38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Decarbonization of a Household through Energy Management Systems, Electric Mobility and Storage Solutions

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Executive Summary

This study examines the role of an Electric Vehicle (EV) and an Electric Storage System (ESS) in managing a common household's energy consumption, grid demand costs, and the carbon impact of energy consumption, while considering the impact of a Photovoltaic System (PV). A Python-based algorithm was developed to optimize the use of stored energy in ESS and EV, reducing grid dependency alongside PV energy production. By prioritizing EV charging and ESS discharging processes to meet household demands, the algorithm was able to achieve a 60% reduction in energy consumption compared to a baseline scenario and a 29% reduction when the PV production is considered.

Keywords: Electric Vehicles, Energy Storage Systems, Battery Management Systems, V2H & V2G, Energy Management

1 Introduction

The climate crisis felt across the globe is by now not indifferent to anyone. Natural disasters like droughts, floods, hurricanes and several other ha reshaped the surface of our planet, so much so that entire ecosystems are completely changed, and several animal and vegetal species are no longer present among life on Earth. Such phenomena is caused by recurrent emission of greenhouse gases (GHG) as a direct consequence of human activity on the planet. As such, the urgency to implement carbon reduction measures is of the essence, and it is by far the greatest challenge Mankind has to endure.

For that reason international communities have come with a goal to reduce the carbon emissions on their economies, by implementing the Paris Agreement, a document signed by 196 country states which aims to hold "the increase of global average temperature to well bellow the 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1,5 ºC above pre-industrial levels [1], by implementing measures that allow for greenhouse gas (GHG) emissions to peak before 2025 and to decline by 43% by, at least, 2030.

As such, international organizations like the EU have come up with a solution, by implementing strategies to mitigate and reduce carbon emissions in their main economic sectors (transport, energy, agriculture, real estate and industry) [2], by introducing legislation and policies to regulate energy consumption from a highly-dependent fossil fuel power grid, to achieve reductions on carbon emissions by 55% in comparison with the values registered in 1990 [3]. Such goal is possible to become a reality, due to the implementation of energy production solutions, mainly renewable energy production sources, and by reducing energy consumption in the most pollutant sectors of the European Union.

1.1 Building Stock

Amongst these, the building sector in one of the most pollutant of them, recording around 35% of total energy related GHG emissions in Europe, mainly due to cooling and heating needs [2]. In response to it, the European Parliament has committed to the creation of legislations such as the EPBD 2010/31/EU on the Energy Performance of Buildings [4] (later replaced by the Directive 2018/844 [5]), that introduces the concept of Near Zero Energy Buildings (nZEBs) as a model to achieve a reduction on carbon emissions in this sector, providing guidelines on energy performance for the construction of new buildings across Europe and by retrofitting existing ones to achieve the same energy performance indicators, by implementing passive solutions (implementation of more sustainable and thermal efficient materials in architectural infrastructures) and active solutions (such the implementation of Renewable Energy Systems), so that the production of energy can compensate the consumption registered in the building, thus reducing the dependency on the energy from the grid.

1.2 Electric Mobility

In addition, the transport sector is also one of the culprits for the excessive GHG emissions in Europe as it is directly and indirectly responsible for 31% of total final energy consumption registered in Europe (roughly 279 567 ktoe in 2021 [6]), due to the burning of hydrocarbon-based fuels to produce energy to move the vehicle. Therefore, Electric Vehicle (EV) technologies have produced interesting results in this matter to be considered a solution for the problem at hand for both public and private transportation means, by replacing the internal combustion engine with electrical solutions. However, in order for EV's to be truly considered zero emissions vehicles, as even though tailpipe emissions are inexistant, the energy stored in the batteries and used by the mentioned power supplies must come from clean, renewable energy sources, which is often not the case [6]. Nonetheless, EV's environmental impact can be significantly lower than internal combustion engines (ICE) vehicles. Teixeira et al. (2018) have produced a study in Brazil where a comparison between the energy consumption of a Diesel five-door taxicab fleet and electrical homonymous. Results have shown that the EV and the Diesel-based taxi register an energy consumption of 0,1084 kWh/km and 0,8873 kWh/km respectively, showing the benefits of adopting electric powertrains in public transports, and that if a quarte of the whole fleet were to be replaced by electrical drivetrains, a reduction in GHG emissions by 85% could be achieved [7].

