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Complementarity of electric vehicles and pumped-hydro as energy storage in small isolated energy systems: case of La Palma, Canary Islands

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Abstract Isolated energy systems in archipelagos are characterized for having a great dependence on fossil sources due to isolation and territorial fragmentation. The island of La Palma is situated on the northwest of the Canary Islands, and its electric system is very small. Sustainability policies planned by local authorities are aimed to increase the share of renewable energies and the reduction of fossil energies. However, intermittence and the concentration of unmanageable renewable energies in few locations may hinder the operation of the system. In order to solve these problems, energy storage plays an essential role. The aim of this paper is to analyse the effects of the introduction of two possible alternatives as a way of energy storage: pumped hydro storage and electric vehicles. For this, we use a simulation model adapted to the features of La Palma, considering different scenarios. Results show that, in the most favourable scenario, the installation of an additional 25 MW from renewables (more than double the current power), supported by 20 MW of pumped hydro storage and a fleet of 3361 electric vehicles, would allow the current share of renewables to increase from 11% (in 2015) to 49%. Furthermore, this would mean a 26% reduction in CO_2 emissions, 10% in costs of generated kWh and 19% in energy dependence.

Keywords Energy storage, Electric vehicles, Vehicle-to-grid, Grid-for-vehicles, Pumped-hydro energy storage, Isolated systems

1 Introduction

Island electric systems are usually dependant on fossil fuels when isolated from the great continental networks. In the case of archipelagos, territorial fragmentation means that, in many cases, islands are also isolated from each other [1–3]. This fact is clearly exemplified by Canary Islands, whose distance is significant from the African and European continents and its dependence on fossil resources lies over 96% [4]. Besides, due to the small size of island systems, a massive integration of intermittent renewable energies hinders the operation of electric systems.

The main goal of the Canary Islands energy policy is to attain an energy system which is environmentally sustainable [5]. In order to achieve this goal, it is essential to increase the penetration of renewables, as well as to reduce the use of fossil fuels, which would also reduce emissions. The interconnection among different island systems would be a potential solution. However, the great depth of the seabed in the archipelago makes that two of the islands (La Palma and El Hierro) remain completely isolated. In these cases, energy storage is almost the only solution in order to increase the share of renewables and, at the same time, guaranteeing the electric supply.

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Although there are different technological alternatives for energy storage [6], pumped hydro energy storage (PHES) is very interesting for the islands, as the orography of most the Canary Islands allows for the use of hydraulic heads [7–10]. For instance, in the island of El Hierro, the hydro-wind plant Gorona del Viento has achieved a renewable share of 44% for 2015, reaching a production of 100% renewables on over a dozen days a year. The energy development strategy includes the PHES as the most important energy storage to increase the renewable share in Canary Islands [5]. However, there are other ways of energy storage, such as the use of a fleet of electric vehicles (EVs) managed by an aggregator. This agent is a commercial middleman between a system operator and plug-in electrical vehicles. Besides, the EV is able to perform other tasks in order to support the electric system, providing security and stability to the network [11–14]. Nevertheless, coordinated management when these vehicles are being charged is an essential aspect to maintain the security of the electric system during high-demand hours [15].

The aim of this paper is to analyse how different alternatives for energy storage could increase the sustainability of the energy system in La Palma, which is an interesting case of study of a completely isolated system where energy and environmental sustainability could be improved due to geographical conditions. These conditions allow energy storages to be used along with a high penetration of renewable energies.

Sustainability is going to be measured by evaluating the effect of these measures on 3 essential dimensions: ①the share of renewables in the electric mix; ②CO_2 emissions; ③ total consumption of fossil fuels. In order to attain this goal, we use the simulation model described in [16]. From that model we will obtain two other variables, such as spilled renewable energy which cannot be introduced in the system due to TSO requirements, and the costs of generated MWh which will provide us with extra relevant information.

Different scenarios have been designed according to the type of storage used. Both penetration of renewable energies and the fleet of EV will be gradually increased in each scenario to reach the goals of the energy planning in the islands.

The rest of the article is structured as follows. Section 2 briefly reviews the literature about energy storages in isolated systems. Section 3 details the description of the electric system in La Palma, followed by the definition of the scenarios, and finally details the model used. Next, Section 4 shows the results obtained and the discussion about them. Lastly, Section 5 concludes the paper with the main findings and energy policy measures.

2 Background of energy storage in Canary Islands

Energy storage systems contribute to the integration of unmanageable renewable energies. The use of these technologies has been widely studied for island isolated systems [17–19]. According to [6], energy storages can be classified into applications of short-term (seconds or minutes), long-term (minutes and hours) and real-long-term (hours and days). The authors recommend the introduction of PHES and Battery Energy Storage (BESS) for real-long-term storage applications. The introduction of these two types of storage will be considered in this study for the island of La Palma. The orography of the island is suitable for the installation of PHES technologies. Regarding the second technology, EVs could function as storage systems by using their batteries.

PHES is a mature technology with over 104 GW installed around the world, out of which, 350 MW belong to isolated systems in the year 2013 [20]. The major advantages of this type of storage are the long lifetime of the installation, the great reliability of the components used and a quick response time, which allow this technology to provide the electric system with ancillary services, even working as base load. However, it has some disadvantages as well, such as water availability which is a scarce resource in the Canaries, lack of suitable sites and the high impact, both landscape and environmental, of the installation.

