Technical-Economic Analysis of a Power Supply System for Electric Vehicle Charging Stations Using Photovoltaic Energy and Electrical Energy Storage System

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Abstract. Electrical energy storage can reduce energy consumption at the time of greatest demand on the grid, thereby reducing the cost of fast charging electric vehicles (EVs). With storage, it is also possible to store mainly energy from renewable sources or to limit the power requested by Public Power Grid (PPG), allowing charging of EVs in areas where power supply is limited via PPG. In this paper, to meet the requirements of an EV charging station and the management of the energy storage system, a lithium-ion battery system with second life batteries is proposed and compared with new batteries. A photovoltaic system that will allow the use of solar energy is also proposed. HOMER Grid software was used to simulate and analyze the different systems from a technical and economic point of view for different cases. It was concluded that HOMER is a powerful tool but some drawbacks are also pointed out.

Keywords: Electric vehicles · Charging station · Energy storage · Lithium-ion battery · Second-life batteries · Photovoltaic system · Homer grid

1 Introduction

The world's demand for energy is increasing rapidly, putting a great strain on existing energy resources, and having a negative impact on the environment and global warming. As governments strive for a green energy economy, electric vehicles (EVs) are playing an increasingly important role in helping to reduce emissions from the transport sector. Electrification of the transport sector is an important step towards a sustainable society. This will bring several benefits, such as reducing oil consumption, reducing emissions and integrating renewable energy sources into the grid [1–3].

The foreseen massive deployment of EVs is driving the solution to the challenge of combating climate change and urban pollution, with the aim of providing a balanced and sustainable response. Nowadays, using an EV to get around a city center is one way to reduce urban pollution and to contribute to the sustainability of our planet.

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The installation of fast charging stations for EVs is essential to encourage widespread adoption of EVs, as this will reduce concerns about "range anxiety" regarding the range of the EV before the battery runs out [2, 4, 5]. Combining the use of EVs and renewable energy sources such as solar and wind power to support EV charging stations should be considered to ensure economical and environmentally friendly charging [6, 7].

Sales of electric cars have increased significantly over the last 10 years, and an important question arises: what to do with EV batteries after they reach the end of their life? [8]. Several solutions have been studied to find a sustainable answer to the question posed. Several electrical energy storage studies have been developed by researchers and major automobile manufacturers like Nissan and others [9–14], bringing up the concept of giving these batteries a new life, i.e., a second-life, reusing them for stationary applications. In this way, it is possible to store a significant amount of energy that can later be injected into the power grid or into consumer devices to support the power grid and be used to charge an electric vehicle [15]. Consequently, energy storage can reduce the peak power consumption of the grid and thus the cost of fast charging of electric vehicles. It can also enable electric vehicle charging in areas where the power grid does not allow it [16]. Furthermore, it is possible to use this type of solution in a smart system where the energy sources are mainly renewable.

So, this work aims to investigate the possibility of incorporating another fast or semi-fast charger into an existing system without having to increase the power contracted with the public grid. For this, it is investigated the technical and economic feasibility of installing a photovoltaic system and a battery storage system, comparing the usage of used lithium-ion batteries (2^{nd} life utilization) or new lithium-ion batteries, for different case studies. Finally, based on the results, to meet the need for fast charging infrastructure and to enable the reutilization of used batteries, photovoltaic panels and energy storage based on second life batteries for fast charging systems for electric vehicles is proposed.

2 Methodology

The methodology is implemented in the software HOMER (Hybrid Optimization Model for Electric Renewables) Grid. The software, HOMER Grid, is a robust optimization model developed by NREL (National Renewable Energy Laboratory) that can be used to simulate various power system configurations or mixes of components, optimize design options for cost efficiency, or perform sensitivity analysis based on inputs of loads, components, and resources [17, 18].

The software HOMER Grid consists of three main operational phases, specifically simulation, optimization, and sensitivity analysis. In the simulation phase, the selection of system components and sizes is presented. The simulations are based on estimates of installation, operation and maintenance costs and electricity tariffs. In the optimization phases, an optimal system is determined after several simulations of configurations of the hybrid system. The final phase is the sensitivity analysis, which is achieved for each system configuration based on the parameters of the sensitivity analysis [17].

