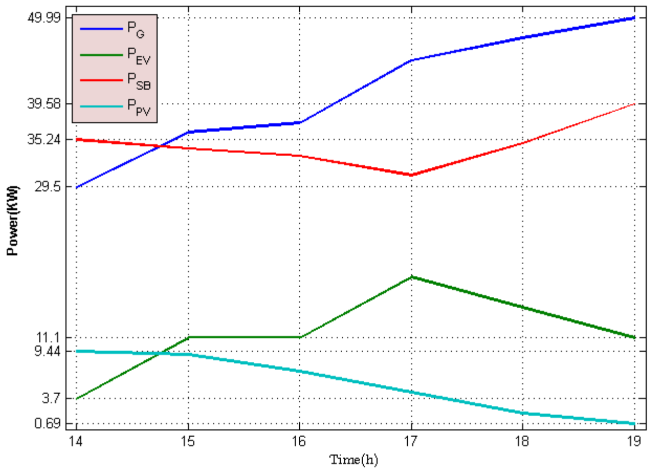

Figure 1 - Power curves analyzed from the building to the base scenario.

A simple analysis indicates that the peak power consumed from the power grid in this scenario reaches 49.99 kW and occurs at 19h. Therefore, the model proposed in this work intends to reduce this value (peak value) with a strategy of optimal scheduling for building resources.

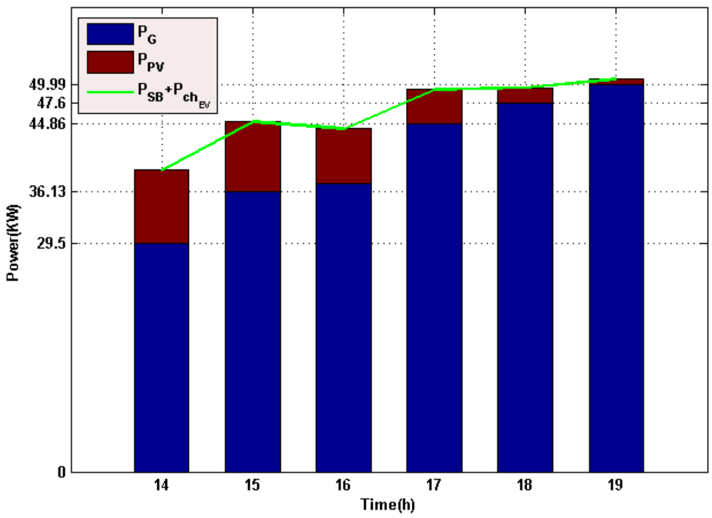

Figure 2 - Amount of grid and PV system power needed to feed the building load and the EVs charging in the base scenario.

It can be seen in Figure 2 that the ideal period for the EVs charging process occurs at the initial moments of the analyzed time horizon. However, the EVs' travel makes this difficult, because not all EVs are connected to the building in the initial periods.

4.3. Scenario 2 – Scheduling of the EVs Charging and Discharging Process

For this scenario, it is assumed that each vehicle starts it's charging process and discharging process in appropriate times that are considered by the model, to reduce the peak load demand from the grid during the period analyzed.

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When analyzing Figure 3, it can be seen that in the periods when the load demanded from the building was low, that is in the initial moments, then the model triggered the charge of the EVs. In the periods when the load demanded from the power grid was very high, therefore the store energy in EVs is discharged. It can be seen that the strategy assumed by the model made the peak load from the power grid to be reduced to 23.35 kW, obtaining 53% reduction when compared to the base scenario.

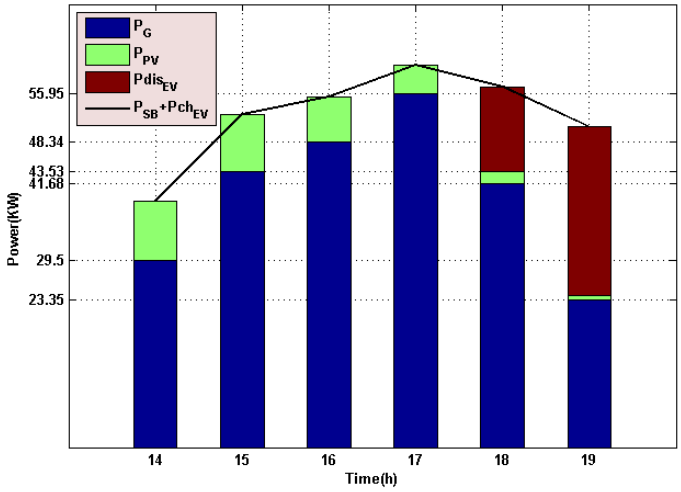

Figure 3 - Specification of each type of source that feeds the building and the EVs charging process in scenario 2.

