Multicriteria power generation planning and experimental verification of hybrid renewable energy systems for fast electric vehicle charging stations

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Abstract

The installation of fast electric vehicle charging stations (EVCS) will be essential to promote the acceptance by the users of electric vehicles (EVs). However, if EVCS are exclusively supplied by the grid, negative impacts on its stability together with possible CO_2 emission increases could be produced. Introduction of hybrid renewable energy systems (HRES) for EVCS can cope with both drawbacks by reducing the load on the grid and generating clean electricity. This paper develops a weighted multicriteria methodology to design the most suitable configuration of HRES for EVCS. This method determines the local renewable resources and the EVCS electricity demand. Then, taking into account environmental, economic and technical aspects, it deduces the most adequate HRES power generation planning for EVCS. Besides, an experimental stage to validate the design deduced from the multicriteria methodology is included. Therefore, the final power generation planning for the HRES in EVCS is supported not only by a complete numerical evaluation, but also by an experimental verification of the demand being fully covered. Methodology application to Valencia (Spain) proves that an off-grid HRES with solar PV, wind and batteries support would be the most suitable configuration for the system. This solution was also experimentally verified.

Keyword

Electric vehicles, charging station, hybrid renewable energy system, multicriteria assessment, modelling, experimental verification.

1. Introduction

By the end of the 20th century, climate change became one of the most disturbing global issues. The exorbitant amount of greenhouse gases (GHG), especially CO_2 emissions, sent to the atmosphere is leading to an environmental destruction, whose effects could be very detrimental for the nature and, as a consequence, for our society [1,2].

The transport sector has traditionally depended on fossil fuels, which are non-renewable resources and the main responsible for CO_2 emissions [3]. For instance, almost 93% of the global transport consumption in 2017 was derived from oil products [4]. Moreover, around 23% of total CO_2 emissions in the world were generated by this sector [5]. For two different reasons: finite oil resources and environmental concerns, efforts have focused on the electrification of the transportation sector [6]. Hence, a high penetration of EVs is expected to happen in almost all developed countries in a short/mid-term future [7,8]. Despite the environmental suitability of these vehicles while riding on the roads, two drawbacks arise in this context. On the one hand, the extra electricity generated to cover the EVs demand could lead to an increase of CO_2 emissions depending on the carbon intensity (CI) of the power sources involved in the electricity generation system [9,10]. On the other hand, this electricity increase could create negative impacts on the grid when recharging strategies remain unscheduled, concentrating the electrical consumption in peak demand hours [11–14].

In this context, microgrids with integration of renewable sources to recharge EVs can tackle this issue. These microgrids, known as Hybrid Renewable Energy Systems (HRES), are small grids that combine the potential of different renewable sources: solar photovoltaic, wind generators, biomass gasifiers, etc., with the possibility to be supported by the grid or by other dispatchable resources such as batteries, diesel generators or even hydrogen systems in the most cutting-edge systems [15]. This configuration allows HRES to supply any kind of loads irrespective their location, distance to the grid or accessibility. Furthermore, the hybrid and smart combination of the different resources overcomes the individual restrictions of traditional stand-alone renewable technologies, since the limitations of one single technology are covered by the other ones [16].

Hence, HRES for the recharge of EVs can cope with the two previously mentioned difficulties [17]. First, the low CI of the renewable sources would decrease the CO_2 emissions generated during the electricity generation stage. Secondly, the pressure on the grid would decrease due to the demand reduction by using these microgrids [18].

Numerous studies consider three main scenarios of recharge: at home, at public buildings, and at electric vehicle charging stations (EVCS) [11]. This last scenario corresponds to fast recharges, where users would stop on purpose to quickly recharge their electric vehicles (EVs), so that they can continue driving. Hence, EVCS turns out to be equivalent to current petrol stations, being a necessary recharging option whose integration in smart charging strategies results essential for the penetration of EVs [19]. However, the number of current EVCS is very limited and nowhere enough to cope with the expected introduction of EVs in the coming years. In fact, the concerns of being unable to find an EVCS to recharge the EVs emerges as one of the highest barriers for potential users to acquire this kind of vehicles [20]. Therefore, the development of fast recharging strategies together with the integration of renewable sources is essential for the integration and acceptance of EVs in our society. Several studies have addressed these topics. For instance, Huang et al. [21] developed a novel Geographic Information System to select the optimal location for the installation of new renewable EVCS depending on the current number of charging stations and renewable potential, with the aim of minimizing the life cycle cost of the EVCS.

Regarding the power generation planning of the HRES for EVCS, some studies have approached this issue, considering the uncertainty behaviour of renewable resources. Chowdhury et al. [22] study the incorporation of a HRES for EVCS supported by the grid at the University Campus in Dhaka (Bangladesh), achieving a 21% of renewable generation and reducing GHG emissions by 52.9 tCO_2/year. Study [23] presents the power generation planning of an energy storage HRES in a rural community of the Democratic Republic of Congo with no access to the electrical grid for the recharge of electric Tuk-tuks (a traditional means of transport of the Democratic Republic of Congo). The installation of this HRES enhances the replacement of the traditional combustion engine Tuk-tuk vehicles by electric ones, together with the future deployment of EVs in these rural areas. Similarly, research in [24] boosts also the use of off-grid HRES systems for EVCS in rural remote areas. Namely, this research discusses the best configuration option for an EVCS in Labuhan Bajo (Indonesia) considering three types of batteries for energy storage: Lead Acid, Li-Ion (NCA) and Lithium Ferro Phosphate (LFP). All these studies use HOMER® software [25] for the optimization process, looking for the lowest NPC configuration. The scientific literature includes other field works that utilize different optimisation techniques for the power generation planning. In this regard, Domínguez-Navarro et al. [26] employ genetic algorithm to determine the HRES configuration for EVCS that maximizes the profit measured by its Net Present Cost (NPC), finally selecting a configuration with renewable generation and storage resources. Narayan et al. [27] introduce a two-stage stochastic programming for renewable HRES planning, with the aim of minimizing cost of investment and risk due to the uncertain behaviour of renewable resources. Wang et al. [28] present an optimization technique based on the location of the HRES, the temporary progression of supporting policies, local energy consumption, electricity price and cost of investment of the system to design HRES and schedule energy storage system and EVs energy exchange, with the aim of maximising the investment return.

The methodologies presented in these above-mentioned studies only rely on economic parameters to design the power generation planning of the HRES for EVCS. However, other studies indicate that more parameters have to be considered for the system optimisation. For instance, Karmaker et al. [29] used also the HOMER ® software to decide the configuration of the HRES in an EVCS, but analized also the technical, economic and environmental feasibility of the selected configuration. Rashid et al. [30] focus the study on the electrical production and cost analysis, whereas Tulpule et al. [31] included environmental impacts, together with economic ones, in the power generation planning.

Another important issue to consider in the application of HRES to EVCS is the experimental validation of any optimized configuration. According to the literature review, most of the researches only focus their investigations in numerical power generation planning methodologies and they do not cross check the theoretical results with experimental ones. However, there are very few studies in this direction, which demonstrate the suitability of the experimental validation in this field of research. In particular [32,33] state that, despite the suitability of numerical methodologies, the experimental verification of the HRES configuration ensures its reliability and real implementation. Research [32] describes the experimental results of a fast EVCS based on solar PV, wind sources and fuel cells and the necessity of implementing these systems in many remote regions of Russia with grid-connection problems. Research [33] focuses on the power system analyses of a microgrid that combines solar PV, utility grid and batteries to supply a fast charging EVCS. The experimental results verify the current flow and power balance of the system that were previously calculated with a simulation software.

Hence, this paper proposes a novel method that tries to cope with both aspects: to develop a weighted iterative multicriteria methodology based on economic, environmental and technical parameters to design the power generation planning of HRES in EVCS, and the daily operation experimental validation of the deduced designs by using power balance and State of Charge (SOC) boundary criteria. The method is based on a previous characterization stage of the system in terms of energy by determination of the electricity demand of the EVCS and the evaluation of the local energy resources. According to [34], the power generation planning embraces the process to decide on new elements of the system, to adequately satisfy the loads for a foreseen future, higher than 10 years.

The study includes the application of the developed methodology, including the experimental verification, to Valencia (Spain). This region is expected to have a steep mobility transition to EVs according to the Electric Mobility Plan [35], approved in 2007 by the Valencian Ministry of Sustainable Economy, Productive Sectors, Trade and Work. The plan aims to achieve an increasing penetration of both EVs and recharging points: 2030 EVs and 105/350 fast/semi-fast recharging points by the year 2020; 78.100 EVs and 210/950 fast/semi-fast recharging points in the year 2025 and 260.000 EVs and 270/2100 fast/semi-fast recharging points by the year 2030. This legal framework boosts the installation of fast recharging points, in form of EVCS in Valencia. Moreover, the use of HRES in these EVCS results very convenient to face both electricity increase difficulties associated to the forecasted EVs introduction. First, the pressure on the grid would decrease due to the demand reduction by using these microgrids [18]. Second, the low CI of the renewable sources would reduce the CO_2 emissions generated during the electricity generation stage, considering that the Spanish electricity mix includes high polluting technologies like coal (19.6%) or fuel (6.7%) [9,10,36]. Regarding this last aspect, the introduction of renewable sources for electricity generation is supported by Valencian Climate Change and Energy Strategy 2030 [37], whose three central goals lie in the reduction of the GHG emissions, the renewable sources increase in electricity generation and a substantial energy efficiency enhancement by 2030. In this context, the application of the methodology presented in this paper for the power generation planning of HRES for EVCS in the roads of Valencia has a remarkable interest.

The paper is organized as follows: section 2 presents the weighted multicriteria methodology, section 3 describes the case study of Valencia and section 4 provides the results and discussion of this application. Finally, the paper conclusions are outlined in section 5.

2. Methodology

This section presents the methodology developed to design the power generation planning of HRES to supply the electricity demand of EVCS. The method contemplates four different stages. The first one comprises the electricity demand modelling of the EVCS, together with the evaluation of the local energy resources analysis to determine the renewable technologies to be considered. The second stage makes an initial preliminary power generation planning of the system based on the NPC optimization by using the software HOMER®. Then, all the obtained configurations are evaluated and ranked in the third stage by using a multicriteria methodology that takes into account the technical, economic and environmental aspects for each of them. Finally, the last stage of the methodology addresses the experimental validation of the best-positioned configurations. Figure 1 represents the flowchart of the proposed methodology.