1.3 Vehicle-to-Everything (V2X) Systems

The savings in energy consumption and carbon emissions in the mentioned sectors can be further enhanced, with the use of Vehicle-to-Everything (V2X) technologies. These exploit the energy stored in the batteries of EV's to add increased value during idle periods, by applying bi-directional charging technologies to provide benefits to the electric grid, reduce energy consumption of buildings, or to provide backup power to electrical loads [8]. V2X systems can be decomposed based on their final application. Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), Vehicle-to-Building (V2B), Vehicle-to-Vehicle (V2V), Vehicle-to-Load (V2L) and Vehicle-for-Grid (V4G) are amongst the most popular systems implemented, and they all work under the same principle: because most of the time electric vehicles are not used for transportation purposes, and because wired charging stations enables bi-directional charging, we can use the energy stored in the EV's battery to dynamically feed energy to electrical infrastructures, reducing grid energy dependency, increase energy efficiency of energy systems, stabilize the use of renewable energy in building energy consumption, amongst other benefits [9]. V2X technologies consider both electrical connections and operational modes, as mentioned, with different applications of energy being applied to the scale of the scenario, depending on the quantity of vehicles and buildings used. For example, Vehicle-to-Home technologies are often applied at a smaller scale, while V2B technologies often require a larger fleet of vehicles to operate at commercial and office buildings [8]. These systems facilitate the implementation of Home Energy Management Systems (HEMS), which improve energy efficiency, performance, and usage in buildings [10], by implementing key energy management tasks, such as overseeing energy costs, automating demand response approaches, detecting energy use anomalies and arranging energy use information [11]. In addition, these systems can help to manage loads and shift energy consumption profiles to higher renewable energy output, improving overall energy efficiency of the system [8], which a particularity of separating the energy exchange activities from the electrical grid, to avoid backflow of electrical power, thus eliminating the risk of EV electrical overload and energy supply problems at a neighborhood level [12].

2 Article's Scope

The foundations of this essay will be focused in the topics described previously ion this document, stating as a contribution to energy consumption analysis and optimization, by exploiting real data from a real building located in Matosinhos, Porto, considering the characteristics of a real vehicle that will play a crucial role in reducing the energy consumption of the household and, consequently, energy costs and carbon impacts of the dependency of energy from the grid. This scenario will be possible, by enabling energy exchanges from and to the EV and from and to an Electric Storage System (ESS). Such results will be obtained through the development of a Python-based algorithm developed for this effect, with subsequent Excel data processing.

For the matter of energy costs, purchasing energy tariffs from the Portuguese Strict Energy Market for the year of 2024 [13] and selling energy prices from a private contractor were considered [14]. Regarding carbon impacts of such energy savings, a coefficient stated from the Portuguese Legislation for CO2 in kg per kWh of consumed primary energy was considered [15].

3 Case Study

The household mentioned is located in a small residential neighborhood near Matosinhos, Porto. The mentioned building is a 2-story residential household, with a gross area of 75,89 sqm. Its electrical consumption is split between auxiliary loads, lighting and appliances. Natural Gas is also used in this household, and hot water as well. The socio-demographic features of the household are provided in Table 1:

Table 1: Socio-Demographic Characteristics of the Household (from INE)

Type of Construction	1981-1990 Residential Building
Occupancy [sqm/person]	50
Standard Labour Situation (considered)	Employed

The people that occupy the household have an occupancy pattern that is specified in Table 2, for weekdays, and weekend days. This feature is of special attention, because it will provide information for the operational parameters of the EV and the ESS:

Table 2: Occupational Pattern of the Household, in percentage (provided by City Energy Analyst database [16])

	Saturday	Sunday	Weekday
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	0.4	0.4	0.4
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0.8	0.8	0.8
14	0.4	0.4	0.4
15	0	0	0
16	0	0	0
17	0	0	0
18	0.4	0.4	0.4
19	0.8	0.8	0.8
20	0.8	0.8	0.8
21	0.8	0.8	0.8
22	1	1	1
23	1	1	1
24	1	1	1

