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ELECTROMOBILITY AS ENHANCER OF RENEWABLE SHARE IN ELECTRIC POWER SYSTEM FOR ISOLATED REGIONS: THE CASE OF CANARY ISLANDS

(La electromovilidad como potenciador de la cuota de renovables en sistemas eléctricos en regiones aisladas: El caso de las Islas Canarias)

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ABSTRACT

This doctoral thesis is divided into three chapters. These are linked to a single common axis, which is the impact of the electromobility in islanded regions, exploring two different approaches: Supply and demand side. Chapter 1 and 2 address the supply side, focusing on the role of the electric vehicles as energy storage system in isolated regions. These two chapters have been published in two international journals, included in the *Journal of Citation Reports*. Chapter 1 was published in *Sustainability Journal* in 2015; and chapter 2, in *Modern Power System and Clean Energy Journal* in 2016. Chapter 3 addresses the demand side, deepening in aspects that define the potential buyer of the electric vehicle. This chapter has been submitted to *Renewable and Sustainable Energy Reviews Journal* and its current state is revised and resubmitted.

Chapter 1. *Impact of Electric Vehicle as Distributed Energy Storage in Isolated Systems: The case of Tenerife.*

Isolated regions are highly dependent on fossil fuels. The use of endogenous sources and the improvement in energy efficiency in all consumption activities are the two main methods to reduce the dependence on petroleum-derived fuels. Tenerife offers excellent renewable resources (extensive long periods of sun and wind). However, the massive development of these technologies could cause important operational problems within the electric power grids, because of the small size of its system. In this chapter, it is explored the option of coupling an electric vehicle fleet as a distributed energy storage system to boost the share of renewable energies in an isolated power system, i.e., Tenerife island. A model simulator has been used to evaluate five key outputs under alternative scenarios, which are: the renewable share, the energy spilled, the CO2 emissions, the levelised cost of generating electricity, and fuel dependence. A total amount of 30 different scenarios have been evaluated in comparison with the current situation, combining a gradual renewable installed capacity and the introduction of an electric vehicle fleet using alternative charging strategies. Results show that the impact of 50,000 electric vehicles would increase the renewable share in the electricity mix of the island up to 30%, reduce CO2 emissions by 27%, the total cost of electric generation by 6% and the oil internal demand by 16%.

Chapter 2. *Complementarity of electric vehicles and pumped-hydro as energy storage in small isolated energy systems: case of La Palma, Canary Islands*.

In this chapter, we analyse a different island in the Canary Islands, which shows different characteristics than Tenerife. The island of La Palma is located on the northwest of the Canary Islands, and its electric system is fairly 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 chapter is to analyse the effects of the introduction of two possible alternatives as a form 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 and the existence of a pumped-hydro energy storage system. Results show that, in the best-case 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 lead to a 26% reduction in CO2 emissions, a 10% in costs of generated kWh and a 19% in energy dependence.

Chapter 3. *Willingness to pay for electric vehicles in island regions: the case of Tenerife, Canary Islands*.

Electric vehicles could be a sustainable solution to reduce final energy consumption and carbon emissions in the road transport sector. Moreover, mobility characteristics of drivers (i.e., the average driving distance) fit better with current electric vehicle technical features on a small island than in mainland. In this chapter, the penetration of electric vehicles in Tenerife (Canary Islands) is analysed, which is still quite low. Based on data collected through a face-to-face contingent valuation method, the *willingness to change* and the *willingness to pay* for an electric vehicle on the island are estimated, which are key factor to understand the potentiality of electric vehicle penetration. In order to provide an appropriate profile of a potential electric car buyer, in the second part of the chapter we analyse the impact of a set of explanatory variables on both *willingness to change* and *willingness to pay*. It has been found that providing information about basic properties of an electric cars and environmental concerns are key factors for *willingness to change*, while income level, mobility patterns, environmental concerns and technological attitude of individuals are found to be important factors to determine *willingness to pay*.

RESUMEN

La presente tesis doctoral está dividida en tres capítulos. La temática que los une es el estudio del impacto de la electromovilidad en regiones aisladas, profundizando a través de dos aproximaciones diferenciadas: la oferta y la demanda. Por un lado, los capítulos 1 y 2 abordan el lado de la oferta, centrándose en el papel que adquieren los vehículos eléctricos funcionando como almacenamiento energético en estas regiones. Ambos han sido publicados en revistas internacionales indexadas por el *Journal of Citation Reports*. El capítulo 1 ha sido publicado en *Sustainability Journal* en el año 2014, mientras que el capítulo 2 ha sido publicado en *Journal of Modern Power Systems and Clean Energy* en 2016. Por otro lado, el capítulo 3 aborda la parte de la demanda, adentrándose en los aspectos que definen al posible comprador del vehículo eléctrico. Actualmente, este último capítulo se encuentra en proceso de revisión en *Renewable and Sustainable Energy Reviews Journal*.

Capitulo 1. *Impacto de los vehículos eléctricos como almacenamiento energético distribuido en sistemas aislados: el caso de Tenerife*.

Las regiones aisladas son altamente dependientes de los combustibles fósiles para su desarrollo. El uso de fuentes de energía endógenas y las mejoras en eficiencia energética en cualquiera de las actividades de consumo son los dos ejes principales para reducir la dependencia de los combustibles derivados del petróleo. Tenerife alberga excelentes recursos renovables –numerosas horas (anuales) de sol y viento–. Sin embargo, el desarrollo masivo de estas tecnologías puede causar importantes problemas en la operación de las redes eléctricas, debido principalmente al pequeño tamaño de los sistemas eléctricos. En este capítulo, se exploran diferentes opciones de acoplamiento de una flota de vehículos eléctricos como almacenamiento para incrementar la participación de las energías renovables en estos sistemas en particular, p.e., en Tenerife. Se ha ejecutado un modelo de simulación del sistema en diferentes escenarios que miden cinco aspectos fundamentales como son: el *share* de renovables, la energía derramada, las emisiones de CO_2, el coste medio de la energía eléctrica y la dependencia energética. Un total de 30 escenarios han sido evaluados teniendo la situación actual como punto de referencia y combinando una penetración gradual de las energías renovables y la introducción del vehículo eléctrico bajo diferentes estrategias de recarga. Los resultados muestran que el impacto de 50.000 vehículos eléctricos incrementarían las energías renovables hasta el 30%, reducirían las emisiones de CO_2 en un 27%, los costes en generación un 6% y la dependencia energética hasta en un 16%.

Capítulo 2. *Compatibilidad del vehículo eléctrico y de los sistemas de almacenamiento por bombeo en sistemas aislados de pequeño tamaño: El caso de La Palma. Islas Canarias*.

En este capitulo, se analiza otro sistema aislado de las Islas Canarias que tiene unas características diferentes con respecto a Tenerife. La isla de La Palma está situada en el noroeste

de Canarias, y su sistema eléctrico es bastante pequeño en relación con el de otras islas. Las políticas de sostenibilidad planteadas por las autoridades locales se centran en incrementar la cuota de penetración de las renovables, reduciendo así el consumo de fuentes fósiles. Sin embargo, la intermitencia y la concentración de las renovables en unas pocas localizaciones pueden amenazar la operación del sistema eléctrico. Con el fin de resolver estos problemas, los almacenamientos energéticos juegan un papel fundamental. El objetivo de este capítulo es analizar el efecto de la introducción de dos posibles alternativas de almacenamiento: el hidro-bombeo y los vehículos eléctricos. Para ello, aplicamos un modelo de simulación adaptado a las características de La Palma, considerando múltiples escenarios posibles. Para el caso del escenario más favorable, si se incluye una instalación de 25MW renovables (más del doble de la que dispone actualmente), apoyada por 20MW de hidro-bombeo y una flota de 3.361 vehículos eléctricos, esto permitiría incrementar la cuota renovable desde el 11% actual hasta el 49%. Además, se contribuiría a una reducción del 26% de las emisiones de CO_2, a un 10% de los costes y a un 19% de la dependencia energética de la isla.

Capítulo 3. *Disposición a pagar por los vehículos eléctricos en regiones aisladas: el caso de Tenerife, Islas Canarias*.

Los vehículos eléctricos podrían ser una solución para la reducción del consumo en energía final y las emisiones de carbono en el sector del transporte terrestre. Las rutinas de movilidad (p.e. la distancia recorrida) por su parte, encajan mejor con las características técnicas del vehículo eléctrico en islas pequeñas que en regiones continentales. En este capítulo, se analiza la penetración del vehículo eléctrico en Tenerife (Islas Canarias). Basándonos en datos recogidos a través de encuestas cara a cara y siguiendo una metodología de valoración contingente, estimamos la disposición al cambio y la disposición al pago por el vehículo eléctrico, que resulta clave para entender la potencial penetración del vehículo eléctrico en la isla. En la segunda parte del estudio, se caracteriza al potencial comprador analizando el impacto de las variables explicativas tanto para la disposición al cambio como para su disposición al pago. Como resultados principales podemos determinar que el proveer de información acerca de las propiedades básicas del coche eléctrico y la preocupación medioambiental de los individuos son factores clave que influyen en su disposición a pagar. Mientras que los ingresos, las rutinas de movilidad, la preocupación medioambiental y la actitud frente a la tecnología son los factores determinantes en la disposición al pago por el vehículo eléctrico.

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INTRODUCTION

Climate change is one of the biggest challenges facing the world today (WEF, 2017). The overwhelming majority of countries have adopted the Paris Agreement at COP21 (Paris, 2015), in order to address climate change. All signatories countries undertook the challenge to limit global temperature rise to well below 2 degrees Celsius, and given the grave risk involved, to strive for 1.5 degrees Celsius. The European Union (EU) leads efforts in the clean energy transition through The Winter Package 2016, in which EU has committed to cut down CO_2 emissions by at least 40% by 2030. This changeover pursues improvements in energy efficiency, leadership in renewable energies and the protection of the European consumer.

Small islands around the world are highly reliant on fossil fuels for their economic development. This unsustainable situation implies high vulnerability to energy shocks that could jeopardize the functioning of their market economies. The Canary Islands clearly exemplify one of these regions. Geographically, this archipelago is located 100 kilometers northwest from the African coast and nearly 1,500 kilometers from the European mainland. It is comprised of seven islands, of which Tenerife is the largest one and El Hierro is the smallest one. From a political point of view, this region is one of the 17 Spanish autonomous communities, and the most populated outermost region of the EU. Its population exceeds 2 million inhabitants and 16 million visitors per year.

Energy dependence is one of the most important challenges faced by the region. According to the last data available from the Canary Islands energy statistics a 98.9% of their primary energy sources come from oil-derivative fuels in 2016. Despite of the fact that this region has an enormous potential for using renewable sources of energy (long hours of sunlight each year, and ocean, wind and geothermal power), the renewable share in the electricity mix stands at approximately 8% a year. One of the major reasons that explain this is the inherent constrains in introducing renewable energy sources in small isolated electric power systems due to technical curtailments. In order to overcome these barriers and to increase largely the renewable share, several measures could be introduced: (i) interconnect islanded systems; (ii) improvements in renewable forecasting (iii) implementation of demand response strategies; (iv) and the introduction of a massive energy storage. However, these solutions are in a pioneer stage of development in the islands, such is the case of El Hierro island, in which a pumped-hydro storage combined with wind turbines produce nearly 60% of its electricity from renewable sources.

Nevertheless, according to the (most recent) energy statistics from Canary Islands (*Gobierno de Canarias,* 2016), the electricity production just represents a 20% of the final energy consumption in the Canaries. Thus, there is an 80% of energy consumption that cannot improve by merely for introducing renewables into the electric system. The largest final consumption sector is the road transport, representing around 34% of the energy consumption. Presently, there exists technology that could replace traditional fuels (gasoline and diesel) used by Internal Combustion Engine Vehicles (ICEVs) by alternatives fossil fuels, such as liquefied petroleum gas (LPG) vehicles or Compressed Natural Gas (CNG) vehicles. Another important innovation is the Hybrid Electric Vehicles (HEVs) technology, which improves the mileage considerably and reduces tailpipe emissions from vehicles. Nonetheless, the greatest change would be the transition to the Electric Vehicles (EVs) –Plug-in Hybrid Electric Vehicles and Battery Electric Vehicles (BEVs)–, that would replace fuel consumption in the road transport sector by consumption within the electricity sector, in which it would be powered by renewable sources.

From the supply perspective, focusing upon the EVs, differs widely in comparison to ICEVs, from the battery energy storage to the energy vector used. In terms of technical features, the electric power train is much more efficient, delivering an excellent acceleration without any noise or direct pollutants emissions. Furthermore, the large-capacity battery of these vehicles has the potential to serve as electricity storage, providing several benefits to the grids. In a first stage, the EVs could work as demand response agent in the electric system, allowing smart charging when there were surplus renewable energy productions. What is more, moving further in the research, the EV could also serve as an energy storage system. In the short-term period, the frequency or the voltage of grids would be regulated. In long-term period, the EV could discharge electricity to the power system in peak hours or support renewables intermittencies.

From the demand perspective, the road transport sector in the Canary Islands is entirely shaped by individual private transport – to the detriment of public transport– and it is also dominated by ICEVs. The vehicle per inhabitant ratio in the Canaries is one of the highest in the EU, which reaches 604 vehicles per thousand inhabitants approximately (DGT, 2017). In terms of market share, the EV only represents the 0.37% of the total sales in the Canaries in 2017, gathering 606 electric vehicles out of a total of 1,274,413 cars. Apart from reducing the ratio vehicle/inhabitant, it is necessary that the authorities promote the purchase of EV technology given the evidence of the environmental benefits related to its utilisation. Identification of early adopters is key to propose measures, which facilitate access and usage of this market innovation.

The aim of this research is to investigate the interaction between EVs and the electric power system, and also the adoption of the technology from the consumer's side in an European isolated region (the Canary Islands). This doctoral thesis is carried out having this purpose as a goal and within the framework describe above, using two analytical perspectives: the supply-side and the demand-side perspectives.

The supply-side perspective (chapter 1 and 2) provides a technical approach of how the EVs could interact within the electrical grids, not only enhancing the renewable share, but also providing ancillary services as energy storage.