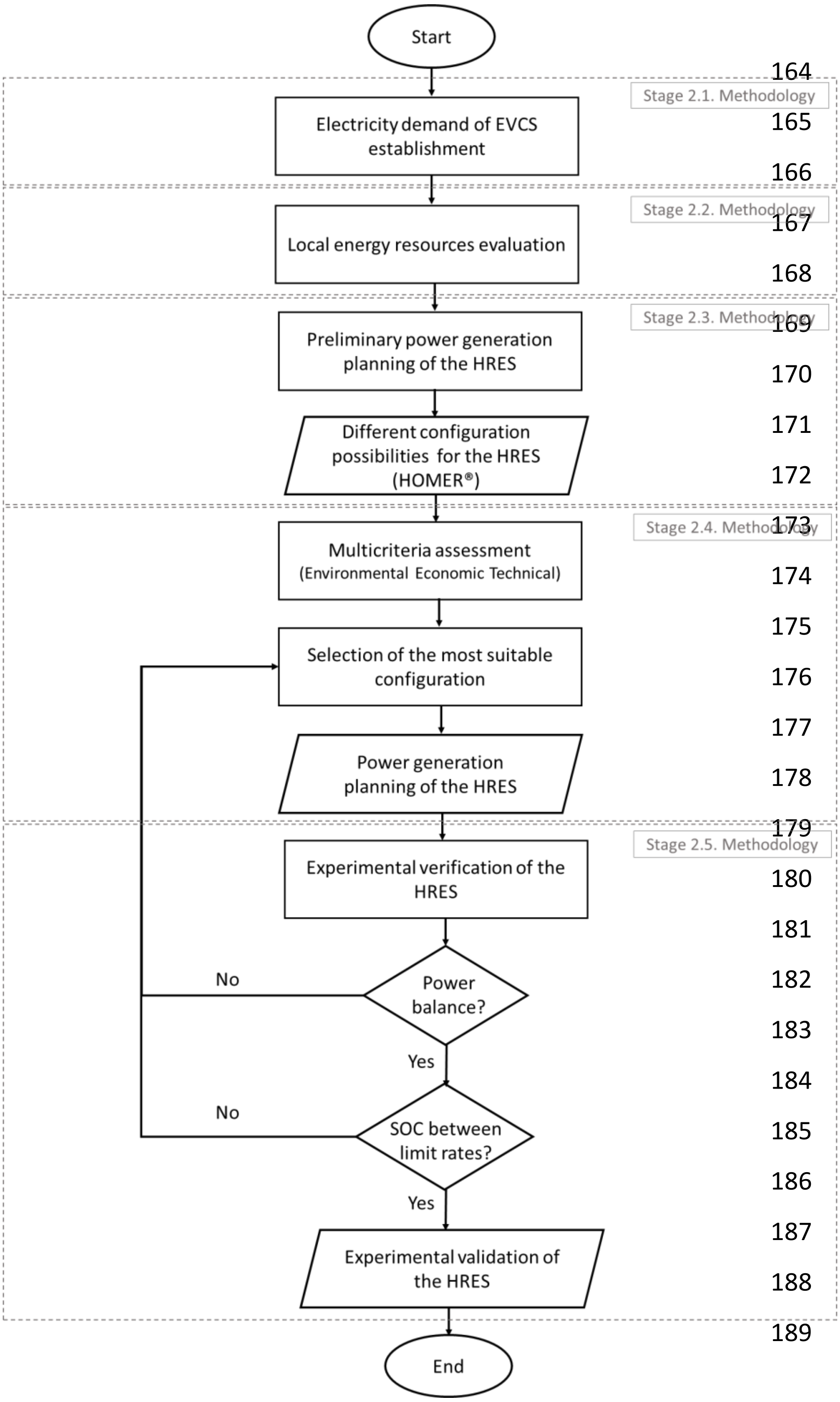


Figure 1. Flowchart of the proposed methodology.

2.1. Electricity demand of electric vehicles charging stations establishment

EVCS demand depends on total amount of EVs refilling their batteries at the station and on the power consumption of each of these EVs. Regarding the first factor, this methodology establishes a profile for each type of EV recharging in an EVCS: Battery Electric Vehicles (BEVs) and Plug-in-Hybrid Electric Vehicles (PHEVs), considering also their nature (cars and motorcycles). Taking a base fleet affected by two rates (penetration and recharge of EVs at the station [11]), the method determines each curve making use of eq.(1):

$$n(i,t) = N(t) \cdot f(i) \cdot r(i) \tag{1}$$

where n(i,t) is the number of EV of type i (i=1 for BEV cars, i=2 for PHEV cars and i=3 for BEV motorcycles) recharging at time t; N(t) represents the total number of vehicles on the road passing by the EVCS at that time or the base fleet, f(i) represents the fraction of these vehicles being electric and r(i) is the rate of those EVs needing recharge.

Referring to the second factor, the capacity of the battery, together with its state of charge (SOC) and the duration of recharging determine the power demand of each EV type [29]. This power demand is given by eq.(2):

$$P_{EV}(i) = \frac{C_{bat}(i) \cdot [SOC_{Max} - SOC]}{T(i)} \tag{2}$$

Where $P_{EV}(i)$ corresponds to the power demand of EVs; $C_{bat}(i)$ represents the capacity of the EVs' batteries; SOC_{Max} is the maximum level of the batteries' state of charge; SOC corresponds to the real level of the batteries state of charge and $T(i)$ represents the duration of the recharging process.

Finally, the power demand of the EVCS, $P_{EVCS}(t)$ is the electrical demand of all types of EV recharging there (eq.(3)):

$$P_{EVCS}(t) = \sum_{i} n(i,t) \cdot P_{EV}(i) \tag{3}$$

2.2. Local energy resources evaluation

At this stage, the methodology should determine the availability of renewable resources to be included in the HRES for EVCS. This implies the determination of the location of the EVCS with the highest possible resolution, of parameters such as the solar irradiation and the clear index average [38], wind speed measured at the wind turbine height [39], the sustainable biomass production availability [40], etc.. Moreover, the necessity to support the HRES system with batteries, the grid or with a generator should be also considered as potential back up to guarantee the reliability of the HRES in the EVCS.

2.3. Preliminary power generation planning of the hybrid renewable energy system

HOMER® Pro software [25] is a well-known and widely used tool in the power generation planning of HRES, including its application to EVCS [24,30]. With the information of the technological options and the local resources to include in the HRES as an input to HOMER®, a list of different configurations for the system, ranked by their NPC, is obtained.

Despite the importance of the economic factor, the power generation planning of HRES for EVCS should also rely on environmental and technological criteria [29]. In line with this consideration, the present method utilizes the software HOMER® only in a pre- power generation planning stage of the HRES for the EVCS.

2.4. Multicriteria assesment

After the preliminary power generation planning stage of HRES, all the configuration options proposed by HOMER® are ranked using the methodology proposed in this section (2.4), based on a weighted multicriteria assessment of environmental, economic and technical parameters. This stage considers an annual evaluation period to obtain the average behaviour of the HRES in question. The section describes the parameters and the multicriteria methodology.

2.4.1. Environmental criteria

The introduction of EVs is intended for a decarbonisation of the transport sector [5,36,41]. However, recharging the EVs exclusively from the grid could even lead to an increase of carbon emissions, depending on the CI generation mix of the grid [9,10,36]. Hence, this methodology proposes two factors to assess the environmental suitability using a HRES for the EVs recharge in EVCS: CO_2 emissions reduction and renewable generation degree.

CO_2 emissions reduction (EmR)

This parameter determines the relative reduction in carbon emissions while using a HRES instead of the grid alone to supply the EVCS. CO_2 emissions reduction (EmR) can be obtained using eq. (4) .

$$EmR = \frac{[E_{grid} \cdot g_{grid}] - [E_{HRES} \cdot g_{HRES}]}{[E_{grid} \cdot g_{grid}]} \tag{4}$$

Where E_{grid} is the electricity demanded from the grid if the EVCS has no any HRES support; g_{grid} is the emissivity of the electricity from the grid; E_{HRES} is the electricity provided to the EVCS from a HRES, and g_{HRES} is the emissivity of the electricity from the HRES.

Specifically, the emissivity for the HRES (g_{HRES}) corresponding to a weighted combination of the generation resources of the system, which depends on their energy generation impact (eq. (5)).

$$g_{HRES} = \sum_j \frac{E_{HRES_j}}{E_{HRES}} \cdot g_j \tag{5}$$

$$E_{HRES} = \sum_j E_{HRES_j}. \tag{6}$$

With E_{HRES_j} the electricity provided by the component j of the HRES and g_j its specific emissivity.

Extreme values for EmR are 0 (no renewable sources in the HRES) and 1 (full renewable system without any CO_2 emission)

Renewable generation degree (ReG)

The contribution of renewable sources to the electricity consumption of the EVCS is another significant factor when analysing the environmental behaviour of the system [42]. Eq (7) determines this parameter (ReG), where not only the renewable contribution to the HRES take part, but also the renewable percentage of the electricity taken from the grid by the HRES.

$$ReG = \frac{\sum_r E_{HRES_r} + x_r \cdot E_{HRES_{grid}}}{E_{HRES}} \quad (7)$$

Being E_{HRES_r} the electricity coming from the renewable source r of the HRES, $E_{HRES_{grid}}$ the electricity taken by the HRES from the grid and x_r the fraction of renewable contribution in $E_{HRES_{grid}}$.

ReG values are in the interval 0 (when no renewable sources are involved in the HRES and in the electricity grid) and 1 (if all the electricity used by the HRES, including the grid, is generated with renewable sources).

2.4.2. Economic criteria

The importance of a thorough economic analysis for the power generation planning of the HRES EVCS appears in a wide range of researches [23,24,43]. In this methodology, the economic study uses the levelized cost of energy (LCOE). This is a widely used parameter to compare and evaluate different electricity generation procedures [15,44,45]. The LCOE indicates the average total cost of building and operating the corresponding energy system per unit of the total electricity generated over its lifetime [46], as eq. (8) shows:

$$LCOE = \frac{\sum_j \sum_{t=1}^{t=n} \frac{\left(I_{tj} + O\&M_{tj} + F_{tj}\right)}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{\left(E_{HRES_t}\right)}{(1+r)^t}} \quad (8)$$

Where I_{tj}, $O\&M_{tj}$ and F_{tj} represent the investment cost, operation and maintenance cost and fuel cost, respectively of each generation resource j in year t into consideration of the lifetime of the system (n), whereas r corresponds to the discount rate.

The methodology introduces a normalized LCOE $(NLCOE)$ to compare the LCOE for an EVCS supplied by the grid $\left(LCOE_{grid}\right)$ with the LCOE for an EVCS supplied by the HRES in study $(LCOE_{HRES})$, as eq. (9) indicates:

$$NLCOE = \frac{LCOE_{grid}}{LCOE_{HRES}} \quad (9)$$

Hence, an economic factor (EcF) for the multicriteria analysis can be defined as:

$$EcF = Min\ (1;\ NLCOE) \quad (10)$$

Again, EcF values range between 0 (for very high $LCOE_{HRES}$) and 1 (if the HRES has a lower LCOE that the grid one).

2.4.3. Technical criteria

The technical study comprises of two remarkable parameters: the security of supply and the adequacy sizing of the system.

<u>Security of supply (SS)</u>

This factor evaluates the guarantee of electricity supply taking into account the different combination of generation sources and back-up systems in the HRES for EVCS [15], as eq. (11) indicates.

$$SS = 1 - \sum_j (1 - f_j) \quad (11)$$

Being f_j the reliability of the generation source *j*.

For non-dispatchable generation sources, i.e.: solar PV and wind generation, we can consider the magnitude of the energy contribution related to the demand and the fraction of the time these sources are available, as eq. (12) indicates.

$$f_j = Min \left\lfloor 1;\ \frac{E_j}{E_{EVCS}} \right\rfloor \cdot\ \delta_j \quad (12)$$

Where E_j represents the electricity provided by the non-dispatchable sources in question, E_{EVCS} is the total electricity demand of the EVCS and δ_j corresponds to the fraction of hours that the source is available.

For dispatchable electricity sources, such as the grid and the backup generator, eq. (13) determines their feasibility as follows:

$$f_j = Min\left\lfloor 1;\ \frac{P_j}{P_{EVCS}} \right\rfloor \cdot\ \delta_j \quad (13)$$

Where P_j represents the generator maximum power and the contracted power from the grid, and P_{EVCS} corresponds to the maximum power of the EVCS. Values for the security factor δ_j are available for diesel generators [47] and for the grid [48,49].