The optimal solution is centered on the Net Present Cost (NPC). After all, HOMER Grid also provides feasible simulation results that allow the user to compare configurations and evaluate them according to their economic, technical, and environmental interest [18, 19].

The total NPC is the main economic output of HOMER, the value by which all system configurations are ranked in the optimization results, and the basis for calculating the total annual cost and the levelized cost of energy. The total NPC of a system is the present value of all the costs the system incurs over its lifetime minus the present value of all the revenues it generates over its lifetime. Costs include capital costs, replacement costs, operation and maintenance costs, fuel costs, emission penalties, and the cost of purchasing electricity from the grid. Revenues include the residual value and sales revenue from the electricity grid [24].

3 Theorical Background: Hybrid System Modeling

The considered system consists of the following components: PV systems, power converter, battery storage, fast charging station for electric vehicles, load profile and grid connection. To evaluate the performance of the different systems and scenarios, HOMER Grid simulates and optimizes the same load profile with the different system components. In the following sections, each component is analyzed individually [20, 21].

3.1 PV Systems

The power output of the PV system is expressed in Eq. 1,

$$P_{PV} = P_{PV,STC} f_{PV} \left(\frac{G}{G_{STC}} \right) \left[1 + \alpha_P \left(T_C - T_{C,STC} \right) \right] \tag{1}$$

where, $P_{PV,STC}$ is the output power at standard test conditions (STC), f_{PV} is the PV derating factor (power losses due to factors such as panel soiling, wiring losses, shading, snow cover, aging, etc.), G is the current irradiance, G_{STC} is the irradiance at STC, α_P is the temperature coefficient of power, T_C is the PV module temperature, $T_{C,STC}$ is the temperature of the PV module under STC, and STC (standard test conditions: $G_{STC} = 1000\, W/m$, $T_{C,STC} = 25$ °C) [21].

The PV array has the configuration of PV modules such as:

$$P_{PV,STC} = (N_S \times N_P) P_{m,STC} \tag{2}$$

where $P_{m,STC}$ is the output power of the PV modules under standard test conditions, N_S is the number of modules connected in series, and N_P is the number of strings connected in parallel [21].

3.2 Solar Energy Sources

The solar irradiance and clearness index data are retrieved from the website HOMER Grid. Entering a specific location into the software, the data from NASA will be recovered from the website. The full solar data is based on the latitude and longitude of the selected area. Figure 1 below shows the clearness index and monthly average solar global horizontal irradiance from the NASA Prediction of Worldwide Energy Resource database via the HOMER Grid software [25].

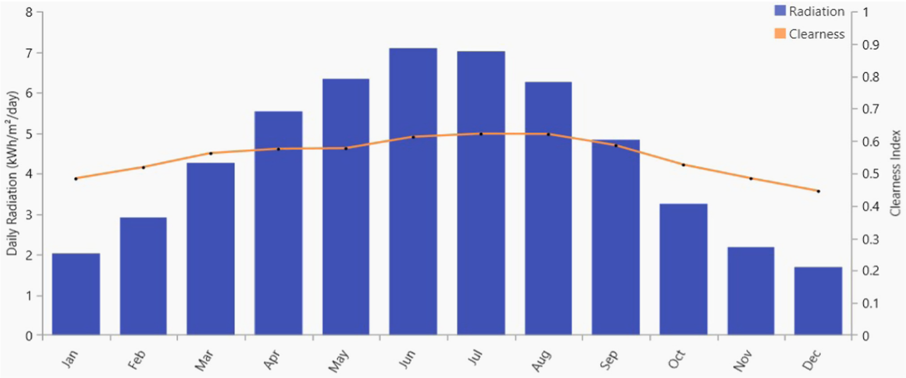


Fig. 1. Monthly average solar global horizontal irradiance data

3.3 Converter

The converter is coupled between the DC bus and the AC bus, as shown in Fig. 2. The converter works bidirectionally depending on the energy flow and acts as an inverter for transferring energy between the PV system and the load AC and as a rectifier for charging the battery bank from the grid.