The architectural features of the building are also important for the analysis, which ultimately describes the energy required for heating and cooling activities (Table 3):

Table 3: Architectural Features of the Household (from City Energy Analyst database [16], [17])

Construvtive Element	Outer Wall	Inner Wall	Roof	Floor	Glazed Surface
Description	Common Clay Brick Wall with Plaster	Common Clay Brick Wall with Plaster	Concrete Rock and Pebbles Finish	Concrete Floor	Single Window, Single Glaze
U [W/sqm.K]	0.987	0.987	2.467	2.9	4.8
G_{window}	-	-	-	-	0.85
F-F [sqm_{frame}/sqm_{window}]	-	-	-	-	0.2
e	0.93	0.93	0.84	-	0.89
a	0.4	0.4	0.55	-	-
r	0.6	0.6	0.45	-	-

Where:

- U – Thermal Transmittance of the Constructive Element;
- Gwindow – Solar Heat Gain Coefficient of the Window;
- F-F – Window Frame Fraction Coefficient;
- e – Emissivity of The External Surface of the Constructive Element;
- a – Solar Absorption Coefficient of the Constructive Element;
- r – Reflectance in the Red Spectrum of The Constructive Element;

Additionally, the household is equipped with the following air conditioning systems (Table 4):

Table 4: Air Conditioning Systems of the Household (from City Energy Analyst database [16])

Type of System	Description
Cooling System	None
Heating System	Radiator (70 / 75 ºC)
Domestic Hot Water System	Medium Temperature Water (45 ºC)
Control System	None
Ventilation System	Window Ventilation

For this case study, a simple Photovoltaic System was considered to further analyze the energy exchanges in the system. The system is composed of an array of monocrystalline silicon panels, with a minimum energy production of 1 W and a maximum energy production capacity of 10 kW, with an electrical efficiency of 16%. In terms of energy production, an inverter was considered, with a 4,9 kWp maximum power output [18]. Additionally, the considered ESS system has a storage capacity of 10 kWp and a max power output of 5kW. Lastly, the EV considered for the energy transactions has the characteristics stated on Table, but with a minor consideration considered: for the purpose of this essay, the charging and discharging efficiencies were considered the same, both for the Electric Vehicle and for the Electric Storage System.

Table 5 - Vehicle Characteristics (adapted from [19])

Parameter	Value
Battery Rated Capacity [Wh]	53000
Max. Charge / Discharge Rate [W/h]	13600
Charge / Discharge Efficiency η	80 %
Initial State of Charge	90 %
Minimum State of Charge	20 %

The energy tariffs are, as mentioned, implemented according to the Portuguese Strict Energy Market, with three tariffs considered: simple, which a purchasing energy price constant throughout the day; bi-hourly, which considers purchasing prices for peak load consumption, and non-peak load consumption; and tri-hourly tariff, which establishes purchasing prices for three different periods of a typical day, each one with their own established energy consumption profile [20]. At last, we will define the considered scenarios for the case study: the base scenario considers the energy consumption of a Business as Usual scenario, without the implementation of the PV, EV and ESS into energy exchanges. The PV Only scenario considers the benefits of the Photovoltaic System into the energy interactions. Finally, the combined scenario, considers all the energy systems mentioned so far in the energy transactions activities.

4 Problem Formulation

To define the problem, it is important to foremost understand how the algorithm should work, and how the energy transactions should occour. The main priority of this algorithm is to be able to sustain energy neutrality and to cut grid-energy dependency as much as possible, without compromising the energy needs of the building. The next step is to ensure that the State of Charge (SoC) of the vehicle, not only for energy transaction activities between the building and the ESS in low-demand periods, but also to guarantee that there is enough electricity in the vehicle's battery to perform transportation duties during the day, ensuring that the lower operating limit is not exceeded. Lastly, the priority is to ensure optimal levels of energy stored in the ESS to further provide to the building and / or to the EV, when the impact of renewables is minimal and when the vehicle is no longer capable of energy transactions in and out of the building.