In the case of the storage battery bank, the feasibility factor can be defined as:

$$f_b = Min\left\lfloor 1;\ \frac{E_b}{E_{EVCS}} \right\rfloor \cdot \delta_b \quad (14)$$

Where E_b is the nominal capacity of the battery bank and δ_b the security factor, also available in [16].

SS values are in the interval of 0 (when the system cannot ensure the electricity supply at all) and 1 (if the security of supply is completely assured), as eq. (15) reflects:

$$SS \in \{0,1\} \quad (15)$$

<u>Electricity sizing adequacy (ESA)</u>

Finally, this last parameter assesses the adequacy of the system in relation to its power sizing. Systems should be designed in such a way that they cover all the demand requirements, but the minimum excess of generation, as eq. (16) indicates.

$$ESA = Min\left\lfloor 1;\ \frac{E_{EVCS}}{E_{HRES}} \right\rfloor \quad (16)$$

ESA values are in the interval between 0 (when the power sizing is not adequate at all) and 1 (if its power sizing is completely achieved).

2.4.4. Multicriteria assessment: selection of the most suitable configuration

In this stage, the proposed methodology evaluates all possible configurations obtained in the preliminary power generation planning stage with HOMER® Pro Software for the HRES EVCS in question. For this evaluation, the methodology applies a weighted multicriteria assessment on each of these configurations. Hence, a merit figure (CP) is deduced for each configuration option.

Table 1 lists the evaluation criteria together with their corresponding weighting factors. Moreover, eq. (17) describes the multicriteria evaluation for each configuration, where constraint (18) applies.

Table 1. Criteria and weighting factors for the evaluation.

	Criteria	Weighting factor
Environmental	CO_2 emissions reduction (EmR)	α_{EmR}
	Renewable generation degree (ReG)	α_{ReG}
Economic	Economic Factor (EcF)	α_{EcF}
Technologic	Security of supply (SS)	α_{SS}
	Electricity sizing adequacy (ESA)	α_{ESA}

$$CP = \alpha_{EmR} \cdot EmR + \alpha_{ReG} \cdot ReG + \alpha_{EcF} \cdot EcF + \alpha_{SS} \cdot SS + \alpha_{ESA} \cdot ESA \tag{17}$$

$$\alpha_{EmR} + \alpha_{RG} + \alpha_{EcF} + \alpha_{SS} + \alpha_{ESA} = 1 \tag{18}$$

Finally, once all the configurations have been analyzed, they are ranked in accordance with their CP values. Hence, the one with the highest value would be the best power generation planning design solution for a HRES in an EVCS, based on a complete study of the system including environmental, economic and technical aspects.

2.5. Experimental verification of the hybrid renewable energy system

The last stage of the methodology consists of an experimental verification of the selected power generation planning design for the HRES in the EVCS after the previously explained multicriteria assessment stage [33,50]. The theoretical design must be accurately reproduced in a laboratory for all required technologies. Therefore, a scaled version of the selected configuration is necessary [42]. The scale factor (SF) is determined by the capabilities of the experimental laboratory system to be used (P_{lab}), and the maximum power of the EVCS (P_{EVCS}) as eq. (19) indicates:

$$SF = \frac{P_{EVCS}}{P_{lab}} \tag{19}$$

Consequently, this scale factor affects the EVCS power demand curve, determined in section 2.1, so that the experimental EVCS power demand $\left(P_{EVCS\,exp}(t)\right)$ is determined by eq. (20). The power of each generation system $\left(P_j\right)$ is scaled as well, being the experimental generation power $\left(P_{j\,exp}\right)$ obtained by eq.(21).

$$P_{EVCS\,exp}(t) = \frac{P_{EVCS}(t)}{SF} \tag{20}$$

$$P_{j\ exp} = \frac{P_j}{SF} \tag{21}$$

For diesel generator scheduling, it is important to consider that these systems should work during continuous periods, no longer than 2 hours [51].

The methodology imposes two conditions to be satisfied before accepting the system configuration [16,39,42]. Firstly, the EVCS load requirements should be covered at each time of the day. To reach this goal the power balance should accept a certain rate of power losses (L) in the system (eq. (22)). Furthermore, for systems with a storage capacity based on batteries, the state of charge (SOC) of these batteries should be all the time in the range between the allowed minimum and maximum values. (eq. (23)).

$$\frac{\left|\sum P_{j\ exp}(t) - P_{EVCS\ exp}(t)\right|}{P_{j\ exp}(t)} \leq L \tag{22}$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \tag{23}$$

Both parameters, power losses and SOC of batteries, need to be checked in a daily evaluation period due to its behaviour. To ensure the suitability of the power generation planning design, this method proposes to choose an average day of the most unfavourable month in terms of non-dispatchable generation for the experimental verification stage. Therefore, the fulfilment of these conditions ensures the correct power generation planning of the HRES for the EVCS. If any of them were not met, the methodology includes an iterative process on the selection of the theoretical power generation planning design of the system, following the rank order deduced from the multicriteria assessment.

3. Case study: Valencia (Spain)

The paper applies the previously explained methodology to Valencia, the capital province of the Comunidad Valenciana, located in the East of Spain.

This region is experiencing a steep ecological transition in terms of mobility motivated by its Electric Mobility Plan [35]. The plan establishes as final 2030 objective that the EVs represent 25% of the market share of the Comunidad Valenciana along with establishing one fast recharge point for every ten EVs. This legal framework boosts the installation of fast recharging points for the expected EVs fleet in Valencia, but two more aspects should be considered. On the one hand, this situation would lead to a considerable electricity increase due to the EVs recharge, that could create negative impacts on the grid when recharging strategies remain unscheduled, concentrating the electrical consumption in peak demand hours [11–14]. On the other hand, the extra electricity generated to cover EVs demand would give rise to an increase of CO_2 emissions since Spanish electricity mix includes high polluting technologies like coal (19.6%) or fuel (6.7%) [9,10,36]. These phenomena would take place if the recharge depends only on the Spanish electricity grid. Hence, the introduction of HRES for the forecasted fast recharging points in Valencia results very convenient to cope with both difficulties. First, the pressure on the grid would decrease due to the demand reduction by using these microgrids [18]. Second, the low CI of the renewable sources would reduce the CO_2 emissions generated during the electricity generation stage. Regarding this last aspect, the introduction of renewable sources for electricity generation is supported by Valencian Climate Change and Energy Strategy 2030 [37], whose three central goals lie in the reduction of the GHG emissions, the renewable sources increase in electricity generation and a substantial energy efficiency enhancement by 2030.

In summary, this legal framework boosts the installation of fast recharge points for the expected EVs fleet in Valencia, namely in the form of EVCS. Moreover, the HRES introduction with renewable supply of such stations arises also as an environmental breakthrough to achieve, in line with the above mentioned 2030 Energy Strategy.

Moreover, this work only considers the recharge of light electric vehicles (LEVs) in EVCS with possibilities to recharge BEV cars, PHEV cars and BEV motorcycles. Nowadays, heavy internal combustion vehicles, like private buses or trucks, represent 15% of the fuel obtained at petrol stations located at roads of Valencia [52]. However, the currently available batteries of their equivalent heavy EVs are not yet developed enough to provide the autonomy desired by these vehicles in roads [11]. Therefore, it is not realistic to assume this type of vehicles are being recharged at EVCS.

3.1. Electricity demand of electric vehicles charging stations

The EVCS electricity demand in Valencia could be deduced from the current flow of light internal combustion engine vehicles (LICEVs) passing by a petrol stations in the region. The accurate traffic information for Valencian territory provided by the Spanish data base [52] allowed us to model the average flow of LICEVs, represented by N(t) in eq. (1) (Figure 2). On average, 94% of this base fleet consists of cars and 6 % of motorcycles.

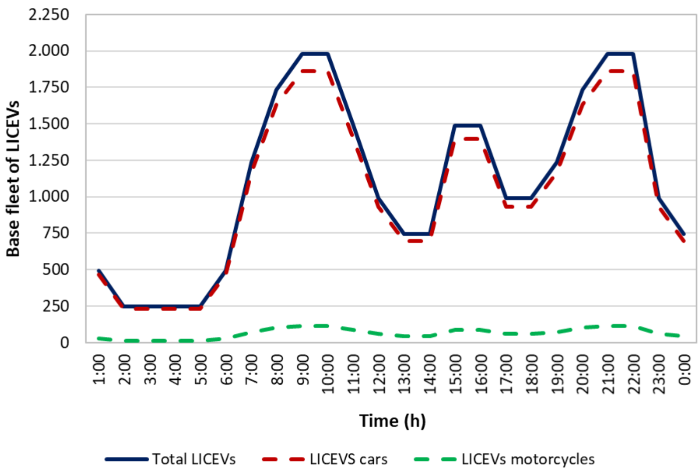


Figure 2. Base fleet of LICEVs for Valencia N(t).

The rate of penetration of LEVs in this base fleet of LICEVs will match the expected penetration in Spain in the imminent future [36]: 2.5% for BEVs cars, 2.5% for PHEVs cars and 5% for BEVs motorcycles, considering just the LEVs with possibilities of recharging in EVCS due to their configuration (BEVs and PHEVs) [53].

Finally, study [54] claims that the percentage of LEVs passing by the EVCS and will finally recharge is expected to be slightly higher than the equivalent traditional refueling behavior. Hence, this percentage increases up to 6%.

Table **2** reflects all parameters to be used in eq. (1).

Table 2. Rate of penetration and recharge of LEVs.

	f (%)	r (%)
BEVS cars	2.5	6
PHEVS cars	2.5	6
BEVS motorcycles	5	6

For the determination of the power consumption of each type of LEV at EVCs, we made a detailed analysis on their battery capacity, SOC and required time for recharging at the EVCS, assuming only a fast recharging mode [11,55]. Regarding the first parameter, researches [56–58] shed light on the determination of battery capacity for BEVs cars and motorcycles, and PHEVs cars. Referring to the initial SOC, we took the hypothesis that the SOC for the LEVs recharging at the EVCS will be 20% [59]. Table 3 indicates the assumed values for the different parameters of the full recharge for the different types of EVs.

Table 3. LEVs' recharging parameters

	C_{bat} (kWh)	SOC_{Max} (%)	SOC (%)	T (min)	P_{EV} (kW)
BEVs cars	40	100	20	40	48
PHEVs cars	14	100	20	14	48
BEVs motorcycles	3	100	20	3	48

Using this data, it is possible to deduce the electricity demand of the EVCS for the Valencian case study, shown at Figure 3. The maximum power demand is 270 kW, and takes place during the early morning (from 9:00 to 10:00) and at early night again (from 21:00 to 22:00). The final average contribution to the electricity demand is 6%, 49% and 45% for BEVs motorcycles, BEVs cars and PHEVs cars, respectively.

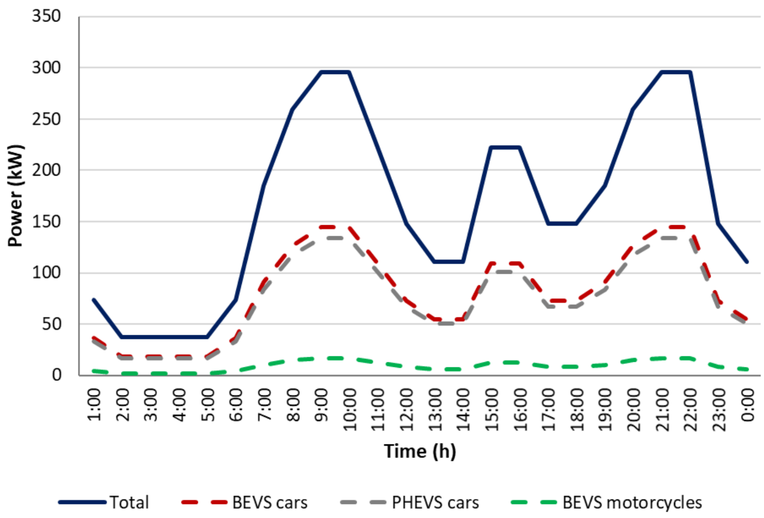


Figure 3. Electricity demand in EVCS.