Both chapters use a model simulator of the electric power system. In the first chapter this model is developed extensively. It consists of simulating the operation of the electric system every 10 minutes during a reference year. Each step is subject to a certain electricity demand, wind and photovoltaic power generation given by the scenario conditions (depending on the renewable installed capacity or the demand growth ratio). Then, the model simulator balance the electricity production with the demand, for which the conventional plants should adapt depending on the renewable energy production and the security operational conditions of the system. However, under high renewable conditions, the production of green electricity could exceed the demand of electricity, forcing the system operator to partially cut off this production to maintain the security of supply. This renewable energy spilled could be harnessed if there were demand response devices in the system, such us an EV fleet performing grid-for-vehicles (G4V) services. These vehicles also could charge at night to flattening the demand of the island increasing the total wind production in the system. A further stage implemented in the model simulator allows the EV to work as distributed energy storage, through vehicle-to-grid (V2G). This system not only delivers electricity as backup for intermittencies of renewable energies, but also contributes to reduce the peak power of the system.

Using the Tenerife island as case of study a set of future scenarios of renewable energies are deployed. These are based on the Canary Islands energy plan (PECAN, 2015) of which all goals have not yet been fully achieved. A total of 30 alternative scenarios have been proposed where the amount of installed renewable capacity grows gradually in six steps starting from the current situation. In addition, different EV fleets are also introduced in the system following G4V, V2G, or a combination of both. These scenarios have been designed in order to capture the effect of renewable energy introduction and the impact of the raise of EV fleet depending on which management strategy is used.

This first chapter provides a case study based on impact simulations of the managed EV fleet on isolated electric power system. Besides, it is essential to evaluate the interaction between the renewable energies and the EV in terms of renewable share, energy spilled, emission reduction, electricity cost and energy dependence of the island. The outcomes obtained are fully exportable to other isolated systems with similar characteristics to the case presented in the present work. The main conclusion from this chapter contributes to two major issues: (i) the electrical system and (ii) in road transport. The positive effect allows larger penetration of renewable energies in the system, reducing the energy spilled by overproduction. In fact, the electricity cost, the emissions and the energy dependence are reduced considerably. The management strategy is also important, although V2G enhance the effects of renewable share, it have the disadvantage of accelerate the aging of the battery.

Chapter 2 is an extension of applications that could be implemented in the Canary Islands, such as the pumped-hydro energy storage. In this chapter, the effects of uncontrolled charge in the isolated electric power systems are also evaluated. Both issues should be analyzed in order to obtain a global vision of the possible alternatives and their complementarity in the islanded electrical systems.

In this second chapter, the model simulator is improved, including the pumped-hydro energy storage extension and the uncontrolled charging situation on the vehicle fleet. In this case the region in which the experiment takes place is the island of La Palma that is the unique island that cannot be linked by submarine cable to another systems, besides of El Hierro. Following a similar process that chapters 1, a set of scenarios are modeled, varying the renewable capacity installed, the charging management strategy (uncontrolled, G4V and V2G) and also the inclusion of pumped-hydro energy storage.

As major insights, we could highlight that the use of storages allows accomplishing the sustainability goals, reducing also the cost of the system. The inclusion of both energy storage systems (pumped-hydro and V2G) could improve the renewable share up to 49% in the scenarios planned. The uncontrolled charge could damage the system, overloading the peak hours, where the most expensive and pollute conventional power plants are running. However, the introduction of the PHES could mitigate this effect, replacing the conventional peak generation by energy stored from renewable sources.

Demand-side perspective is addressed in Chapter 3. Once technical experiments have been tested in previous chapters, it is important to question whether the consumers are ready to adopt this innovation and changes brought by the EVs in the Canary Islands. Chapter 3 performs an evaluation about the attitude of the private car users towards the EV in island regions. These regions are clearly strategically to implement EVs due to the territorial limitation that cutover the range anxiety suffered by drivers. First 250 surveys are collected from car drivers, in which a contingent valuation experiment about willingness to pay has been performed. Besides, it also gathers information about mobility routines, socio-economic and technological and environmental concern issues. Thus, this chapter attempts to evaluate a potential EV market based on the current prices of the cars and the WTP disclosed by the car users in the survey. In addition, an initial assessment of the EV adopter profile is performed. To carry out the evaluation, a first model explores the probability to change to a EV after and before provide information to the surveyed of a set of explanatory variables. Secondly, a multiple regression model assesses the determinants of the willingness to pay for the EVs to understand which and how is the impact of the explanatory variables.

The contribution of this chapter goes deeper into the characteristics of the possible EV buyer, emphasizing the role of the possible early adopter and the attributes which defines it. According to the WTP and market prices, we could approach a potential market in terms of sales in the Canary Islands. Furthermore, the results could contribute on the characterisation of the potential adopter that could facilitate focus the efforts on marketing and policies to boost proper campaigns and measures.

The key insights are that there is a potential market in the Canary Islands with a share of 3.7% approximately. But this gap between real sales and the estimation is due to the lack of information and campaigns, and the shortages of variety by the automakers. The possible early adopter meets with the current EVs market prices and their characteristics are the following: (i) environmental awareness, (ii) predisposition to technological innovations (iv) high socioeconomic status, (v) mobility characteristics that fits with range limitations of the car.

In summary, this doctoral thesis aims to evaluate the effects that EV could produce in the island both in terms of renewable introduction and of impacts on the energy dependence and on the consumer attitude, in the context of insular systems. As is discussed in the following chapters and general conclusions, this thesis make a starting framework and also stimulate the quest to solve unresolved questions that will be addressed on further research on this topic.

Chapter 1.

Impact of electric vehicle as distributed energy storage in isolated systems: the case of Tenerife

1.1 Introduction

Most of the island regions in the world are extremely dependent on fossil natural energy resources for their socio-economic development (Jensen, 2000; Perez & Ramos Real, 2008). The Canary Islands are not an exception, and their energy dependence is almost absolute, with petroleum-derived fuels representing almost 98.9% of the total primary energy use in 2013 (Dornan, 2015; Gobierno de Canarias, 2013; IRENA, 2014; Weisser, 2004). Part of the blame for this situation lies with their power generation system, which relies almost completely on the use of fossil fuels (Elahee, 2011; IRENA, 2012; Red Eléctrica de España, 2013; Szabó, Kougias, Moner-Girona, & Bódis, 2015): 7.3% of the electric generation comes only from renewable sources (4.1% wind power, 3.2% photovoltaic, 0.1% thermal and 0.03% small-hydro), and the rest of the mix is covered by oil power plants (combined cycle power plants, 34.7%; steam turbines, 29.6%; internal combustion engines, 24.0%; and gas turbines, 4.2%) (Gobierno de Canarias, 2013). Their distance to the Spanish coast (about 2000 km) and the fact that the archipelago is composed of seven islands (off the Moroccan coast) with six differently-sized isolated systems, limit the penetration of renewables and the inclusion of other more traditional sources, such as coal or nuclear.

In addition, the electric generating cost of using fossil fuel plants on the Canaries is higher than for the Spanish continental power system. This additional cost implies that producing electricity on the islands with renewables would be less expensive than producing electricity with fossil fuels (E-SIOS. Red Eléctrica de España, 2015; G. A. Marrero, Perez, Petit, & Ramos-Real, 2015; G. a. Marrero & Ramos-Real, 2010; F. J. Ramos-Real, Moreno-Piquero, & Ramos-Henríquez, 2007): about 47% less expensive for wind; and recently, the cost for the solar photovoltaic (PV) power has reached parity with fossil fuels (Guerrero-Lemus Ricardo, González-Díaz, Ríos, & Dib, 2015). Moreover, renewables are clearly less polluting in terms of carbon emissions. Thus, a challenging issue on the Canaries would be to increase the penetration of renewables in the generation of electricity, which would reduce not only the energy dependence, but also the cost of generating electricity and carbon emissions. However, introducing unpredictable energy sources (such as photovoltaic and wind) could generate important operational problems for the grid, especially in isolated systems, such as for islands. One possible solution to reduce these problems is to generate energy storage systems that would drastically reduce the intermittency problems of renewables and facilitate their penetration into the electricity system (Rious & Perez, 2014). In this chapter, we explore the option of coupling an electric vehicle (EV) fleet as a distributed energy storage system in order to increase the participation of renewables. This alternative is especially appealing in isolated systems due to the difficulty of integrating a large renewable capacity into such vulnerable systems.

In order to analyse the introduction of renewable energy sources (RES), we use a model simulator of the electric power system for Tenerife in 2013. The baseline setting depends on the observed operation data from the power system operator, as well as the electric demand and the wind and solar time series for 2013 on Tenerife. This scenario uses real-time operation data from the Tenerife electrical system in 2013 and reflects the current situation on the island. Data are taken every 10 min, for all technologies used on the island (combined cycle, steam turbine, gas turbine, diesel engines, wind power and solar photovoltaic) and from the transmission system operator (Red Eléctrica de España, 2013). Next, we use the model simulator under alternative levels of installed power capacity of renewables. The model has been designed for the special situation of an island power system. It includes restrictions on the minimum operation range, the amount of reserves required and the maximum installed capacity, for the conventional units. Thus, this model allows us to evaluate and compare different scenarios (with and without energy stored systems) in a short compilation time. The installed capacity of renewables goes from the 2013 levels of 37 MW for wind and 114 MW for PV up to the 402 MW for wind and 151.2 MW for PV targeted in the government energy strategy (2006–2015), PECAN (*Plan Energético de Canarias*) (Consejería de Industria, 2006). The Canaries (and Tenerife in particular) are nowadays far away from that target. The following set of outputs are obtained from the simulation (all are average for a year): share of renewables, cost of generating electricity, CO2 emissions, energy spilled and fossil fuel saved (in electricity and in road transport). In the second stage, these simulations are repeated for alternative energy storage systems, considering a vehicle-to-grid storage system and assuming different amounts of EV as part of the vehicle fleet on the island.

The comparison of the results under these alternative scenarios allows us to analyse the consequences of introducing energy storage systems in the penetration of renewables, as well as to evaluate their effects in terms of electricity generating cost and carbon emissions. For example, results show that the impact of 50,000 EVs in the Tenerife electrical power system, which is an average amount targeted by local authorities for the medium term for the island in 2024, could achieve an introduction of renewables of up to 29.6% in the electricity mix of the island (greater than the PECAN target), and at the same time, it would help to reduce CO2 emissions by 27% and the total cost of electric generation by 6%.

The rest of the chapter is structured as follows. Section 1.2 shows a brief background about the concept of vehicle-to-grid (V2G) and the energy storage systems in island regions. Section 1.3 describes the situation of the Tenerife electric power system; followed by the methodology of the model simulation and a summary of the alternative scenarios considered in our analysis. Section 1.4 shows the results of the alternative scenarios in terms of RES share, energy spilled, carbon emissions and cost and oil internal market. Finally, Section 1.5 is devoted to summarizing the main conclusions and extensions of the work.

1.2 Vehicle to grid and energy storage in isolated systems

Letendre & Kempton (1996) are some of the pioneers in the study of V2G systems. They analyse the concepts about the interaction between EVs and the electric power grid. These authors emphasize that EVs could provide additional advantages to the electric system operation, such as frequency regulation, backup supply and peak-hour savings. The EVs could help the system in the frequency regulation and demand response, first with the flexibility of loads, disconnecting the EVs instantaneously. In the first reaction, the EVs could contribute by helping the system in the primary frequency regulation and, seconds later, as a secondary reserve support. Sometimes, when the RES production falls unexpectedly, the EVs could help with sending energy into the electrical grids as a fast backup supplier. Finally, when we have a large EV fleet, we can inject energy into the system in peak hours to reduce the peak power and to reduce the contribution of gas turbines, which are more expensive and inefficient (Dietrich et al., 2012). Meanwhile, Kempton & Tomić (2005) show the contribution of EVs using a V2G strategy to participate in three different electric markets, the said peak power market, a spinning reserves market and a frequency regulation market. Applied to the U.S., they conclude that injecting energy from V2G in peaks is not competitive; however, using EVs as ancillary services could be profitable for the EV user.

The role of EVs as an energy storage mechanism has been widely explored by multiple researchers during the last five years. Turton & Moura (2008) detail the potential of V2G systems over the long term (2100) using energy system modelling. Additionally, they debate the paradigm shift in how the energy and mobility markets are related. Farhoodnea et al., (2013) analyse the impact of the high-penetration of EVs combined with renewable energy based on the distribution system. They create a model simulator, the results of which show that the presence of massive EV fleet introduction and distributed renewables could cause severe problems, such as frequency and voltage fluctuations, voltage drop, harmonic distortion and power factor reduction. However, Dang et al,. (2015) evaluate the impact of photovoltaic power introduction and electric vehicles in the operation of the power transformer within an eco-district. They assume the interaction of an energy management system operator with V2G capabilities. The results show that EVs and photovoltaic power have an important impact on the overloading periods, however mitigating the energy flows and peak power with the operation of the management system. Haidar et al., (2014) assess the impact of the grid-integrated vehicles on future smart grids. Their results show that the EV penetration in the grids could reduce the cost of energy to charge. A general conclusion from this recent literature is that EVs could supply energy storage services to the grids, including smart grids. Nowadays, there are some experiments around the world testing the technical feasibility of this interaction (the VtoG project in Delaware, the Nikolai Project in Denmark, Jeju Island in Korea, the U.S. army in California, etc.).

From a technical point of view, the islanded power system is more tightly dimensioned and, therefore, less able to respond to shocks (the loss of a group has a greater impact on the network than in a continental grid); second, the voltage drops have a significant effect in the grids; third, the balance of the system (between the production and demand) is much more difficult to achieve, requiring more reserves to secure the operation of the system; and finally, each isolated system is different from the other ones and depends to a large degree on the weather, the population and the economic activity developed in the region. In this sense, isolated regions have specific characteristics, as emphasized by Rious & Perez (2014). These authors analyse the Island of Reunion and estimate that the level of penetration of unmanaged RES (i.e., PV or wind energy) must be below 30% in order to maintain the security balance between production and demand. They propose alternative energy storage systems in order to increase the level of penetration of renewables, proposing the use of batteries as an appropriate solution to achieve this target in the short run for the island. Following this line of inquiry, Rodrigues et al., (2014) conclude that introducing large-scale energy storage systems could help to increase the penetration of renewables in the electric generation mix.