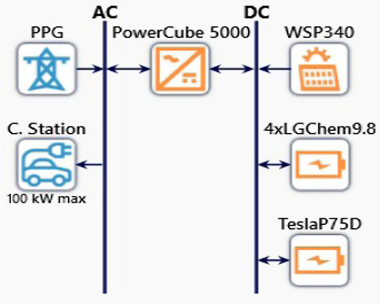


Fig. 2. System model

For this study, the bidirectional Huawei Power Cube 5000 converter with a capacity of 60 kW (2 modules) and a rated output voltage of 380/400/415 AC, available on HOMER database, was initially selected. The investment cost for this converter is 1500 €/kW and the replacement cost per year is the same. However, since this model is quite expensive, looking at the current market, other solutions were considered, and finally it was selected and manually added to the database, the SMA America STP24000-US-10 (480 V) bidirectional converter, which can be connected to get the same capacity, and at a much lower price (139.58 €/kW) according to the present price list of a Portuguese company FF SOLAR [27]. The number of inverters is optimized based on HOMER Grid optimizer. The efficiency of the Huawei Power Cube 5000 is 96% with a lifetime of 15 years and the efficiency of the SMA America STP24000-US-10 is 98% with a lifetime of 15 years.

3.4 Battery Storage

Battery charging helps store excess generation from mixed sources for use later when consumption is higher than generation.

The charging or discharging power of the battery is regulated by the output power of the power system (PV and grid) and the load demand at a given time. At any given hour, the state of charge of the battery (SOC) is expressed as follows:

$$SOC(t) = SOC(0) + \eta_c \sum\nolimits_{k=0}^{t} P_c(k) + \eta_d \sum\nolimits_{k=0}^{t} P_d(k) \tag{3}$$

where, $SOC(0)$ is the initial SOC of the battery, P_c is the charged power, P_d is the discharged power, η_c is the charge efficiency, η_d is the discharge efficiency.

The available capacity of the battery bank shall not be less than the minimum allowable capacity B_{min} and not greater than the maximum allowable capacity B_{max} [22],

$$\begin{cases} B_{min} \le SOC \le B_{max} \\ B_{min} \le (1 - DOD \le B_{max} \end{cases} \tag{4}$$

where B_{min} and B_{max} are the minimum and maximum power limits, respectively, and DOD is the depth of discharge.

Moreover, the discharged power of the battery should satisfy the condition [22]

$$0 \le P_d(k) \le P_{max} \tag{5}$$

where P_{max} is the maximum hourly discharge.

3.5 Grid Connection

The electric vehicle charging station under investigation is connected to the public power grid (PPG). The connection between the electric vehicle charging station and the PPG is made in low voltage (three-phase, 400 V), with a three-phase 75 kW connection [26]. The rate of consumption is shown in Fig. 3 as a function of the time of day and the day of the year.

In Portugal, the price of energy varies throughout the day, the month, and the year. Figure 3 shows a variation of the energy price over the year by color band. For example, the red color band means that the energy price varies between 0.07 and 0.14 €/kWh.

3.6 Load Profile

It was modeled a daily energy profile in the HOMER Grid software as can be seen in Fig. 4. This profile is based on one-month data from the electric vehicle charging station in Coimbra. The average daily energy is equivalent to 320 kWh, and by extension this value was considered for the remaining months.