3.2. Generation resources analyses

Valencia is a province located in the east of Spain, next to the Mediterranean Sea. Its geographical position corresponds to the coordinates 39°28′00″North 0°22′30″West and it has an elevation of 16 meter above sea level. The analysis of the renewable potential of Valencia highlights solar resources as the most suitable ones, followed by wind resources.

According to PVGIS-CMSAF [60], Valencia has an average annual irradiation of 1735 kWh/m^2/year with the monthly dependence shown in Figure 4. The highest irradiation data corresponds to the summer months, reaching its peak value in June and July, with approximately 7.8 kWh/m^2/day. On the contrary, the lowest irradiation values correspond to the winter months, specifically December and January, with 2.1 and 2.5 kWh/m^2/day, respectively. From this data, we can deduce an average solar daily irradiation of 5 kWh/m^2/day and a clearness average index of 0.65.

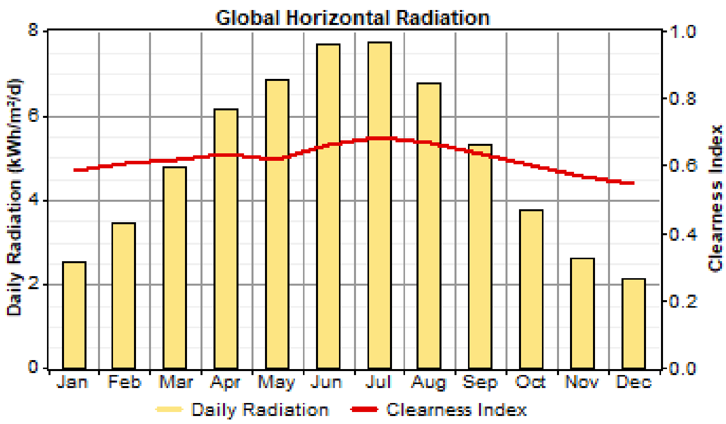


Figure 4. Average solar daily irradiation and clearness index in Valencia.

Moreover, data from [61] indicated that the average wind speed of Valencia is 3.6 m/s, measured at 18 m above the ground. Figure 5 reflects the daily average data for each month. These values reveal the suitability of wind resources in Valencia, although they do not have the high potential of the solar resources. The availability of this resource presents a trend which is ideal for the HRES: solar irradiation offers its highest values during summer months; meanwhile wind speed reaches the highest values during the winter months. Hence, each type of renewable generation would ideally complement the other, supporting the reliability of the HRES.

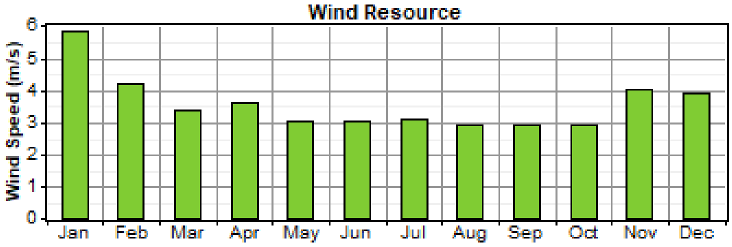


Figure 5. Wind speed in Valencia.

Regarding back-up systems, grid connection is a feasible possibility for EVCS [30], since Valencia is a complete electrified area. Furthermore, batteries and diesel generators can be also considered as possibilities to support the HRES, especially if the EVCS is intended to be off-grid [23].

3.3. Inputs for the power generation planning of the hybrid renewable energy system

Taking into account the power demand from the EVCS and the availability of solar and wind resources in Valencia, an initial estimation of the HRES system configuration to be used as an input for the HOMER simulation was defined (Table 4).

Table 4. HRES EVCS components sizing.

Solar PV (kW)	Wind (kW)	Grid connection (kW)	Diesel Generator (kW)	Battery (kWh)
500	330	270	280	960, 1920, 2880, 4800

To ensure a reliable supply, the maximum acceptable capacity shortage of the system was established to be 10% for the HOMER® simulations. HOMER ® results provided a list with 55 configuration possibilities ordered by their NPC values. Before applying the multicriteria evaluation, configurations without renewable generation were discarded. Besides, alternatives including grid and diesel generator were also rejected, considering the generator was not necessary in the presence of the grid. Table 5 summarizes the discarded power generation planning design options, meanwhile Table 6 reflects the 27 selected configurations to be analysed with the multicriteria methodology.

Table 5. Discarded power generation planning design options.

Discarded scenario	HOMER option	Reason
Grid	2	Lack of renewable generation.
Grid + gen	5	
Grid + bat	13, 22, 28, 36	
Grid + gen + bat	17, 24, 31, 40	
Gen + bat	50, 51	
Gen	55	
Ren + grid + gen	3, 7, 14	The diesel generator does not contribute to energy generation, due to the presence of the grid.
Ren + grid + gen + bat	8, 12, 19, 20, 21,26 27, 33, 34, 35, 41,42	

gen: diesel generator; bat: batteries; ren: renewable resources.

Table 6. Selected configuration options to be analysed by the methodology.

	HOMER Option	Solar PV (kW)	Wind (kW)	Grid connection	Generator (kW)	Battery (kWh)
Ren + grid	1	500	0	Yes	0	0
Ren + grid	4	0	330	Yes	0	0
Ren + grid + bat	6	500	0	Yes	0	960
Ren + grid + bat	9	500	0	Yes	0	1920
Ren + bat	10	500	330	No	0	4800
Ren + grid	11	500	330	Yes	0	0
Ren + grid + bat	15	500	0	Yes	0	2880
Ren + grid + bat	16	0	330	Yes	0	960
Ren + grid + bat	18	500	330	Yes	0	960
Ren + grid + bat	23	500	0	Yes	0	1920
Ren + grid + bat	25	500	330	Yes	0	1920
Ren + grid + bat	29	500	0	Yes	0	4800
Ren + grid + bat	30	0	330	Yes	0	2880
Ren + grid + bat	32	500	330	Yes	0	2880
Ren + gen + bat	37	500	330	No	280	4800
Ren + grid + bat	38	0	330	Yes	0	4800
Ren + grid + bat	39	500	330	Yes	0	4800
Ren + gen + bat	43	500	330	No	280	2880
Ren + gen + bat	44	500	330	No	280	1920
Ren + gen + bat	45	500	0	No	280	4800
Ren + gen + bat	46	500	0	No	280	2880
Ren + gen + bat	47	0	330	No	280	2880
Ren + gen + bat	48	0	330	No	280	4800
Ren + gen + bat	49	0	300	No	280	1920
Ren + gen	52	500	330	No	280	0
Ren + gen	53	500	0	No	280	0
Ren + gen	54	0	330	No	280	0

The application of the multicriteria methodology to the Valencian case study required the definition of some input parameters regarding the environmental, economic and technical criteria, as well as the weighting factors.

Environmental criteria

The relative decrease of CO_2 emissions achieved when using a HRES instead of the traditional grid for charging vehicles in EVCS together with the renewable generation degree comprise the environmental factors to assess each power generation planning option for the system. Thus, the emissivity of each renewable source is of utmost importance, as well as the emissivity of the Spanish grid. A wide study of renewable and non-renewable sources' emissivity is available in [29] and [36,62], which contain all information regarding the Spanish electricity mix. Using this information, Table 7 summarizes the emissivity values used in this study.

Table 7. Emissivity for generation sources and renewable contribution to the grid.

	Solar PV	Wind	Diesel	Spanish grid
g (g CO_2/kWh)	40	20	600	318.1
X_r (%)	-	-	-	27.1

Economic criteria

This paper uses the NLCOE to assess the economic behavior of each power generation planning option, where the economic modelling of such parameter includes the investment, operation and maintenance and fuel costs for each element of the HRES, as well as its corresponding discount rate (r) and the time planning horizon of the project (n). A thorough research was made in [39,42,63] to accurately determine these values for this case study. These are presented in Table 8. Moreover, Figure 6 plots the annual variation of the Spanish inflation rate since 2000, with monthly basis [64].

Table 8. Economic modelling.

	Investment cost	O&M cost	Fuel cost	n	r
Solar PV module	1200 €/kW	40 €/kW	-	-	-
Wind turbine	2020 €/kW	60 €/kW	-	-	-
Diesel generator	380 €/kW	1.5 €/h	1.05 €/L	-	-
Batteries	950 €/unit	10 €/unit	-	-	-
Grid	-	0.15 €/kWh	-	-	-
Converter	165 €/kW	150 €/kW	-	-	-
General project	-	-	-	25 years	8 %

Figure 6. Spanish Inflation Rate. Monthly basis. Annual Variation.

<u>Technical criteria</u>

The technical evaluation of the methodology includes an analysis of the power selected for each power source together with the application of a security coefficient for each source to ensure the feasibility of the system. To determine this security coefficient for dispatchable technologies, study [47] quantifies its value for diesel generator, and [48,49] for the Spanish grid. Moreover, the security coefficient for batteries matches its depth of discharge according to [25]. This coefficient varies for non-dispatchable sources, depending on the number of equivalent hours (1735 for solar PV [60] and 1889 for wind in Valencia [61]). Table 9 summarises the security coefficient data for each generation source in the HRES.

Table 9. Security coefficient for the generation sources (δ_j).

Solar PV (%)	Wind (%)	Diesel generator (%)	Spanish Grid (%)	Batteries (%)
19.8	21.6	85.7	98	70

<u>Multicriteria assessment</u>

The methodology presented in this paper allows users to arbitrarily decide through a series of weighting factors the importance that each criteria will have during the evaluation process. For this study, we have chosen a balanced evaluation process, where each criterion has the same weight of 20%.

3.4. Experimental verification: Laboratory of Distributed Energy Resources

To conclude the complete power generation planning process of the HRES for EVCS, the selected alternatives through the multicriteria assessment must be experimentally validated. In this case study, the laboratory chosen for this aim was the Laboratory of Distributed Energy Resources (labDER) [50] of the Institute for Energy Engineering of the Polytechnic University of Valencia (Spain). This laboratory includes a hybrid combination of generation resources (2 kW_p solar PV, 1.5 kW wind turbine, 10 kW biomass gasifier, 1.7 kW diesel generator, optimal grid connection and 1.2 kW fuel cell). It also includes storage systems (12 kWh batteries and 7 kW hydrogen system) and a programmable load system (from 0.5 to 9.2 kW) that allows to simulate any time dependency of the demand. Figure 7 represents the general setup of labDER, where the elements used for this research are framed in blue.