Other works analyse the role of EVs as a distributed energy storage system in isolated regions. One exception is Camus & Farias (2012), which studies the island of Sao Miguel in the Azores archipelago and combines the introduction of geothermal power plants and wind power supplies with a grid for vehicle (G4V) management system. In the most favourable scenario (5900 EVs, 30% of additional geothermal and 10 MW of wind power), the paper concludes that 52 million Euros can be saved, and this could allow an introduction of 64% of RES on weekdays and 70% on weekends. Another exception is Blyth (2011), which analyses Samsoe Island (Denmark). They reach 100% renewable electricity production, and so, the EV could be considered as a well-to-wheels zero emissions vehicle, reducing fossil fuel use and oil imports drastically on the island. Finally, McCarville (2009) analyses the situation of Prince Eduard Island, which assumes a total of 18,726 EVs by 2030. They expect an annual CO2 emissions reduction of around 115,000 tonnes by that date. A general conclusion from all of these works shows the capacity of EVs to integrate larger amounts of unmanaged RES into isolated power systems.

For the Canary Islands, there are few works that analyse the impact of alternative energy storage systems. Bueno & Carta (2006) focus on the introduction of pumping hydro stations as energy storage systems on El Hierro and Gran Canaria. They use two reservoirs with a difference in height between both of 281 m and a capacity of 5,000,000 m3 used in each. The system includes a 20.4-MW wind power plant, and according to this plant, they propose a 17.8-MW flexible pumping station and a 60-MW hydroelectric power plant. This solution increases by 1.93% the penetration of unmanaged RES on the islands. Marrero et al., (2015) analyse the introduction of an EV fleet as energy storage in order to evaluate the impact on the electric efficient frontier of the islands. Following a mean-variance portfolio theory, the authors estimate different electric efficient frontiers under alternative scenarios, with and without EVs as a storage system. They conclude that EVs can reduce the use of fossil fuel technologies and increase the maximum feasible share of wind, thus reducing carbon emissions and the electricity generating cost.

Our work attempts to contribute to this recent literature, which combines the energy storage capacity of EVs with the degree of penetration of renewables and with the peculiarities of isolated systems, such as the Canary Islands.

1.3 The electric power system on Tenerife: description and model simulator

In this section, we first show the basic characteristics of the electric system on Tenerife, and secondly, we present the simulation model used for the electric power system on Tenerife. Regarding the observed data from 2013, two variations will be analysed mainly. The first one assumes gradual increases of the renewable installed capacity; the second takes into consideration an energy storage system through the use of a fleet of EVs.

1.3.1 Tenerife electric power system

The Canary Islands archipelago is composed of six-isolated electric systems in which Gran Canaria and Tenerife are the largest in terms of power installed and electricity demand. Figure 1.1 shows the main characteristics of the different systems on the Canary Islands during 2013 (Gobierno de Canarias, 2013). The islands of Tenerife and Gran Canaria are the two largest isolated systems with a similar maximum demand of around 540 MW. Lanzarote and Fuerteventura represent one electric system (they are connected by an underwater cable), which is medium sized (around 240 MW of maximum power); the rest of the islands have small electric systems (less than 45 MW of maximum demand). All of the conventional power plants use fuel oil, gas oil and diesel oil. Thus, the Canary Islands systems are highly polluting, with overruns, and are also highly inefficient (Perez & Ramos Real, 2008). The two biggest systems have installed combined cycle power plants and steam turbines in order to build the base load of the power production, while the rest of the islands use diesel engines to cover the majority of the electricity demand and offer more flexibility to the demand response.

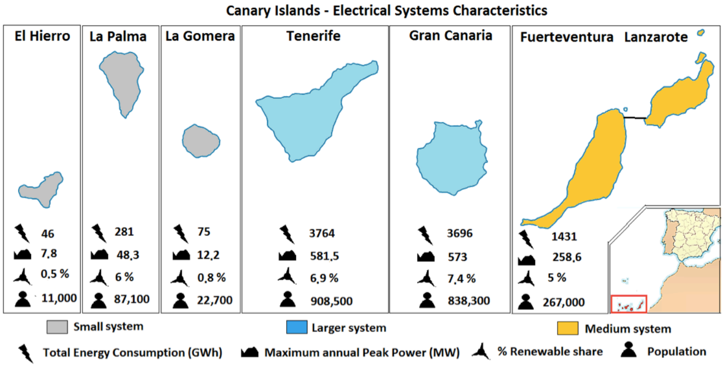

Figure 1.1: Main data for the Canary Islands electric power system in 2013

There is neither a wholesale nor a secondary market of electricity generation with hourly biddings on the Canary Islands. Thus, the price of electricity is not determined by a market mechanism. Instead, there exists an “order of merit” for each power plant, giving priority to the generation of renewables (wind and PV for the case of the Canaries). This merit order dispatch [Order ITC/913/2006 (Ministerio de Industria Turismo y Comercio. & España, 2006)] is managed by the Transmission System Operator (TSO) which is *Red Eléctrica de España* (REE). The Order is mainly based on a set of electricity generation variable costs published by REE. They only publishes the average cost per hour in the Canary Islands system, but a detailed analysis by technologies is missing, which the comprehension of the entire process difficult. Given these variable costs, companies participating in the production of electricity are remunerated through a particular system, which is supported by the Spanish regulation. On the one hand, fossil fuel (ordinary regimen) technologies are compensated for their higher costs compared to the mainland. The compensation depends on the difference between the declared cost and the average annual price of the Spanish continental region. On the other hand, renewable energies and co-generation (special regime) technologies are remunerated through a feed-in tariff (FIT) device. See for a more detailed discussion about this issue in (Ministerio de Industria Comercio y Turismo. Gobierno de España, 2010; Ministerio de Industria Turismo y Comercio. Gobierno de España, 2006).

We take Tenerife as our case study; first, because it is the biggest island and the one that consumes the most energy on the Canary Islands; second, the system includes all of the possible conventional technologies used in the archipelago; third, we can use data from the travel routines of drivers to calibrate the equations of EVs as energy storage systems (F. Ramos-Real, Ramírez-Díaz, Díaz, & Perez, 2018). The system on Tenerife is characterized by having two conventional power plants. The first is located in the municipality of Granadilla de Abona, in the south of the island. It has a total installed capacity of 774 MW, including two blocks of combined cycles, which are composed of two gas turbines and one steam turbine. Additionally, we have the Candelaria power plant, which is an old conventional power plant. It is roughly composed of two stream turbines, three diesel engines and six gas turbines. Table 1.1 shows the most important technical characteristics of the installed power capacity on Tenerife.

Table 1.1. Summary of the characteristics of the power plants installed on Tenerife in 2013.

Technology	**No.**	**Power per Unit**	**Total Power**	**Minimum Operation Range**	**LCOE**	**Type of Fuel Used**	**Emissions Rate**
		MW	MW	MW	€/MWh	-	$KgCO_2$/MWh
Combined Cycle	2	220	440	110	169	Gas Oil	650–700
Steam Turbine	3	80	240	45	165	Fuel Oil	850–900
Gas Turbine	6	35	210	8	320	Gas Oil	1200–1250
Diesel Engines	3	24	72	12	130	Fuel Oil	750–800
Wind Power	-	-	37	-	72	-	-
Photovoltaic	-	-	114	-	118	-	-

In this chapter, we consider the minimum operation range as a parameter that covers the minimum capacity range of a power plant that permits secondary reserves downwards around half of their secondary reserve capacity upwards. The minimum operation ranges for the combined cycle, steam turbine, gas turbine and diesel engines are 110 MW, 38 MW, 8 MW and 12 MW, respectively. Additionally, the maximum operation range is limited by the capacity installed. Following the same order, the maximums are 440 MW, 240 MW, 210 MW and 72 MW. For the steam turbine and diesel engines, the capital cost is zero, due to the power plants having an age of more than 25 years on average. However, we consider the double cost on the (Operation and Maintenance) O&M; see Appendix 1 for more details about the Levelized Cost of Energy (LCOE).

The main renewable facilities are located in the south of the island. The wind power plants are obsolete compared to current production technologies, as they have an average age of 12 years. In this period, the technology and the size of the wind turbines have experienced a huge development. However, the photovoltaic power installed is less than seven years old and is relatively modern. Thus, regarding power capacity and the introduction of renewables into the electric grid, the main problem is located in the south area of the island.

In order to have a better understanding of the electric system on Tenerife, two representative days in 2013 have been chosen: one winter weekday with a significant introduction of renewables, but with intermittence (6 February 2013); a second day corresponding to a summer weekend day, with an acceptable renewable introduction and not much intermittence (1 September 2013). Figure 1.2 shows the renewables load factor (wind and solar) on the selected days. Sharp curves represent summer days, and continuous curves represent winter days. The wind curves represent the usable wind resource in relation to what could be obtained working at a 100% load. The solar resource has a more stable behaviour in summer. On the contrary, in winter, the resource intermittence makes the solar resource curve unpredictable.

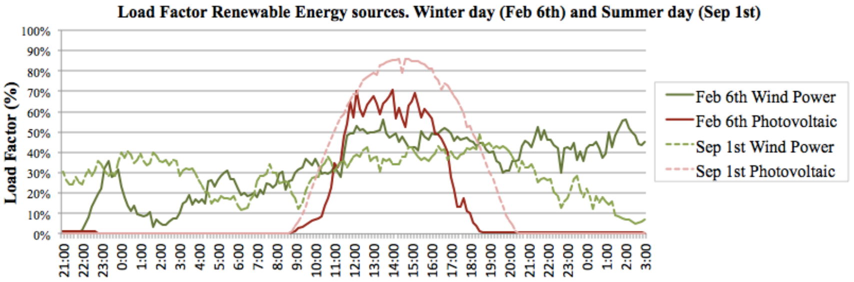

Figure 1.2. Load factor for the renewable energy source: (**a**) 6 February wind power; (**b**) 6 February photovoltaic; (**c**) 1 September wind power; (**d**) 1 September photovoltaic.

For the same days, we also show daily demand curves, as well as load curves for each technology that operated on those days (Figure 1.3, winter; Figure 1.4 summer). In both cases, the blue curve represents the system's demand. During the off-peak hours, when demand is low, the system's core technologies are operating (steam turbine (ST) and combined cycle (CC)), the combined cycle being the one that adjusts in order to balance the system and to keep the introduction of renewables at the maximum (wind power (WP) and photovoltaic (PV)). However, at certain times, the energy produced by renewables is quite high, and the system is unable to insert it into the grid in order to maintain security conditions. This happens during the daytime for the winter graphic and during most of the day in the summer. In those circumstances, a great loss of energy is noticed (energy spilled). Moreover, the gas turbine (GT) would only operate during system peaks, whereas the diesel engines (DE) are at relatively high loads in order to maintain the frequency of the system constant.

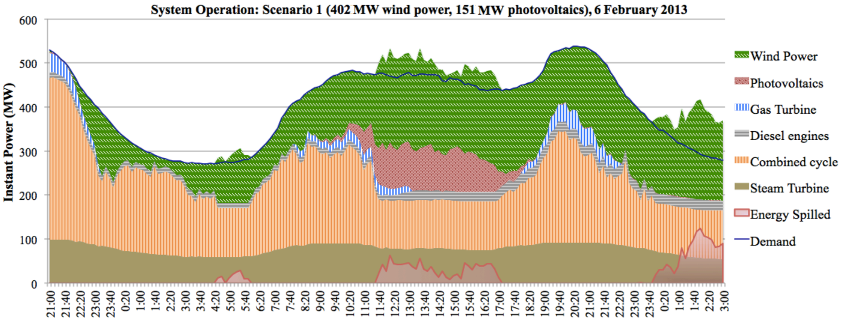

Figure 1.3. Winter operation of the system (Scenario 1, 402 MW wind power and 151 MW photovoltaic). 6 February 2013.

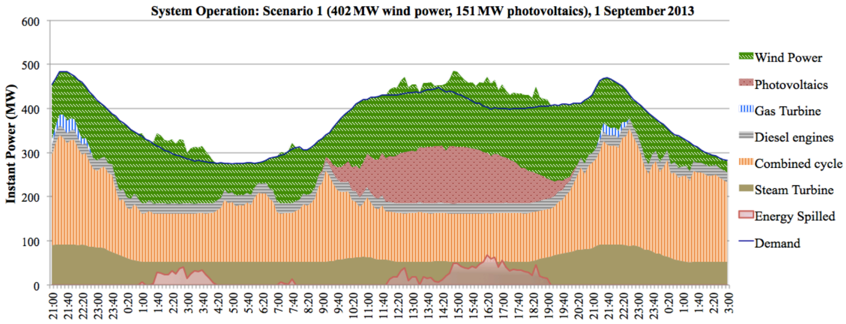

Figure 1.4. Summer operation of the system (Scenario 1, 402 MW wind power and 151 MW photovoltaic). 1 September 2013.

1.3.2 Methodology: Simulation of the electric power system on Tenerife

The simulation of an electric power system attempts to characterize the instant operation of alternative power technologies during a particular period of time. The purpose of our exercise is to characterize relevant outputs for energy management—renewable share, generation cost, CO_2 emissions, energy spilled and oil internal market—under alternative scenarios and taking into account the particular characteristics of an isolated island, such as Tenerife. Thus, while the application of an optimizing methodology, such as unit commitment (Soliman & Abdel-Aal Hassan Mantawy, 2010), will be a natural and promising extension of the chapter, our simulation model just attempts to represent the current operation of the power system on Tenerife and the resultant outputs consistent with the real-life conditions of the island.

The scenarios considered attempt to measure the impact of two aspects on the electric power systems on Tenerife: more installed capacity of renewables (wind and PV) and the introduction of EVs as an energy storage system. This way, when comparing the results under different scenarios, we will obtain important conclusions about the changes in the renewable share, electricity production costs, CO_2 emissions, energy spilled or internal fuel consumption on the island, which will be of great use for the design of the islands’ energy policy.

1.3.2.1 Scenarios

The baseline scenario represents the observed data for the current electricity power system on Tenerife during 2013. For the entire year, combined cycles accounted for 42.7% of the mix, steam turbines 35.2%, diesel engines 8.1%, gas turbine 6.4% (with cogeneration) and, finally, renewables 7.6% (5.5 photovoltaic and 2.1% wind power) (Gobierno de Canarias, 2013). For this mix and the data in Table 1.1, the share of renewables is about 7.5%; LCOE is 165.53

€/MWh; and the emissions rate is about 0.729 kgCO_2/kWh. This 7.5% level is far from the 25% targeted by the PECAN in 2006 and to be achieved by 2015. In order to achieve this 25% share, the PECAN predicts that the installed capacity of renewables must increase up to 402 MW for wind and 151 MW for PV.