EVs have undergone a major expansion in recent years, which means there are now over 1 million units running around the world. Growing technological improvements, better energy efficiency and their easy adaptation to island regions make EVs a real market alternative. Considering this phenomenon, the local government has designed a strategy to boost the EV, targeting 2030 [21], with the purpose of improving sustainability of ground transportation in the archipelago. In order for the EV to be considered as electric energy storage in the electric system, the energy flow has to be bidirectional, that is, vehicle-grid and grid-vehicle. The development of this technology is being tested in several projects around the world [22–24]. According to [13] one major advantage of this type of storage is the high-speed response, which allows for primary regulation. Once greater levels of integration are achieved, the EV can provide ancillary services and peak shavings. What is more, as its energy is distributed around different points on the grid, the load of the transformation stations is reduced [25]. Nevertheless, there are some disadvantages, such as lack of commercial maturity, lack of awareness of users [26], and wear of batteries due to a greater use of the load-unload cycle [27].

Some research on the two types of energy storage considered in this paper has already been done in the Canary Islands archipelago. Regarding PHES, some studies have been conducted in La Palma [10], el Hierro [7], and Gran Canaria [8, 9]. The main conclusions drawn from these studies are that they seem to be an adequate instrument in order to achieve a massive introduction of unmanageable renewable energies. This is so because they minimize the spilled renewable energy, they increase the share of renewables and they provide security to the system against the expected intermittence. In addition, there exists a PHES plant known as 'Gorona del Viento' on the island of El Hierro. However, its 11.32 MW installed only represent 0.4% of total in the archipelago and contributed 0.1% to the demand coverage in the Canaries for 2015 [28]. Likewise, the Canary Islands energy planning [29] provides for the installation of some 299 MW of PHES, targeting a 30% share of renewables, thus reducing the degree of energy dependence under 10%. While La Palma would be provided with 30 MW.

Moreover, the introduction of EVs in the Canaries has been considered by the policy of the local government. Governmental forecasts have been detailed in the study for EV boosting in the Canaries [21], where a penetration of EVs of up to 413359 is expected for 2030, which would mean almost 25% of the vehicle fleet of the Canaries. What is more, the possibility of its use as energy storage has been recently analysed by two studies. On one hand, Ref. [12] analyses the introduction of a fleet of EVs as energy storage to evaluate the impact on the electric mix efficiency border in the Canaries. The authors conclude that the use of EVs could reduce the use of fossil fuels and increase the share of wind power, thus reducing carbon emissions and costs. On the other hand, according to [16], the inclusion of a fleet of 50000 electric vehicles with V2G capabilities could increase the renewables capacity up to 30%, reduce total emissions by 27% and reduce the consumption of fossil fuels by 16% for the island of Tenerife.

3 Methodology

In this section we are going to describe the simulation model for the electric system in the island of La Palma, in order to give a response to the goals set out in the introduction. The first step is to present the information of the electric system in La Palma. Next, we describe the simulation model and the different scenarios that we are going to take into account for our empirical study.

3.1 La Palma energy system and road transport

La Palma is the third smallest electric system out of the six which currently exist in the Canaries. The systems are sorted by size as follows: El Hierro (7 MW peak), La Gomera (9 MW peak) and La Palma (43 MW peak) are the smallest isolated systems. Followed by the interconnected system of Fuerteventura-Lanzarote which is medium sized (230 MW peak). Finally, Gran Canaria and Tenerife, with approximately 540 MW peak each, are the largest [31]. On the side of the supply, the generation system is composed of two types of conventional technologies (diesel engine and gas turbine), which represent almost 90% of the installed power, whereas renewables only represent 10% [4]. Despite the small installed capacity of renewables, a penetration of over 11% of renewable share was achieved in 2015. The installed capacity in La Palma is shown in Table 1.

Examining the technical features of the generators, Table 2 describes the minimum operational rates of the different units, the emissions per kWh produced and lastly, the average costs of generation, which are measured following the levelized cost of energy (LCOE) technique [32]. The parameters that the LCOE takes into consideration are the expected lifetime costs including construction, financing, fuel, maintenance, taxes, insurance and incentives, which are then divided by the system's lifetime expected power output. All these features are going to be important for our empirical study.

In order to reduce the energy dependence and also reduce carbon emissions, the energy planning proposed by the Canary Islands Government (PECAN, 2015) [29], suggested 28 MW of wind power and 7.91 MW of photovoltaic in La Palma for 2015. However, these goals were

Table 1 Installed capacity in La Palma (2015)

Technologies	Number of units	Total installed power capacity (MW) [31]	Electricity generation for 2015 (GWh) [30]
Diesel engines	10	74.82 (69.65%)	239.29 (88.38%)
Gas turbine	1	21.6 (20.11%)	0.94 (0.36%)
Wind power	4	6.9 (6.42%)	23.43 (8.65%)
Photovoltaic		4.1 (3.85%)	7.10 (2.62%)

Table 2 Technical characteristics in La Palma (2015)

Technologies	Minimum operational rate (MW) [33]	Emission rate (kgCO$_2$/kWh) [30]	LCOE (€/MWh) [16]
Diesel engines	6.63	0.75	130.17
Gas turbine	4.85	1.15	320.01
Wind power		0	71.80
Photovoltaic		0	118.12

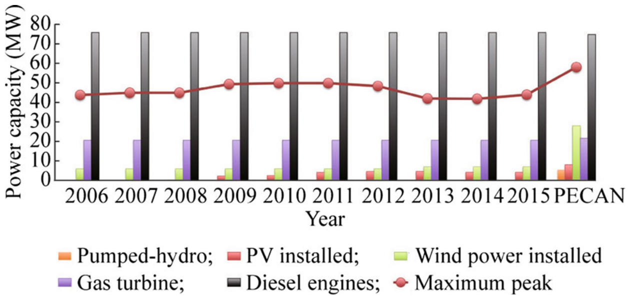

Fig. 1 Installed power capacity and peak power of La Palma electrical system

not fulfilled, being the current installed capacity 6.9 MW of wind power, and 4.1 MW of photovoltaic. In Fig. 1, we can see the evolution of the installed power during the validity period of PECAN, highlighting the stagnation of the conventional and renewable installed power. Besides, we can highlight the stabilisation of the demand peak due to the economic crisis, being currently around 44 MW, and below 50 MW reaching a historic maximum in 2010 and 2012.