As such, the problem must consider the following variables that define the main operations in the energy transactions (Table 6):

Table 6 - Algorithm's Main Variable

Parameter	Description
PV_t	Photovoltaic Production, at instant *t* [kWh]
$Loads_t$	Electrical Demand from the Household, at instant *t* [kWh]
$H2G_t$	Home to Grid interactions, at instant *t* [kWh]
$G2H_t$	Grid to Home interactions, at instant *t* [kWh]
Occ_t	Occupation Variable (Binnary Value), at instant *t*

The Energy Storage System is defined by the following variables (Table 7)

Table 7 - ESS' Operating Variables

Parameter	Description
n_{ESSch}	ESS Charging Efficiency [%]
n_{ESSdis}	ESS Discharging Efficiency [%]
SOC_{ESSmax}	Maximum ESS State of Charge [kWh]
SOC_{ESSmin}	Minimum ESS State of Charge [kWh]
SOC_{ESSt}	ESS' State of Charge at instant *t* [kWh]
$SOC_{ESStplus1}$	ESS' State of Charge at instanT *t+1* [kWh]
$SOC_{ESStinit}$	ESS' State of Charge at instant *t = 0* [kWh]
OS_{ESSt}	ESS' Operating System Variable
$EFESS_t$	Energy Flow from the ESS to the HEMS, at instant *t* [kWh]
$E2ESS_t$	Energy Flow to the ESS, at instant *t* [kWh]

And the EV is represented by the following variables (Table 8):

Table 8 - EV's Operating Variables

Parameter	Description
n_{VEch}	EV Charging Efficiency [%]
n_{VEdis}	EV Discharging Efficiency [%]
SOC_{VEmax}	Maximum EV State of Charge [kWh]
SOC_{VEmin}	Minimum EV State of Charge [kWh]
SOC_{VEt}	EV's State of Charge at instant *t* [kWh]
$SOC_{VEtplus1}$	EV's State of Charge at instant *t+1* [kWh]
$SOC_{VEtinit}$	EV's State of Charge at instant *t = 0* [kWh]
OS_{VEt}	EV's Operating System Variable
$EFVE_t$	Energy Flow from the EV to the HEMS, at instant *t* [kWh]
$E2VE_t$	Energy Flow to the EV, at instant *t* [kWh]

An Operating System variable was introduced for both the EV and the ESS, that defines the activity state of each system, in the same way: if the system is discharging, this variable takes the value -1, if the system is in idle mode, the variable is equal to 0, and if the system is performing charging activities, the value 1 is attributed to the variable. Figure 1 represents a schematic of these variables, and the corresponding flows in the Home Energy Management System:

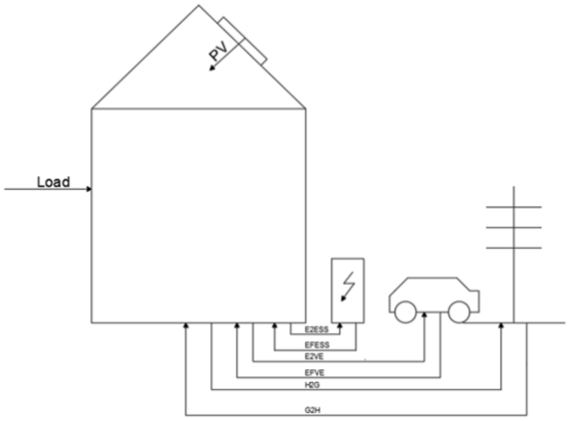

Figure 1 - Home Energy Management System (HEMS) Schematic

To properly define the energy transactions in the most efficient way, it is important to define a strategy for these events to work properly.

Firstly, energy transactions scenarios can be defined by the Equation 1, that states the energy situation of the household.

$$demand_t = Load_t - PV_t \quad (1)$$

When the variable demandt smaller than 0, there is an energy surplus from the PV system that surpasses the household's energy demands; when it is equal to 0, the energy requirements are fulfilled; and when it is greater than 0, the production of energy form the PV system cannot overcome the energy demands of the building. This equation paves the way to define the behaviour of the ESS alone. When no human occupation is registered inside the building (Occ = 0), this means that the EV cannot be part of the energy transactions in the building (OSVE = EFVE = E2VE = 0). When this happens, the ESS recharges and discharges energy, according to the scenario that is currently on. In either scenario, the HEMS redirects the energy to the grid, H2G, if there is a surplus of energy, or draws energy from the grid, G2H, if the ESS cannot fulfil the energy requirements.