Thus, we will modify the baseline scenario and simulate the Tenerife electric power system under alternative levels of MW installed for renewables. We will gradually increase the MW from the baseline scenario until the 553 MW targeted by the PECAN is achieved.

In the second stage, two different scenarios will be proposed for the introduction of the electric vehicle to the electric system. A fleet of 10,000 EVs will be included in the first scenario and 25,000 in the second. In these two scenarios, EVs will only be able to receive energy from the grid (G4V). Fleets will be managed by an aggregator (aggregator managing) that will allow an over-night charging in order to increase the off-peak of the system and flatten the total demand curve. In addition, this manager will be able to send spare renewable energy to the batteries of the connected electric vehicles so that the charge energy is cleaner. Government estimates suggest 10,000 EVs in 2019 and 25,000 in 2021–2022 (Instituto Tecnológico de Canarias S.A, 2013).

Finally, another two scenarios with EVs will be analyzed. In these two cases, the V2G system is considered with two fleets of vehicles (25,000 EVs and 50,000 EVs). In the V2G scenarios, besides the over-night charging, a strategy of injecting energy into the grid in peak hours has been added. Therefore, a bidirectional V2G system will be used in order to support the grid, both as a backup for the intermittence of renewables partially replacing the diesel engine and the combined cycle (less than 0.5% of the total year production). The other contribution occurs during peak hours partially replacing the open-cycle gas turbine (less than 2.5% of the total year's production). The V2G contribution to the system will be analyzed by comparing the results of the 25,000 EV scenario with and without V2G. The amount of 50,000 EVs will be considered as a long-term goal, which could be achieved by 2024 according to(Instituto Tecnológico de Canarias S.A, 2013). This same number was used in (F. Ramos-Real et al., 2018), to study the impact of an EV fleet on the electricity generating efficient frontier on Tenerife.

1.3.2.2 The simulation strategy

Next, we describe the main features, equations and restrictions on which our strategy to simulate Tenerife's electric system under different levels of installed RES is based. In this first part, we set aside the introduction of EVs as a storage system. We set 2013 as our reference year, taking the electricity demand patterns and the renewables' load curves as representatives. We also establish the conventional sources' installed power for each case (combined cycle, steam turbine, gas turbine and diesel engines).

Given these aspects, this interesting simulation exercise consists of increasing the renewables' installed power on Tenerife, while keeping the installed capacity of conventional power plants constant, but adjusting their use so that certain restrictions of the electric system (the balance of the system, the minimum operation range, the maximum operation range and the secondary reserves condition) remain fulfilled.

$$\boldsymbol{D_t = \sum_{n=1}^{4} P_{n,t} + P_{wind,t} + P_{pv,t}} \tag{1.1}$$

where D_t is the electricity demand at each time t; $P_{n,t}$ represents production with conventional energies; and the last two terms are production with wind and *PV*. As renewables have a priority when entering the grid, the production of those will depend on the installed power and also on their load curves for each time. A set of technical restrictions, which must be fulfilled at each time, will be described below.

Thus, the simulation exercise could be described as follows. For each period of time, we take the demand and the wind and photovoltaic load curves as given. Thus, when the renewable installed power increases (for instance, we go from 37 MW–402 MW of wind and from 99 MW–151 MW of *PV*), Equation (1.1) would be unbalanced for most of the periods analyzed in 2013. In fact, balance could only be maintained for periods in which no electricity was generated with renewables or in times with a low penetration of renewables during 2013.

We start by making some adjustments in the conventional energies' production levels. For simplicity, these adjustments are carried out proportionally and for the whole of 2013. First, we adjust (raise) the diesel engines in order to cover the greater cost of intermittence, as there is more RES installed. Secondly, we reduce the gas turbine production in order to increase the renewable capacity during peaks, as long as the combined cycle is able to cover the shortage in the case of a renewable deficit. Third, we reduce the load of the steam turbine at the base of the system in order to introduce a greater renewable capacity into the mix. Thus, the left-hand side of Equation (1.2) shows the electricity produced with the combined cycle technology, which is obtained as a residual of existing electricity demand minus the production of the other three conventional technologies and the renewable production under the new scenarios (for example, under the PECAN scenario). The combined cycle technology is used as the buffer in Equation (2), because, in large isolated systems, such as Tenerife, it acts as the base load of the system, but it also shows a high flexibility to adapt to the renewables' intermittencies.

$$\boldsymbol{P^{1}_{cc,t} = D_t - \sum_{n=1}^{3} P^{\,1}_{n,t} + P^{1}_{wind,t} + P^{\,1}_{pv,t}} \tag{1.2}$$

where, now, the superscript "1" refers to the new situation. In all of these adjustments, we must impose two boundary constraints based on the minimum operation range ($L_{min,\,n}$) and the maximum operation range ($L_{max,\,n}$) for each power plant. Additionally, no unit can produce below zero or above its installed capacity (see Table 1.1).

Lastly, we have to point out that in Equation (2), when the production of renewable is very high, $P_{cc,t}^{1}$ could be zero or negative, which is unfeasible. In this situation, the simulation model must additionally cut down the production of electricity with renewables in order to maintain the equilibrium condition Equation (1) under the new circumstances. Thus, some renewable energy produced is lost or spilled out of the system.

For the correct operation of the electric power system, our model accomplishes some additional restrictions and requirements concerning the determination of the primary and secondary reserves. The following production units compose the base load of the system: steam turbines and combined cycle. These are responsible for maintaining the stability and the inertia of the system. According to the TSO requirements for the Canary Islands' power system the production of these units must be greater than 40% of the instant power generated at each moment of time (every 10 min in our case) in order to guarantee the security and the stability of the power system on the island, see for more details (Ministerio de Industria Turismo y Comercio. & España, 2006). This restriction limits the penetration of renewable energies up to 60% of total generation in a particular period of time. Whenever the generation of electricity with renewables exceeds this share, the system cannot absorb the extra energy generated, and the energy is spilled.

While primary reserves are ensured by the operation of the generators in a short period of time (less than 5 min), secondary reserves, which are covered by the combined cycle, the diesel engine and the gas turbine in most of the situations, are the ones used to manage the intermittency of renewables (*i.e.*, to guarantee the aforementioned 40%). Thus, we focus on secondary reserves and leave aside the control of primary reserves, which plays a minor role for our purposes. See the ITC/913/2006 for more details about this point.

Additionally, the spinning reserves are covered by diesel engine technology. It must be constantly connected to the system, and its production must be at least 6% of the total coverage of the system for the entire year. Moreover, two additional percentage points are added to the 6% every 100 MW of installed capacity of renewable energy to cover the extra intermittency impact.

Finally, tertiary reserves, which are used to guarantee reliable grid operation (between 15 min and 1 h), are covered every period in our case. Since Tenerife has 210 MW of gas turbines capacity and 72 MW of diesel engines, we have at least 200 MW offline, but ready to start up in less than 15 min. Since this quantity is more than enough to cover the system requirements in terms of tertiary reserves, tertiary reserves are not explicitly modeled.

For each case, we will obtain yearly values from the following outcomes, which will help us compare each of the considered scenarios. These outcomes are: (i) renewable share (%), which is defined as the total renewable energy introduced into the electric grids compared to the total energy consumed; (ii) the cost (€/MWh) of generating electricity, which is calculated according to the LCOE for each technology (see Table 1.1), and the average value is the weighted sum of the cost per technology divided by the total energy consumed; (iii) carbon emissions (kgCO_2/kWh), which are calculated following an emission rate by technology (see Table 1.1); the average of the emissions rate is the total emissions produced during the year per each kWh generated; (iv) energy spilled (%), which is the total renewable energy that could not be injected into the system, and it is measured as the total renewable energy that is not injected into the system between the total renewable energy available; (v) oil internal market (%), which is calculated as the total TOE (tonnes of oil equivalent) reduction (in transport due to the EV use plus electricity production) divided by the total oil imports from the internal market of Tenerife.

1.3.2.3 Electric vehicle fleet characterization

In this section, we describe the impact of the introduction of an EV fleet on the electricity-generating system on Tenerife. Thus, the simulation model for the system operation explained above is complemented by the introduction of electric vehicles with energy storage.

We consider two groups of EVs: first, the type of EVs that are only used for road transport, thus the energy flows only in one direction (grid for vehicle); the second type of EV contains the V2G capability, which could manage the electricity in a bidirectional way (grid for vehicle and vehicle to grid). In both cases, the smart charging management can recover spilling energy from renewables' overproduction. However the EVs with the V2G function could provide additional services to the system, such as backup supply and peak power shaving.

When the EV is considered, some additional features appear in the model, such as the number of EVs (N_{EV}), the average millage in road transport (EC_{road}) and the EVs' total storage capacity (S_{EV}). Moreover, the model also considers a security factor of the minimum operation state of charge (SOC_{sec}) of 15% to refrain from jeopardizing the batteries. The model also contemplates the characterization of the electric vehicle supply equipment (EVSE). We create two groups of EVSE: "at home" and "at the workplace". For each type of EVSE, the model requires a number of charging points (N_{home}, N_{work}); the power considered (P_{home}, P_{work}); and the efficiency of the charger (Eff). We use (F. Ramos-Real et al., 2018) to pick average values for these parameters and others described above, which are all summarized in Table 1.2.

Table 1.2. Summary of the EV fleet parameters. V2G, vehicle to grid.

PARAMETER	ABBREV	UNITS	QUANTITY
Average millage in road transport	EC_{road}	kWh/km	0.18
Number of EVs	N_{EV}	-	10,000/25,000/50,000
EVs' total storage capacity (10,000; 25,000; 50,000)	S_{EV}	MWh	204/510/1020
Minimum operation state of charge	SOC_{sec}	%	15
Efficiency of the charger	Eff	%	86
Number of charging points at home	N_{home}	-	10,000/25,000/50,000
Number of charging points at the workplace	N_{work}	-	500/1500/3000
Power of the charging point at home	P_{home}	kW	7
Power of the charging point at the workplace	P_{home}	kW	22
Total V2G installed capacity (Scenarios 4 and 5)	P_{v2g}	MW	208/416
Average distance travelled (weekdays/weekends)	D_{trav}	km	35/40
Minimum demand required for injection in peaks	$P_{min, peak}$	MW	450
Minimum renewable drops for the reserves	$F_{min, backup}$	MW	15
Minimum state of charge to inject energy	$SOC_{min, V2G}$	%	40

Given these parameters, the total installed capacity (in MW) that the V2G fleet can provide to the system at each moment ($C_{V2G,t}$) is defined in Equation (1.3): the total number of vehicles connected at period t ($N_{V2G,ON,home,t}$; $N_{V2G,ON,work,t}$) multiplied by the average capacity of the charging stations and their charging efficiency,

$$C_{V2G,t} = (N_{EV,ON,home,t} \cdot P_{home} \cdot Eff)_{at\ home} + (N_{EV,ON,work,t} \cdot P_{work} \cdot Eff)_{at\ work} \qquad (1.3)$$

In addition, the EV fleet requires energy to charge the batteries according to their use (kilometers driven). Thus, in the scenario where a fleet of EVs is included, the overall demand of electricity in the power system (D_t in Equations (1.1) and (1.2)) increases. For simplicity, we focus on an overnight charging strategy, instead of on an uncontrolled charging mode. The over-night charging mode allows raising the off-peak of the system and increasing the penetration of renewables. To represent the over-night charging mode in the model, we create a charge variable ($D_{EV,t}$), and we also define the efficiency of the charging station and the state of charge of the battery ($SOC_{EV,t}$). Thus, when simulating the model under the presence of an EV fleet, we must include the new demand in Equations (1.1) and (1.2) in substitution of the baseline demand (D_t), composed of the baseline demand plus the EV electricity demand. The energy in the EVs could be consumed in three different ways: road trips, backup supply and peak shavings.

For road trips, the EV energy consumption depends on the particular average distance travelled (D_{trav}), the number of vehicles and the average millage of the fleet. This consumption is located outside the charging station. However, for EVs using a V2G capacity, cars provide energy from the batteries to the grid. Thus, in order to keep the reliability of the system stable, the batteries of the EVs could send energy to the system in order to cover drops ($E_{backup,t}$) when the renewable drop 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 ($P_{min,\ peak}$). Additionally, the condition of a minimum state of charge ($SOC_{min,\ V2G}$) must be fulfilled. Thus, we must consider the inclusion of the instant power from the backup ($P_{backup,t}$) and the instant power from peak shavings operations ($P_{peak,t}$) in Equations (1.1) and (1.2) as a part of covering the instant demand.

The injection of energy into the system is limited by the capacity of stored energy in the vehicle's battery at each moment. This restriction is measured by the average SOC of vehicles' batteries connected to the grid at each moment. Appendix 1.B contains the formulas to calculate the stored energy in the batteries at each considered moment, as well as the corresponding state of charge.

1.4 Results and discussion

In this section, we describe the results obtained from the simulation model mentioned above. First, we analyze the effect of introducing different levels of renewable installed power in Tenerife's electric system (wind and photovoltaic). We use the supply and demand conditions that define Tenerife's system for 2013 (Red Eléctrica de España, 2013). From this starting scenario, progressive increases of renewable power installed are considered until reaching the 402 MW of wind and 151 MW of PV suggested by the PECAN (2006) (Consejería de Industria, 2006). Afterward, a second simulation exercise is carried out, which not only considers the current generating technologies and the progressive increase of renewable installed power, but also the presence of EVs as an energy storage system. The four alternative cases that we analyze were already described in detail in the previous section: 10,000 EVs; 25,000 EVs; 25,000 V2G; 50,000 V2G.

As was also mentioned above, the different simulation scenarios are compared in terms of the effect on the RES share, electricity generating cost, carbon emissions, energy spilled and consumed oil in the internal market. These four variables are of great importance when it comes to making decisions in the field of energy policy.

1.4.1 An increase of renewable installed capacity on Tenerife

Figure 1.5 summarizes the main results of the first simulation exercise. It shows the effects on the result variables of the model for different levels of RES installed capacity. The curve representing the RES share shows the total value in the percentage reached by this variable. The same applies to energy spilled, which represents the percentage of renewables loss in relation to the whole resource. However, for the rest of the variables, the percentage reached is represented on the starting point of the base scenario (100%).