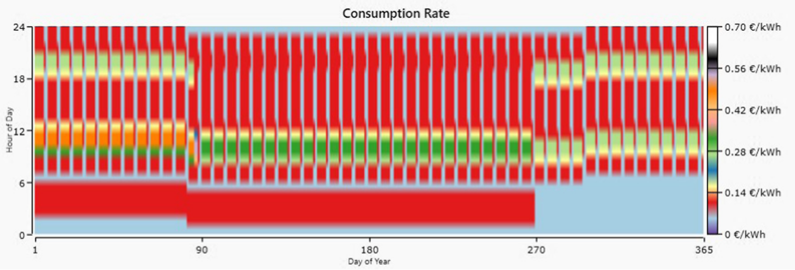


Fig. 3. Consumption rate

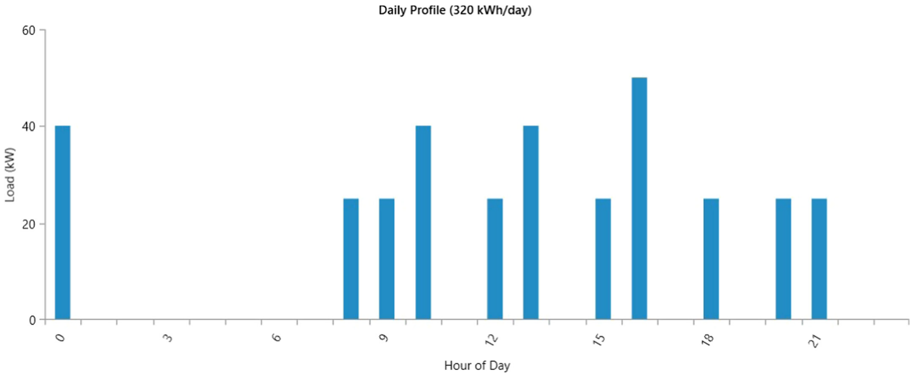


Fig. 4. Daily profile

3.7 Dispatch Algorithm

The dispatch algorithm is responsible for deciding at each time step how the electric load should be served by the available generation sources. One of the many decisions it makes is whether to charge the EV from storage battery, from the grid, or from both. It worth noting that dispatching in HOMER Grid has “perfect prediction”, which means that it knows [23]:

- The electric demand for each time step in the future;
- The utility rate schedule;
- PV production for each time step in the future.

HOMER Grid optimizes and finds the least cost system by lowering demand charges and doing energy arbitrage if feasible. If this system is feasible, i.e., the electric demand can be served at each time step without exceeding the peak load limit, the economic efficiency of the system is calculated. In the final results table, the system is ranked in the order of NPC [23].

4 Case of Study

The present case concerns a real EV charging station in Coimbra, Portugal. The charging station has a 50 kW charger of the Portuguese company Efacec, model QC50. This charger has three different sockets, namely the CCS2, CHAdeMO and Mennekes sockets, but can only charge one vehicle at a time. Analyzing in detail the charging events of August 2020, several occasions were detected where there was at least one EV waiting for the charger to be freed to be able to charge, so at least one more charger would be needed. However, the connection to the PPG has limitations. So, in order to expand the system, and thus increase the availability of services without increasing the contracted power to the PPG, other solutions would have to be considered, such as energy storage and solar panels.

5 Simulation and Optimization Results

5.1 Proposed Scenario

The system shown in Fig. 2 was modeled in Homer Grid software, keeping the connection to the PPG (75 kW), and including a photovoltaic panel system and a battery storage system. The proposed scenario allows simultaneous charging of two electric vehicles, as an additional 50 kW charger has been added, for a total of 100 kW. Table 1 shows the characteristics of the proposed scenario.

Table 1. Characteristics of the proposed scenario

Charger output power (kW)	Mean time connected (hr)	Number of chargers	Scaled Avg Sessions/day
2 × 50	0.6	2	15

Figure 5 shows the new annual energy profile based on the proposed scenario modeled in the HOMER Grid software. In the figure, the vertical bar on the right side represents the charging power of the electric vehicles, in kW, where the warmer colors (orange, red) represent the higher power, and the colder colors (blue, black) represent the lower power. This means that several vehicles can be charged at the same time, as the warmest color range corresponds to the power range between 70 kW and 100 kW.

Based on the characteristics of the electric vehicles visiting the charging station in Coimbra, two types of generic EVs were modelled taking August of 2020 as a reference. Generic EV 1 corresponds to 76% of the EV population visiting the charging station and generic EV 2 corresponds to 24%. Both have different energy requirements. The first one requires 15 kWh and can be charged with a power of up to 26 kW, while the second one requires 24 kWh and can be charged with a power of up to 50 kW. For a better illustration, Table 2 can be seen.