Following the historical tendency that hydroelectric energy has had in La Palma, new PHES projects have been suggested. Firstly, the old El Mulato plant is repowering which is currently out of service, from 800 kW to 5.2 MW, planned by PECAN. Also, another PHES power plant of up to 15 MW turbine and pumping, has been planned in Las Cancelitas ravine. Both plants would flow into the Barlovento reservoir, which has a capacity of about 3000000 m^3. Its current use is general supply and irrigation. Table 3 summarizes other additional features to the already mentioned related to the two PHES power plants.

Regarding ground transport, the island of La Palma has a vehicle fleet of 66123 units. Our object of study will be private cars, which represent 60% of the total. According to a report about the introduction of the electric vehicle in the Canary Islands [21], a total of 1085 electric cars will be running by 2020, whereas there will be 3361 by the end of 2024.

For our empirical study, we will consider the current situation regarding the installed conventional power. However, we will take some steps to increase the renewable energy power in order to achieve the goals put forward by PECAN. Besides, we will consider the increase of the demand expected by SEPLAN (2020) [31], which would mean annual demand increases of 1.2%. This is a document passed by the Spanish Government, which describes all the investments planned according to the estimations about the Spanish electric system for the period 2015–2020. Additionally, the two aforementioned PHES power plants, with a total capacity of 20.2 MW, will be introduced. Finally, we will consider the increase in the fleet of EVs suggested by strategy of the Canary Islands Government [21] from 2016 to 2024.

Table 3 PHES plants in La Palma

Variables	Unit	PHES of “El Mulato”	PHES of “Las Cancelitas”
Hydropower head	m	929	370
Upper reservoir	m^3	6000	3000000
Lower reservoir	m^3	300000	3000000
Autonomy estimated	h	1 h 53 min	18 h 33 min
Flow rate	m^3/s	0.58	4.5
Number of turbines		1	3
Turbine power	MW	5.2	5.0
Total turbine power	%	5.2	15
Number of pumps		1	14/1
Pumping power	MW	0.70	0.75/2.25
Total pumping power	%	0.70	12.75

3.2 Methodology: simulation of electric power system in La Palma

We simulate the electricity power system of La Palma following the model of [16]. Different scenarios have been considered to measure the impact of renewables (wind and PV) at the same time as two energy storage systems (PHES and V2G) are implemented. Thus, when comparing the results under these different scenarios we will obtain yearly values from the following outcomes:

1) Renewable share, which is defined as the total renewable energy injected into the electric grids compared to the total energy consumed.
2) Oil internal consumption, which is calculated as the total TOE (Tones of Oil Equivalent) reduction in the transport sector due to the use of EVs and electricity production. Also, it is divided by the total oil consumption from the internal market in La Palma.
3) Carbon emissions, which calculated following an emission rate by technology, are shown in Table 1. The emissions rate average is the total emissions produced during the year per each kWh generated.
4) Cost of generating electricity, which calculated according to the LCOE for each technology, is shown in Table 1. The average value is the weighted sum of the cost per technology divided by the total energy consumed.
5) Spilled energy, which is the total renewable energy that could not be injected into the system. It is measured as the total renewable energy that is not injected into the system over the total renewable energy available.

3.2.1 Scenarios

We want to analyse the role of the two types of energy storage which can be accomplished in La Palma in the medium term. Each scenario will have 5 stages every two years, for a period from 2016 to 2024, in which we will increase the installed capacity of renewables to meet the goals of PECAN. Accordingly, we will consider the increase of EVs expected by the EV boosting strategy in the Canaries [21]. The detail of the different scenarios is as follows.

3.2.1.1 Scenario 1: baseline scenario This scenario is characterized by not considering energy storage. Two sub-scenarios will be considered where we will vary the kind of load management of the electric vehicle.

1) Sub-scenario 1A. In this scenario we will consider no control over the charging of the EV (Plug&Charge situation).
2) Sub-scenario 1B. EVs will work on demand response, and smart-charging strategies, thus encouraging overnight charge and recovery of spilled energy from renewable sources. Therefore, it will function as Grid-for-vehicle (G4V).

3.2.1.2 Scenario 2: PHES scenario In this second scenario we will repeat the two previous sub-scenarios (2A and 2B), except for the fact that we will include PHES technology. As it was mentioned in Section 3.1, 20.2 MW of PHES, with a pumping capacity of 15.75 MW, will be installed.

3.2.1.3 Scenario 3: V2G scenario This third scenario will evaluate the same case as in scenario 1, but assuming that the fleet of EVs has V2G capabilities. Thanks to this scenario we will be able to compare the advantages and disadvantages of V2G-EVs against PHES. This scenario is unique, as the whole fleet of vehicles is supposed to have, in all the stages, load management with V2G capabilities, instead of the Plug&Charge situation and the G4V strategy.

3.2.1.4 Scenario 4: PHES + V2G scenario Finally, this last scenario will evaluate the potential of combining the two storage technologies simultaneously. In this case, PHES will be given priority for the collection of renewable surplus, as it is a more robust technology and both turbine and pumping capacities will be 100% available for the periods considered.

Table 4 shows the temporal evolution of the main variables that determine the model. These variables are common to all the scenarios. Therefore, by combining the five stages from the table and the four scenarios including the two sub-scenarios for Scenarios 1 and 2, we will obtain 30 possible situations to evaluate the five essential variables calculated by the model.