The first remarkable fact is the close relationship between the renewable installed capacity, the percentage of renewable energy produced and renewable energy spilled in relation to the total. In the first case, it is shown that as the installed capacity increases, the percentage of renewable energy in the mix rises, but at a decreasing rate, so it shows a concave relationship. However, the increase of the renewable energy losses in relation to the total results in an increasing rate, so the curve is convex. This is due to the starting balance conditions in which the electric system is not able to absorb all of the renewable energy produced. Therefore, the more renewable capacity is installed, the larger the loss level becomes.

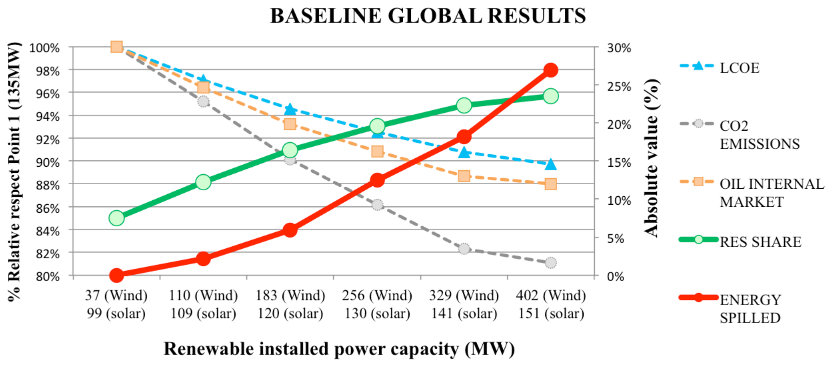

Figure 1.5. Baseline global results. (**a**) Renewable share; (**b**) cost; (**c**) emissions; (**d**) energy spilled; and (**e**) oil internal market.

This technical relationship between installed capacity and the penetration of renewables also explains the shape (decreasing and concave) of the other three curves. As more renewable capacity is introduced, carbon emissions, electric generating cost and fuel consumption decrease, but each time at a lower rate. This is because of the direct relationship between a larger amount of renewable energy and the lower use of fossil energies. As discussed in Section 1.3, the cost of renewable energy is lower than the cost of fossil energies on the Canary Islands with the current conventional generation technologies employed as detailed in Table 1.1 (G. A. Marrero et al., 2015; G. a. Marrero & Ramos-Real, 2010; F. J. Ramos-Real et al., 2007). For greater detail of the costs, Appendix 1.A shows all of the variables involved in calculating the levelised cost of energy.

In short, our model simulation allows us to compare energy and emissions outcomes under the renewable installed capacity of Tenerife at the beginning of 2013 (37 MW of wind and 99 MW of photovoltaic) with outcomes generated under the renewable installed capacity targeted by the PECAN (402 MW of wind power and 151 MW of photovoltaic). To focus on the role of renewable energies and make these two scenarios comparable, we use in both cases the same installed capacity for conventional technologies, the same demand of electricity and equal weather conditions, taking 2013 as our reference year. Electric vehicles are still not considered under these two scenarios.

According to our simulation results, installing the capacity of renewables proposed by the PECAN would allow one to achieve almost 23.5% of renewables in electricity generation, to reduce around 10.3% the cost of generation, as well as the consumption of fuel to generate electricity, to reduce carbon emissions up to 18.9%; however, that supposes a waste of energy (coming from renewable sources) of almost 27%. As we will see next, scenarios including EVs will reduce the energy spilled by a significant amount.

1.4.2 Scenarios using an electric vehicle fleet

This section shows the results obtained from the simulation of the electrical system on Tenerife under the four EV alternative scenarios described in Section 1.3. To analyze the effect of the progressive introduction of EVs and for illustrative purposes, we will analyze the results focusing on each outcome considered individually. Thus, Figure 1.6 compares the results of the renewable share; Figure 1.7 compares those of energy spilled; Figure 1.8 those of electric generating cost; Figure 1.9 those of carbon emission; and lastly, Figure 1.10 shows the results of the fuel consumed considering the use for electricity generation and road transport.

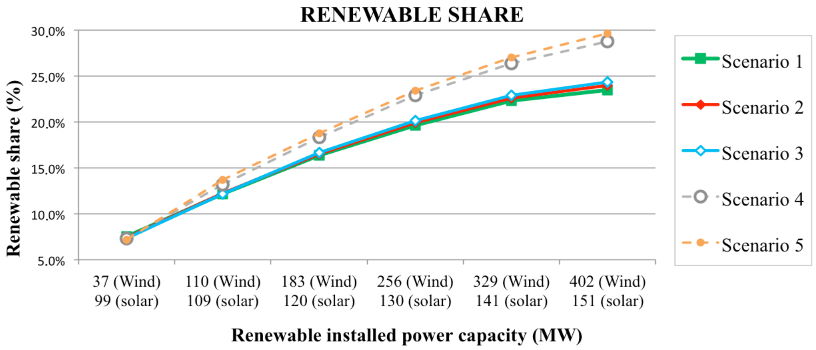

Figure 1.6. Renewable share. (**a**) Scenario 1 (baseline); (**b**) Scenario 2 (10,000 EVs); (**c**) Scenario 3 (25,000 EVs); (**d**) Scenario 4 (25,000 EVs using V2G); and (**e**) Scenario 5 (50,000 EVs using V2G).

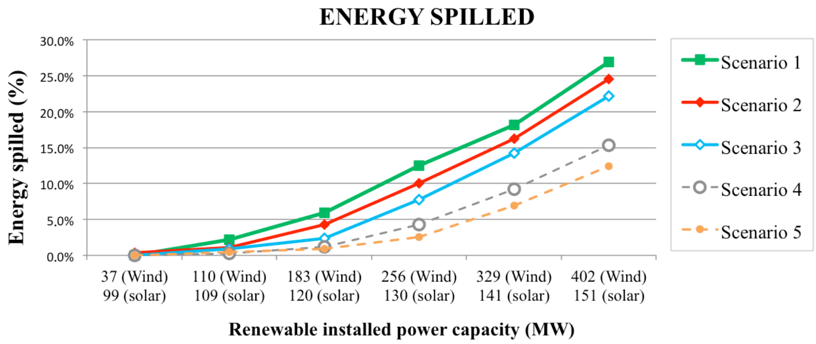

Figure 1.7. Energy spilled. (**a**) Scenario 1 (baseline); (**b**) Scenario 2 (10,000 EVs); (**c**) Scenario 3 (25,000 EVs); (**d**) Scenario 4 (25,000 EVs using V2G); and (**e**) Scenario 5 (50,000 EVs using V2G).

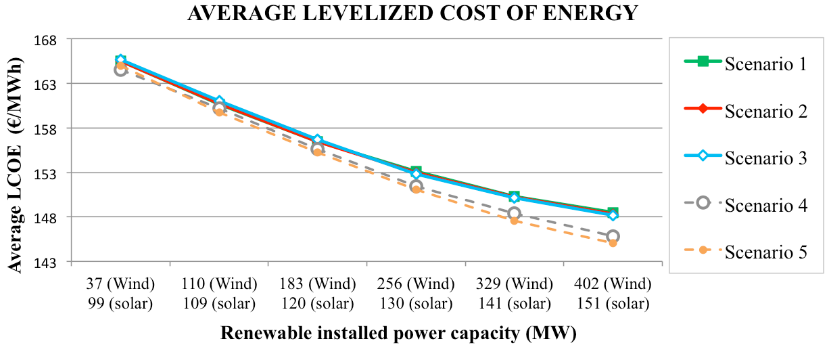

Figure 1.8. Levelized cost of energy. (**a**) Scenario 1 (baseline); (**b**) Scenario 2 (10,000 EVs); (**c**) Scenario 3 (25,000 EVs); (**d**) Scenario 4 (25,000 EVs using V2G); and (**e**) Scenario 5 (50,000 EVs using V2G).

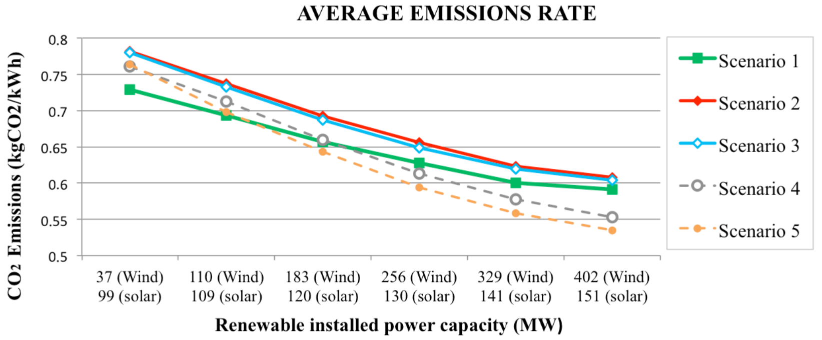

Figure 1.9. CO_2 emissions. (**a**) Scenario 1 (baseline); (**b**) Scenario 2 (10,000 EVs); (**c**) Scenario 3 (25,000 EVs); (**d**) Scenario 4 (25,000 EVs using V2G); and (**e**) Scenario 5 (50,000 EVs using V2G).

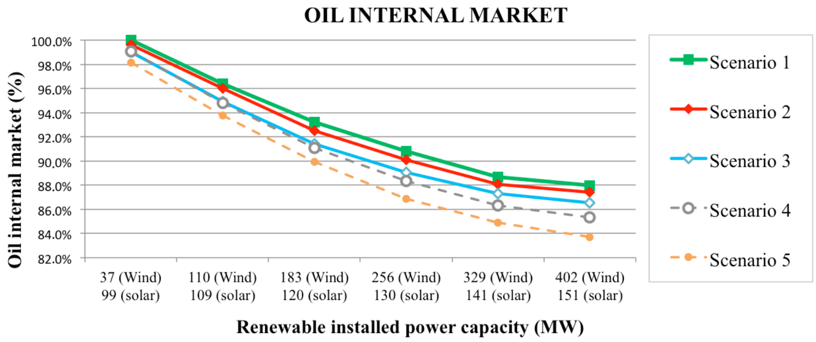

Figure 10. Oil internal market. (**a**) Scenario 1 (baseline); (**b**) Scenario 2 (10,000 EVs); (**c**) Scenario 3 (25,000 EVs); (**d**) Scenario 4 (25,000 EVs using V2G) and (**e**) Scenario 5 (50,000 EVs using V2G).

In general, we can highlight two important facts. First, it is observed that the introduction of the EV as a storage system allows for an improvement in all dimensions and in absolute terms. The greatest benefits are noticed especially in Scenarios 4 and 5 in which V2G technology is used. Once we are in a V2G system, doubling the fleet (from 25 thousand in Scenario 4 to 50 thousand in Scenario 5) offers benefits in all dimensions, but they are lower than those observed when moving from EV to the V2G technology. Secondly, the degree of concavity and convexity of the curves is also reduced in general terms. This means that the introduction of the EV attenuates the decreasing rate of marginal improvements as a larger renewable capacity is installed in terms of the different variables considered. In short, the process by which improvements are increasingly less important is delayed. Table 1.3 summarizes the percentages of improvement as renewable capacity increases by comparing scenarios 1 (S1) and scenario 5 (S5).

Table 1.3. Rate of change of the variables in Scenarios 1 and 5. RES, renewable energy source.

	RES	**Renewable Share**		**LCOE**		**CO2 Emissions**		**Energy Spilled**		**Oil Internal Market**	
	MW	**S1**	**S5**	**S1**	**S5**	**S1**	**S5**	**S1**	**S5**	**S1**	**S5**
1	135	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2	219	4.7%	6.5%	−2.9%	−3.2%	−4.8%	−9.1%	2.2%	0.5%	−3.6%	−4.3%
3	303	4.2%	5.1%	−2.5%	−2.7%	−5.1%	−7.5%	3.7%	0.4%	−3.2%	−3.8%
4	386	3.2%	4.6%	−2.0%	−2.5%	−4.0%	−6.7%	6.6%	1.6%	−2.4%	−3.1%
5	470	2.7%	3.6%	−1.7%	−2.1%	−3.8%	−4.9%	5.6%	4.4%	−2.2%	−1.9%
6	553	1.2%	2.6%	−1.1%	−1.5%	−1.2%	−3.2%	8.8%	5.5%	−0.7%	−1.2%

Regarding the renewable share achieved, it can be seen that the use of EVs as a storage system allows larger shares for the same renewable installed power than Scenario 1. As discussed in the above paragraph, the greatest difference can be seen when using the V2G systems (Scenarios 4 and 5). For Level 6 of renewable power (553 MW), we would move from 23.5% in Scenario 1 to almost 28.7% and 29.6% in Scenarios 4 and 5; whereas in Scenarios 2 and 3 without the V2G charging technology, the increase is very small (24.2%). Then, it is mainly the V2G charging technology what allows the introduction of the electric car to increase the share of renewable energy in the generation mix. This can be confirmed by the fact that in Scenario 5, the goal of 25% of renewables could be achieved with an installed power of about 420 MW (285 MW of wind power and 135 MW of photovoltaic), which represents approximately 24% below the 553 MW suggested by the PECAN.

This greater penetration of renewables due to the introduction of EVs as a storage system is closely related to a lower renewable energy losses. Thus, for the two scenarios using the V2G system, the energy losses with 553 MW of installed renewable energy is 15.3% in Scenario 4 and 12.4% in Scenario 5; whereas it is above 25% in the baseline scenario. The difference between the baseline scenario and Scenarios 2 and 3 with the introduction of EV is very small, being 0.5% and 1% higher in renewable energy injected into the system, respectively.

Once again, it is made clear that, given a certain size of EV fleet (for example 25 thousand) and the characteristics and size of Tenerife, the charging system (V2G) is more important than increasing the fleet.