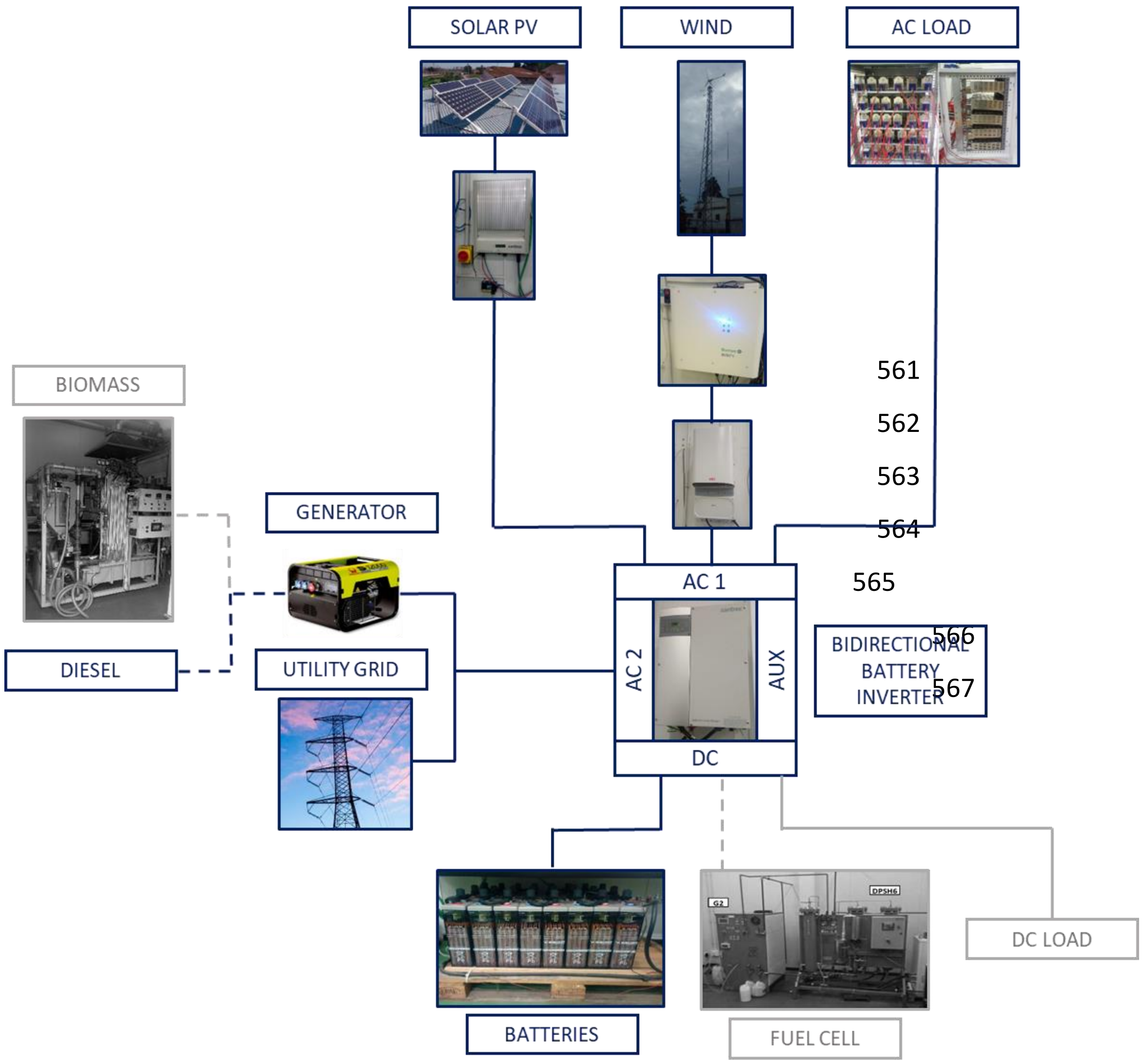


Figure 7. General setup of labDER HRES.

The elements used for this research are framed in blue.

All the elements include network analyzers, where the main parameters can be visualized: voltage, current, power, frequency or SOC for batteries (Figure 8 (a)). In order to register these parameters and to control the HRES, labDER incorporates two PLCS, a control software (CX Programmer ®) and SCADA (CX Supervisor ®).

Regarding the programmable load, it consists of a combination of resistors that can be manually or remotely selected. For the remote management, it contains another PLC (Figure 8(b)) and the software CoDeSys®.

Figure 8. Control elements from labDER HRES. (a) Protection and measurements system. (b) Programmable load.

4. Results and discussion

This section presents the results of the application of the methodology described above to the Valencian case study. It exposes the selected power generation planning designs of the HRES in EVCS of Valencia after applying the multicriteria assessment, together with the experimental validation of such designs in the Laboratory of Distributed Energy Resources (LabDER) of the Polytechnic University of Valencia (UPV) [50].

4.1. Power generation planning of the hybrid renewable energy system: multicriteria assessment

The application of the multicriteria methodology presented in this paper to the Valencia case study gave rise to a rank ordered list of the power generation planning options for the HRES in EVCS. As section 2.4 indicated, these results correspond to an annual evaluation period, so that the obtained design options match the average behavior of the system. Table 10 reflects the individual percentage assessment of the environmental, economic and technical criteria for each option, as well as the final evaluation considering equal ponderation values for all of them.

Table 10. Multicriteria assessment of the HRES configurations. Selected power generation planning designs for the HRES in EVCS.

Configuration	**HOMER option**	**Multicriteria method option**	**EmR (%)**	**ReG (%)**	**EcF (%)**	**SS (%)**	**ESA (%)**	**Total (%)**
Ren + bat	10	1	88,84	100	83,13	83,29	88,85	88,82
Ren + gen + bat	37	2	67,95	91,04	68,56	98,14	80,89	81,32
Ren + grid	11	3	49,05	80,96	88,08	98,44	65,64	76,43
Ren + gen + bat	43	4	56,65	86,83	63,94	96,17	77,15	76,15
Ren + grid + bat	18	5	49,05	80,96	83,13	98,73	65,65	75,50
Ren + grid	4	6	31,70	57,81	97,79	98,20	88,62	74,83
Ren + grid	1	7	31,11	64,80	100,00	98,26	79,53	74,74
Ren + grid + bat	25	8	49,09	80,97	78,24	99,02	65,66	74,59
Ren + grid + bat	6	9	31,12	64,80	95,68	98,58	79,54	73,94
Ren + grid + bat	32	10	49,11	80,98	74,30	99,31	65,67	73,87
Ren + grid + bat	39	11	49,67	81,18	67,86	99,67	65,91	72,86
Ren + grid + bat	9	12	31,12	64,80	89,86	98,91	79,53	72,84
Ren + grid + bat	16	13	31,71	57,81	83,65	98,54	88,63	72,07
Ren + grid + bat	15	14	31,12	64,80	84,18	99,05	79,54	71,74
Ren + grid + bat	23	15	31,74	57,82	78,70	98,80	88,65	71,14
Ren + grid + bat	30	16	31,76	57,82	75,14	98,80	88,67	70,44
Ren + grid + bat	29	17	31,13	64,81	75,57	99,05	79,55	70,02
Ren + gen + bat	44	18	40,15	81,35	56,60	94,55	72,28	68,98
Ren + grid + bat	38	19	31,76	57,82	67,86	98,80	88,67	68,98
Ren + gen + bat	45	20	0	56,46	47,16	94,71	86,84	57,04
Ren + gen + bat	46	21	0	54,94	45,70	94,71	84,50	55,97
Ren + gen + bat	47	22	0	40,97	39,00	93,33	86,19	51,90
Ren + gen + bat	48	23	0	41,11	38,55	93,33	86,49	51,89
Ren + gen + bat	49	24	0	40,78	38,55	93,33	85,81	51,69
Ren + gen	52	25	0	59,77	25,63	91,30	53,11	45,96
Ren + gen	53	26	0	40,47	23,54	90,30	62,24	43,31
Ren + gen	54	27	0	31,69	22,06	90,01	66,67	42,09

EmR: CO_2 emissions reduction **ReG**: Renewable generation degree **EcF**: Economic factor **SS**: Security of supply **ESA**: Electricity sizing adequacy

Note: the dimension values (kW or kWh) of each option can be found in Table 6.

It is possible to see the difference between the method hereby presented and the one followed by HOMER® when assessing the alternatives. For instance, the best-valued option of this method corresponds to the 10th option of the HOMER® ranking, whereas the best-valued option using HOMER ® corresponds to the 7th option of the multicriteria method. This outcome is coherent with the behavior of both tools and verify one of the aims of the work: whilst HOMER ® bases its evaluation just on the NPC optimization, our method takes into account every factor that could affect HRES in EVCS, resulting in a more complete and realist evaluation.

Figure 9 shows the evaluation of each of the multicriteria parameters for each of the analyzed configurations. Regarding their environmental parameters (EmR and ReG), the configurations with renewable generation and batteries are by far the most influential. The configurations that include renewable generation, batteries and the support of diesel generators (ren + gen + bat) result also influential in environmental criteria for the options that use diesel generator during short periods. However, the power generation planning design options that use diesel generators for long time periods have the worst environmental impact. Alternatives including renewable generation with the support of the grid are the best economic options (EcF), and they also present good technical criteria (SS, ESA). However, configurations with renewable generation and diesel generators result are the worst choice in all the aspects: environmental, economic and technical.

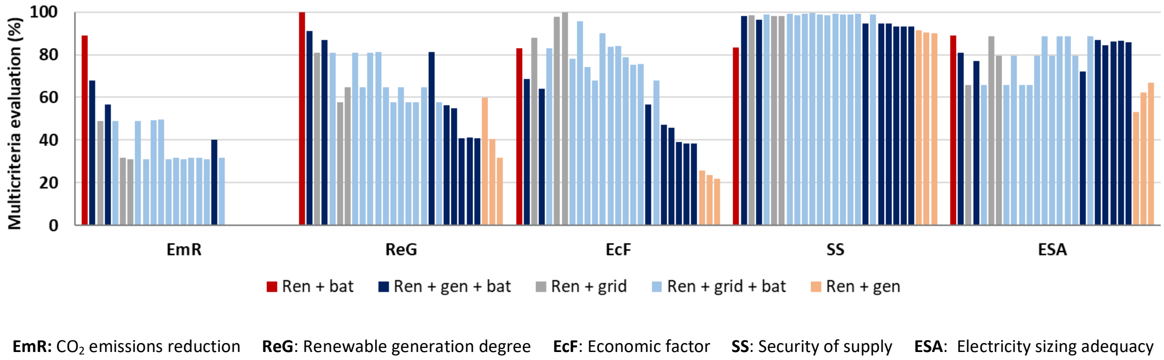
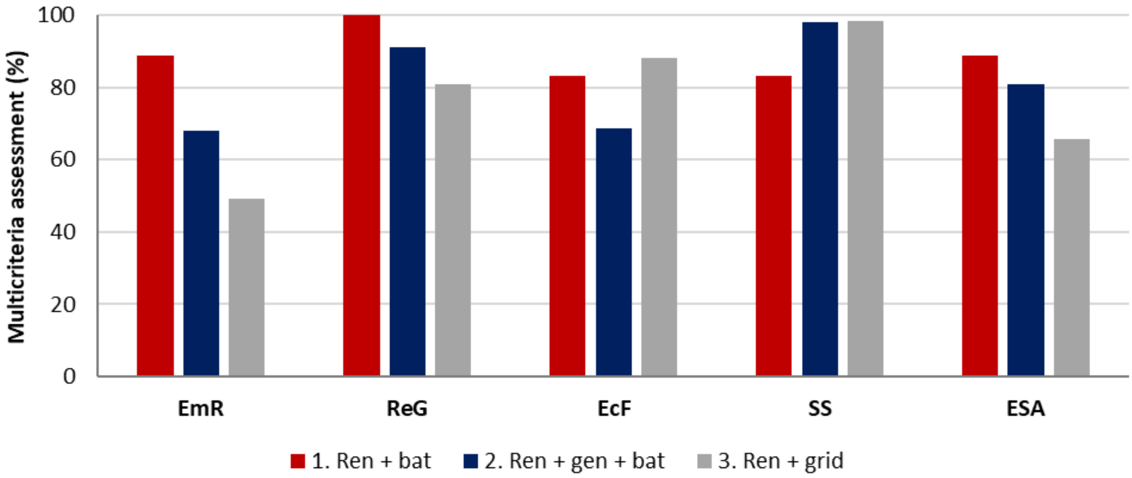


Figure 9. Multicriteria assessment.