3.2.2 Simulation model

In this section, we briefly describe the equations and restrictions of the simulation model. We choose 2015 as reference year; due to it is representative of the demand and the renewable generation in the island. Our model is based on [s] considering the characteristics of La Palma. In this isolated electric power system there exist two main conventional technologies i.e., gas turbine (GT) and diesel engines (DE). The empirical exercise considers the growth of the renewable power in the island while keeping the installed capacity of conventional power plants constant. Moreover, the model takes into account certain restrictions of the electric system including the demand equilibrium, the minimum operation range, the maximum operation range, and the secondary reserves condition.

$$D_t = P_{DE,t} + P_{GT,t} + P_{WP,t} + P_{PV,t} \tag{1}$$

where D_t is the demand at each time t; $P_{DE,t}$ and $P_{GT,t}$ are the production with conventional technologies (GT and DE), and the last two terms are production with wind power (WP) and PV production. As renewables introduction is a priority, their production will depend on their installed power and the load curves at any time (renewable patterns). For each period of time we take the demand and the wind and photovoltaic load curves as given. Thus, when the demand and the renewable installed power increase, (1) would be unbalanced for most of the periods analysed in 2015.

The starting point is to introduce a set of adjustments in the production levels of conventional plants. Diesel engines

Table 4 Stages of scenarios proposed

Stage	Year expected	Wind power installed (MW) [29]	Photovoltaic installed (MW) [29]	Number of EVs [21]	Increase of demand (%) [31]
1	2016	6.91	4.1	135	
2	2018	12.25	5.0	475	2.4
3	2020	17.50	5.9	1085	4.8
4	2022	22.75	6.9	2030	7.2
5	2024	28.00	7.9	3361	9.6

are used as the buffer in (2) (on left hand), because, they function as the base load of the system but they also show a high flexibility to adapt to the intermittencies of renewables. Thus, the diesel engines production is obtained as a residual of existing electricity demand minus the production of the gas turbine and the renewable production under the new scenarios.

$$P_{DE,t}^{s,n} = D_t^{s,n} - P_{GT,t}^{s,n} + P_{WP,t}^{s,n} + P_{PV,t}^{s,n} \tag{2}$$

where superscript 's' refers to the new scenario proposed; 'n' shows the stage. The demand shown in Table 3 will increase depending on the stage. In each adjustment, we will impose two boundary restrictions based on the minimum operation range ($L_{min,n}$) and the maximum operation range ($L_{max,n}$) for each power plant. As a reminder of Tables 1 and 2, the minimum operation range for each diesel engine is 6.63 MW and for the gas turbine is 4.85 MW. Additionally, the maximum operation range for each unit is 11.5 MW for diesel engines and for gas turbine is 21.6 MW. Thus, the units cannot produce under the minimum operation rate required by TSO rules [33] or zero in the renewable case or beyond the maximum power capacity.

Furthermore, we mention an unusual situation that may occur in (2). When the production of renewables is very high, $P_{DE,t}^{s,n}$ could be zero or negative, which is impossible. The model must cut down the renewable flow in order to maintain the balance of the system (1) under the new conditions. Thus, a part of the renewable production which spilled out of the system is lost.

The diesel engine units are responsible for maintaining the equilibrium and the inertia of the electric power grids. According to the TSO requirements for La Palma, at least two diesel engines must be working in order to guarantee its security conditions [33]. However, when the energy storages are included, only one diesel engine must work. When the renewable generation exceeds this condition, the system cannot absorb the extra energy generated and the energy is spilled.

Other TSO rules about the security of the system have been considered. Primary reserves are ensured by the operation of the generators in a short period of time (less than 5 minutes of response). On a second stage, secondary reserves are covered by the diesel engine and the gas turbine at any time in order to manage the intermittency of renewables. Thus, the model does not consider the control of primary reserves, which plays a minor role for our purposes, and is treated by other studies [10]. Finally, the availability of the gas turbine during the analysis is enough to cover the system requirements in terms of tertiary reserves. More details about the performance of the model are specified in [16]. Furthermore, the details about the modelling of the energy storages and the description of parameters are shown in Appendices A and B of this paper.

4 Results

As we mentioned in the previous sections, we are going to evaluate the evolution of a series of variables over a period of 8 years for different scenarios of energy storage. We have to take into account that for the last year of the period, the goals from the local energy planning must be achieved in all cases. Goals by PECAN suggest the installation of 28 MW of wind power and 7.9 MW of photovoltaic in order to accomplish a 30% share of renewables in the electric mix [29]. Besides, forecasts about the penetration of EVs must be achieved reaching 3368 units this year, as it was detailed in Section 3, according to the forecasts by the local government [21]. In this section, we will look briefly at how all the variables that measure sustainability evolve during the period for the different scenarios. Then, we are going to compare the final results for the last year of the period considered in each scenario according to the variables we have defined. This comparison will allow us to evaluate the advantages and disadvantages in each scenario, in order to make recommendations regarding energy policy.

As shown in Figs. C1, C2, C3, the analysis of the results starts by addressing the evolution of the renewable share, the spilled energy and the mix generation costs. The results are presented for all levels of installed power in each period, which are common to all scenarios. Beginning with the Scenarios 1A and 1B where there is no storage, it is worth mentioning that the renewable share has a maximum limit of 30% for Scenario 1A and 35% for Scenario 1B. In both cases, the spilled energy increases exponentially over the period but the mix generation costs do not decrease in relation to their initial values. However, the spilled energy value is quite different for Scenarios 1A and 1B (40% and 20% respectively), which explains the difference in costs between the two scenarios.