With regard to the costs of electricity generation, the average difference between Scenarios 1 and 5 is about 7%, and it increases as more renewable capacity is installed (see Appendix 1.A for more cost details). The difference between these two scenarios in the last level of renewable capacity is 12.4%, representing 20.5 Euros/MWh and 26.4 million for the generation system of the island. The same as in the case of the renewable share and energy losses, Scenarios 4 and 5 are clearly different from the other three in the cost of generation. The reason is that a greater use of renewable capacity allows for a lower average cost, because a larger amount of fossil energy, which is more expensive, is being replaced. Regarding these costs, only the electricity generation is being considered. However, there are other important costs derived from the fuel import savings on the part of the vehicle fleet that is powered from the grid. The costs for automotive gasoline imports is 0.45 €/L (Comisión Nacional de los Mercados y Competencia, 2015). Furthermore, we consider average fuel consumption (gasoline) of 8.5L/100 km for pre-2002 vehicles. This reduction is equivalent to 5.4 M€ for 10,000 EVs, 13.3 M€ for 25,000 EVs and 26.5 M€ for 50,000 EVs. Therefore, for Scenario 5, the total savings for the island would reach 52.9 M€ per year comparing to the current scenario (135 MW of renewables). If we compare to the scenario without EVs, the total cost reduction in fossil fuel imports is around 23.72M€.

In the case of emissions, we highlight that, when there is little renewable capacity, scenarios with the introduction of EV produce a higher level of emissions per kWh generated. This is because vehicles generate a greater demand for electricity that cannot be covered by renewables. This is corrected as more renewable capacity is installed. In fact, for 553 MW, Scenarios 4 and 5 reduce emissions per kWh significantly (26.6% between 5 and 1). This savings is only considering the electrical system. However, a very important reduction of emissions occurs on roads. This reduction is equivalent to 24,960 (Tonnes of CO_2) tCO2 for 10,000 EVs, 62,410 tCO2 for 25,000 EVs and 124,830 tCO2 for 50,000 EVs.

Regarding total fuel consumption, the most remarkable fact is that the introduction of EV produces greater savings due to the combined effect of a lower consumption in power generation and transportation. When comparing Scenarios 1 and 5, the difference for the higher level of capacity is 4% (the difference between 12% and 16%).

To end this section of results, and in order to better understand the role of EVs as an energy storage system, we replicate Figures 1.3 and 1.4 shown in Subsection 1.3.1 but, in this case, we consider the introduction of a fleet of 50,000 EVs (V2G) for the same dates.

Thus, Figure 1.11 represents 6 February, in which it can be seen how the EVs support covering the required energy at peaks (filler waves, purple) maintaining conventional technologies at the minimum. In addition, despite the amount of spare renewables (energy above the dashed line, orange), the EV is able to capture much of that energy and incorporate it into the batteries (narrow curve, black). The effect on the batteries is observed in the second graphic, where the SOC of vehicles connected to the grid is represented.

In Figure 1.12, representing 1 September 2013, the SOC of batteries is very low during night peak hours. This is due to the fact that, in these hours, users come to their homes with a flat battery. In addition, possible injections to the system as a backup for conventional energy (dashed line, orange) have reduced its capacity. To conclude, if we compare both curves with respect to the previous case, we can see that the energy spilled has been significantly reduced, also adding extra renewable energy to the system. However, it can be seen how energy demand rises mainly in the off-peak hours.

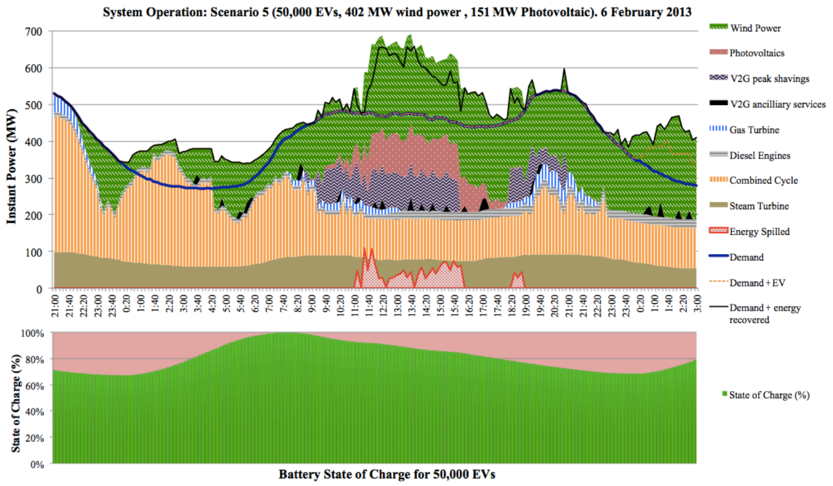

Figure 1.11. Winter operation of the system (Scenario 5, 402 MW wind power, 151 MW photovoltaic and 50,000 EVs using V2G). 6 February 2013.

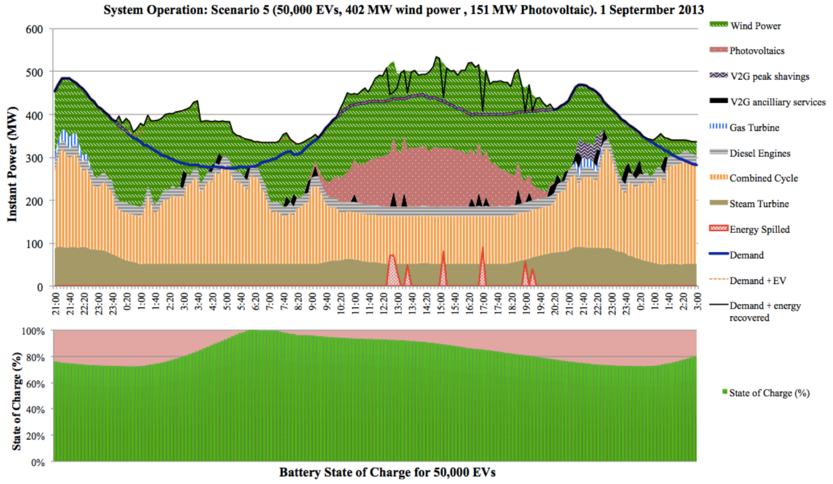

Figure 1.12. Summer operation of the system (Scenario 5, 402 MW wind power, 151 MW photovoltaic and 50,000 EVs using V2G). 1 September 2013.

1.5 Conclusions

In this chapter, we have used a model simulator to evaluate the introduction of renewable energy and an energy storage system based on EVs, both unidirectional (grid for vehicle) and bidirectional (vehicle to grid), in the Tenerife electric power system. The installation of renewables reduces the cost, the carbon emissions and the fossil fuel importations on Tenerife. However, when a massive amount of renewables is introduced, the reduction rate decreases, and more importantly, exponential increases of energy spilled are observed. These problems are significantly reduced when a fleet of EVs is introduced into the system.

Summing up, the introduction of an EV fleet shows two main benefits: (i) in the electrical system; (ii) in road transport. First, the EVs increase the limit of the penetration of renewables in the electric power system. Because of that, using the same capacity installed, the share of renewables can increase, and the amount of energy spilled is reduced. This impact is more important when a V2G strategy (bidirectional) is used. The second set of benefits refers to the impact on road transport, such as the reduction of noise, fuel consumption and emissions in road transport. With respect to the baseline scenario (no EVs), the cost reduction in fossil fuel imports when introducing 50,000 EVs is around 23.72 M€. Additionally, the reduction of carbon emissions in urban areas could be around 124,830 tCO2.

From the point of view of the energy policy, the PECAN objectives are very ambitious. Since the PECAN was approved in 2006, no new wind turbines have been installed on Tenerife. Thus, to meet the target in PECAN, the island needs the current 37 MW to be refurbished and an additional 365 MW installed. According to our results, the EV fleet with the V2G system could help to fulfill the 25% of renewables share with less installed capacity of renewables (about 133 MW lower).

An alternative energy storage system proposed on Tenerife (and not analyzed in this chapter) is the pumping hydro station. This technology is much more mature than the V2G system. Furthermore, this technology has been tested on the island of El Hierro with great success by achieving an 80% of renewables share for some periods of time. However, a big amount of fuel is still consumed on El Hierro (28% of total energy) in road transport. Thus, the solution to reduce this share is the introduction of plug-in electric vehicles.

The introduction of EVs as energy storage could provide some additional advantages with respect to the pumping hydro stations. First, the EVs reduce the environmental impact caused by these huge power plants, which is an important issue, because 50% of the total surface of the Canary Islands is protected. In addition, the storage system through EV charging reduces problems by reducing the requirements of the nodes and the burden-sharing network. However, the most important feature is that the EVs reduce noise and carbon emissions in urban areas and replace conventional vehicles, which consume fossil fuels in transportation.

A promising extension of this chapter would be to enter into detail the operation of the system and its security requirements using a unit commitment model. Indeed, it is important to study in detail the uncontrolled charge in comparison with other charging strategies. Additionally, it would be interesting to evaluate the complementarity between the V2G technology and pumping hydro stations.

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Appendix 1.A. Levelised cost of energy of technologies on Tenerife

The Levelized Cost of Energy (LCOE) is calculated following the formula shown in the Open Energy Information (2015). The capital cost of each Tenerife power plant is shown in ITC/913/2006 (Ministerio de Industria Turismo y Comercio. Gobierno de España, 2006). However, the steam turbines and gas turbines are considered to have a cost of zero, due to being at the end of their life cycle, and the inversion is completely covered. In the case of renewables, we use the Lazard 2014 report (Soliman & Mantawy, 2010). Finally, we assess the capital cost of V2G as 800–1200 €/MWh. On the other hand, the capacity factor is estimated with the relationship between the total energy generated in a year and the total power capacity generating during 8760 h. The fixed and variable (Operation and Maintenance) O&M costs are from the Lazard 2014 report (LAZARD, 2014), except the cost of V2G. We assume a cost of around 40 €/MWh injected into the grid. Finally, the cost of fuel price includes the logistic price in terms of €/MWh. The reference is the ITC/914/2006 (Ministerio de Industria Turismo y Comercio. Gobierno de España, 2006), where it is explained that the fuel cost is shown in the European Marketscan, and it is 2.96 €/MWh for gas oil and 5.53 €/MWh for fuel oil (Marketscan, 2014). We assume the investment in cars as a private user expenditure. The discount Rate (D) is fixed as the 7%, and the Capital Cost Recovery factor (CRF) is 0.094. The main parameters covered by the LCOE are detailed in Table 1.A.1.

Table 1.A.1. Levelized cost of energy parameters.

Variable	**Capital Cost**			**N**	**D**	**CRF**	**Capacity Factor**		**T**	**Investment Cost (Overnight)**			**Fixed Cost O&M**	**Variable Cost O&M**	**Plant Efficiency**		**Fuel Price**			**Intermittency Price**	**CO_2/ Price**	**Levelized Cost of Energy**		
Units	€/kW			years	%	L/years	%	%	%	€/MWh			€/MWh	€/MWh	%	%	€/MWh			€/MWh	€/MWh	€/MWh		
	min	max	avg				min	max		min	max	average	average	average	min	max	min	max	avg	avg	avg	min	max	avg
Combined Cycle	1000	1092	1046	20	7	0.094	45	60	0.392	23.2	33.8	28.5	1.13	3.2	42	47	103.3	160.6	131.1	0	4.55	134.3	204.4	169.38
Steam Turbine	0	0	0	20	7	0.094	18	24	0.392	0.0	0.0	0	20.28	11.22	30	35	107.7	159.3	124.1	0	7.7	127.4	202.8	165.12
Gas Turbine	325	770	5475	20	7	0.094	20	25	0.392	17.7	52.3	35.0	7.19	7.0	20	26	186.8	337.3	275.3	0	8.75	220.6	419.5	320.01
Diesel Engines	0	0	0	20	7	0.094	40	50	0.392	0.0	0.0	0	13.35	15.02	38	46	82.0	125.8	98.0	0	5.6	104.3	156.0	130.17
Wind Power	950	1200	1075	20	7	0.094	29	33	0.392	34.4	49.4	41.9	13.92	0	100	100	0	0	0	16	0	62.5	81.2	71.84
Photovoltaic	1300	1600	1450	20	7	0.094	16	18	0.392	86.3	119.5	102.9	11.25	0	100	100	0	0	0	4	0	98.5	137.7	118.12
V2G	800	1200	1000	20	7	0.094	16	16	0.392	53.9	80.8	67.34	40.20	0	100	100	0	0	0	0	0	74.9	140.2	107.55

Appendix 1.B. Energy storage formulation

The model needs also to assess the battery energy balance. The features used in the evaluation of the battery energy balance are the total energy composition in road transport, the energy load in charging stations at night and the energy recovered by the overproduction of renewables ($E_{spill,\ rec,t}$). Furthermore, in the case of V2G capacity, the model adds the energy consumption in the peak-hour shavings (E_{peak}) and the backup loads (E_{backup}). Thus, the total energy in the batteries of the EVs connected each timestamp ($B_{EV,t}$) is defined by the energy in the batteries in the last timestamp ($B_{EV,t-1}$), plus the energy charged in batteries, minus the energy consumption on the road.

$$\mathrm{B_{EV,t}} = \mathrm{B_{EV,t\text{-}1}} + \mathrm{E_{spill,\ rec,t}} + \frac{E_{EV,t}}{Eff} - \frac{Dwd,wk,t \cdot NEV \cdot ECroad}{1{,}000} - \frac{E_{backup,t} - E_{peak,t}}{Eff} \tag{B.1}$$

The energy charged for the EVs ($E_{EV,t}$) is the energy required for the EVs in the charging process. Finally, the third summand is the energy consumed in road transport each moment. This is composed by the distance travelled each timestamp ($D_{wd,wk,t}$) depending on weekdays or weekend, the number of vehicles in the fleet (N_{EV}) and the average rate of energy consumption in road transport (Dang et al., 2015). For the energy exchange between the battery and the network and *vice versa*, this has taken into account by the average efficiency of the charger (*Eff*). All summands are expressed in MWh.

Finally, the real-time state of charge (SOC) of the EVs' batteries are shown in Equation (B.2). This formula expresses the energy storage in the batteries divided by the total energy storage capacity, defined as a percentage.

$$\mathrm{SOC_{EV,t}} = \frac{\mathrm{B_{EV,t}}}{S_{EV}} \cdot 100\% \tag{B.2}$$

where: $\mathrm{SOC_{EV,\ t}}$: state of charge (%) of the batteries (V2G) connected each timestamp (t); $\mathrm{S_{EV}}$: total battery capacity (V2G) since 15–95% of the state of charge (MWh).

Chapter 2.