If human occupation is registered in the household, we can the Ev's influence on energy exchanges with the system (OSVE = 1 or OSVE = -1, depending on the Ev's state at instant t). Therefore, and as with the case of the ESS, the EV will behave similarly, in conjunction with the Electric Storage System.

Within the algorithm, there are certain guidelines for the correct operation of the EV and the ESS under energy management and exchange activities. For example, in a scenario with demand < 0, and according with the charging priorities established previously, the algorithm into consideration the necessary amount of electricity to charge the vehicle, updating the State of Charge of the vehicle for a new iteration, if SOCVEt is set between the boundaries established. If there still is a surplus on energy production after this step, and the ESS' State of Charge is between the established limits, this remaining energy is transferred to the Electric Storage System and stored in its battery. The same happens if, for instance, the vehicle's SoC is full. In situations when both batteries are at full capacity, this remaining energy is injected into the grid (H2G), with an established selling price [14]. The same thing happens when the variable demand is positive, with the difference that, instead of injecting energy into the grid when a surplus exists, the algorithm requires that energy from the grid must be provided to the household to meet energy demands (G2H). The whole algorithm only works if the limits of both ancillary systems are not exceeded.

Besides the behaviour in the household, the behaviour of the vehicle when not performing energy transactions with the building was also considered, by randomly simulating the vehicle's State of Charge by 50 % every time the vehicle is performing transportation duties, with this value being set when the vehicle is at the beginning of the energy exchanging cycle

5 Results

As mentioned, the excepted results of the algorithm were to analyse energy costs savings, However, carbon emissions and energy reductions, across different energy fees were also taken into consideration, with the carbon impacts being calculated by a coefficient in the Portuguese Legislation [15], according to Equation 2

$$F_c = 0{,}144\ [kgCO_2/kWh] \tag{2}$$

Additionally, the Self-Sufficiency and Self-Consumption Index were calculated, which take in consideration the amount of energy that is consumed and the net energy registered in the building, as well as the amount of energy produced in relation to the net energy demand of a building (Equation 3 and 4).

$$SSI_t \frac{Load_t - |demand_t|}{Load_t} \tag{3}$$

$$SCI_t = \frac{PV_t - |demand_t|}{PV_t} \tag{4}$$

Thus, these parameters can be computed based in the actual energy that the household consumes with or without the implementation of the HEMS, across the various mentioned scenarios (Equation 5):

$$\begin{aligned} demand_t = (Loads_t + E2ESS_t + E2VE_t + H2G_t) \\ - (PV_t + G2H_t + EFESS_t + EFVE_t)[kWh] \end{aligned} \tag{5}$$

And considering the energy tariffs from the Portuguese Legislation [13], the algorithm has produced the results shown in Table 9:

Table 9 - Energy Parameters for Each Scneario Analyzed

Scenario	Base	PV Only	Combined
Net Demand [kWh]	7980,45	5641,57 (-29%)	3194,43 (-60%)
Simple Tariff Fee [€]	-973,61	-761,10 (-22%)	-493,23 (-49%)
Double Tariff Fee [€]	-977,35	-664,73 (-32%)	-358,05 (-63%)
Triple Tariff Fee [€]	-974,89	-685,59 (-30%)	-388,22 (-60%)
Carbon Impact [$kgCO_2$]	1149,18	958,03 (16%)	667,02 (-42%)
Mean Annual SSI	0%	22%	62%
Mean Annual SCI	0%	23%	29%

As shown, the algorithm is effective in reducing the energy dependency from the grid, by enhancing the electric capabilities of the vehicle and the ESS from 29 to almost 60%. As shown, the energy costs are reduced significantly for simpler tariffs and with the contribution of selling energy to the grid when there is an excess of energy in the system. In addition, significant carbon emission reductions can be visualized, even though no LCA study was conducted on the EV and the ESS, and only the direct effect on energy demand, and the consequent impact on carbon emission was considered.