Regarding the two previous Scenarios 1A and 1B, the introduction of PHES always means lower values of spilled energy as well as lower mix generation costs. There is also a considerable increase in the share of renewables, to almost 50% in Scenarios 2A and 2B. The evolution of these variables is lineal, taking into account the small quantity of spilled energy. In this case, load management does not generate significant differences, mainly because the unmanaged demand from EVs is covered by PHES during peak hours.

Replacing PHES as storage system with V2G-EV means that a higher level of renewables and a lower generation cost are accomplished. Besides, the spilled energy value is very low in the previous case. However, due to V2G not being feasible at first, the effects begin from the year 2018. The possibility of EVs working as energy storage through a

V2G system requires an important number of EVs within the vehicle fleet of the island. Therefore, we will not be able to offer this kind of storage capacity to the system before stage 3 when we reach 1086 EVs. Finally, the case of the combined scenario (Scenario 4) obtains the best results, except for the costs, which are slightly worse than those for the V2G scenario.

With regards to emissions, we can highlight that they will be drastically reduced as long as there is storage shown in Fig. C4. The cases of Scenarios 3 and 4 are the ones in which this reduction is more pronounced. For the cases of scenarios with no storage, the load management from EVs reduces the electric system's emissions. Therefore, the larger the share of EVs, the greater the reduction in emissions.

We finish the study on the evolution of the variables by focusing on the domestic consumption of fossil fuels. The reduction of the energy dependence is calculated assuming that a 100% represents the total consumption of La Palma in 2015 (90241 TOE). The introduction of energy storage systems helps to reduce the consumption of fossil fuels throughout the period. The combined scenario is the one with the best results, showing a more pronounced linear reduction than the other cases in Fig. C5. On the contrary, the maximum reductions of energy dependence to be about 10% for the period considered is caused without using storage systems causes, with respect to the initial situation that in Scenario 4 it is almost double.

Next, we are going to focus on the results for the last year. We should remember that the last year of study is 2024, when the PECAN goals regarding the installed power of renewables (28 MW of wind power and 7.9 MW of photovoltaic) would have to be accomplished. Similarly, the demand will increase by 9.6% following the national energy planning [31], and some 3363 EVs will be running around La Palma, according to the local government [21]. In Table 5, results are summarized, and will be analysed next.

First, focusing on Scenario 1, we observe that the share of renewables is about 30%. This would result in a tight accomplishment of the goals imposed by PECAN [29] in matter of penetration of renewables. What is more, emissions will be reduced by 10% when there is no managed charging, and 15% when there is managed charging of EVs, with respect to the initial situation. However, the average cost increases slightly in one of the cases, around 1%, and in the other case it decreases by a mere 4.5%.

The introduction of the PHES technology causes the share of renewables to be increased by 10% points, thus far exceeding the goals imposed by PECAN. This increase is due to the almost disappearance of spilled energy. Furthermore, costs and carbon emissions decrease by approximately 10% and 17% respectively comparing Scenario 1A with Scenario 2B. The existence of a load management system for EVs in this scenario does not produce significant differences, as it was the case in the previous scenario. This fact is due to PHES collecting the renewable energy surplus. Besides, unmanaged demand during demand peak hours is covered by PHES mostly, and therefore, the impact of fossil resources' consumption is reduced.

The use of the V2G technology to replace PHES improves all the variables which measure sustainability in this study. The share of renewables will increase up to four percentage points more with respect to the previous scenario, while costs decrease by an additional 3%, and emissions by 10%. This fact is due mainly to a better efficiency in storage compared with the PHES system and its low LCOE in comparison with PHES

Finally, when we combine both storage technologies in Scenario 4, all the key variables related to sustainability are improved, except for the mix generation costs (2% lower in Scenario 2). Thanks to this combination we can reach levels close to 50% of penetration of renewables, thus reducing the energy dependence in about 19%–20% with respect to the starting point.

Although in the last scenario the cost is 2% higher than V2G, we believe the combined scenario is the most advisable from the perspective of energy policy. This opinion is based, firstly, on the fact that it is the one which presents the best results for all the variables related to sustainability. Second, for technological reasons, we consider that the maturity of the PHES technology could compensate for the possible uncertainty about the success

Table 5 Results of scenarios (Stage 5)

Scenario	Storage	EV management	Renewable share (%)	Energy spilled (%)	Electricity mix LCOE (€/MWh)	Electric power system emissions (kTonnes CO_2)	Reduction of energy dependence (%)
1A	NO	NO	28.2	47.3	125.72	141.3	8.02
1B	NO	G4V	33.3	22.6	118.8	133.2	10.69
2A	PHES	NO	42.8	3.6	113.3	121.4	14.58
2B	PHES	G4V	43.9	1.8	111.9	117.4	15.94
3	V2G	V2G	47.1	3.2	109.4	109.0	18.70
4	PHES + V2G	V2G	48.8	0.7	111.7	108.9	18.73

of the EV implementation. Given these factors, we believe there is a complementarity between these types of storage in this case of study.

5 Conclusion

In this study, we have analysed the role of energy storage as a mean to accomplish sustainability in an isolated energy system. The island of La Palma represents an interesting case, partly because of its situation of isolation, and partly because it presents favourable conditions to introduce PHES, and a fleet of EVs.

Using a simulation model adapted to the particular features of our case of study, we have evaluated sustainability through the following variables: share of renewables, spilled energy, mix generation costs, carbon emissions and energy dependence. From the results of this study, the most interesting conclusions are the following.

The use of storage systems allows to accomplish goals related to environmental and energy sustainability which are more ambitious than those suggested by the local energy policy (PECAN). These goals are achieved even reducing the costs of the generation mix. Regarding external dependence, the goals achieved are also more ambitious than the 10% suggested by PECAN. In relation to the specific storage system, we believe that a combination of both systems is the most suitable choice, because although in relation to other options, only marginal improvements are achieved, the cost is not much higher and it is a safer alternative.