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

2.1 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 (Jensen, 2000; Perez & Ramos Real, 2008; Szabó, Kougias, Moner-Girona, & Bódis, 2015). 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% (Gobierno de Canarias, 2013). 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 (CATPE. Centro Atlántico de Pensamiento Estratégico, 2013). 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.

Although there are different technological alternatives for energy storage (Rodrigues, Godina, Santos, Bizuayehu, & Contreras, 2014), 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 [(Bueno & Carta, 2006; Martínez-Lucas, Sarasúa, Sánchez-Fernández, & Wilhelmi, 2015; Padrón et al., 2011; Portero, Velázquez, & Carta, 2015)]. 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. 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 [(Bessa & Matos, 2010; Dietrich, Latorre, Member, Olmos, & Ramos, 2012; Letendre & Kempton, 1996; Marrero, Perez, Petit, & Ramos-Real, 2015)]. 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 (Huang & Infield, 2010).

The aim of this chapter 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: the share of renewables in the electric mix; CO2 emissions; and total consumption of fossil fuels. In order to attain this goal, we use the simulation model described in (Díaz, Ramos-real, Marrero, & Perez, 2015). 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 2.2 briefly reviews the literature about energy storages in isolated systems. Section 2.3 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 2.4 shows the results obtained and the discussion about them. Lastly, Section 2.5 concludes the chapter with the main findings and energy policy measures.

2.2 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 [(Camus & Farias, 2012; Rious & Perez, 2014; Taylor et al., 2012)]. According to Rodrigues et al., (2014), 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 (NHA, 2012). 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 (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 (Instituto Tecnológico de Canarias, 2013), 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. This is known as V2G. The development of this technology is being tested in several projects around the world [(Binding et al., 2010); (Blyth, 2011); (Kempton et al., 2008)]. According to Letendre & Kempton (1996), 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 (Dang et al., 2015). Nevertheless, there are some disadvantages, such as lack of commercial maturity, lack of awareness of users (Ramos-Real et al., 2018), and wear of batteries due to a greater use of the load-unload cycle (Guenther et al., 2013).

Some research on the two types of energy storage considered in this chapter has already been done in the Canary Islands archipelago. Regarding PHES, some studies have been conducted in La Palma (Martínez-Lucas et al., 2015), el Hierro (Bueno & Carta, 2006), and Gran Canaria (Padrón et al., 2011; Portero et al., 2015). 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 (Red eléctrica de España, 2016). Likewise, the Canary Islands energy planning (Consejería de Industria, 2006) provides for the installation of some 299 MW (La Palma would be provided with some 30 MW) of PHES, targeting a 30% share of renewables, thus reducing the degree of energy dependence under 10%.

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 (Instituto Tecnológico de Canarias, 2013), where a penetration of EVs of up to 413,359 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, Marrero et al., (2015), analyse 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 Díaz et al., (2015), the inclusion of a fleet of 50,000 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.

2.3 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.

2.3.1 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 (Table 2.1). 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 (Ministerio de Industria, 2014). 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% (Gobierno de canarias, 2015). Despite the small installed capacity of renewables, a penetration of over 11% of renewable share was achieved in 2015.

Table 2.1 Installed capacity in La Palma (2015)

Technologies	Number of units	Total Installed Power Capacity MW	%	Electricity generation for 2015 GWh	%
D. 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

Examining the technical features of the generators, Table 2.2 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 (Open Energy Information, 2015). 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 (kWh). All these features are going to be important for our empirical study.

Table 2.2 Technical characteristics in La Palma (2015)

Technologies	**Minimum Operational Rate**	**Emission rate**	**LCOE**
	MW	**kgCO2/kWh**	**€/MWh**
D. Engines	6.63	0,75	130.17
Gas turbine	4.85	1.15	320.01
Wind Power	-	0	71.8
Photovoltaic	-	0	118.12

In order to reduce the energy dependence and also reduce carbon emissions, the energy planning proposed by the Canary Islands Government (PECAN, 2015) (Consejería de Industria, 2006), suggested 28 MW of wind power and 7.91 MW of photovoltaic in La Palma for 2015. However, these goals were not fulfilled, being the current installed capacity 6.9 MW of wind power, and 4.1 MW of photovoltaic. In Figure 2.1, 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.

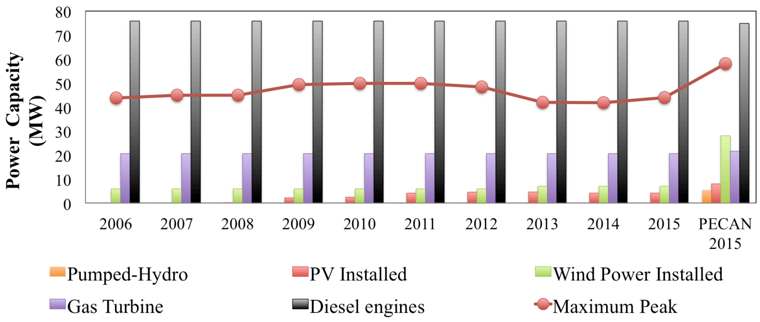

Figure 2.1 Installed Power Capacity & Peak Power of La Palma electrical system

Following the historical tendency that hydroelectric energy has had in La Palma, new PHES projects have been suggested. Firstly, repowering the old *El Mulato* plant, 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 3,000,000 m^3. Its current use is general supply and irrigation. Table 2.3 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 66,123 units. Our object of study will be private cars, which represent 60% of the total. According to a report about the introduction of the EVs in the Canary Islands (Instituto Tecnológico de Canarias, 2013), a total of 1,085 electric cars will be running by 2020, whereas there will be 3,361 by the end of 2024.

Table 2.3 PHES plants in La Palma

Variables	**Unit**	**PHES (El Mulato)**	**PHES 2 (Las Cancelitas)**
Hydropower head	m	929	370
Upper reservoir	m^3	6,000	300,000
Lower reservoir	m^3	3,000,000	3,000,000
Autonomy estimated	hour	1h 53’	18h 33’
Flow rate	m^3/s	0.58	4.5
Number of turbines	-	1	3
Turbine power	MW	5,2	5
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

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 Ministerio de Industria (2014), 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 from 2016 to 2024 (Instituto Tecnológico de Canarias, 2013).

2.3.2 Methodology: Simulation of electric power system in La Palma

We simulate the electricity power system of La Palma following the model of Díaz et al., (2015). 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:

i. Renewable share (%), which is defined as the total renewable energy injected into the electric grids compared to the total energy consumed.

ii. 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 plus electricity production) divided by the total oil consumption from the internal market in La Palma.

iii. Carbon Emissions (kgCO$_2$/kWh), which are calculated following an emissions rate by technology (see Table 2.1). The emissions rate average is the total emissions produced during the year per each kWh generated.

iv. Cost (€/MWh) of generating electricity, which is calculated according to the LCOE for each technology (see Table 2.1), and the average value is the weighted sum of the cost per technology divided by the total energy consumed.

v. 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.

2.3.2.1 Scenario

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 (Instituto Tecnológico de Canarias, 2013). Table 2.4 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. The detail of the different scenarios is as follows.

Table 2.4 Stages of the scenarios proposed

Stages		**1**	**2**	**3**	**4**	**5**
Year expected		2016	2018	2020	2022	2024
Wind Power Installed	MW	6.91	12.25	17.50	22.75	28.00
Photovoltaic Installed	MW	4.10	5.00	5.90	6.90	7.90
Number of EVs	-	135	475	1,085	2,030	3,361
Increase of the demand	%	-	2.4	4.8	7.2	9.6

2.3.2.1.1 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.

a) Sub-scenario (1A). In this scenario we will consider no control over the charging of the EV (Plug&Charge situation).

b) Sub-scenario (1B). EVs will work on demand response, and smart-charging strategies, thus encouraging over-night charge and recovery of spilled energy from renewable sources. Therefore, it will function as Grid-for-Vehicle (G4V).

2.3.2.1.2 Scenario 2: PHES scenario

In this second scenario we will repeat the two previous sub-scenarios (2A y 2B), except for the fact that we will include PHES technology. As it was mentioned in section 2.3.1, 20.2 MW of PHES, with a pumping capacity of 15.75 MW, will be installed.

2.3.2.1.3 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.

2.3.2.1.4 Scenario 4: PHES + V2G

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.

2.3.2.2 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 Díaz et al., (2015) considering the characteristics of La Palma. In this isolated electric power system there exist two main conventional technologies (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 (the demand equilibrium, the minimum operation range, the maximum operation range, and the secondary reserves condition).

$$D_t = P_{DE,t} + P_{GT,t} + P_{WP,t} + P_{PV,t} \tag{2.1}$$

where D_t is the demand at each time t; $P_{DE,t}$ and $P_{GT,t}$ represent 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, the Equation (2.1) 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 are used as the buffer in equation 2.2 (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.

$$P_{DE,t}{}^{s,n} = D_t{}^{s,n} - P_{GT,t}{}^{s,n} + P_{WP,t}{}^{s,n} + P_{PV,t}{}^{s,n} \tag{2.2}$$

where now superscript 's' refers to the new scenario proposed, and 'n' shows the stage. The demand will increase depending on the stage (Table 2.3). 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 Table 2.1 and Table 2.2, the minimum operation range for each diesel engine is 6.63MW and for the gas turbine is 4.85MW. Additionally, the maximum operation range for each unit is 11.5MW for diesel engines and for gas turbine is 21.6MW. Thus, the units cannot produce under the minimum operation rate required by TSO rules (Ministerio de Industria Turismo y Energía, 2015) or zero (in the renewable case) or beyond the maximum power capacity.

Furthermore, we mention an unusual situation that may occur in Equation 2.2. 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 (2.1) under the new conditions. Thus, a part of the renewable production is lost (spilled out of the system).

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 (Ministerio de Industria Turismo y Energía, 2015). 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 (Martínez-Lucas et al., 2015). 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 Díaz et al., (2015). Furthermore, the details about the modelling of the energy storages and the description of parameters are shown in appendices 2.A and 2.B (V2G and PHES respectively) of this chapter.

2.4 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 28MW of wind power and 7,9MW of photovoltaic in order to accomplish a 30% share of renewables in the electric mix (Consejería de Industria, 2006). Besides, forecasts about the penetration of EVs must be achieved reaching 3,368 units this year, as it was detailed in section 2.3, according to the forecasts by the local government (Instituto Tecnológico de Canarias, 2013). 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.

The analysis of the results starts by addressing the evolution of the renewable share (Figure 2.C.1, appendix 2.C), the spilled energy (Figure 2.C.2, appendix 2.C) and the mix generation costs (Figure 2.C.3, appendix 2.C). The results are presented for all levels of installed power in each period, which are common to all scenarios. Beginning with the scenarios where there is no storage (1A and 1B), it is worth mentioning that the renewable share has a maximum limit of 30% for 1A and 35% for 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 cases 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 1,086 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 (Figure 2.C.4, appendix 2.C). 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 (90,241 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 (Figure 2.C.2, appendix 2.C). On the contrary, not using storage systems causes the maximum reductions of energy dependence to be about 10% for the period considered, with respect to the initial situation (in scenario#4 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 (Ministerio de Industria, 2014), and some 3,363 EVs will be running around La Palma, according to the local government (Instituto Tecnológico de Canarias, 2013). In Table 2.5, results are summarized, and will be analysed next.

Table 2.5 Results of the scenarios (Stage 5)

	Scenario 1A	**Scenario 1B**	**Scenario 2A**	**Scenario 2B**	**Scenario 3**	**Scenario 4**
Storage	NO	NO	PHES	PHES	V2G	PHES+ V2G
EV Management	NO	G4V	NO	G4V	V2G	V2G
Renewable share (%)	28.20	33.30	42.80	43.90	47.10	48.80
Energy spilled (%)	47.30	22.60	3.60	1.80	3.20	0.70
Electricity mix LCOE (€/MWh)	125.72	118.8	113.3	111.9	109.4	111.7
Electric power system emissions (ktonnes CO_2)	141.3	133.2	121.4	117.4	109.0	108.9
Reduction of energy dependence (%)	8.02	10.69	14.58	15.94	18.70	18.73

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 (Consejería de Industria, 2006) 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 percentage 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 1A with 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 (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 of the EV implementation. Given these factors, we believe there is a complementarity between these types of storage in this case of study.

2.5 Concluding remarks

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 2.A. EV fleet modelling

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 Ramos-Real et al. (2018). 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), 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}).

Table 2.A.1 Summary of the EV fleet parameters modeling parameters

PARAMETER	**Abr.**	**Stg. 1**	**Stg. 2**	**Stg. 3**	**Stg. 4**	**Stg. 5**
Average millage in road transport (kWh/km)	EC_{road}	0.20	0.2	0.2	0.2	0.2
Number of EVs	N_{EV}	135	1,085	1,085	2,030	3,361
EVs total storage capacity (MWh)	S_{EV}	4.05	32.55	32.55	60.00	100.83
Minimum Operation State of Charge (%)	SOC_{sec}	20	20	20	20	20
Efficiency of the charger (%)	Eff	90	90	90	90	90
Number of charging points at home	N_{home}	135	1,085	1,085	2,030	3,361
Power of the charging point at home (kW)	P_{home}	3.7	3.7	3.7	3.7	3.7
Average distance travelled (week, weekends) (km)	D_{trav}	35/40	35/40	35/40	35/40	35/40
Minimum demand required for injection in peaks (MW)	$P_{min, peak}$	-	35	35	30	28
Minimum renewable falls for the reserves (MW)	$F_{min, backup}$	10	10	10	10	10
Minimum State of Charge to inject energy (%)	$SOC_{min, V2G}$	40	40	40	40	40
LCOE (€/MWh)	$LCOE_{V2G}$	-	108.75	108.75	108.75	108.75

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 detailed Table 2.A.1.

The drivers' mobility patterns Ramos-Real et al., (2018) 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 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 (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 ($D_{EV,t}$). Diaz et al. (2015) contains more details of the EV fleet characterization and the model simulator equation and restrictions.

Appendix 2.B. PHES modelling

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 subsection 2.2.3.1, 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: i) Availability of stored water capacity. For this, we set a security limit of minimum storage capacity SC_{min}; ii) Amount of renewable injected at that moment into the system; iii) the production is subjected to the peak condition of the system, $P_{peak,\ turb}$. Table 2.B.1 summarizes all the parameters considered for the design of the PHES.