6 Conclusions and Further Developments

Society is facing one of its most challenging periods. Due to human activity, climate change is no longer a subject that can be ignored - decisions must be made to save the planet and preserve ecosystems from collapse. Thus, it is fundamental to mitigate the emission of greenhouse gases to the atmosphere, and stop carbon-intensive activities, changing to more carbon-neutral and sustainable technologies, services, and activities.

Action is being taken into place by international organizations, by implementing policies and regulations for carbon-intensive sectors. Among them, the transport sector has come as the most revisited due to the constant emission of carbon and other pollutant particles, by burning petrol or Diesel in Internal

Combustion Engines. One of the solutions is the implementation of electric and hybrid powertrains, that rely mainly on electricity to make vehicles move, thus eliminating the dependency on fossil fuels.

But these drivetrains can also aid in so much in the matter of carbon mitigation. By the implementation of Vehicle-To-Grid and Vehicle-To-Building technologies, it is possible to increase grid independence by exploiting the energy harnessed in these vehicle's batteries.

Although the present work shows a glimpse on the reaching of carbon neutrality in households, some key aspects can be improved in future work. The implementation of stricter coordination strategies, in order to reduce the dependency from the grid to recharge the ancillary systems must be conducted. And even though there are significant reductions, both in energy consumption and carbon emissions, the degradation of the ancillary systems, especially the batteries, affects the performance of the Energy Management System and the potential of energy consumption reduction. Moreover, the implementation and later replacement of these systems have an ecological impact inherent to them. which was not considered in this study and may affect the results. So, a dedicated and thorough Life Cycle Assessment (LCA) and investment and acquisition study must be conducted, to fully analyze the impact of the algorithm in real-life scenarios. Also, implementing a solution for energy sharing in communities is a key aspect that can be taken into consideration.

Regarding the transport sector, the implementation of different powertrain technologies (hybrid, fuel cell, etc) and their interactions with households should be a topic of further investigation. Also, the consideration of multiple vehicles in the building and their interaction is a subject that must be addressed, especially if we consider other buildings such as office and commerce buildings, and their impact on the grid and on the energy consumption of the building.

Lastly, the implementation of real-time monitoring and decision-making regarding the purchasing and selling of energy to the grid is a topic of research, with real-time and day-ahead predictions of the Iberian Energy Market MIBEL energy prices, to determine the optimal timing for the energy transactions to take place.

All these solutions can be implemented all at once, in a single building or in entire neighborhoods, in order to meet climate standards and goals towards a more sustainable future.

Acknowledgments

The authors gratefully acknowledge Fundação para a Ciência e Tecnologia for funding this research through the following programs: IN+ Strategic Project (1801P.00962.1.01 - IN+ UIDP/EEA/50009/2020 - IST-ID). The authors also acknowledge the Project BE.Neutral – Agenda de Mobilidade para a Neutralidade Carbónica nas Cidades, contract number 35, funded by the Resilience and Recovery Plan (PRR) through the European Union under the Next Generation EU.

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Presenter Biography

Ricardo Oliveira is currently part of IN+ - Center for Innovation, Technology and Policy Research, as a PhD Student in Sustainable Energy Systems. He has a BSc and a MSc degree in Mechanical Engineering from Instituto Superior de Engenharia de Lisboa, where he developed a computational tool that allowed the management and control of the energy flow between a house with almost zero needs and a mobility vehicle. As a PhD student, Ricardo is working to extrapolate the development of the tool to urban centers, exploring the impact of electric mobility networks on long-term residential consumption, in order to create isolated energy clusters and large-scale microgrid systems.

Patrícia Baptista received the Ph.D. in Sustainable Energy Systems (2011) from Instituto Superior Técnico, Portugal. She is currently a Principal Researcher at IN+ Center for Innovation, Technology and Policy Research. Her main research topics have been on the quantification of energy and environmental impacts of alternative transport options, on how to influence user behavior by using ICT to characterize driving behavior and policy design for more sustainable transports.

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