Energetic, Economic and Environmental Viability of Off-Grid PV-BESS for Charging Electric Vehicles: Case Study of Spain

Luis Santiago Azuara Grande, Imene Yahyaoui*, Santiago Arnaltes Gómez

Electrical Engineering Department, University of Carlos III of Madrid, Spain

e-mails: luis.azuara.grande@gmail.com; imene.yahyaoui@uc3m.es; arnalte@ing.uc3m.es

*Corresponding author: Imene Yahyaoui

E-mail address: imene.yahyaoui@uc3m.es

Tel: 0034 983 184 859

Fax: 0034 983 423161

Highlights

- Study of viability and rentability of off- grid PV- BESS for charging Electrical Vehicles.
- Energetic and economic studies using HOMER software.
- Environmental benefits of the proposed system.
- Load- Shifting effects on the rentability of PV- BESS.

Abstract:

Nowadays, the optimum technical design of Photovoltaic and Battery Energy Storage System (PV-BESS) is crucial for ensuring their economic feasibility, which implies the minimum cost sizing of the system components. In fact, a good design of the off-grid PV-BESS system allows the outages to be avoided, ensures the quality and the security of the power supply, from the one hand, and guarantees the economic and environmental benefits, from the other one. In this context, this paper analyses the technical and economic viability of an off-grid PV-BESS for Charging Electric Vehicles (EVs). The study is performed using HOMER software and meteorological data of Madrid, Spain, and by applying the load shifting principle.

In order to verify the effectiveness and rentability of the studied system, its efficiency has been compared to grid- connected charging points, considering the environmental aspects. The obtained results demonstrate that the off-grid PV-BESS are technically and economically viable and reliable. Moreover, they are profitable while allowing a significant reduction of the air pollution.

Keywords: Photovoltaic energy; Electric vehicles; BESS; Charge point; Grid parity; Emissions reduction; charge- shifting.

1. Introduction

The Spanish energy model shows signs of unsustainability, runaway growth in demand and CO_2 emissions, as well as very high dependence on fossil fuels (Fig. 1). It highlights the impact of hydrocarbons in the Spanish energy supply (Fig. 2). The oil crisis in the seventies not only meant a return to coal and the problematic development of nuclear energy, but also resulted in high inflation and low economic growth. A strong growth in energy demand following the 2008 crisis was based on lower oil prices, although they rebounded in 2012 (Girard, Gago, Ordoñez, & Muneer, 2016). In the period 2008-2012, the CO_2 emissions decreased for the first time, but the objective established in the Kyoto protocol was not reached (the reduction of 5% with respect to the emissions of the year 1990).

The largest contribution of atmospheric pollutant emissions in urban areas today is from on-road transport (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2015). In Spain, the transport sector was responsible for 41,6% of the total final energy consumed in 2015 (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2015), and it was a prime target for the implementation of energy efficiency policies (Román Collado & Sanz Díaz, 2017). In the urban areas, several air quality problems are faced, related mainly to the emission of NO_2 and particulate matter (Román Collado & Sanz Díaz, 2017). In recent years, there have been significant efforts to study the effects of strategies designed to reduce on-road traffic emissions and the subsequent impacts of these emissions on air quality (Román Collado & Sanz Díaz, 2017). Currently, the main objectives of these strategies are to reduce the emission per vehicle and to adopt mobility management strategies that allows the vehicle kilometres travelled to be reduced. In this sense, fleet electrification is one of the strategies under consideration for improving urban air quality (Soret, Guevara, & Baldasano, 2014).

In fact, the Electric Vehicles (EVs) offer many important environmental benefits. For instance, in urban areas, where most transport activities take place, the impact of transport on air pollution is significant (Andersen, Mathews, & Rask, 2009) (De Gennaro, Paffumi, & Martini, 2015) (Heidrich, et al., 2017). While EVs do not emit any emissions during driving, the electricity they consume can be produced from fossil fuels that emit air pollutants like CO_2. Therefore, emissions must be considered on a well-to-wheel basis in comparing their CO_2 emissions to conventional vehicles (Poullikkas, 2015). Well-to-wheel emissions depend on the efficiency of the EV and the source mix of electricity generation, which differs greatly across countries. Following the International Renewable Energy Agency (IRENA)' report, by 2030, countries would have a much higher share of renewable energies in their total power generation mix (International Renewable Energy Agency (IRENA), 2017). Hence, the CO_2 emissions per kWh of electricity generated and, therefore, the well-to-wheel emissions of EVs will decrease. Thus, increasing power generation from renewable sources is fundamental, for improving the environmental benefits of EVs.

The potential for solar energy in Spain is massive. In fact, Spain receives annually an average global irradiation of 1640 kWh/m^2 on its horizontal surface (Fig. 3), and it is considered among the sunniest countries in Europe (Girard, Gago, Ordoñez, & Muneer, 2016). Besides, the global Photovoltaic (PV) market has grown 20-25% in the last years and reached 290 GW of installed power by the end of 2016 (International Renewable Energy Agency (IRENA), 2017). Consequently, it is estimated that the cost of PV technology will decrease from 1,8 $/W in 2015 to 0,8 $/W in 2025, while a 57% of cost reduction has been achieved in the last 10 years. Therefore, it is obvious that PV energy is an alternative to generate electricity, for many applications (Yahyaoui, I., Yahyaoui, A., Chaabene, M., & Tadeo, F., 2016), in particular, charging EVs.

Indeed, in the literature, several research papers focused on grid-Connected PV systems, which are destined to charging EVs (Mouli, Bauer, & Zeman, 2016) (Mihaylova Ilieva & Penchev Iliev, 2016) (Goli & Shireen, 2014) (Marano, Yurkovich, Rizzoni, & Tulpule, 2013). For instance, Brenna et al (Brenna, Dolara, Foiadelli, Leva, & Longo, 2014) examined the potential and the technical benefits of using such systems. Moreover, Traube et al studied the chargers and the energy storage sizing, based on the PV system rating, the desired maximum ramp rate and the solar irradiation characteristics of the studied site (Traube, et al., 2013). Indeed, the authors found that small amounts of energy storage could accomplish large reductions in powers fluctuations. Additionally, Gurkaynak et al designed a residential PV system for plug-in hybrid electric vehicle, in addition to regular residential requirements (Gurkaynak & Khaligh, 2009). More precisely, the authors established a power management algorithm that controls the power flow between grid and batteries pack, according to the load profile, within one-year period. Hence, generally, the research papers concentrates mainly in the power control of EVs' fast chargers or energy management.

In the present paper, the proposed work focuses on the technical, economic and environmental benefits of using off-grid PV-BESS for charging EVs, using meteorological data of the city of Madrid, Spain. Therefore, this research paper aims to design a system that requires the lowest investment among the alternatives available, while reducing the emissions and, providing a highly efficient off-grid PV-BESS system. Then, the off-grid PV-BESS is compared to a grid- connected systems, to evaluate the profitability and reliability of each solution. Hence, a typical off-grid PV-BESS, which is composed by a PV plant, a BESS and an EV charger, is considered (Fig. 4). The BESS is used to ensure the security of supply, by storing the energy that cannot be used instantly, and using it when the PV power cannot satisfy the demand. The batteries inverter is responsible, at each sample time, of managing the delivering and the storage of the available energy.

The study is performed by using HOMER software, since it is characterized by a high performance for evaluating the energetic, economic and environmental aspects of renewable energy based projects (HOMER, 2017). In this research, the most significant contribution is the evaluation of the optimum sizing of the off-grid PV-BESS for charging EVs and then enhancing the results using the loads' shifting strategy. As per the authors' knowledge, this energetic-economic and environmental research of the off-grid PV-BESS for charging EVs based on the load' shifting represents an original contribution and it is not published elsewhere.

The paper is organized as follows: in Section 2 the methodology is explained. In Section 3, the off-grid PV-BESS installation is described in detail, including the site, the load and the system components descriptions. The results of the study are presented in Section 4. Finally, the conclusions and the future work are summarized in Section 5.

2. Methodology

2.1. HOMER Software for Sizing

In the literature, several software tools are used to evaluate the optimum design of PV installations, namely PVsyst, RETScreen or HOMER. In fact, PVsyst is a software for studying, sizing, simulating and analysing complete PV systems. It deals with grid-connected, stand-alone and pumping systems. Moreover, it includes extensive meteorological and PV systems components databases, as well as general tools for solar energy analysis. PVsyst generates a "Loss Diagram", which is particularly useful for identifying the weaknesses of the system design (Yahyaoui, 2016), (Yahyaoui, 2016)

On the other hand, RETScreen deals with the study of renewable system efficiency, energy management and the feasibility analysis for renewable energy systems, namely cogeneration projects, as well as ongoing energy performance analysis (RETScreen, 2017).