In Figure 4 it is also possible to verify the impact of the model strategy. Note that some EVs had considerable variations during the period, but always respecting the minimum limit (50% of the capacity) that is defined for the entire period of analysis. It is still possible to verify that all vehicles have a SOC with at least 65% of the capacity at the end of the period.

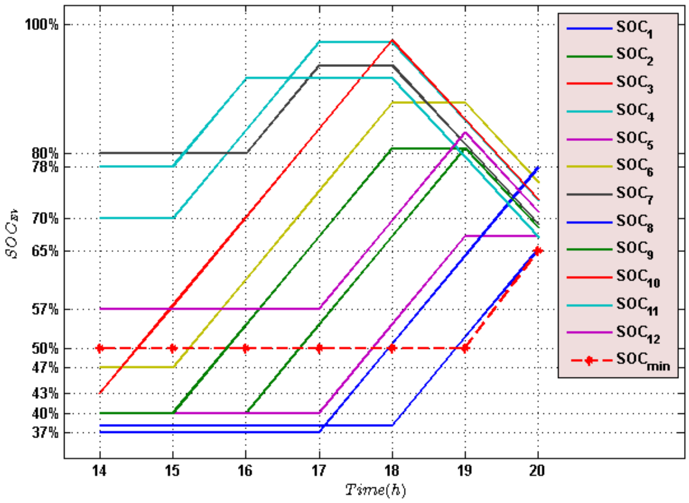

Figure 4 – SOC variation of each EV in scenario 2.

4.4. Scenario 3 - Scheduling of the EVs and BESS Charging and Discharge Process

In scenario 2, it was intended to minimize the peak load demand identified in scenario 1, which was able to manage the process of charging and discharging of each EV in the most appropriate way to comply with the objectives of the problem, without the presence of a BESS.

In scenario 3, a BESS with 80% initial SOC will be added to the model. It can be seen in Figure 5 that the model maintained the charging process of the EVs in the initial periods.

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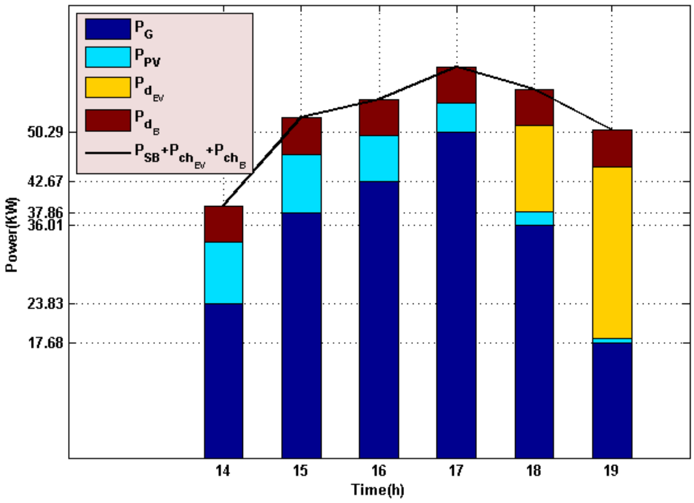

Figure 5 - Specification of each type of source that feeds the building and the EVs charging process in scenario 3.

By Figure 5, it is still possible to show that the BESS plays a fundamental role in the reduction of the peak load consumed from the power grid. Note that initially, it had a high initial SOC, 80%. It was possible to use the stored energy in the system to feed the building load and the EVs charging process, mainly in the time periods that it was needed to consume a significant electrical energy from the grid. It is also possible to observe that the stored energy in the EVs in the initial periods was discharged (in yellow) in the final periods. This process contributes to significantly reduce the peak load consumption from the grid and prove an effective adopted strategy by the developed model aligned with the objectives proposed in this study. Thus, it can be seen that the model was able to reduce the peak load consumed from the power grid to 17.68 kW, being this a reduction of 65% in comparison with scenario 1.