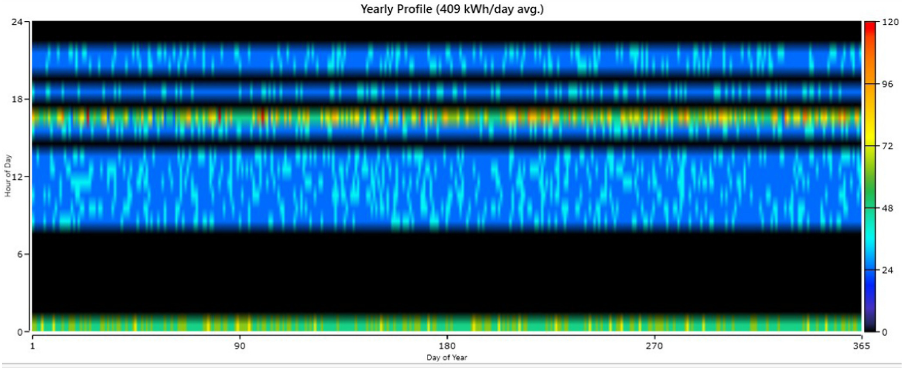


Fig. 5. Annual profile of the proposed scenario

Table 2. EV features

Name	Proportion of EV population (%)	Max. charging power per EV (kW)	Required charge energy per EV (kWh)
Generic EV 1	76	26	15
Generic EV2	24	50	24

5.2 Results

The software HOMER Grid simulated 137 solutions, omitting 22 solutions due to lack of a converter and 1 solution due to an unnecessary converter, and of the 137 solutions, all were feasible. The four cases which have been considered are as follows:

1. PV + Energy Storage System (Tesla: Second Life Battery) + Converter + Grid;
2. PV + Energy Storage System (LGChem: New Battery) + Converter + Grid;
3. PV + Converter + Grid;
4. Grid (base case).

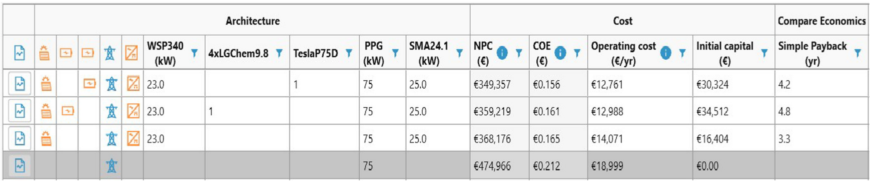
For simplicity, it was considered a nominal discount rate (the rate at which one could borrow money) and an expected inflation rate both equal to 0%. Electricity costs in the base case (highlighted) amount to 0.212 € per load unit (kWh), while they decrease by 26.42% in the winner case (1. PV + Energy Storage System (Tesla Second Life Battery) + Converter + Grid) as shown in Table 3.

The cheapest case is the one in which the EV is charged with the help of solar panel, storage system, converter, and grid. In this case, the unit cost of electricity is 0.156 €/kWh. The comparison can also be seen in Table 4 and Table 5.

The IRR (Internal Rate of Return) for this system is 22% and the simple payback period is 4.2 years. Also, the ROI (Return on Investment) is 17%.

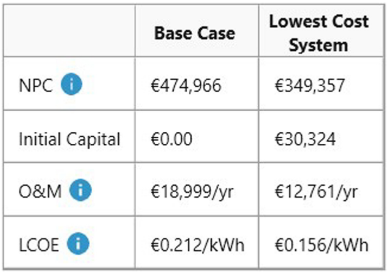
The cash flow diagram for the winning system can be found in Fig. 6. We can see that at the beginning of the project, the PV system, the energy storage systems and the