HOMER is a software aimed to design optimized hybrid microgrids (HOMER, 2017). In fact, it allows obtaining a viable system configuration and sizing by testing all possible combinations of elements following the chosen sensitivity factors, namely the inflation rate and the rate of return (HOMER, 2017). Indeed, HOMER simulates the operation of the considered microgrid for an entire year, in time steps from one minute to one hour. Then, it examines all the possible combinations for the system in a single run, and then sorts and identifies the least-cost options for microgrids or other distributed generation systems. The simulation results give the system viability and profitability over the life- time of the installation. Therefore, various possibilities for the system can be compared in a single run. Consequently, this allows to visualize the impact of the variables (HOMER, 2017). Therefore, in this paper, HOMER has been selected to design the off-grid PV-BESS.

2.2. Modelling

In the following subsections, the different models used by HOMER are presented (HOMER, 2017).

2.2.1. PV Modules

The following equation (1) is used to calculate the power generated by the PV array:

$$\boldsymbol{P_{PV}} = \boldsymbol{Y_{PV} f_{PV}} \left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right)\left[\mathbf{1} + \boldsymbol{\alpha_p}\left(\boldsymbol{T_c} - \boldsymbol{T_{c,STC}}\right)\right] \tag{1}$$

where:

Y_{PV}: the rated capacity of the PV array, meaning its power output under standard conditions (kW),

f_{PV}: the PV derating factor (%),

$\overline{G_T}$: the solar radiation incident on the PV array in the current time step (kW/m^2),

$\overline{G_{T,STC}}$: the incident radiation at standard conditions (1kW/m^2),

α_p: the temperature coefficient of power (%/°C),

T_c: the PV cell temperature in the current time step (°C),

$T_{c,STC}$: the PV cell temperature under standard conditions (25°C).

2.2.2. Solar Resource

HOMER calculates the global radiation on the tilted PV array using equation (2):

$$\overline{G_T} = (\overline{G_b} + \overline{G_d} A_i) R_b + \overline{G_d}(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

where:

$\overline{G}$: the global horizontal radiation on the earth´s surface averaged over the time step (kW/m^2),

$\overline{G}=\overline{G_b}+\overline{G_d}\begin{cases}\overline{G_b}: \text{the beam radiation (kW/m}^2\text{)}\\ \overline{G_d}: \text{the diffuse radiation (kW/m}^2\text{)}\end{cases}$,

$\overline{G_o}$: the extra-terrestrial horizontal radiation averaged over the time step (kW/m^2),

A_i: the anisotropy index $\rightarrow A_i=\frac{\overline{G_b}}{\overline{G_0}}$,

R_b: the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface,

$\rightarrow R_b=\frac{\cos\theta}{\cos\theta_z}\begin{cases}\theta: \text{the angle of incidence (°)}\\ \theta_z: \text{the zenith angle (°)}\end{cases}$,

β: the slope of the surface (°),

f: the cloudiness $\rightarrow f=\sqrt{\frac{\overline{G_b}}{\overline{G}}}$,

ρ_g: the ground reflectance, which is also called the albedo (%).

2.2.3. Batteries

The number of batteries in the BESS is calculated using equation (3):

$$N_{batt} = \frac{A_{batt} L_{prim,ave}(1000Wh/kWh)}{V_{nom} Q_{nom}\left(1 - {q_{min}}/{100}\right)(24h/d)} \tag{3}$$

where:

A_{batt}: BESS autonomy (h),

V_{nom}: nominal voltage of a single battery (V),

Q_{nom}: nominal capacity of a single battery (Ah),

q_{min}: minimum state of charge of the battery (%),

$L_{prim,ave}$: average primary load (kWh/d).

2.3. Economic analysis

In this section, an economic study of the considered off-grid PV-BESS is detailed. In fact, the following indicators are used to evaluate the rentability of the studied system.

- Net Present Value (NPV) is the difference between the value being recovered and the cost of a project (Asquith & Weiss, 2016). It is evaluated using the expression given by equation (4).

$$NPV = -C_0 + \sum_{i=1}^{N} \frac{C_i}{(1+r)^i} \tag{4}$$

where:

C_0: initial investment (€),

C_i: cash flow for period i (€),

r: discount rate (%),

N: life of the project (years),

i: period of investment (year).

- Internal Rate of Return (IRR) is the discount rate that makes the NPV equal to zero (Asquith & Weiss, 2016). It is given by equation (5).

$$0 = -C_0 + \sum_{i=1}^{N} \frac{C_i}{(1+IRR)^i} \tag{5}$$

where:

C_0: initial investment (€),

C_i: cash flow for period i (€),

N: life of the project (years),

i: period of investment (year).

- Return on Investment (ROI) is the benefit to an investor resulting from an investment (Sandborn, 2017). It is described using equation (6).

$$ROI = \frac{Net\ Income - Expenses}{Expenses} \tag{6}$$

- Payback period is the time duration that must elapse to recover the initial investment (Lefley, 1996).

- Cash Flow is the difference between income and expenses of a company in each period (Gilchrist & Himmelberg, 1995). It is given by equation (7).

$$C_N = -C_0 + \sum_{i=1}^{N}(I_i - E_i) \quad (7)$$

where:

C_N: cash flow at the end of the project (€),

C_0: initial investment (€),

I_i: income for period i (€),

E_i: expenses for period i (€),

N: life of the project (years),

i: period of investment (year).

3. Application to a Case Study

3.1. Location of the off-grid PV-BESS

The location of the present project is the city of Madrid, Spain (latitude= 40º.41, longitude: 3º.43). Over the last decade, the air quality level of the city has not been improved, due to the increase of the population and traffic (Borge, et al., 2014). However, some pollutants like nitrogen dioxide (NO_2) still exceed the limit values established by the European legislation (Borge, et al., 2014).

The process of charging EVs needs more time than filling pumps need to top up the tanks of Internal Combustion Engine (ICE) vehicles. Thus, it is more likely that EV customers use the extra time to perform other activities while charging, in opposition to drivers of ICE vehicles (Madina, et al., 2015). Therefore, it is advisable that the locations of the charging station be close to areas of leisure or recreation.

Madrid is a city characterized by its high level of solar radiation, as it can be seen in Fig. 5, with an average annual solar irradiation of 5360 Wh/m^2/day, and a clearness index high (0,5; 0,7); which means that the amount of clouds is low and that the solar radiation that reaches a PV array is high. Indeed, the solar radiation reaches its maximum in the summer months (for instance, 7425 Wh/m^2/day in July and 7100 Wh/m^2/day in August (Fig. 5)). Therefore, due to the high level of the air pollution and the important solar energy resource of the city, it is obvious to study the off-grid PV-BESS viability and profitability for charging EVs in this city.

3.2. Load profile of the off-grid PV-BESS

The rate of charge can vary among different EVs' models and depends on the vehicle battery's charge acceptance rate, which is managed by the battery' energy management system (Motoaki & Shirk, 2017). For instance, in 2012, Nissan Leaf limited the charging rate up to 50 kW. At this rate, the charging point can recharge a Leaf battery from 10% to 80 % of State of Charge (SOC) in 30 min (Nissan, 2012). Moreover, unlike gasoline refuelling, the rate of charge is not constant over time. Idaho National Laboratory stated that the charging rate must be slower as the SOC increases. For instance, when SOC is below 30% at the beginning of charge, the rate of charge is about 0,72 kWh per minute. However, when the SOC reaches 80%, the rate of charge drops to 0,16 kWh per minute, which is less than a quarter of the rate at the beginning of charge (Idaho National Laboratory, 2017).

In fast charging, there is some hysteresis effects when the battery is close to its full load, so it is only able to charge at fast speed until 80% of SOC (Madina, et al., 2015). The fast charging devices have an output nominal power of 50 kW, and it delivers the charge through direct current (DC) from a three-phase electrical grid. In this paper, the EV battery size used is 60 kWh and the fast charging process would be carried out in 1-hour time. Thus, the fast charger is established in one hour load of 52,8 kW, as it is described in equation (8) (ABB Electric Vehicle Charging Infrastructure, 2017) (Alexander & Sadiku, 2013).

$$\begin{cases} \text{PF=0,96} \\ \text{S=55 kVA} \end{cases} \Rightarrow P = S \cdot PF = 55 \cdot 0{,}96 = 52{,}8\ kW \quad (8)$$

where:

PF: the power factor (%),

S: apparent power (kVA).

Due to the increase of EVs, it is of utmost importance to provide a public charging infrastructure that adequately caters to the needs of all EV users (Morrissey, Weldon, & O´Mahony, 2016). In fact, fast charging infrastructure is expected to be mainly used by long-distance travellers, EV customers with high daily distance requirements (taxis, delivery fleets…) and EV customers that cannot have access to home charging (Madina, et al., 2015).