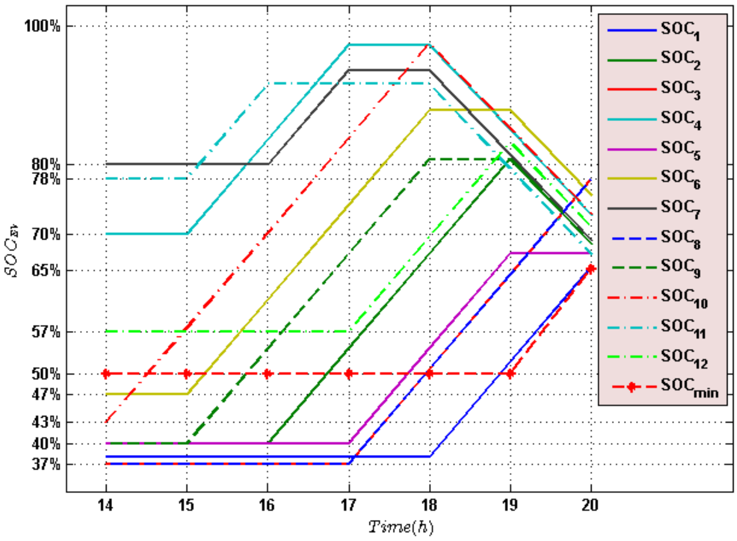

Figure 6 - SOC variation of each EV in scenario 3.

Finally, it is possible to confirm that at the end of the period all vehicles have a SOC at least 65% of their maximum capacity. It can also be observed that the variations pointed out in scenario 2 were maintained, respecting the minimum and maximum limits that are defined for the SOC of the EVs.

4.5. Economic analysis

By law, typically, each apartment has a contracted power value from a certain electricity supplier (in an electricity market environment). The considered building is formed by 12 apartments and a common area in which 6 apartments have a contracted power of 6.9 kW and the other 6 have a contracted power of 10.35 kW. The defined billing only takes into consideration the energy tariff, in €/kWh. In this way, it is possible to verify how much the building would spend with the electrical energy consumption bill considering real used tariffs [23]. Thus, by considering the contract power by each apartment individually, the building would spend €50.34 considering the electric energy spent in the analyzed period.

4.5.1. Comparison between Scenarios 1 and 2

In this part of the work, it is proposed that instead of hiring an individual power demand for each apartment, the building manager hires a value that covers the needs of apartments and common areas, managing the required demand for the EVs charging process. Thus, based on real load profiles, it is proposed to reach a contracted power for the entire building than can cover all power needs of 41.4 kW and a penalty of 3 €/kWh that exceeds this value.

It is possible to verify that the exceeded power demand values are not significant which allows considering a model of DR for the users that requiring a reduction in their consumption as soon as the exceedance of the proposed contracted power value of the building.

For this purpose, a subsidy (10% of the contracted demand tariff per each kWh reduction) is proposed to users join the DR. In this way, DR measures are advantageous for the building manager, who does not need to pay the overtaking penalty, and for the user who adhere to this measure receives a bonus on the electricity bill. Therefore, for scenario 1, a total building billing was € 46, 85, corresponding a reduction of 7% in the billing for the analyzed period. For scenario 2, there are 4 periods in which the grid power supply exceeds its proposed contracted limit, and these should present penalties. As a result, the billing for the period under analysis in scenario 2 would be € 42.38, corresponding a decrease of 10% in comparison with scenario 1.

4.5.2. Comparison between Scenarios 1 and 3

In this step, the same considerations made in the previous topic are assumed that is, the possibility to penalize the manager of the building for each exceeded kWh and the possibility of DR usage. Thus, in scenario 3 it is possible to verify that the electricity consumption exceeds the value of the proposed contracted power at two times (16h and 17h). The strategy adopted by the model in scenario 3, applying the appropriate tariffs, provided a 28.4% reduction in the costs concerning electricity consumption, resulting in a bill of € 36.05 for the analyzed period, and also, with a comparison with scenario 1, there was verified a reduction of 23%.

5. Conclusions and Further Work

In this work, three scenarios were considered in the case study. The first scenario considers that the EVs start their charging process as soon as they are connected to the building and the process is stopped as soon as their SOC reaches 65% of its total capacity. It is not considered the use of the storage system. The second one the charging and discharging process of EVs were optimized. The third one considered the optimization of the charging and discharging process of EVs and BESS. In addition, an economic analysis was presented among the scenarios, considering a time-of-day tariff (TOU).

Figure 7 depicts the curve of power consumption in several scenarios. When considering the possibility of managing the EVs and BESS charging and discharging process, positive results were obtained, where it was able to charge enough power in the initial periods and discharge it at a time when it needed a high building demand. With this, the reductions in the peak of the consumed power reached up to 65%.