Note: the power generation planning design options are ordered according to Table 10-Multicriteria methodology.

From the configuration ranking in Table 10 we can extract the three most suitable configuration options for the HRES in the Valencia case study. The highest-scored option is related to an off grid energy scenario that includes renewable generation (500 kW solar PV and 330 kW wind) and the support of a group of batteries (4800 kWh). The second alternative corresponds to another off grid scenario, similar to the first one, but with the support of a diesel generator (280 kW). The third-highest scored option finally represents an on-grid scenario, where the grid supports the renewable generation (500 kW solar PV and 330 kW wind).

Most of the pioneering HRES EVCS' projects developed in regions where grid connection results possible tend to rely on such kind of support for the system [29,65] mainly motivated by its ease of use, security of supply and economic performance. However, the multicriteria assessment presented in this paper reveals the influence of the environmental aspects in the selection process favoring off grid solutions, if possible. Figure 10 presents a comparison of the three most suitable scenarios.



EmR: CO_2 emissions reduction **ReG**: Renewable generation degree **EcF**: Economic factor **SS**: Security of supply **ESA**: Electricity sizing

Figure 10. Selected power generation planning designs for the HRES in EVCS.

Note: the power generation planning design options are ordered according to Table 10-Multicriteria methodology.

The off grid configuration with renewable generation and batteries storage presents the best environmental behavior, since it does not depend on polluting sources. However, the second off grid configuration (renewable generation with diesel generator and batteries) is penalized by the use of the diesel generator. Moreover, the on-grid configuration, given the dependence of the Spanish electrical mix on some high polluting sources [62], is the worst in terms of environmental influence, especially when considering the CO_2 reduction. However, this on-grid configuration arises as the most economic one, having the second off-grid configuration the lowest economic parameter due to the expenses of the diesel generator and its fuel. On the contrary, the on grid configuration together with the off grid configuration that includes a diesel generator have the highest security of supply, since they both count with dispatchable support sources.

4.2. Experimental verification of the hybrid renewable energy system

To conclude the complete design process of the HRES for EVCS for the case study, the selected design alternatives through the multicriteria assessment were experimentally validated in the Laboratory of Distributed Energy Resources (labDER) [50] of the Institute for Energy Engineering of the Polytechnic University of Valencia (Spain). This laboratory was described in section 3.4.

Each scaled experiment comprise a complete day of simulation for the three most suitable HRES designs for EVCS. For each simulation, the batteries SOC limits were fixed to 30% and 100%, according to their discharge limits. Moreover, the authors added a maximum acceptable rate of power losses of 5%, considering previous experimental studies in such field [42,50].

Power losses and SOC of batteries limits, need to be checked in a daily evaluation period due to its behaviour. According to section 3.2, March arises as the most unfavourable month in terms of non-dispatchable renewable generation (solar PV and wind) for this case study. Hence, an average day profile of March in Valencia was chosen for the experimental verification stage , as methodology in section 2.4 proposed.

4.2.1. Highest-scored configuration: renewable generation and batteries

<u>LabDER HRES setup and control algorithm</u>

LabDER HRES setup and control algorithm for the highest-scored configuration, which includes renewable generation and the support of batteries, are represented in Figure 11 and Table 11, respectively.

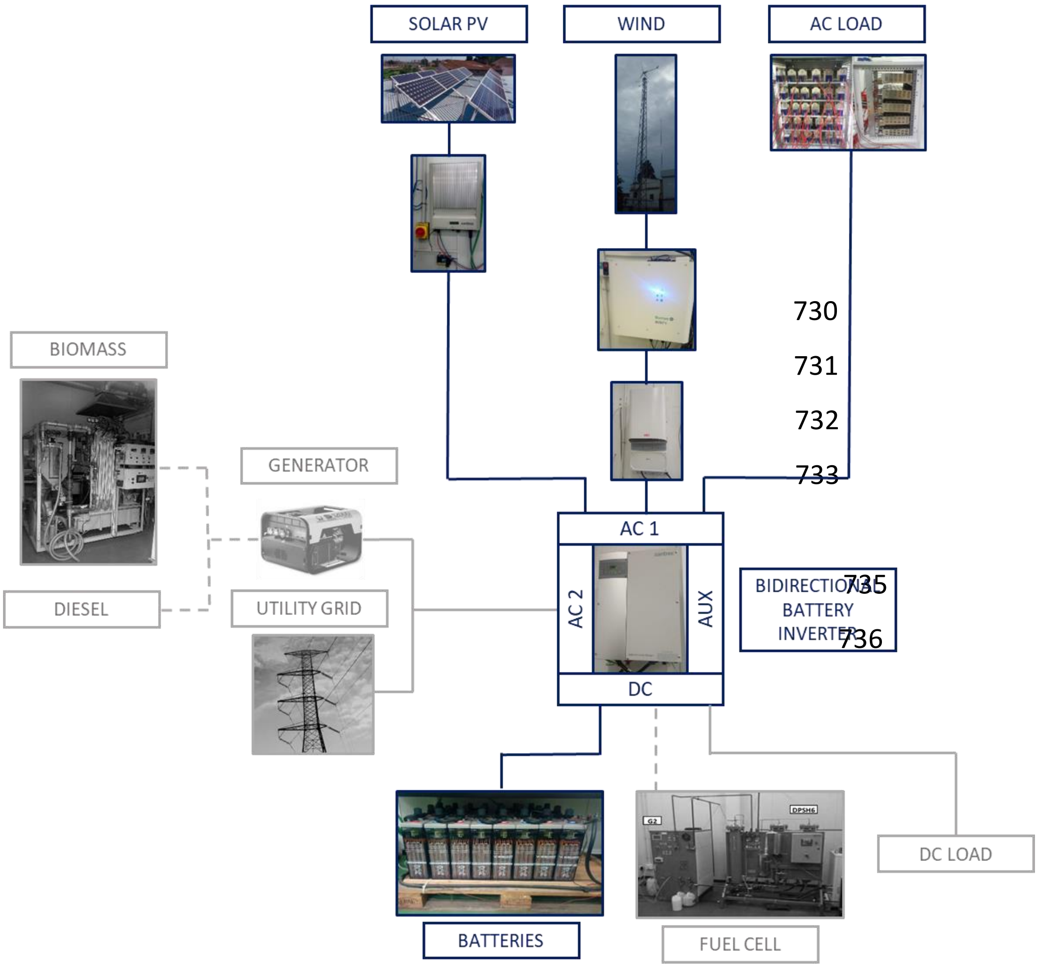


Figure 11. LabDER HRES setup for the highest-scored configuration.

Table 11. LabDER HRES control algorithm for the highest-scored configuration.

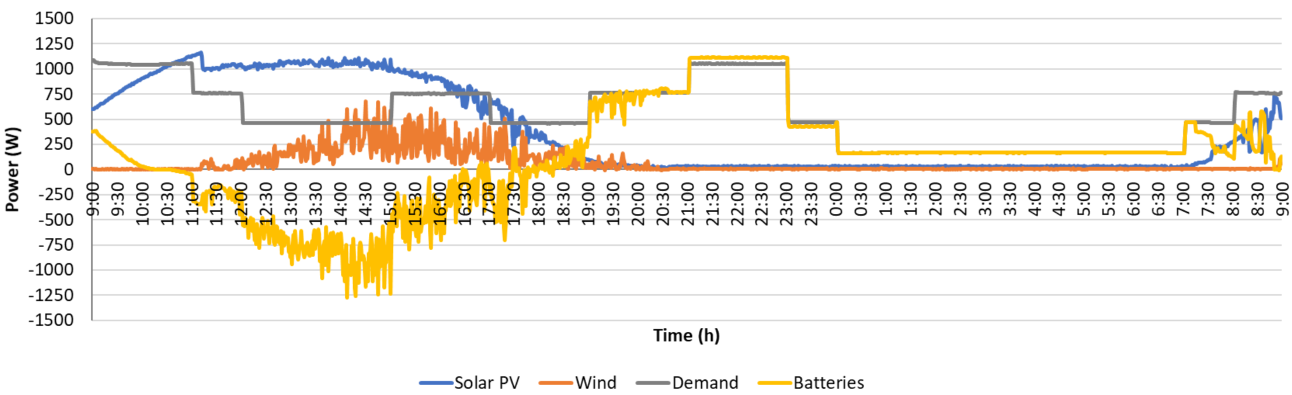
Non-dispatchable generation: Solar PV and Wind	Surplus of energy	Batteries	Element that creates the AC grid of the HRES.
They supply all the load demand	No	-	Bidirectional battery inverter
They supply all the load demand	Yes	Recharge	Bidirectional battery inverter
They do not supply all the load demand	No	Discharge	Bidirectional battery inverter

<u>Experimental results</u>

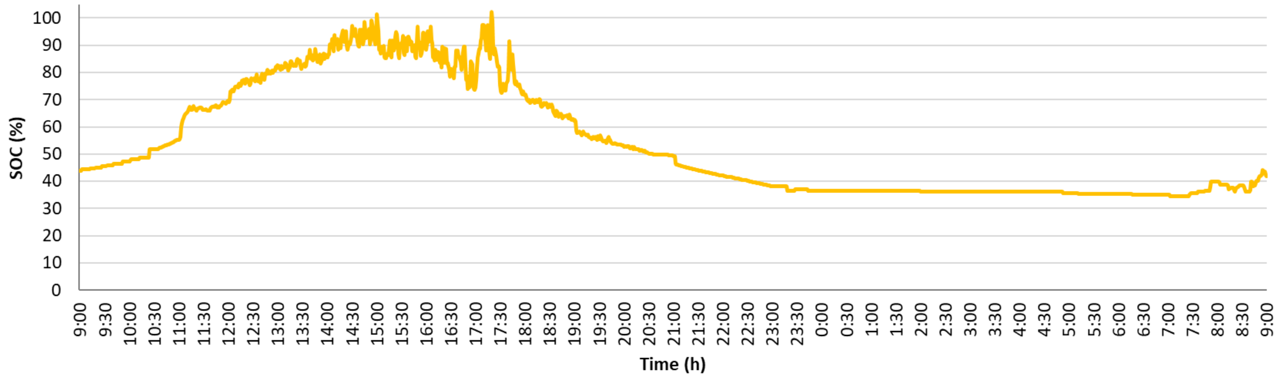
Figure 12 (a) and Figure 12 (b) plot the energy balance and SOC results, respectively, for the highest-scored configuration, which includes renewable generation and the support of batteries.

As Figure 12 (a) represents, at the beginning of the experiment, the demand requirements were the highest. However, at that period, solar irradiation was still low and wind contribution was practically zero. Therefore, batteries contributed in part to meet electricity demand. Later, solar PV and wind contribution reached their maximum values. Hence, the HRES was able to meet the EVCS supply with an excess of energy, which was used to recharge batteries. The SOC of batteries increased during this period, achieving its full charge status (Figure 12 (b)). The highly fluctuating behavior of the wind turbine, characteristic in small wind turbines like the labDER one [50], is also reflected in the power supplied by the batteries (Figure 12 (a)) and in their SOC (Figure 12 (b)). In the late afternoon, solar irradiation declined and the wind contribution was low (Figure 12 (a)). Finally, at night, both solar and wind contribution were zero and load supply was based exclusively on batteries (Figure 12 (a)), reaching their lowest SOC value of the experiment in the early morning (Figure 12 (b)), when solar irradiation was again available and recharge was initiated again.