In Spain due to the lack of public EVs' charging infrastructure and the high costs of fast charging, the users who have access to private home charging are expected to be the early adopters of EVs, as their total cost of ownership can be lower than the cost of ICE vehicles, thanks to the low price of the energy in this type of recharge (Madina, Zamora, & Zabala, 2016). To convince a potential EV buyer without private home charging, commercial agreements with automobile brands that guarantee the availability of a daily charge at that station are required. Therefore, these off-grid PV-BESS are the alternative to those who cannot charge at home, while providing competitive prices.

In the present study, the installation has to be sized to set 12 complete recharges per day, as shown in Fig. 6. In addition, the use is also posed for sectors such as taxis (in July 2017 there were 30 electric taxis in Madrid (Ayuntamiento de Madrid, 2017)) or delivery companies, since as mentioned before, they are also interested in using EVs' fast charging points.

3.3. Description of the Installation Components

3.3.1 Components of the off-grid PV-BESS

The following components are chosen for the designing of the installation, as shown in Table. 1. A standard 400 V AC bus has been selected, for which all the components (solar inverter, battery inverter and charger) are connected. The technical parameters of these components are described in Table 1.

3.3.2 Costs of the off-grid PV-BESS components

To perform the economic analysis, updated costs of all the PV- BESS components are required. Table. 2 shows the installation components costs, used in the simulation performed with HOMER, to obtain the optimum sizing of the system' components.

The PV investment cost includes cabling, module support structure, civil engineering, turnkey contractor´s margin and other costs. The annual costs of operation and maintenance include insurance, management, land rent and maintenance.

4. Results and discussion

4.1. Base Case Study

4.1.1. Analysis of the technic and energetic criteria

Using HOMER software, the sizing is performed using the components parameters detailed in Table. 1. The optimum tilt angle used for PV modules is 30°, since it allows the PV power generated to be maximum and the unmet load is minimum. Moreover, the optimal angle of orientation is 0°, as the installation is in the northern hemisphere. The simulation results are described in Table. 3.

Following Table. 3, this installation requires a peak PV power of 281,52 kWp, which corresponds to 828 PV modules, which cover 1606 m^2 of surface, approximately. Moreover, 420 kWh of batteries are needed to store the excess of energy, and that will be consumed later by the EVs, thanks to a load shifting between the backup batteries and the EV. According to Fig. 7, there is only unsatisfied load in the months of January, February, October, November and December, i.e winter and autumn seasons. The objective is to ensure the greatest amount of energy possible for the 12 daily recharges established, so that a 13.5 hours of autonomy provided by the battery' is sufficient (this is equivalent to 12 recharges of 35 kWh). In addition, choosing higher number of autonomy' days will increase the installation' cost without getting energetic benefits.

Following the simulation performed using HOMER, two 100 kW of inverters are needed. This result fits with the total installed PV power (281,52 kWp) and the system' components parameters. Therefore, the PV modules will be distributed in 2 x 140,76 kW, each is formed by 18 strings of 23 modules in series, with a peak voltage of 871,7 V and a peak current of 161,46 A at the input of each inverter.

4.1.2. Analysis of the economic criteria

In this paragraph, the investment analysis is carried out through the evaluation of the NPV (4), IRR (5), ROI (6) and Payback indicators, whose results are shown in Table. 4. In the base case study, thirteen years are considered for the life of the batteries. Hence, they have to be replaced at the middle of the project life. While the PV module and the inverter have a useful life of 25 years, which is the period for which the whole investment is analysed.

The annual cash flow (7) and the period of the investment recovery during which the project is evaluated, are illustrated in Fig. 8.

The energy price is established at 0,4 €/kWh, which is similar to internal combustion engine (ICE). According to the data obtained in Table. 4 and Fig. 8, the investment decision would be favourable since the NPV is positive, the IRR is quite good, and the final cash flow is too high (almost 1.200.000,00 €). Following the obtained results, the positive annual cash flows allow recovering the initial investment in the 7th year, and reaching a final profit of 1.179.901,37 €.

4.2. Improved case study

As it is described in Fig. 7, there is a high energy surplus generated by the PV. Moreover, it is possible to decrease the prices for the recharges compared to the base case. This is can be fulfilled by installing two additional chargers with five daily loads, at 11h, 12h, 13h, 14h and 15h (which corresponds to the excess of the PV energy generated), as it is shown in Fig. 9. The aim of this improvement proposal is to reduce the costs of the installation, taking advantage of the solar resource, and to store the excess energy in the batteries. Therefore, with the same installation, it will be possible to charge more EVs (Fig. 9).

In Fig. 10 and Fig. 11, it can be seen that the implementation of the additional chargers allows a better match between the power generated and demanded to be made, which avoids the energy overproduction.

It is possible to transfer the demand to the central hours of the day by setting different prices for energy, depending on the time of use (for example, 0,4 €/kWh for the hours of low solar production (8h to 11h and 15h to19h) and 0,25 €/kWh for the high production hours (11h-15h)).

4.2.1. Analysis of the energetic criteria

The obtained results that correspond to the energetic criteria for the improved case study are presented in Table. 5. As it can be seen, they are better than those obtained by the base case study (Table. 3), since the power consumption has increased during the hours of maximum PV power generation, which is reflected by a reduction in the PV energy in excess. Thus, this allows the excess energy to be reduced about 32,5%, with respect to the base case study, as it makes better use of the available solar resource.

4.2.2. Analysis of the economic criteria

The economic analysis of the improved case study is shown in Table. 6. The annual cash flows and the period of recovery of the investment are presented in Fig. 12. The energy price is variable according to the moment in which it is consumed (0,4 €/kWh during periods of low PV energy generated and 0,25 €/kWh during periods of high PV energy generated).

According to the data obtained in Table. 6 and Fig. 12, the investment decision would be favourable, since the NPV is positive, the IRR is quite good, and the final cash flow is too high. In fact, the positive annual cash flows allow recovering the initial investment in the year 7th, and reaching a final profit of 1.490.589,5 €. Thanks to the increase in the energy sales revenues fulfilled using the additional chargers and simultaneously it has also allowed to reduce the price of recharges. Which has not had negative repercussions in the economic analysis.

Consequently, the obtained results of the energetic and the economic analysis indicates that benefits that are more positive can be obtained using the improved case study. The environmental impact and the grid parity analyses are analysed in the next paragraph.

4.2.3. Environmental study

Following the International Renewable Energy Agency (IRENA), the EVs can be considered 100% free of polluting emissions if the energy used to charge the batteries is 100% renewable (International Renewable Energy Agency (IRENA), 2017). However, charging the batteries of EVs can be performed using the electric grid. Therefore, a comparison of the CO_2 emissions of diesel, gasoline, grid- connected and off- grid PV- BESS charging stations are compared (Table. 7). Following the Spanish Electrical System, the generation of 1 kWh emits an average of 308 g CO_2 (Red Eléctrica de España (REE), 2016). Currently the cost of emitting 1 ton of CO_2 is 7,61 € (SENDECO2, 2017).

Following the results in Table. 7, the off-grid PV-BESS allows the emissions of EVs to be eliminated, providing about more two million kilometres per year. The biggest advantage of the off-grid PV-BESS compared to those that have a small backup PV generator, is that the penetration of renewables in the electric mobility is 100%, and therefore, it not only reduces emissions and pollutants, but also eliminates them completely. Therefore, off-grid PV-BESS could become the main agents against pollution in the cities and climate change, especially in the areas characterized by important solar energy.

4.2.4. Grid parity study

In this paragraph, the cost of charging EVs using the off-grid PV-BESS is compared to the cost of using grid-connected charging stations (Table. 8). In fact, the energy sales prices of some charging providers in Spain and Europe are used. Indeed, the cost of charging EVs using off-grid PV-BESS is compared to the prices offered by IBIL, which is the most representative charging provider in Spain. In addition, updated data from FASTNED have been used, to compare the profitability of off-grid PV-BESS with a charging provider in Europe, which uses 100% of renewable energies to charge EVs (Table. 8).

Following the obtained results, the proposed price (0.4 €/ kWh during [15h to 19h] and [8h to 11h], and 0.25 €/kWh during [11h to 15h]) applied for the off-grid PV-BESS is quite competitive compared to the grid-connected charging stations. This is quite important, since a daily 100 km distance costs 20805 € per year for the user when an off- grid PV- BESS fast charger is used, which represent almost two thirds of the cost when fast chargers of IBIL or FASTNED. Thus, the economic and environmental advantages over the internal combustion engine vehicles and grid-connected systems is very clear, and it can be enhanced, thanks to higher expansion and investment of this technology in the coming years.