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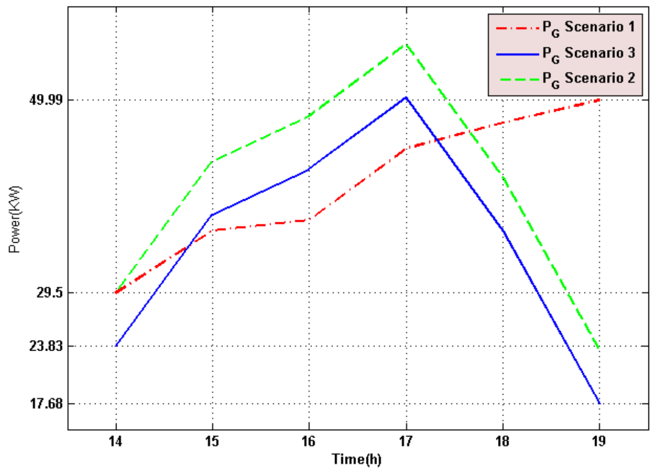

Figure 7 - Variation of the demanded power from the grid in all analyzed scenarios.

When carrying out an economic analysis, the data from scenarios 1, 2 and 3 were submitted to a TOU tariff structure, in accordance with the Portuguese legislation. Therefore, it was considered the possibility of the building contracting a single power to meet all its electricity demand, assuming a penalty for overtaking and a bonus for users that adheres to DR calls. With this, it was possible to obtain a reduction up to 28% with the costs in electricity, as shown in Figure 8.

When analyzing the obtained results, it is noticed that the management of energy resources in buildings is feasible and proves to be advantageous to its users. In this way, it is possible to conclude that the method developed in this work was effective, meeting the initially proposed objectives.

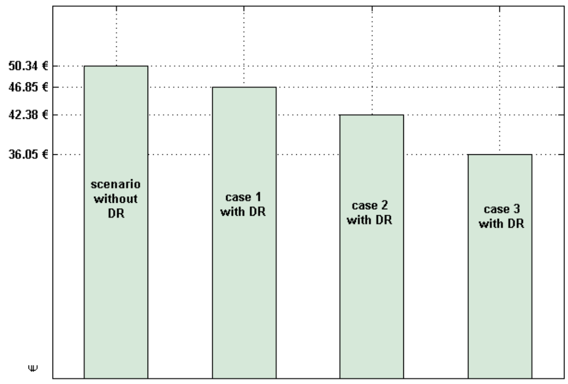

Figure 8 – Billing comparison among the several scenarios

5.1. Further Works

As discussed, some EVs were not able to perform the V2G process with the building, possibly due to the fact that the time horizon is relatively short (only 6 hours). Better results could be obtained for a greater time horizon, being able to increase the capacity of the model to more efficiently stagger the charging processes of the EVs.

In addition to the time horizon, it is suggested as future work, a two-level optimization. This is justified by the fact that the input data for the problem comes from forecasting methods. These, however, are not 100% consistent with reality and may present discordant with real-time situations. Thus, a two-level optimization would consider the data from forecasting methods to generate a schedule for the next day, and thereby perform a second-level optimization, considering next-day scheduling as input information for the model, and data from real-time measurements. With this approach, it could be possible to significantly increase the robustness of the model.

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Finally, it is suggested the possibility of associating a degradation cost to the EVs battery. Currently, the price of batteries is still very high, which hinders the economic viability of models that consider the process of charging these vehicles. As discussed in the state of the art, works that considered the cost of EV battery degradation has concluded that it is not economically feasible to use the vehicles for this purpose. With the development of new technologies, reducing the price of their batteries increases the chances of making their use, as a resource to be managed, viable in the near future.

Acknowledgment

This work has received funding from FEDER Funds through COMPETE program and from National Funds through FCT under the project UIDB/00760/2020 and BENEFICE – PTDC/EEI-EEE/29070/2017. João Soares is supported by FCT grant CEECIND/02814/2017.