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Appendix A: EV fleet modeling

In this appendix, the introduction of an EV fleet in the power system is described. We consider three different management situations (uncontrolled charge, G4V, and V2G). For the first situation, the uncontrolled charge is detailed by a plug&charge EV demand curve, according to the mobility characteristics of the island [26]. For the second and third situations, the smart charging management can recover spilled energy from renewables overproduction. However, only with the last strategy (EVs with V2G function), the additional services to the system, such as backup supplier and peak power shaving, could be provided.

A set of parameters have been considered when introducing the EV in the model, such as the number of EVs in the island (N_{EV}), total battery capacity of EV fleet (S_{EV}) and the average millage of the EV (EC_{road}).

The Electric Vehicle Supply Equipment (EVSE) is also modelled. For each stage, it is measured the power of the charger (P_{home}), the total number of charging points (N_{home}), and the efficiency of the charger (Eff). The simulator also considers a minimum Operation State of Charge (SOC_{sec}) of 40% to refrain from jeopardizing the batteries. All these parameters are shown in Table A1.

The drivers' mobility patterns [26] are introduced to obtain the total storage capacity of each timestamp (each hour). This storage capacity ($C_{V2G,t}$) is defined as the total number of vehicles connected at period t ($N_{home,t}$) multiplied by the power capacity of the charging station (P_{home}).

The energy of the EVs could be consumed in three different ways: road trips, backup supplier and peak shavings. First, the road consumption depends on the particular average distance travelled (D_{trav}), the number of vehicles considered on the step and the average millage of the fleet. This consumption is located outside the charging station. Secondly, the V2G capacity could provide energy from their batteries to the grid. This consumption is situated when the

Table A1 Summary of EV fleet parameters modeling parameters

Stage	EC_{road} (kWh/km)	N_{EV}	S_{EV} (MWh)	SOC_{sec} (%)	Eff (%)	N_{home}	P_{home} (kW)	D_{trav} (km)	$P_{min,peak}$ (MW)	$F_{min,backup}$ (MW)	$SOC_{min,V2G}$ (%)	$LCOE_{V2G}$ (€/MWh)
1	0.2	135	4.05	20	90	135	3.7	35/40	–	10	40	
2	0.2	473	14.55	20	90	473	3.7	35/40	–	10	40	108.75
3	0.2	1085	32.55	20	90	1085	3.7	35/40	35	10	40	108.75
4	0.2	2030	60.00	20	90	2030	3.7	35/40	30	10	40	108.75
5	0.2	3361	100.83	20	90	3361	3.7	35/40	28	10	40	108.75

EV is connected into the electrical grid. In this stage, the batteries could send energy to the electrical grid in order to cover falls ($E_{backup,t}$) when the renewable fall is over a reference value ($F_{min,backup}$). Furthermore, the EVs could inject energy into the system in peak hours ($E_{peak,t}$) only if the total demand is above a particular limit ($P_{min,peak}$).

Furthermore, the EVs, which are connected into the electrical grids, could recover renewable energy when the renewable source overwhelms the capacity of system. Anywise, the introduction of the EV produce an increment of the overall demand of electricity in the power system (D_t in (1) and (2)). On the scenario with energy management strategies (Scenarios 1B, 2B, 3 and 4) the over-night charging mode allows to increase the off-peak. The over-night charging mode is represented by a variable ($D_{EV,t}$). Reference [16] contains more details of the EV fleet characterization and the model simulator equation and restrictions.

Appendix B: PHES modeling

The inclusion in the simulator model means that we have to take into account 3 essential situations, such as the pumping of water, production through the turbine, and the storage situation in the upper tank. As it was described above in Section 3.1, two PHES will be installed. In order to simplify the model, both plants will be considered as one production technology, adjusting the parameters as much as possible to the projected situation.

The storage situation in the upper tank is the most important feature to be taken into account for the proper functioning of PHES. This capacity will vary for timestamp (1 hour), SC_t, and will depend on the amount of energy turbined P_{PHESt} (the tank loses capacity); and the energy pumped (this is added to the total storage capacity of the tank). Losses owing to leaks in the subsoil, evaporation processes or other consumptions have not been considered in this model.

For the pumping of water, the most important parameters taken into account are, the number of pumps considered N_{pump}, the power of each pump, P_{pump}, and the efficiency of the pumping process Eff_{pump}. The renewable energy surplus will set the conditions for pumping. Thus, it will be guaranteed that all of the energy produced by the hydroelectric plant comes from renewable energies. However, the energy surplus recovered is limited by the total pumping capacity P_{PHESt}. Besides, one restriction to be taken into account regarding pumping is the maximum capacity of the tank, SC_{max}. Therefore, pumping will be restricted when the maximum capacity of the tank is reached.

What is more, in order to consider the production of electric energy through the Pelton turbines, the following parameters will be taken into account. The number of turbines N_{turb}, and their power, P_{turb}. One of the major difficulties for the installation of this plant in the island of La Palma is the great distance from the upper reservoir to the station where the turbines are located. This will reduce the performance of the turbine process, Eff_{turb}. Finally, for the process of energy production, these 3 conditions must be fulfilled simultaneously: 1) Availability of stored water capacity. For this, we set a security limit of minimum storage capacity SC_{min}; 2) Amount of renewable injected at that moment into the system; 3) the production is subjected to the peak condition of the system, $P_{peak,turb}$. Table B1 summarizes all the parameters considered for the design of the PHES.