5. Conclusions

In this paper, an energetic, economic and environmental study of an off-grid PV-BESS has been performed. Three objectives have been achieved: to obtain an economic and non-polluting charging process for EVs, which ensures the system efficiency and the reduction in emissions, while being technically and economically feasible.

In this study, due to the intermittent character of the solar radiation, an energy storage system is used. Moreover, it has been proved that it is possible to optimize the use of the PV energy through the reduction of the unused generated energy and the unmet load, thanks to the load consumption displacement. Therefore, it is possible to recuperate the initial investments in 7 years and achieve higher economic benefits at the end of the installation life- time (25 years) using competitive prices of the kWh, compared to well-known companies in EVs fast chargers.

As a conclusion, off-grid PV-BESS can be considered not only a good solution for emissions reduction in industrial countries characterized by a good amount of solar radiation, but also a profitable projects that are economically rentable and energetically reliable. Therefore, a higher capacity installation must be considered, due to future growth forecasts in the electric mobility sector and new high-power chargers (150 kW or even 350 kW). In addition, given the great improvement of the batteries, it would be of great interest to verify the performance of the new battery technologies and design control systems that allow to manage in the most efficient way the solar resource, the backup batteries and the recharges of the EVs in off-grid PV-BESS.

References

ABB Electric Vehicle Charging Infrastructure. (2017). *Terra 53 multi-standard DC charging station.* Retrieved October 2017, from http://search-ext.abb.com/library/Download.aspx?DocumentID=4EVC204303-LFEN&LanguageCode=en&DocumentPartId=&Action=Launch

Alexander, C. K., & Sadiku, M. N. (2013). *Fundamentos de circuitos eléctricos* (5ª ed.). Mc Graw Hill.

Andersen, P. H., Mathews, J. A., & Rask, M. (2009). Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles. *Energy Policy*, 2481-2486.

Asquith, P., & Weiss, L. A. (2016). *The Time Value of Money: Discounting and Net Present Values, in Lessons in Corporate Finance: A Case Studies Approach to Financial Tools, Financial Policies, and Valuation.*

Ayuntamiento de Madrid. (2017). *Flota de vehículos taxi por combustible.* Retrieved October 2017, from http://www.madrid.es/portales/munimadrid/es/Inicio/Movilidad-y-transportes/Taxi?vgnextfmt=default&vgnextoid=4813dc0bffa41110VgnVCM1000000b205a0aRCRD&vgnextchannel=220e31d3b28fe410VgnVCM1000000b205a0aRCRD&rm=%2C4813dc0bffa41110VgnVCM1000000b205a0aRCRD%2Ca7

Borge, R., Lumbreras, J., Pérez, J., de la Paz, D., Vedrenne, M., de Andrés, J. M., & Rodríguez, M. E. (2014). Emission inventories and modeling requirements for the development of air quality plan. Application to Madrid (Spain). *Science of the Total Environment*, 809-819.

Brenna, M., Dolara, A., Foiadelli, F., Leva, S., & Longo, M. (2014). Urban Scale Photovoltaic Charging Stations for Electric Vehicles. *IEEE Transactions on Sustainable Energy*, 1234 - 1241.

CanadianSolar. (2017). *PV Module Product Datasheet CS6U-M (1500 V).* Retrieved October 2017, from https://www.canadiansolar.com/fileadmin/user_upload/downloads/datasheets/en/new/Canadian_Solar-Datasheet-MaxPower_CS6U-M__1500V__en.pdf

De Gennaro, M., Paffumi, E., & Martini, G. (2015). Customer-driven design of the recharge infraestructure and Vehicle-to-Grid in urban areas: A large-scale application for electric vehicles deploment. *Energy*, 294-311.

European Environment Agency (EAA). (2016). *Electric Vehicles in Europe.*

FASTNED. (2017). *Choose the price plan that suits you*. Retrieved May 2017, from https://fastned.nl/en/choose-your-priceplan

Fathabadi, H. (2017). Novel grid-connected solar/wind powered electric vehicle charging station with vehicle-to-grid technology. *Energy*, 1-11.

Gilchrist, S., & Himmelberg, C. P. (1995). Evidence on the role of cash flow for investment. *Journal of Monetary Economics*, 541-572.

Girard, A., Gago, E., Ordoñez, J., & Muneer, T. (2016). Spain´s energy outlook: A review of PV potential and energy export. *Renewable Energy*, 703-715.

Goli, P., & Shireen, W. (2014). PV powered smart charging station for PHEVs. *Renewable Energy*, 280-287.

Gurkaynak, Y., & Khaligh, A. (2009). Control and Power Management of a Grid Connected Residential Photovoltaic System with Plug-in Hybrid Electric Vehicle (PHEV) Load. *Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE*.

Heidrich, O., Hill, G., Neaimeh, M., Huebner, Y., Dawson, R., & Blythe, P. (2017). How do cities suppot electric vehicles and what difference does it make? *Technological Forecasting & Social Change*.

HOMER. (2017). *Microgrid Software for Designing Optimized Hybrid Microgrids*. Retrieved July 2017, from http://www.homerenergy.com

Huld, T., Müller, R., & Gambardella, A. (2012). A new solar radiation database for estimating PV performance in Europe and Africa. *Solar Energy*, 1803-1815.

Idaho National Laboratory. (2017, October 10). *Charging System Testing*. Retrieved from https://avt.inl.gov/content/ charging-system-testing

Ingeteam. (2017). *INGECON SUN 3Play TL 100kW.* Retrieved October 2017, from https://www.ingeteam.com/Portals/0/Catalogo/Producto/Documento/PRD_2365_Archivo_ingecon-sun-3play-tl-100kw.pdf

Institute for Energy and Transport (IET). (2017). *Photovoltaic Geographical Information System (PVGIS)*. Retrieved May 2017, from http://re.jrc.ec.europa.eu/pvgis/

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2011). *Plan de Energías Renovables 2011-2020.*

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2015). *Consumos por sectores (Año 2015).*

Instituto para la Diversificación y Ahorro de la Energía (IDAE). (2017). *Consumos e intensidades mensuales (Año 2016).* Retrieved October 2017, from http://www.idae.es/informacion-y-publicaciones/estudios-informes-y-estadisticas

International Energy Agency (IEA). (2016). *CO2 Emissions from Fuel Combustion.*

International Renewable Energy Agency (IRENA). (2016). *The Power to Change: Solar and Wind Cost Reduction Potential To 2025.*

International Renewable Energy Agency (IRENA). (2017). *Electric Vehicles Technology Brief.*

International Renewable Energy Agency (IRENA). (2017). *Renewable Capacity Statistics.*

Lefley, F. (1996). The payback method of investment appraisal: A review and synthesis. *International Journal of Production Economics, 44*, 207-224.

Li, Y., Yang, J., & Song, J. (2017). Design structure model and renewable energy technology for rechargeable battery towards greener and more sustainable electric vehicle. *Renewable and Sustainable Energy Reviews*, 19-25.

Madina, C., Zabala, E., Gómez, I., Barlag, H., Gereke, T., Jundel, S., . . . O´Mahony, M. (2015). *Deliverable 9.4 Part 2 Envisaged EU mobility models, role of involved entities, and Cost Benefit Analysis in the context of the European Clearing House mechanism.* Green eMotion project, European Union Seventh Framework Programme FP7/2007-2013 under Grant Agreement no. 265499.

Madina, C., Zamora, I., & Zabala, E. (2016). Methodology for assessing electric vehicle charging infraestructure business models. *Energy Policy*, 284-293.

Marano, V., Yurkovich, S., Rizzoni, G., & Tulpule, P. J. (2013). Economic and environmental impacts of a PV powered workplace parking garage charging station. *Applied Energy*, 323-332.

Martínez-Lao, J., Montoya, F., Montoya, M., & Manzano-Agugliaro, F. (2017). Electric vehicles in Spain: An overview of charging systems. *Renewable and Sustainable Energy Reviews*, 970-983.

Mihaylova Ilieva, L., & Penchev Iliev, S. (2016). Feasibility assessment of a solar-powered charging station for electric vehicles in the North Central region of Bulgaria. *Renewable Energy and Environmental Sustainability*.

Miranda Hernández, J. M., & González, N. I. (2015). Las Infraestructuras de Recarga y el Despegue del Vehículo Eléctrico. *Observatorio Medioambiental, 18*, 57-85.

Morrissey, P., Weldon, P., & O´Mahony, M. (2016). Future standard and fast charging infraestructure planning: An analysis of electric vehicle charging behaviour. *Energy Policy*, 257-270.