These results demonstrated the energy achieved with the HRES in question could cope with the assumed electricity demand. Moreover, the maximum rate of power losses in this experiment was 4.5% (Figure 12 (a)) and the rates of batteries SOC alternated between 35% and 100% (Figure 12 (b)). Hence, the experiment met the limited requirements. Finally, the SOC at the end and at the beginning of the experiment were similar, about 40% (Figure 12 (b)), which ensured the adequacy of the batteries for the next experimental cycles.



(a)



(b)

Figure 12. Experimental validation for the highest-scored configuration. (a) Energy Balance. (b) SOC.

Furthermore, Table 12 compares the evaluation criteria values between experimental and simulated results for the highest-scored configuration (renewable generation and the support of batteries). The similarity of both kind of outcomes demonstrates the suitability of the applied methodology. Some criteria remain unchangeable, like Renewable generation degree or the Economic factor, whereas the highest divergence corresponds to Security of supply criteria (3%). Considering equal ponderation values (20%), as section 3.3 indicated, the final evaluation of the highest-scored evaluation turns out to be almost the same for both experimental and simulated results.

Table 12. Comparison of evaluation criteria values: experimental results and simulated results. Highest-scored conf.

Highest-scored configuration: Renewable + batteries						
	EmR (%)	**ReG (%)**	**EcF (%)**	**SS (%)**	**ESA (%)**	**TOTAL (%)**
Experimental results	90,4	100	83,1	80,8	91,3	89,1
Simulated results	88,8	100	83,1	83,3	88,9	88,8

EmR: CO_2 emissions reduction **ReG**: Renewable generation degree **EcF**: Economic factor **SS**: Security of supply **ESA**: Electricity sizing

4.2.2. Second highest-scored configuration: renewable generation, batteries and diesel generator

<u>LabDER HRES setup and control algorithm</u>

LabDER HRES setup and control algorithm for the second highest-scored configuration, which includes renewable generation and the support of batteries and a diesel generator, are represented in Figure 13 and Table 13, respectively.

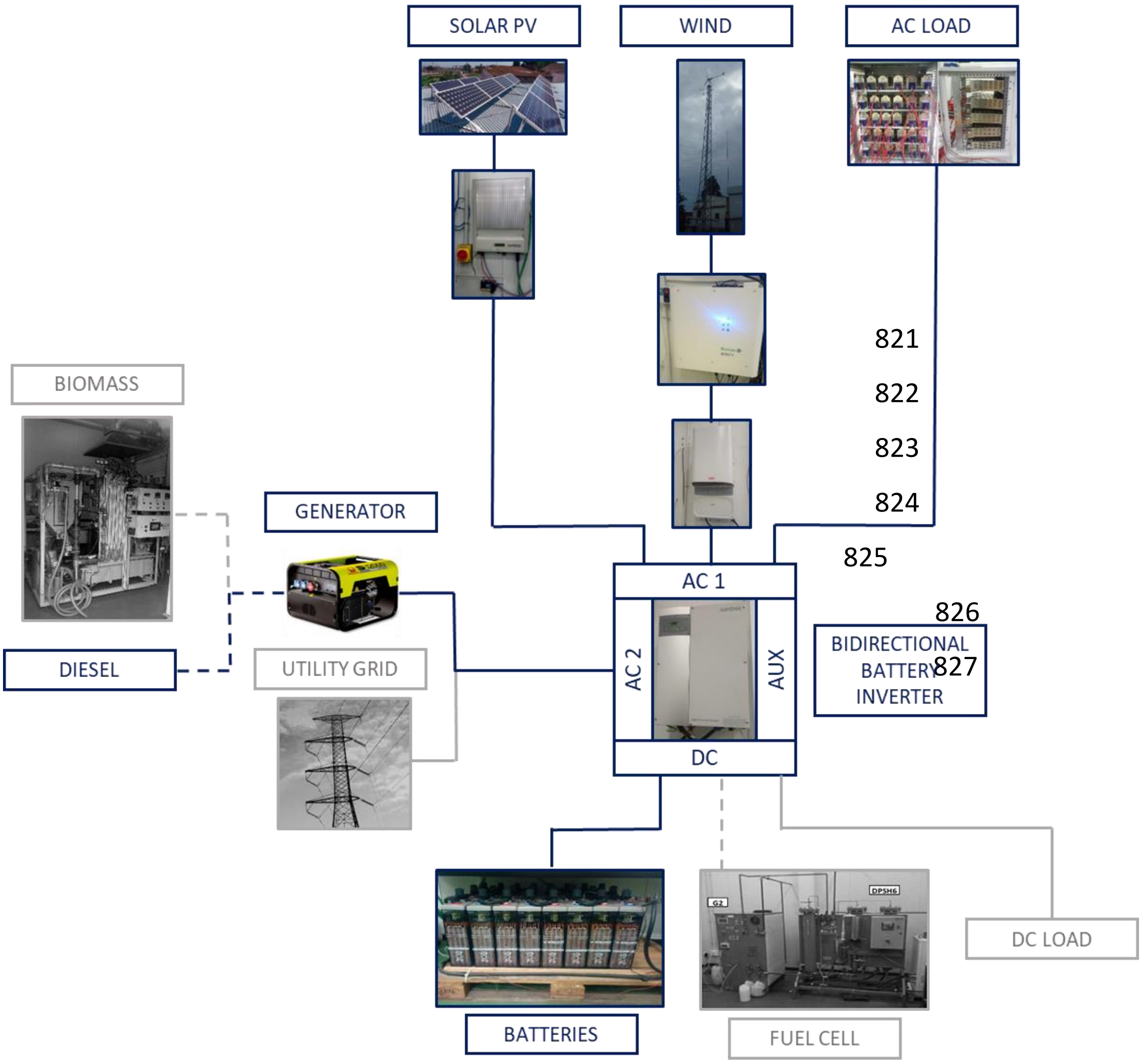


Figure 13. LabDER HRES setup for the second highest-scored configuration.

Table 13. LabDER HRES control algorithm for the second highest-scored configuration.

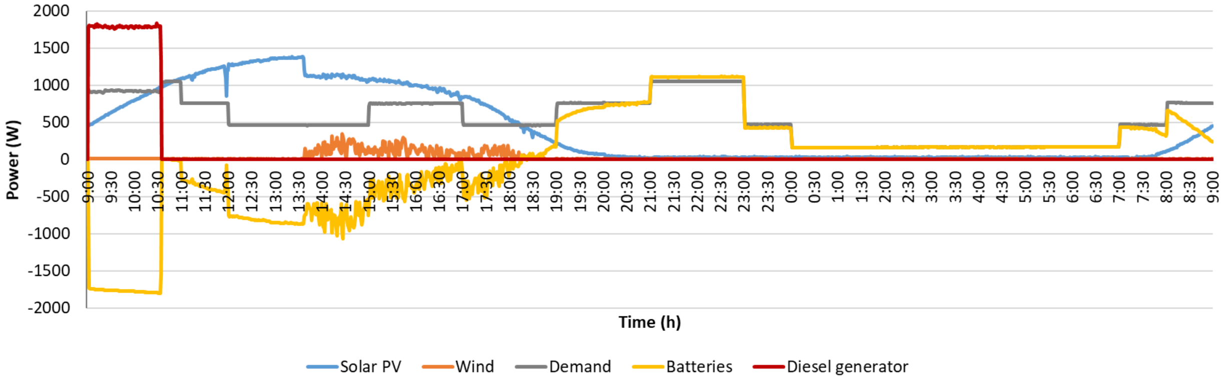
Non-dispatchable generation: Solar PV and Wind	Surplus of energy	Diesel generator	Batteries	Element that creates the AC grid of the HRES.
They supply all the load demand	No	-	-	Bidirectional battery inverter
They supply all the load demand	Yes	-	Recharge	Bidirectional battery inverter
They do not supply all the load demand	No	Working	-	Diesel generator
	No	-	Discharge	Bidirectional battery inverter
	No	Working	Discharge	Diesel generator

Experimental results

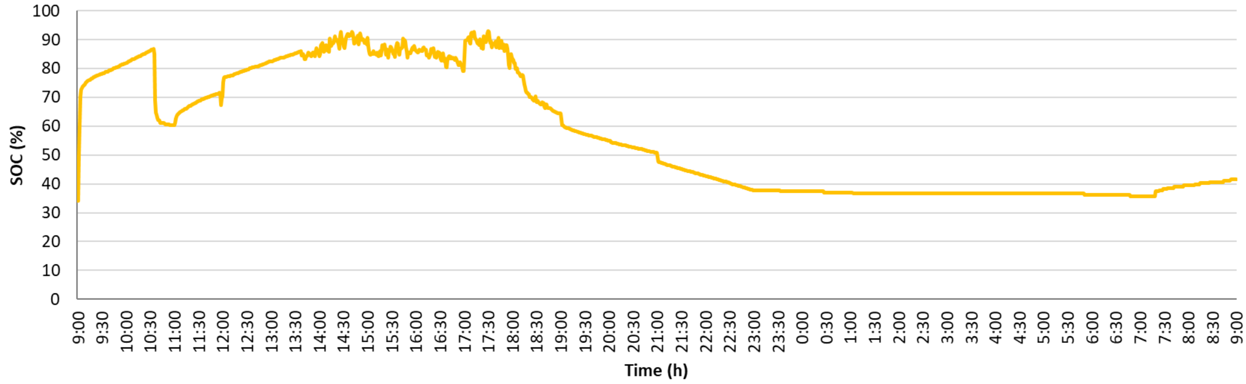
Figure 14 (a) and Figure 14 (b) plot the energy balance and SOC results, respectively, for the second highest-scored configuration, which includes renewable generation and the support of batteries and a diesel generator.

The energy balance presented in this experiment (Figure 14 (a)) is comparable to the previous one (Figure 12 (a)), with one main difference: the contribution of the diesel generator. The generator supplied energy during the first 1.5 hours, as Figure 14 (a) indicates. This option is very convenient because it guarantees the electricity supply during the period where the load demand is highest and solar irradiation and wind are still very low. Besides, the contribution of the diesel generator led to an increase of the batteries SOC from 35% to 85% (Figure 14 (b)).

The optimal use of the diesel generator demonstrated its suitability for the experiment: the rate of power loss was 4% (Figure 14 (a)), and the battery SOC at the end of the experiment (41%) was slightly higher than this value at the beginning of the experiment (35%) (Figure 14 (b)), ensuring therefore the adequacy of the batteries for future energy cycles.



(a)



(b)

Figure 14. Experimental validation for the second highest-scored configuration. (a) Energy Balance. (b) SOC.

Table 14 compares the evaluation criteria values between experimental and simulated results for the second highest-scored configuration (renewable generation and the support of batteries and a diesel generator). The similarity of both kind of outcomes demonstrates the suitability of the applied methodology. The Economic factor value remains again unchangeable, whereas the highest divergence corresponds in this case to Renewable generation degree criteria (4,67%). Considering equal ponderation values (20%), as section 3.3 indicated, the final evaluation of the second highest-scored evaluation presents a slight difference between experimental and simulated results (1,56%).

Table 14. Comparison of evaluation criteria values: experimental results and simulated results. Second highest-scored conf.