Table B1 Summary of PHES modeling parameters

Parameters	Value
SC_{max}	130.22 MWh
SC_{min}	25.5 MWh
N_{pump}	21
P_{pump}	0.75 MW
Eff_{pum}	0.84
N_{turb}	4
P_{turb}	5 MW
Eff_{turb}	0.82
$P_{peak,\ turb.}$	28 MW
$LCOE_{PHES}$ [20]	152 €/MWh

Appendix C: evolution of main variables

In this appendix we detail the evolution of the sustainability variables considered in the analysis throughout the period studied. First, Fig. C1 shows the share of renewables in the electric mix of the system.

Next, as backup variables, Fig. C2 shows spilled energy, measured as the renewable energy surplus above the total

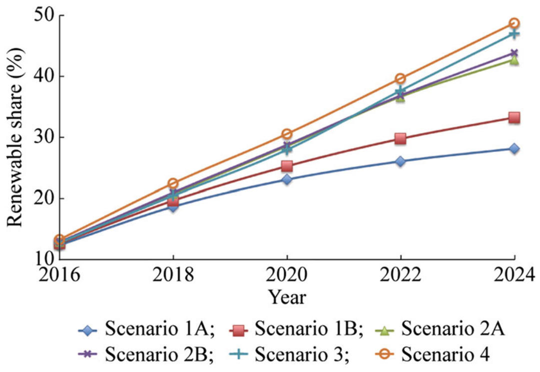

Fig. C1 Evolution of renewable share

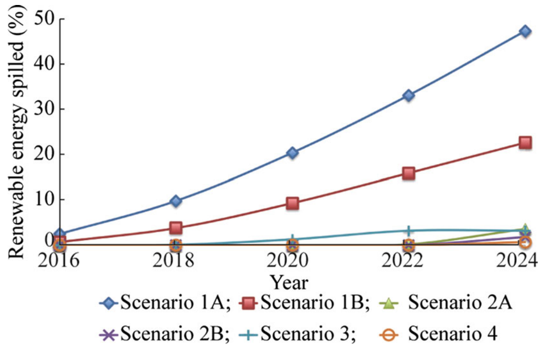

Fig. C2 Renewable energy spilled

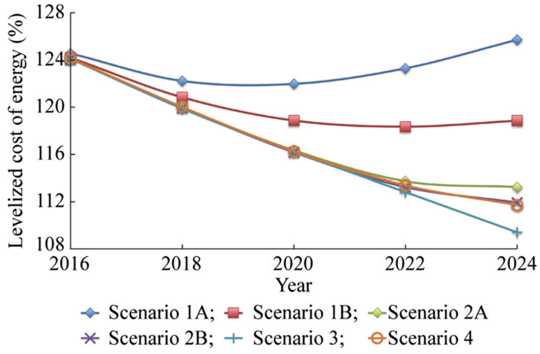

Fig. C3 Average LCOE of electricity mix

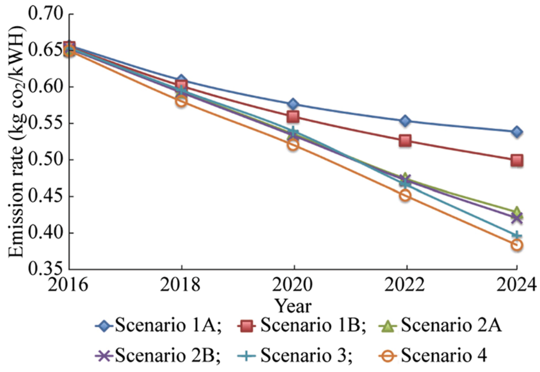

Fig. C4 Emission rate in electricity production

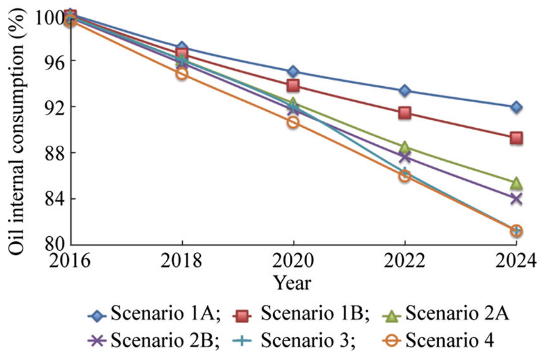

Fig. C5 Reduction in oil internal consumption

renewable, in percentage. Also, Fig. C3 shows the average generation costs of the electric system.

Figure C4 shows the ratio of the electric system's CO_2 emissions.

Finally, in Fig. C5 we observe the reduction in the domestic consumption of fossil fuels, measured in percentage of reduction over current starting point.