Motoaki, Y., & Shirk, M. G. (2017). Consumer behavioral adaption in EV fast charging through pricing. *Energy Policy*, 178-183.

motor.es. (2017). *¿Cuánto cuesta cargar un coche eléctrico?* Retrieved May 2017, from https://www.motor.es/noticias/cuanto-cuesta-cargar-coche-electrico-201734364.html

Mouli, G. C., Bauer, P., & Zeman, M. (2016). System design for a solar powered electric vehicle charging station for workplaces. *Applied Energy*, 434-443.

Nissan. (2012). *2012 Leaf Owner´s Manual.* Retrieved October 10, 2017, from https://www.nissanusa.com/electric-cars/ leaf/owner-questions/ev-charge-time

Official Journal of the European Union, L307/1, 28 October 2014. (n.d.). *Directive 2014/94/EC of the European Parliament and of the Council of 22 October 2014.* Retrieved October 2017, from http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&from=EN

Poullikkas, A. (2015). Sustainable options for electric vehicle technologies. *Renewable and Sustainable Energy Reviews*, 1277-1287.

Rauf Bhatti, A., Salam, Z., Junaidi Bin Abdul Aziz, M., Pui Yee, K., & Ashique, R. H. (2016). Electric vehicles charging using photovoltaic: Status and technological review. *Renewable and Sustainable Energy*, 34-47.

Red Eléctrica de España (REE). (2016). *Avance del Informe del Sistema Eléctrico Español 2016.*

RETScreen. (2017). *Clean Energy Managment Software*. Retrieved July 2017, from http://www.nrcan.gc.ca/energy/software-tools/7465

Román Collado, R., & Sanz Díaz, M. T. (2017). Analysis of energy end-use efficiency policy in Spain. *Energy Policy*, 436-446.

Sabihddin, S., Kiprakis, A., & Mueller, M. (2015). A Numerical and Graphical review of Energy.

Sandborn, P. (2017). *Return on Investment (ROI). Cost Analysis of Electronic Systems: 2nd Edition.*

Schroeder, A., & Traber, T. (2012). The economics of fast charging infraestructure for electric vehicles. *Energy Policy*, 136-144.

SENDECO2. (2017). *Sistema Europeo de Negociación de CO2*. Retrieved November 2017, from http://www.sendeco2.com/es/

Soret, A., Guevara, M., & Baldasano, J. (2014). The potential impacts of electric vehicle on air quality in the urban areas of Barcelona and Madrid (Spain). *Atmospheric Environment*, 51-63.

Šúri, M., Huld, T., Dunlop, E., & Ossenbrink, H. (2007). Potential of solar electricity generation in the European Union member states and candidate countries. *Solar Energy*, 1295–1305.

Talavera, D., de la Casa, J., Muñoz-Cerón, E., & Almonacid, G. (2014). Grid parity and self-consumption with photovoltaic systems underthe present regulatory framework in Spain: The case of the University of Jaén Campus. *Renewable and Sustainable Energy Reviews*, 752-771.

Tesla Energy. (2017). *Tesla Powerpack 2 Datasheet.* Retrieved October 2017, from https://www.tesla.com/es_ES/powerpack?redirect=no

Tesla Motors. (2017). *Superchargers*. Retrieved June 2017, from https://www.tesla.com/es_ES/support/supercharging

Traube, J., Lu, F., Maksimovic, D., Mossoba, J., Kromer, M., Faill, P., . . . Casey, L. (2013). Mitigation of Solar Irradiance Intermittency in Photovoltaic Power Systems With Integrated Electric-Vehicle Charging Functionality. *IEEE Transactions on Power Electronics*, 3058 - 3067.

Xu, R., Ni, K., Hu, Y., Si, J., Wen, H., & Yu, D. (2017). Analysis of the optimum tilt angle for a soiled PV panel. *Energy Conversion and Management*, 100-109.

Yahyaoui, I. (2016). *Specifications of photovoltaic pumping systems in agriculture: Sizing, fuzzy energy management and economic sensitivity analysis.* Oxford: Elsevier.

Yahyaoui, I., Yahyaoui, A., Chaabene, M., & Tadeo, F. (2016). *Energy management for a stand-alone photovoltaic-wind system suitable for rural electrification. Sustainable Cities and Society, 25, 90-101.*

Nomenclature

AC	Alternating Current
BESS	Battery Energy Storage System
CCS	Combined Charging Standard
CO_2	Carbon Dioxide
DC	Direct Current
EVs	Electric Vehicles
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
MPPT	Maximum Power Point Tracker
NO_2	Nitrogen Dioxide
NPV	Net Present Value
O&M	Operation & Maintenance
PF	Power Factor
PV	Photovoltaic
PV-BESS	PV and Battery Energy Storage System
ROI	Return on Investment
S	Max. Rated input power
SOC	State of Charge
V_{mp}	Opt. Operating Voltage module
V_{oc}	Open Circuit Voltage module

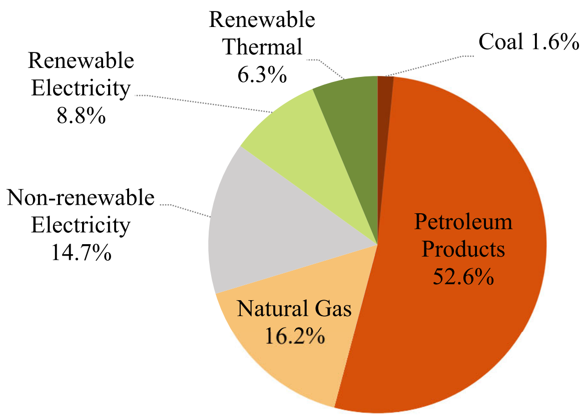

Fig. 1. Final Energy Consumption in Spain 2016. (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2017)

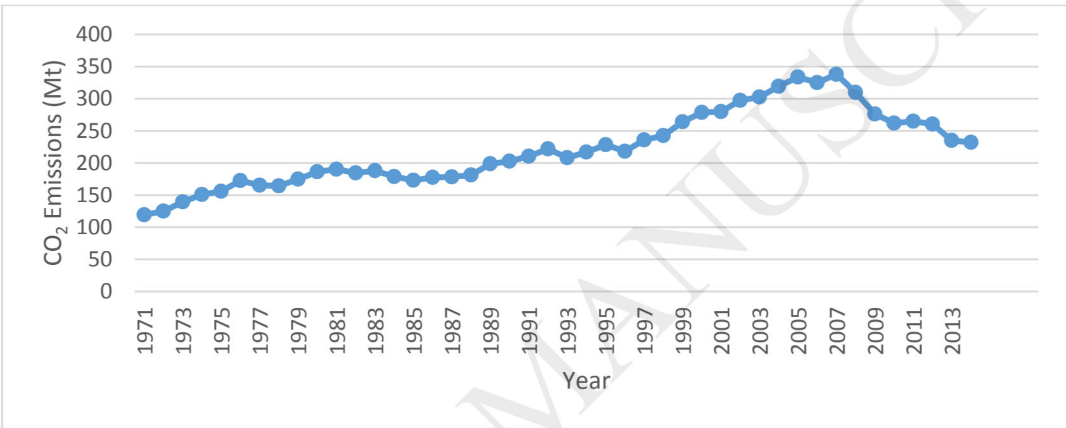

Fig. 2. CO_2 Emissions from Fuel Combustion in Spain. (International Energy Agency (IEA), 2016)

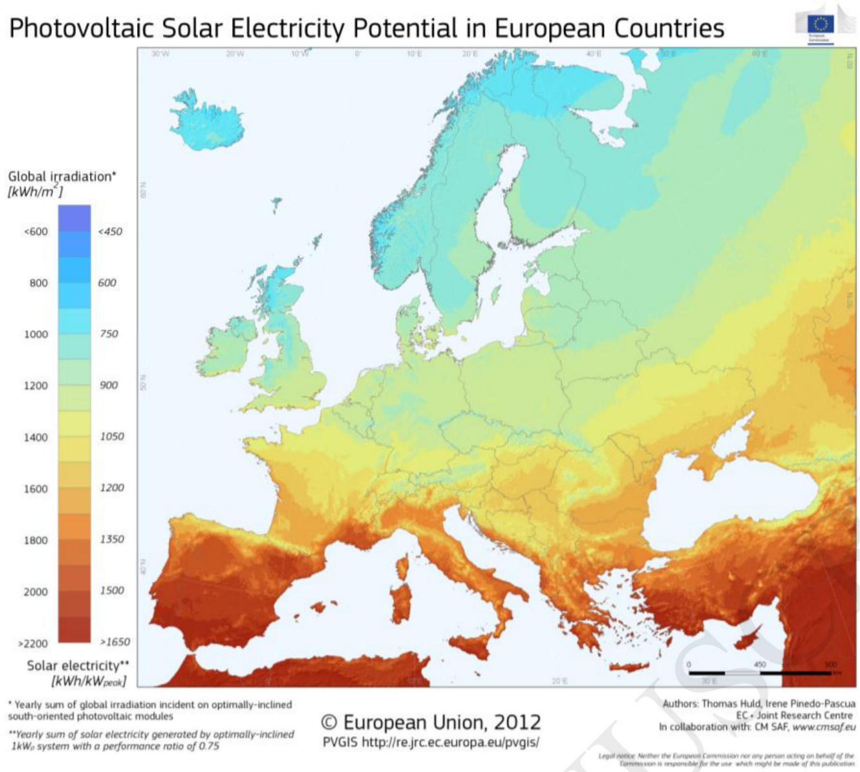

Fig. 3. PV Solar Electricity Potential in European Countries. (Institute for Energy and Transport (IET), 2017)