References

1. Jiménez, V. Eco-Economy Indicators - World Sales of Solar Cells Jump 32 Percent | EPI Available online: http://www.earth-policy.org/indicators/index/solar_power_2004 (accessed on Feb 12, 2020).
2. International Energy Agency 100 000 Roofs Solar Power Programme – Policies Available online: https://www.iea.org/policies/3476-100-000-roofs-solar-power-programme (accessed on Feb 12, 2020).
3. REN21 Renewables 2018 Global Status Report Available online: http://www.ren21.net/gsr-2018/ (accessed on Feb 12, 2020).
4. Santos, P.M.C. O Automóvel Híbrido Como Elemento Fornecedor-Consumidor de Electricidade,. MSc Thesis, Lisboa: Electrical and Computer Engineering - IST, 2009.
5. Joench, R.L.; Soares, J.; Lezama, F.; Ramos, S.; Gomes, A.; Vale, Z. A Short Review on Smart Building Energy Resource Optimization. In Proceedings of the 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia); 2019; pp. 440–445.
6. Soares, J.; Pinto, T.; Lezama, F.; Morais, H. Survey on Complex Optimization and Simulation for the New Power Systems Paradigm. *Complexity* **2018**, *2018*, 2340628.
7. Lezama, F.; Soares, J.; Vale, Z.; Rueda, J. Optimal Scheduling of Distributed Energy Resources Considering Uncertainty of Renewables, EVs, Load Forecast and Market Prices. *WCCI 2018 Competition Evolutionary Computation in Uncertain Environments: A Smart Grid Application* **2018**, 1–19.
8. Dabhi, D.; Pandya, K. Enhanced Velocity Differential Evolutionary Particle Swarm Optimization for Optimal Scheduling of a Distributed Energy Resources With Uncertain Scenarios. *IEEE Access* **2020**, *8*, 27001–27017.
9. Haidar, N.; Attia, M.; Senouci, S.-M.; Aglzim, E.-H.; Kribeche, A.; Asus, Z.B. New consumer-dependent energy management system to reduce cost and carbon impact in smart buildings. *Sustainable Cities and Society* **2018**, *39*, 740–750.
10. Molina, D.; Hubbard, C.; Lu, C.; Turner, R.; Harley, R. Optimal EV charge-discharge schedule in smart residential buildings. In Proceedings of the IEEE Power and Energy Society Conference and Exposition in Africa: Intelligent Grid Integration of Renewable Energy Resources (PowerAfrica); 2012; pp. 1–8.
11. Thomas, D.; Deblecker, O.; Bagheri, A.; Ioakimidis, C.S. A scheduling optimization model for minimizing the energy demand of a building using electric vehicles and a micro-turbine. In Proceedings of the 2016 IEEE International Smart Cities Conference (ISC2); 2016; pp. 1–6.
12. Thomas, D.; Deblecker, O.; Genikomsakis, K.; Ioakimidis, C.S. Smart house operation under PV and load demand uncertainty considering EV and storage utilization. In Proceedings of the IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society; 2017; pp. 3644–3649.

Peer-reviewed version available at *Energies* **2020**, *13*, 1719; doi:10.3390/en13071719

13. Thomas, D.; Ioakimidis, C.S.; Klonari, V.; Vallée, F.; Deblecker, O. Effect of electric vehicles' optimal charging-discharging schedule on a building's electricity cost demand considering low voltage network constraints. In Proceedings of the 2016 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe); 2016; pp. 1–6.
14. Sabillón A., C.F.; Franco, J.F.; Rider, M.J.; Romero, R. A MILP model for optimal charging coordination of storage devices and electric vehicles considering V2G technology. In Proceedings of the 2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC); 2015; pp. 60–65.
15. Deepak Mistry, R.; Eluyemi, F.T.; Masaud, T.M. Impact of aggregated EVs charging station on the optimal scheduling of battery storage system in islanded microgrid. In Proceedings of the 2017 North American Power Symposium (NAPS); 2017; pp. 1–5.
16. Balasubramaniam, K.; Saraf, P.; Hazra, P.; Hadidi, R.; Makram, E. A MILP formulation for utility scale optimal demand side response. In Proceedings of the 2016 IEEE Power and Energy Society General Meeting (PESGM); 2016; pp. 1–5.
17. Chandra Mouli, G.R.; Kefayati, M.; Baldick, R.; Bauer, P. Integrated PV Charging of EV Fleet Based on Energy Prices, V2G, and Offer of Reserves. *IEEE Transactions on Smart Grid* **2019**, *10*, 1313–1325.
18. van der Meer, D.; Chandra Mouli, G.R.; Morales-España Mouli, G.; Elizondo, L.R.; Bauer, P. Energy Management System With PV Power Forecast to Optimally Charge EVs at the Workplace. *IEEE Transactions on Industrial Informatics* **2018**, *14*, 311–320.
19. Erdinc, O.; Paterakis, N.G.; Mendes, T.D.P.; Bakirtzis, A.G.; P. S. Catalão, J. Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR. *IEEE Transactions on Smart Grid* **2015**, *6*, 1281–1291.
20. Calvillo, C.F.; Czechowski, K.; Söder, L.; Sanchez-Miralles, A.; Villar, J. Vehicle-to-grid profitability considering EV battery degradation. In Proceedings of the 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC); 2016; pp. 310–314.
21. BMW i3: Tecnical Data Visão geral Available online: https://www.bmw.pt/pt/all-models/bmw-i/i3/2017/visao-geral.html (accessed on Feb 12, 2020).
22. Battery storage power station. *Wikipedia* 2020.
23. SU ELETRICIDADE Available online: https://sueletricidade.pt/pt-pt/home (accessed on Feb 12, 2020).