Table 3. Architectural combination



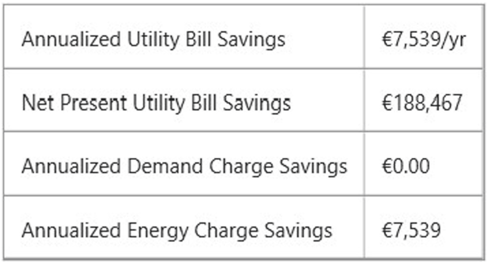
Architecture					Cost				Compare Economics
WSP340 (kW)	4xLGChem9.8	TeslaP75D	PPG (kW)	SMA24.1 (kW)	NPC (€)	COE (€)	Operating cost (€/yr)	Initial capital (€)	Simple Payback (yr)
23.0		1	75	25.0	€349,357	€0.156	€12,761	€30,324	4.2
23.0	1		75	25.0	€359,219	€0.161	€12,988	€34,512	4.8
23.0			75	25.0	€368,176	€0.165	€14,071	€16,404	3.3
			75		€474,966	€0.212	€18,999	€0.00	

Table 4. Cost summary



	Base Case	Lowest Cost System
NPC	€474,966	€349,357
Initial Capital	€0.00	€30,324
O&M	€18,999/yr	€12,761/yr
LCOE	€0.212/kWh	€0.156/kWh

Table 5. Savings



Annualized Utility Bill Savings	€7,539/yr
Net Present Utility Bill Savings	€188,467
Annualized Demand Charge Savings	€0.00
Annualized Energy Charge Savings	€7,539

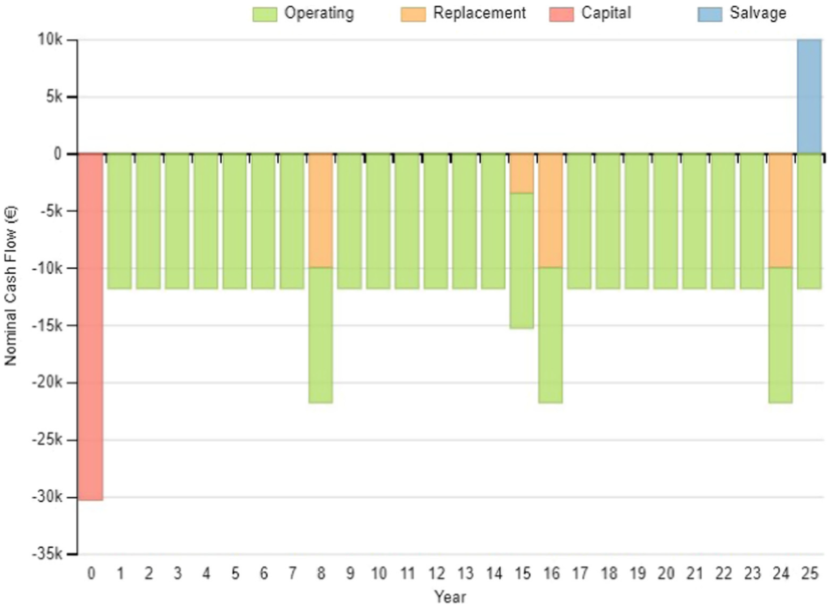


Fig. 6. Cash flow diagram for the winning system

inverter will incur in capital costs of 30,324 euros, while in years 8, 16 and 24, the batteries of the storage system and in year 15, the inverter will also incur in replacement costs. During the project lifetime of 25 years, the system will also incur in operation and maintenance costs.

The HOMER Grid software also simulated energy exchange with the grid. The plots in Fig. 7 and Fig. 8 show the energy exchange with the grid for the first 7 days of a typical summer and winter month in Portugal, respectively.