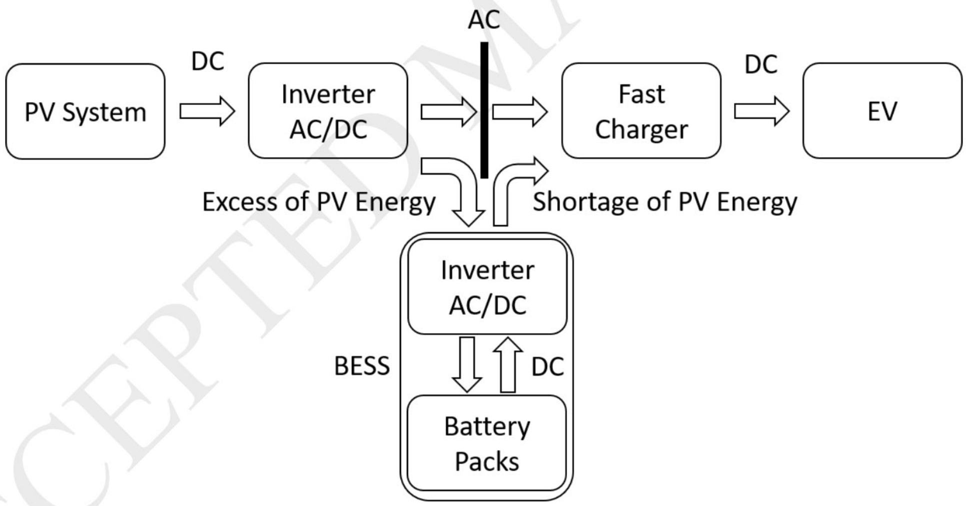

Fig. 4. Architecture of the off-grid PV-BESS studied.

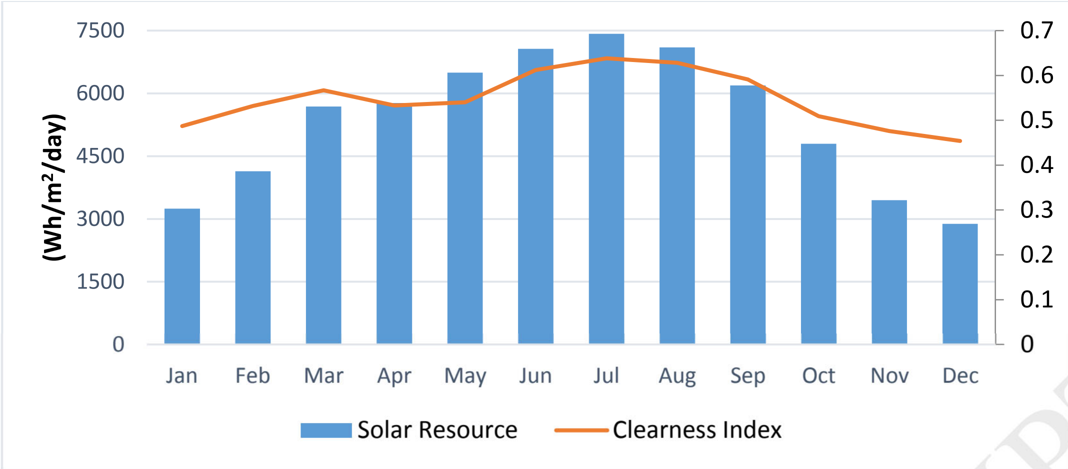

Fig. 5. Solar Resource and clearness index of Madrid. (Institute for Energy and Transport (IET), 2017)

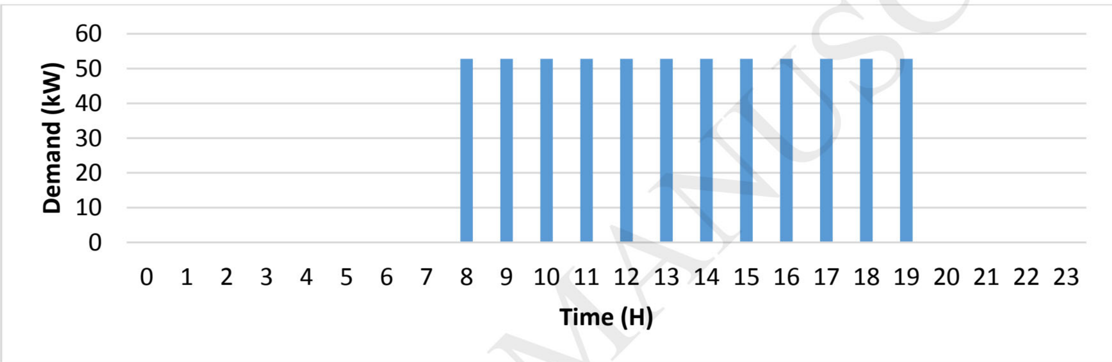

Fig. 6. Load profile scheme

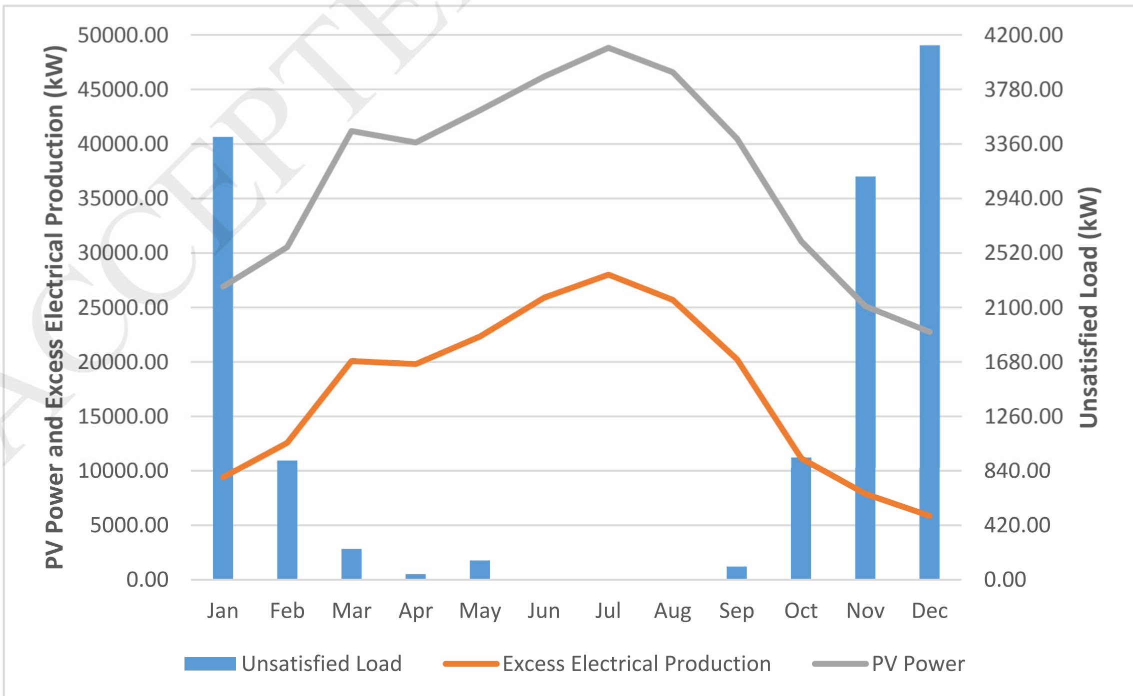

Fig. 7. PV Power, Excess Electrical Production and Unsatisfied load.