References

[1] Jensen TL (2000) Renewable energy on small islands, 2nd edn. Forum for Energy and Development (FED), Copenhagen
[2] Perez Y, Ramos-Real FJ (2008) How to make a European integrated market in small and isolated electricity systems? The case of Canary Islands. Energy Policy 36(11):4159–4167
[3] Szabó S, Kougias I, Moner-Girona M et al (2015) Sustianable energy portfolios for small island states. Sustainability 7(9): 12340–12358
[4] Anuario energético de Canarias (2013) Consejería de Empleo, Industria y Comercio, Gobierno de Canarias. http://www.gobcan.es/ceic/energia/galerias/ficheros/20141125-A-ENERGETICO-CANARIAS-2013.pdf. Accessed Nov 2014
[5] Politica Energética en Canarias, Horizonte (2030) Centro Atlántico de Pensamiento Estratégico (CAPTE). http://www.catpe.es/wp-content/uploads/downloads/2013/06/CATPE_Politica_Energetica.pdf. Accessed Jun 2013
[6] Rodrigues EMG, Godina R, Santos SF et al (2014) Energy storage systems supporting increased penetration of renewables in islanded systems. Energy 75:265–280
[7] Bueno C, Carta JA (2005) Technical-economic analysis of wind-powered pumped hydrostorage system, part II: model application to the island of El Hierro. Solar Energy 78(3):396–405
[8] Portero U, Velázquez S, Carta JA (2015) Sizing of a wind-hydro system using a reversible hydraulic facility with seawater: a case study in the Canary Islands. Energy Convers Manag 106:1251–1263
[9] Padrón S, Medina JF, Rodríguez A (2011) Analisys of a pumped storage system to increase the penetration level of renewable energy in isolated power system, Gran Canaria: a case study. Energy 36(12):6753–6762
[10] Martinez-Lucas G, Sarasúa JI, Sánchez-Fernández JÁ et al (2016) Frequency control support of a wind-solar isolated system by hydropower plant with long tail-race tunnel. Renew Energy 90:362–375
[11] Bessa RJ, Matos MA (2010) The role of an aggregator agent for EV in the electricity market. In: Proceedings of the 7th Mediterranean conference and exhibition on power generation, transmission, distribution and energy conversion (Med-Power'10), Agia Napa, 7–10 Nov 2010, 9 pp
[12] Marrero GA, Perez Y, Petit M et al (2015) Electric vehicle fleet contributions for isolated systems: the case of canary islands. Int J Automot Technol Manag 15(2):171–193
[13] Kempton W, Letendre S (1996) The V2G concept: a new for model power? Public Util Fortn 140(4):16–26
[14] Dietrich K, Latorre JM, Olmos L et al (2012) Demand response in an isolated system with high wind integration. IEEE Trans Power Syst 27(1):20–29
[15] Huang SK, Infield D (2010) The impact of domestic plug-in hybrid electric vehicles on power distribution system loads. In: Proceedings of the 2010 international conference on power system technology (POWERCON'10), Hangzhou, 24–28 Oct 2010, 7 pp

[16] Ramirez-Díaz A, Ramos-Real FJ, Marrero GA et al (2015) Impact of electric vehicles as distributed energy storage in isolated system: the case of Tenerife. Sustainability 7(11): 15152–15178

[17] Rious V, Perez Y (2014) Review of supporting scheme for island power system storage. Renew Sustain Energy Rev 29:754–765

[18] Camus C, Farias T (2012) The electric vehicles as a mean to reduce CO_2 emissions and energy cost in isolated regions: the São Miguel (Azores) case study. Energy Policy 43:153–165

[19] Taylor P, Bolton R, Stone D et al (2012) Pathways for energy storage in the UK: a report for the centre for low carbon futures. Yükseköğretim Dergisi 1(2):88–94

[20] Challenges and opportunities for new pumped storage development. National Hydropower Association's (NHA's) Pumped Storage Development Councill, Washington, DC

[21] Estudio para la implantación del vehículo electric en Canarias. Instituto Tecnológico de Canarias (ITC), Gobierno de Canarias. http://ve.renovae.org/files/Estudio_Implantacin_Vehculo_Elctrico_-_Noviembre_2013.pdf. Accessed Nov 2013

[22] Blyth PL (2011) Electric cars on the 100% renewable energy island of samsø. Master Thesis. Aalborg University, Aalborg

[23] Binding C, Gantenbein D, Jansen B, et al (2010) Electric vehicle fleet integration in the Danish EDISON project: a virutual power plant on the island of Bornholm. In: Proceedings of the 2010 IEEE Power & Energy Society general meeting, Minneapolis, MN, 25–29 Jul 2010, 8 pp

[24] Kempton W, Udo V, Huber K et al (2008) A test of vehicle-to-grid (V2G) for energy storage and frequency regulation in the PJM sytem. University of Delaware, Newark

[25] Dang XL, Petit M, Codani P (2015) Transformer operation conditions under introduction of PV and EVs in an eco-district. In: Proceedings of the 2015 IEEE Power & Energy Society general meeting, Denver, CO, 26–30 Jul 2015, 5 pp

[26] Marrero GA, Ramos-Real FJ, Perez Y, et al (2014) Willingness to pay for the electric vehicles and their attributes in Canary Islands. In: Proceedings of the 2nd Chaire Armand Peugeot international conference on electromobility: challenging issues, Paris, 18–19 Dec 2014

[27] Guenther C, Schott B, Hennings W et al (2013) Model-based ingestigation of electric vehicles battery aging by means of vehicle-to-grid scenario simulations. J Power Sources 239(10):604–610

[28] Aplicación demanda en tiempo real (La Palma) año 2016. REE (Red Eléctrica de España). https://demanda.ree.es/visionaCan/VisionaLaPalma.html

[29] Plan Energético de Canarias (PECAN) (2006) Consejería de Industria, Comercio y Nuevas Tecnologías, Dirección General de Industria y Energía. http://www.gobcan.es/ceic/energia/doc/planificacion/pecan/DOCUMENTO_REVISION_PECAN2006.pdf

[30] Sistema Eléctrico Español: Avance (2015) REE (Red Electrica de España). http://www.ree.es/sites/default/files/downloadable/avance_informe_sistema_electrico_2015_v2.pdf

[31] Planificación Energética Plan de Desarrollo de la Red de Transporte de Energía Eléctrica 2015–2020. Ministerio de Industria, Turismo y Comercio. Gobierno de España. https://www.boe.es/boe/dias/2015/10/23/pdfs/BOE-A-2015-11398.pdf

[32] Open Energy Information (OpenEI). http://en.openei.org/apps/TCDB/levelized_cost_calculations.html#lcoe. Accessed 24 Jun 2016

[33] Boletín Oficial del Estado (BOE), Núm 183, Sábado 1 de agosto de 2015. https://www.boe.es/boe/dias/2015/08/01/pdfs/BOE-A-2015-8646.pdf

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