Second highest-scored configuration: Renewable + generator + batteries						
	EmR (%)	**ReG (%)**	**EcF (%)**	**SS (%)**	**ESA (%)**	**TOTAL (%)**
Experimental results	65,9	86,8	68,6	97,3	81,7	80,1
Simulated results	67,9	91	68,6	98,1	80,9	81,3

EmR: CO_2 emissions reduction **ReG**: Renewable generation degree **EcF**: Economic factor **SS**: Security of supply **ESA**: Electricity sizing

4.2.3. Third highest-scored configuration: renewable generation and the grid

<u>LabDER HRES setup and control algorithm</u>

LabDER HRES setup and control algorithm for the third highest-scored configuration, which includes renewable generation and the support of the grid, are represented in Figure 15 and Table 15, respectively.

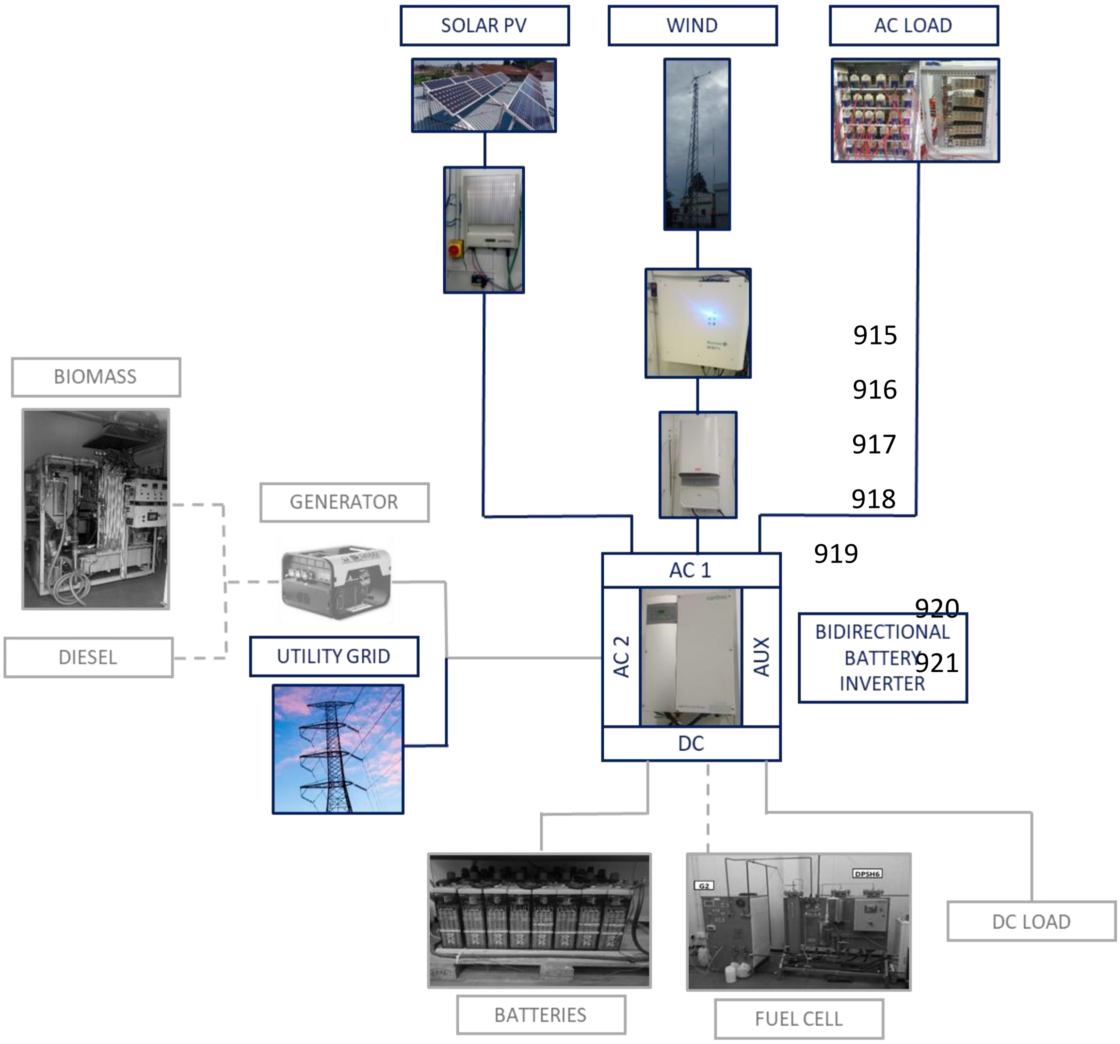


Figure 15. LabDER HRES setup for the third highest-scored configuration.

Table 15. LabDER HRES control algorithm for the third highest-scored configuration.

Non-dispatchable generation: Solar PV and Wind	Surplus of energy	Grid	Element that creates the AC grid of the HRES.
They supply all the load demand	No	-	Bidirectional battery inverter
They supply all the load demand	Yes	To the grid	Grid
They do not supply all the load demand	No	From the grid	Grid

Experimental results

Figure 16 plots the energy balance results for the third highest-scored configuration, which includes renewable generation with the support of the grid.

As Figure 16 reflects, in the morning the grid covered the low solar irradiation at the period of maximum load demand. Later, there was an excess in generation from solar PV that was inyected into the grid. During this period, solar irradiation was available and wind contribution was higher than in the previous configuration checks. Hence, the grid was also responsible for absorbing the variability of the wind generation. Besides, the grid supplied the required electricity during the evening and night time. For this experiment, power losses acquired the value of 4%, meeting therefore the limit conditions.

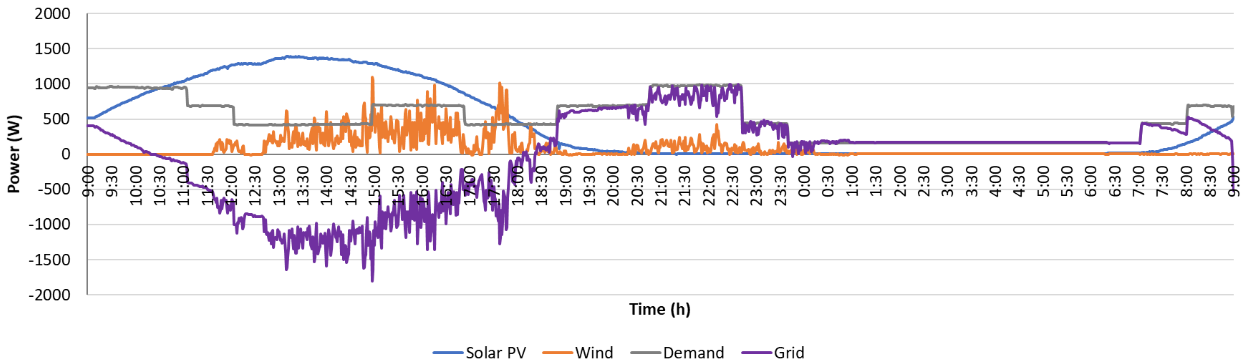


Figure 16. Experimental validation for the third highest-scored configuration. Energy Balance.

Table 16 compares the evaluation criteria values between experimental and simulated results for the third highest-scored configuration (renewable generation and the support of the grid). The similarity of both kind of outcomes demonstrates the suitability of the applied methodology. Some criteria remain unchangeable, like the Economic factor or the Security of supply criteria, whereas the highest divergence corresponds again to Renewable generation degree factor (3,5%). Considering equal ponderation values (20%), as section 3.3 indicated, the final evaluation of the third highest-scored evaluation turns out to be almost the same for both experimental and simulated results.

Table 16. Comparison of evaluation criteria values: experimental results and simulated results. Third highest-scored conf.

Third highest-scored configuration: Renewable + grid						
	EmR (%)	**ReG (%)**	**EcF (%)**	**SS (%)**	**ESA (%)**	**TOTAL (%)**
Experimental results	48,4	78,1	88,1	98,4	67,5	76,1
Simulated results	49,1	81	88,1	98,4	65,6	76,4

EmR: CO_2 emissions reduction **ReG**: Renewable generation degree **EcF**: Economic factor **SS**: Security of supply **ESA**: Electricity sizing

On the one hand, the low divergences between the assessment criteria of both experimental and simulated results verified also the adequacy of the applied methodology. On the other hand, these experimental results demonstrated the energy balance suitability of the three selected configurations for the HRES in EVCS, both on the level of power losses and batteries' SOC limits and with a full time coverage of the load demand.

5. Conclusions

A high penetration of EVCS is expected to happen to cope with the electricity requirements of the also foreseeable high introduction of EVs in the medium-term future for almost all developed countries. This electrification of the transport sector arises as an environmental solution since EVs emit zero emissions when driving on the road. Careful attention should be paid to the emissions in the generation of the electricity they need. The use of microgrids based on renewable generation (HRES) in EVCS seems necessary, since it would decrease both the CI content of the electricity generation and the pressure on the grid that the recharge of EVCS would produce. Choosing the most suitable configuration for HRES in EVCS whilst taking into account the different power generation planning (technical, economic and environmental) is therefore required.

This paper has defined a novel multicriteria methodology that takes into consideration all the above-mentioned constraints and includes an experimental stage to verify the configuration of the HRES for EVCS. The methodology, after the determination of the available renewable resources and the electricity demand of the EVCS, uses HOMER® software to deduce possible HRES configurations and evaluates them with a new multicriteria analysis, considering weighted technical, economic and environmental parameters to rank them. This stage considers an annual evaluation period to obtain the average behaviour of the HRES in question. Finally, configurations with the highest scores are experimentally tested to check their reliability, power balance and SOC range. These parameters need to be checked in a daily evaluation period due to its behaviour. In this regard, the method proposes to choose an average day of the most unfavourable month in terms of non-dispatchable generation for the experimental verification stage. Hence, the selected final configuration design ensures the suitability of the HRES for the EVCS, supported not only by a complete numerical evaluation, but also by an experimental verification.

To illustrate the viability of the methodology, the article applies the method to the case study of Valencia, the capital province of Comunidad Valenciana, (in the east of Spain). This province is immersed in a remarkable mobility transition, with the aim of increasing the quantity of EVs and EVCS, together with a significant introduction of renewable sources in the electricity generation system.

Results for the electricity demand modelling of these vehicles in EVCS led to a maximum load demand of 270 kW that takes place during the early morning (from 9:00 to 10:00 h) and at early night again (from 21:00 to 22:00 h). The generation resources analysis revealed the suitability of solar PV and wind resources, with an average solar daily irradiation of 5 kWh/m^2/day and an average wind speed of 3.6 m/s at 18 m, respectively. Regarding back-up systems, batteries, diesel generator and grid connection were contemplated.

An initial simulation of the system considering both restrictions (generation resources availability and electricity demand) and making use of HOMER ® resulted in a starting filtered list of 27 configuration alternatives. These options were later evaluated by means of the hereby presented multicriteria methodology, with the same weights for the different constraints. Simulation results indicated that the most suitable configuration for the case study is an off-grid system with renewable generation and batteries support, followed by another off-grid system that includes also the support of a diesel generator. The third highest-scored configuration resulted in an on-grid system with renewable generation.

The selected configurations were experimentally validated in the Laboratory of Distributed Energy Resources (labDER) at the Polytechnic University of Valencia (Spain). Both the generation and demand resources were scaled according to the laboratory components with a factor of 1:250. Results indicated that the demand was fully covered in all the scenarios, with maximum power losses of 4.5% and SOC of batteries between 35% and 100%. Besides, the evaluation criteria values between experimental and simulated results for the selected configurations presented very slight divergences, lower than 5%.

To conclude, this study provides a methodology that ensures the suitability of the HRES for the EVCS, supported not only by a complete multicriteria assessment, but also by an experimental verification. Its application to the case study of Valencia proves the viability of applying HRES for recharging EVs at EVCSs in a technical, economic and environmental acceptable way.

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