Fig. 7. Energy exchange with the grid for first 7 days of typical summer

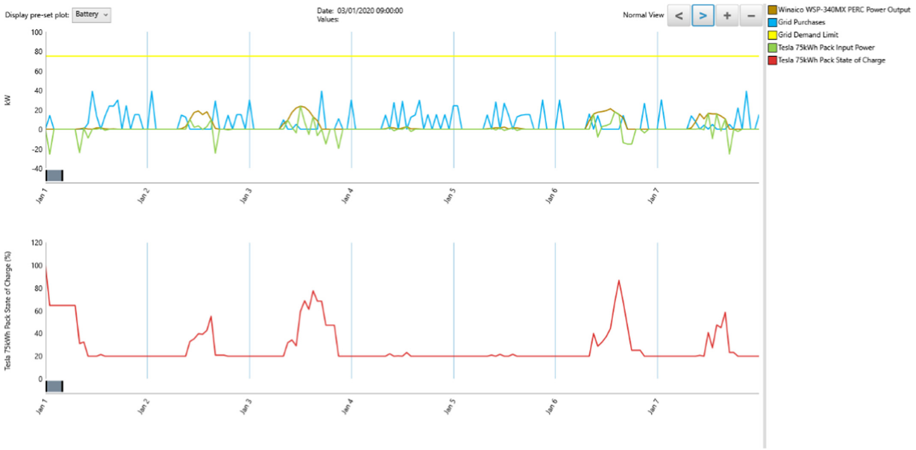


Fig. 8. Energy exchange with the grid for first 7 day of typical winter

6 Discussion

The software HOMER Grid proved to be a very powerful tool, able to economically and technically evaluate all possible combinations of the proposed system and select a winning system in less than 15 s.

As presented, the winning system consists of a photovoltaic panel, a storage system with second-life lithium batteries from Tesla's EVs, a converter and a 75 kW power grid connection. The initial capital of this system is equal to 30,324 €, a return on investment of 17%, an internal rate of return of 22%, and with an investment recovery from the 4.2th year. The annual savings of this system are 7,539 € per year.

The second winning case is similar to the first case, but uses new lithium batteries (LG Chem), making this solution less economically viable than the first case, with an initial capital of 34,512 €, a return on investment of 13.4%, an internal rate of return of 18.3%, and a simple payback of 4.8 years.

The third winning case considers only the photovoltaic panels, the inverter, and the connection to the grid, but not the storage system. This results in an initial capital reduction of 13,920 €, which is almost half of the initial investment of the first case. This shows that the storage system makes the solution more expensive in the first case. The third winning case has a return on investment of 26%, an internal rate of return of 30.4%, and obviously a lower simple payback (3.27 years), since in this case the initial investment was reduced by almost half (16,404 €).

The fourth winning system, which corresponds to the base case (currently installed), consists only of connection to the power grid. This system cannot meet the load when two EVs want to charge at 50 kW at the same time, which limits the availability of the service (75 kW).

The software HOMER Grid also simulated power exchange with the grid and ensured that most of the load was met. It made forecasts and predictions of solar power generation and load to make the best decision on when to charge the batteries and buy power from the grid.

Finally, from what was seen, HOMER software is a very powerful and usefully tool. However at least two important drawbacks have to be pointed out:

First, HOMER Grid software operates as a black box, i.e., users do not have access to the internal decision system. For loads such as a charging station in the HOMER Grid, we are limited to the internal strategies of the software, i.e., with this version 1.8 of the software HOMER Grid, it is, for example, not yet possible to force the battery to charge when power is available from the grid, in particular during the night, to ensure power availability (more than the PPG allowed) for next EV's charging events.

Second, the best case using the HOMER's database proposed Huawei Power Cube 5000 inverter would lead to a simple payback of 11 years instead of 4.2 years. So, even if using HOMER's database components is very easy and convenient, it is very advisable to check the present market components and costs, and manually introduce new models/prices as they can have dramatic impact on the economic indicators obtained.

7 Conclusion

The presented work shows the result of a project development, in which a photovoltaic energy generation system and a battery storage system were considered that can cover most of the needs of a charging station for EVs connected to the grid. Despite the limitations of the software HOMER Grid, which does not allow to create our own strategy where the user can decide when to charge the batteries from the grid or not, it proved to be a very powerful tool to analyze the economic viability of a system, if proper care is taken as pointed out, namely checking the currently available models and prices of the considered components. HOMER Grid has also shown that a system consisting of a storage system with second-life batteries can be an advantage over new batteries because of the latters' higher cost. This study also suggests that with the use of PV and a storage system, it is possible to increase the available power beyond the contracted power.

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