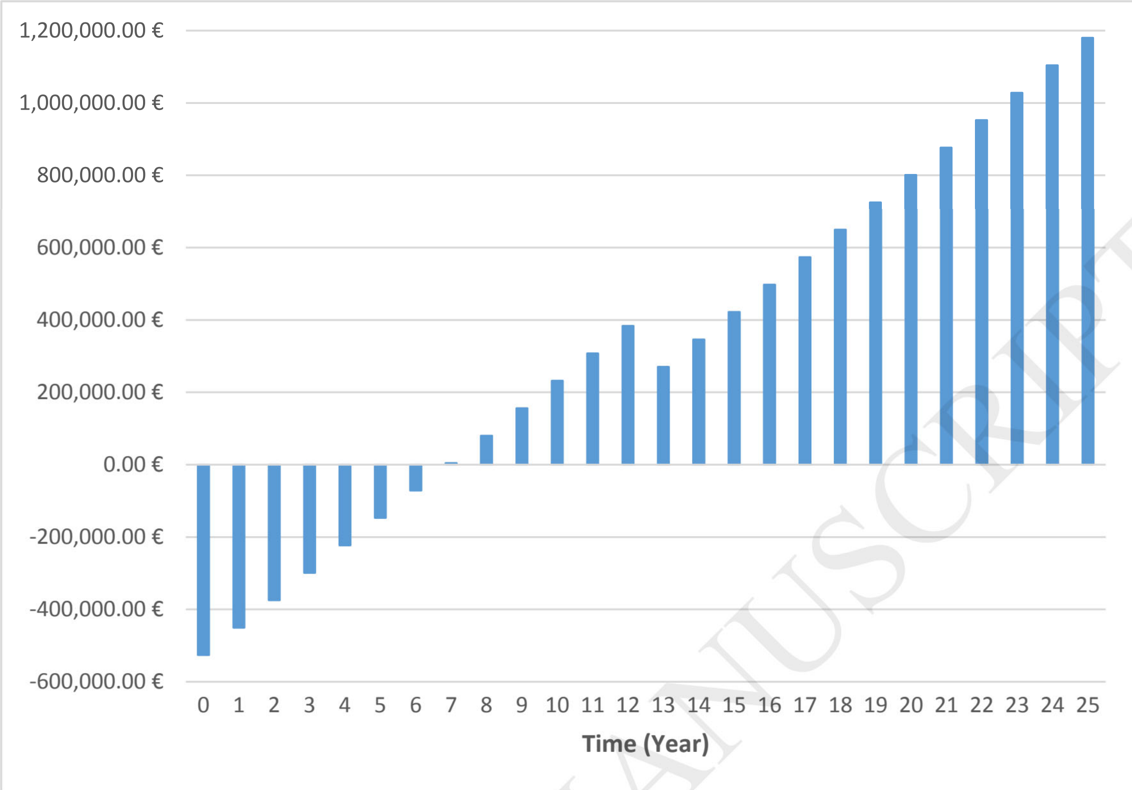

Fig. 8. Cash flow of the base case study

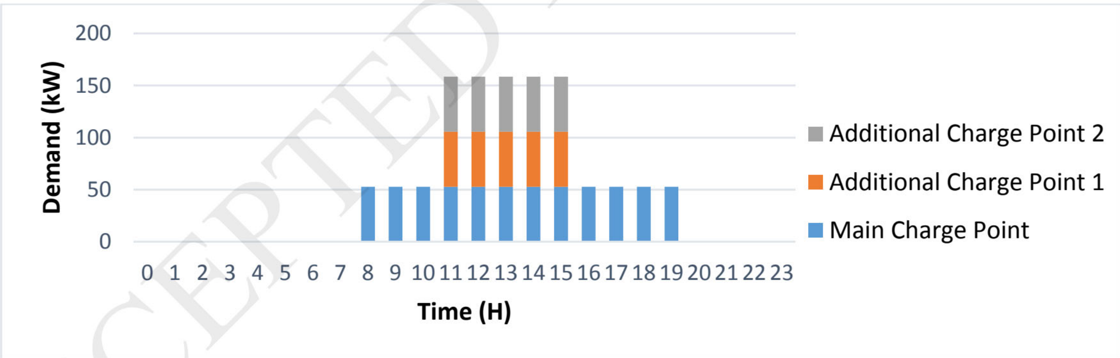

Fig. 9. Load profile of the improved case study

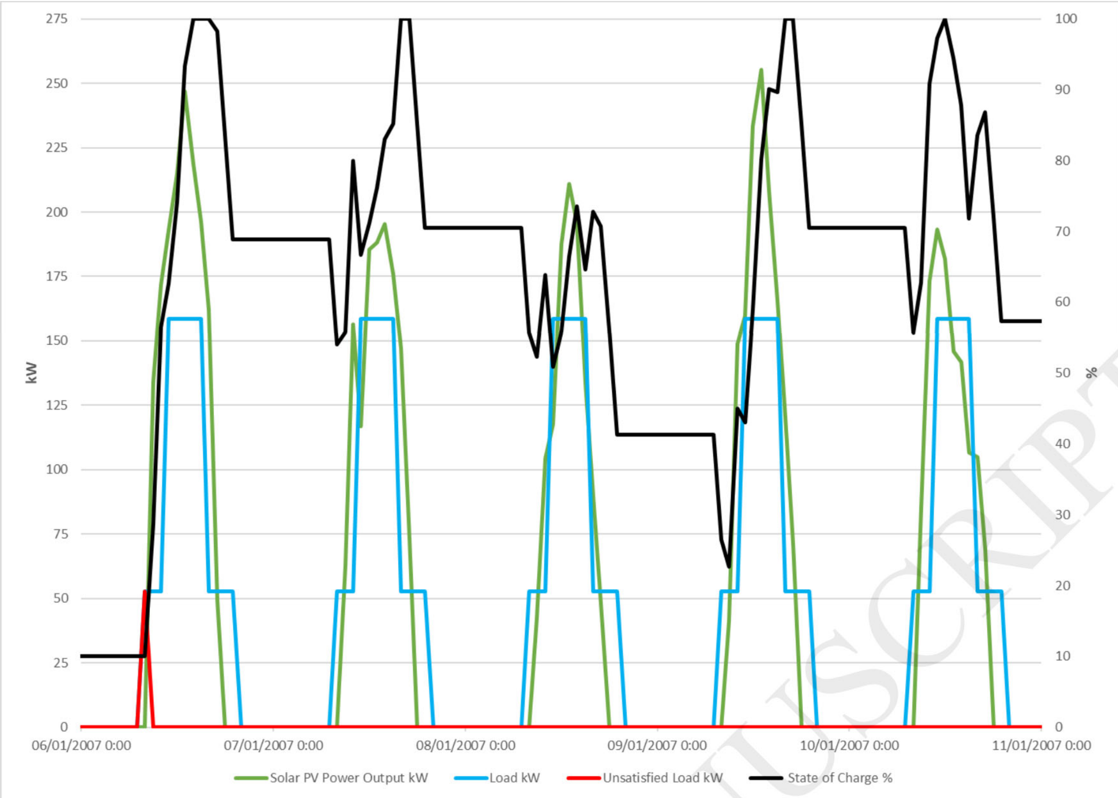

Fig. 10. HOMER simulation' results of the improved case study using climatic data of a typical day in Winter

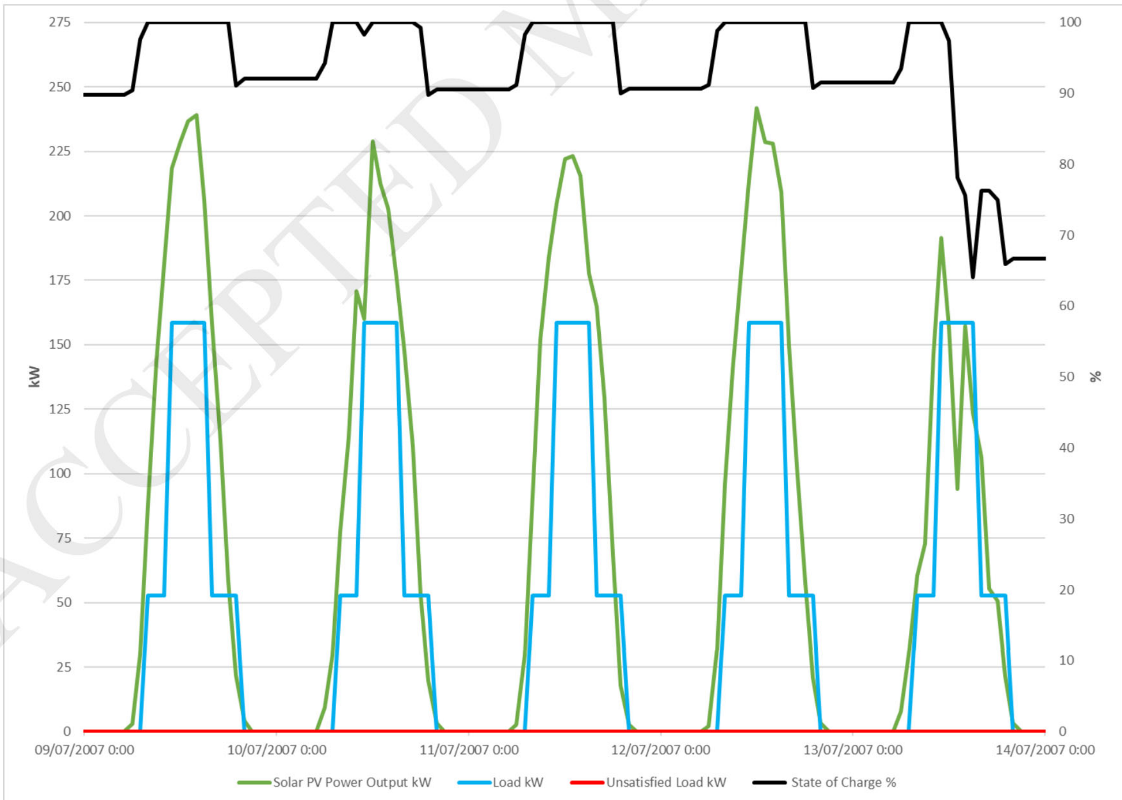

Fig. 11. HOMER simulation' results of the improved case study using climatic data of a typical day in Summer

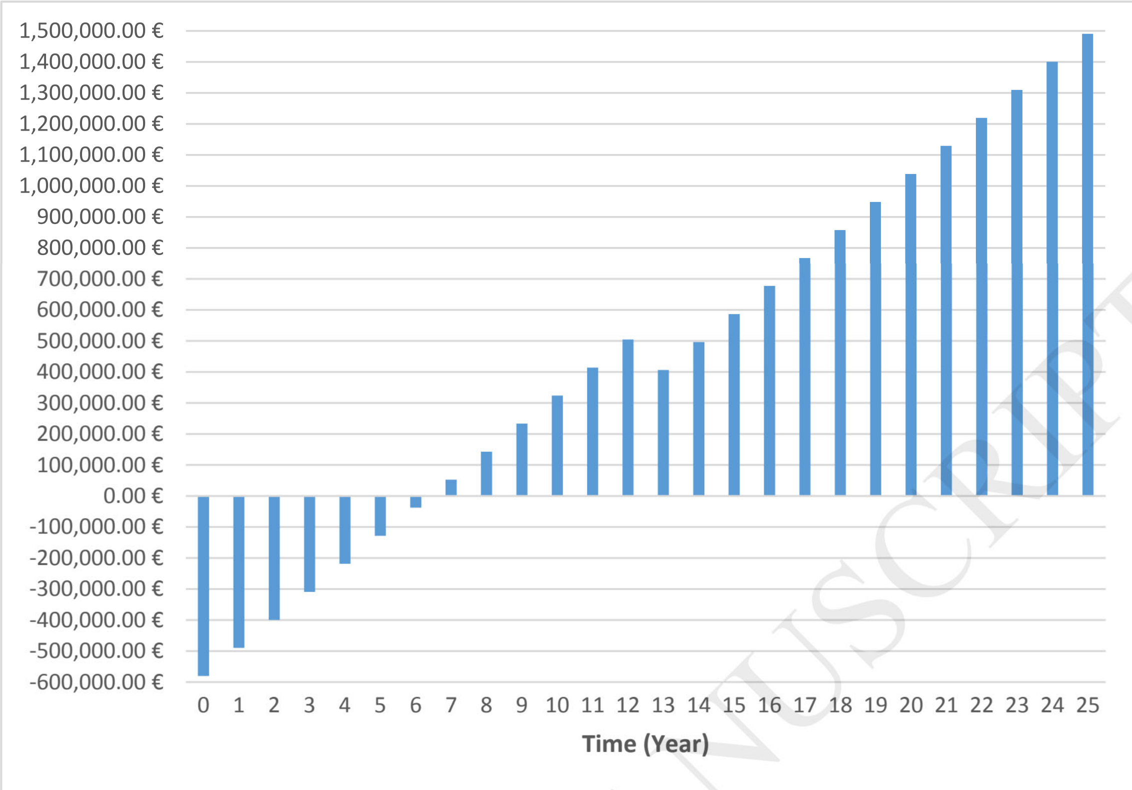

Fig. 12. Cash flow of the improved case study.

Table. 1 Characteristics of the PV module, PV Inverter, BESS and Fast Charger. (CanadianSolar, 2017), (Ingeteam, 2017), (Tesla Energy, 2017), (ABB Electric Vehicle Charging Infrastructure, 2017)

PV Module	Standard Conditions	PV Inverter	Data	BESS	Data	Fast Charger	Data
$P_{\max}$	340 W	$P_{PV,\max}$	103 - 160 kWp	Type	Lithium-ion	Charging standard	CCS and CHAdeMO
V_{mp}	37,9 V	$U_{DC,mpp}$	570 to 850 V	Energy	From 210 kWh	Maximum output power	50 kW
I_{mp}	8,97 A	$U_{\max(DC)}$	1100 V	Power	From 50 kW	Output voltage range	50 - 500 V_{DC}
V_{oc}	46,2 V	$I_{\max(DC)}$	185 A	AC Voltage	400 V	Maximum output current	125 A_{DC}
I_{sc}	9,48 A	$P_{N(AC)}$	100 kW			Input voltage range	400 V_{AC}
Surface	1,94 m^2	$I_{N(AC)}$	145 A			Max. Rated input current	80 A
Efficiency	17,49%	$U_{N(AC)}$	400 V			Max. Rated input power	55 kVA
		Efficiency	98,80%			Power factor	0,96

Table. 2 Costs of the installation' components. (Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2011), (International Renewable Energy Agency (IRENA), 2017), (ABB Electric Vehicle Charging Infrastructure, 2017)

PV Investment Cost (€/kW)	Annual O&M (€/kW)	BESS Investment Cost (€/kWh)	Inverter Investment Cost (€/kW)	Charger Investment Cost (€/Charger)
990	40,828	450	160	27.000

Table. 3 Technical and energetic results of the base case study

PV power (kW)	Batteries (kWh)	Generated energy (kWh/year)	Consumed Energy (kWh/year)	Excess energy (kWh/year)	Excess energy (%)	Unmet load (kWh/year)	Unmet load (%)	Autonomy (h)
281,52	420	442,854	218.227	208.141	47,2	13.037	5,64	13,5

Table. 4 Economic analysis results of the base case

Devices	Investment (€)	Discount Rate (%)	NPV (€)	IRR (%)	ROI (€)	Payback (Years)	Cash Flow (€)	Price (€/kWh)	Battery Replacement (€)	Annual O&M (€)
PV Modules	278.368,20									
Inverter	32.000,00									
BESS	189.000,00									
Chargers	27.000,00									
Total	526.368,20	7,00	278.670,78	12,72	2,24	7	1.179.901,37	0,40	189.000,00	11.480,02

Table. 5 Technical and energetic results of the improved case study

Generated energy (kWh/year)	Consumed energy (kWh/year)	Excess Energy (kWh/year)	Excess energy (%)	Unmet load (kWh/year)	Unmet load (%)	Autonomy (hr)
442.600	354.334	65.062	14,7	69.650	16,4	7,38

Table. 6 Economic analysis results of the improved case study

Devices	Investment (€)	Discount Rate (%)	NPV (€)	IRR (%)	ROI (€)	Payback (Years)	Cash Flow (€)	Price (€/kWh)	Battery Replacement (€)	Annual O&M (€)
PV Modules	278.368,20									
Inverter	32.000,00									
BESS	189.000,00									
Chargers	81.000,00									
Total	580.368,20	7,00	394.667,72	14,19	2,57	7	1.490.589,5	0,40 or 0,25	189.000,00	11.480,02

Table. 7 Vehicles Emissions of CO_2

1 Year	Distance Travelled (km)	Electrical Energy Consumed (kWh)	Emissions (g CO_2)	Total Emissions (Tons CO_2)	Cost of Emissions (€)
Grid-Connected Charging Station	2.362.226,67	354.334	308/kWh	109,135	830,52
Off-Grid PV-BESS Charging Station	2.362.226,67	354.334	0	0	0,00
Diesel Vehicle	2.362.226,67	-	94/km	222,05	1.689,8
Gasoline Vehicle	2.362.226,67	-	104/km	245,672	1.869,57

Table. 8 Prices of the different charging providers (motor.es, 2017), (FASTNED, 2017)

Charging Provider	Off-Grid PV-BESS	IBIL	FASTNED
Price (€/kWh)	0,4 or 0,25	0,54	0,59
Cost of 100 km daily (€/ year)	20805	32522	35533