Table 2.B.1. Summary of the PHES modeling parameters

Parameters	Abr.	Unit	
Maximum Storage Capacity of the reservoir	SC_{max}	*MWh*	130.22
Minimum Storage Capacity of the reservoir	SC_{min}	*MWh*	25.5
Number of Pump	N_{pump}	-	21
Power Capacity of the pump	P_{pump}	*MW*	*0,75*
Efficiency of the Pumping process	Eff_{pum}	-	*0.84*
Number of turbines	N_{turb}	-	*4*
Power Capacity of the turbines	P_{turb}	*MW*	*5*
Efficiency of the Turbine process	Eff_{turb}	-	*0.82*
Minimum Peak injection conditions	$P_{peak,\ turb.}$	*MW*	*28*
LCOE [20]	$LCOE_{PHES}$	*€/MWh*	*152.00*

Appendix 2.C. Evolution of main variables

The In this appendix we detail the evolution of the sustainability variables considered in the analysis throughout the period studied. First, Figure 2.C.1 shows the share of renewables (%) in the electric mix of the system.

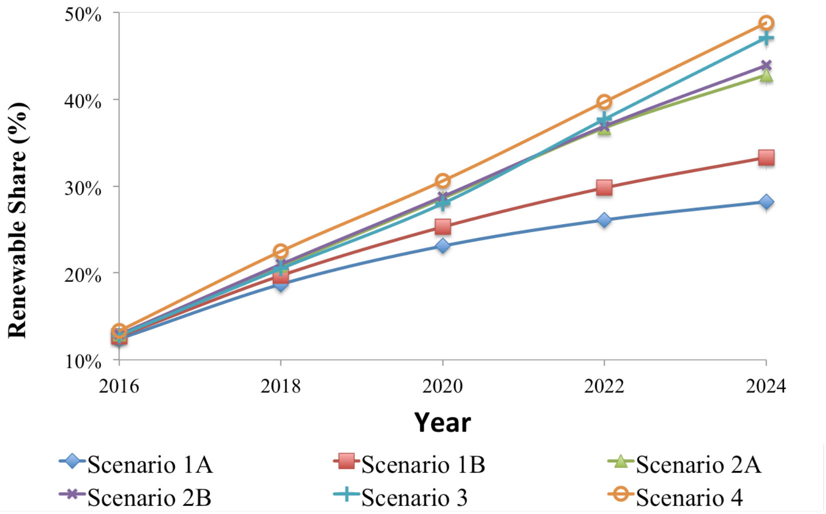

Figure 2.C.1. Evolution of the renewable share (%)

Next, as backup variables, Figure 2.C.2 shows spilled energy, measured as the renewable energy surplus above the total renewable, in percentage. Also, Figure 2.C.3. shows the average generation costs of the electric system, measured in €/MWh generated.

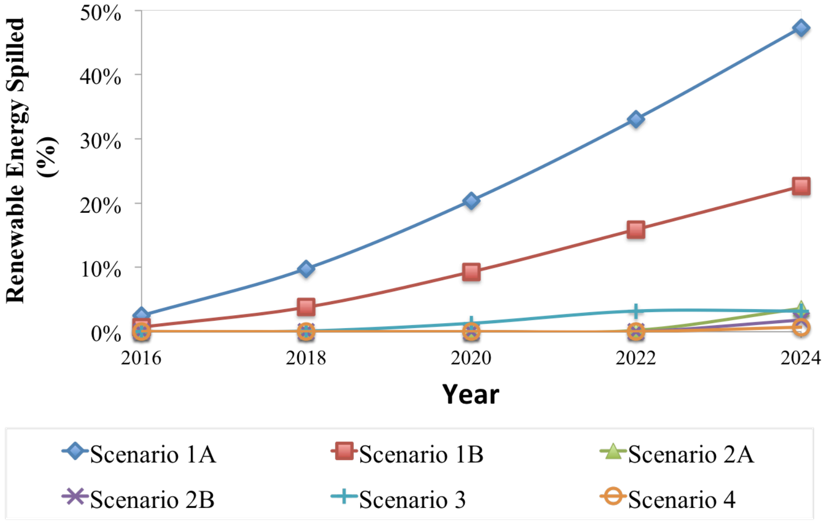

Figure 2.C.2 Renewable energy spilled

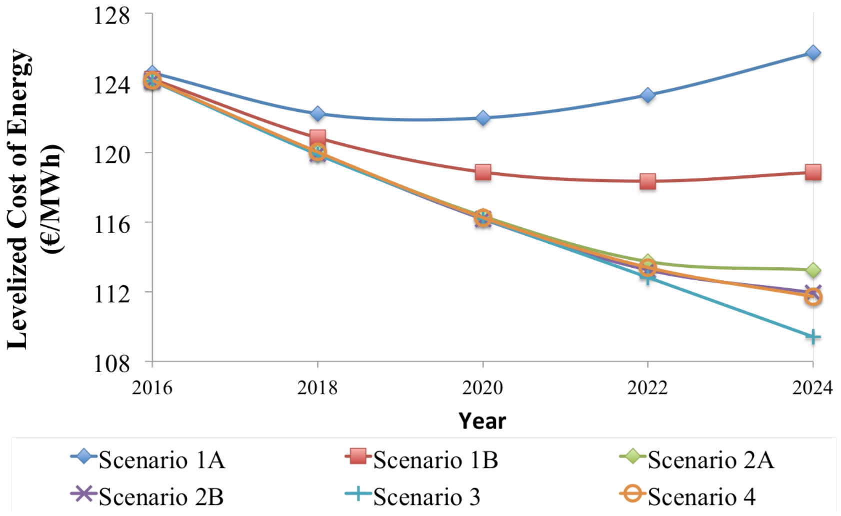

Figure 2.C.3. Average LCOE of the electricity mix

Figure 2.C.4. shows the ratio of the electric system's CO_2 emissions, measured in $kgCO_2$/ kWh generated.

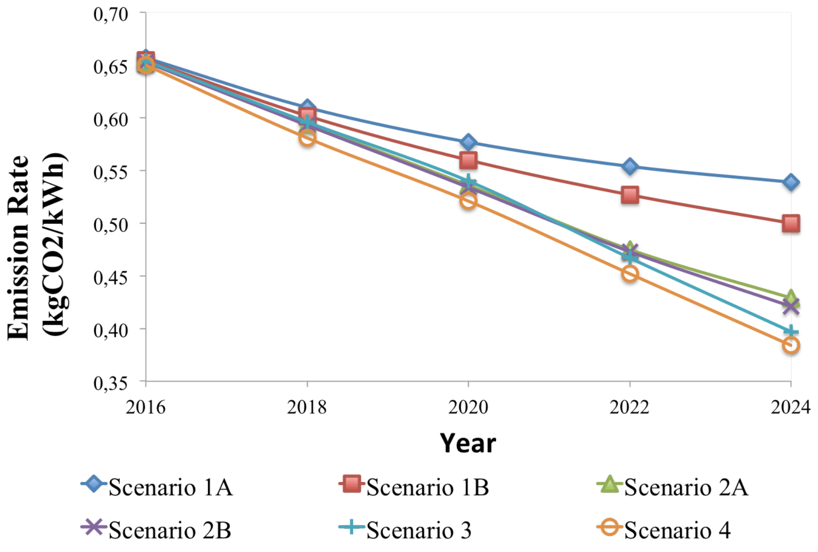

Figure 2.C.4. Emission rate in the electricity production

Finally, we observe the reduction in the domestic consumption of fossil fuels, measured in percentage of reduction over current starting point in figure 2.C.5.

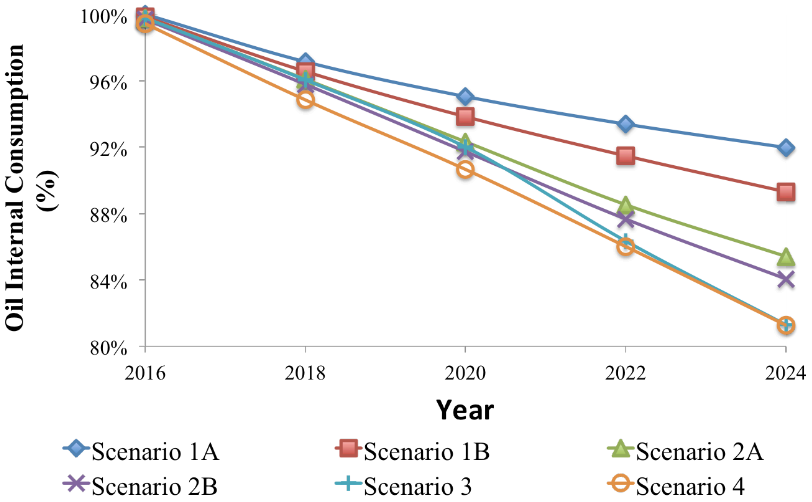

Figure 2.C.5. Reduction in oil internal consumption

Chapter 3.

Willingness to pay for electric vehicles in island regions: the case of Tenerife (Canary Islands)

3.1 Introduction

In the 2015 Climate Change Conference recently held in Paris, the big leaders, experts and scientists from around the world discussed the challenges and new policies for mitigating climate change issues (Nations, 2015). In response, the EU established the Winter Package promoting new measures to boost the provision of renewable energies and create new energy markets in EU (European Commission, 2016). The task is even more challenging for Europe's isolated regions, like the Canary Islands (Spain), mainly due to their specific geographic conditions. Nowadays, the Canary Islands archipelago is almost totally dependent on fossil fuels as a primary energy source reaching a 98.9% of the energy uses, where only 8.4% of electricity generation in the islands comes from renewables (Gobierno de canarias, 2015; Ramos-Real, Moreno-Piquero, & Ramos-Henríquez, 2007; REE, 2015). Marrero & Ramos-Real (G. a. Marrero & Ramos-Real, 2010) highlight the enormous inefficiency in the island electricity sector, the overruns, the high fuel price volatility risk, and the high rate of CO_2 in the final product. However, introducing renewable sources such as wind or photovoltaics is not an easy task in small and isolated islands, mainly due to the intermittency and small size of the power systems (Ramirez-Diaz, Ramos-Real, & Marrero, 2016). To overcome this problem, energy storage could be a solution as it adds stability to the electric power systems (Díaz, Ramos-Real, Marrero, & Perez, 2015; Erdinc, Paterakis, & Catalão, 2015; Rious & Perez, 2014), which may help increase the share of renewables.

Electric vehicles (EVs) could be part of the solution for isolated system, as they can be used not only as an energy storage systems but also as demand–side response devices (G. A. Marrero, Perez, Petit, & Ramos-Real, 2015; Rious & Perez, 2014). Moreover, EVs provide other benefits to electric power system, including voltage and frequency regulation, backup for renewable intermittency, and peak shaving (Hidrue & Parsons, 2015; Sioshansi & Denholm, 2010; Weiller & Neely, 2014). However, in order to benefit from these advantages, it is first necessary to introduce specific regulatory reforms to overcome certain market barriers (Borne, Korte, Perez, Petit, & Purkus, 2018). Various strategies based on sharing EV cars in cities have been tested around the world (Bignami et al., 2017; Firnkorn & Müller, 2012), and similar initiatives could be applied to the Canary Islands, where traffic congestion is a serious issue (EUROSTAT, 2017).[1] According to (Díaz et al., 2015), the introduction of 50,000 EVs as distributed energy storage in the island of Tenerife (Canary Islands) could increase the share of renewables by up to 30% and reduce CO_2 emissions by 27%. However, despite both these

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[1] The Canary Islands counted 631 vehicles per thousand inhabitants in 2015, a rate that is higher than the Spanish average (481) and the EU-28 average (497).

potential benefits and the Spanish government support through financial incentives, EV sales in the islands remain sluggish compared to the mainland (DGT, 2016; MOVEA, 2016).[2]

In addition to the benefits mentioned above, the Canary Islands present a set of characteristics that make the introduction of EV even more attractive. The small size of the territory dictates driver mobility routines, as the short average travel distance reduces the effects of range anxiety. There is therefore a need to promote new business models based on 'e-mobility' (Beeton & Meyer, 2014; Bohnsack, Pinkse, & Kolk, 2014; Sadek, 2012). Studies assessing the characteristics of early adopters (Plo¨tz, Schneider, Globisch, & Du¨tschke, 2014; Vassileva & Campillo, 2017) have found that identifying these customers and their characteristics facilitates the promotion of EVs in the market. Furthermore, policy-makers and private companies could use experiences with EV and barriers to EV adoption as a startpoint to design strategies geared to wider adoption of this disruptive technology.

Two concepts are useful for analyzing the profile of a potential EV buyer. First is the willingness to change (WTC) to an EV, and second is the willingness to pay (WTP) for an EV. From an empirical point of view, an early adopter can be defined as an individual who is willing to change from a conventional car and also willing to pay the most for an EV (Gärling & Thøgersen, 2001). Contingent valuation (CV) is a widely used method for tackling this issue. The CV method is to directly interview consumers, creating a realistic (but hypothetical) market scenario that starts by describing a good or service and ends by getting respondents to directly state their willingness to acquire or pay for it (Carson, 2000; Mitchell & Carson, 1989).

The aim of this chapter is to analyze the EV market in the Canary Islands and the characteristics of EV early adopters. W performs a two-step evaluation of WTC towards EVs in order to evaluate the impact before and after providing general information on EVs (Thiel, Alemanno, & Scarcella, 2012). The WTP for an EV is also calculated in order to quantify potential EV sales. To achieve these goals, an original survey was performed in Tenerife by collecting data from a representative sample of 250 private car drivers. Binary logistic (Logit and Probit) and continuous (Tobit) regression approaches are used to analyze the impacts of a set of explanatory variables on WTC and WTP for EVs. We explore the inclusion of two relevant issues measured through synthetic indexes, i.e. *environmental concerns* and use of *Information and Communication Technologies* (ICT) that could be decisive in shaping individual attitude to EVs.

This work brings an important empirical contribution to the literature by identifying the potential reservoir of EV early adopters within an isolated island region. The results reveal that mobility routines affect early-adopter decisions in island conditions due to the kilometers

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[2] According to the *Dirección General de Tráfico* [Spanish 'Directorate-General of Traffic'], a total of 127 EVs have been sold in the Canary Islands (0.21% of overall car sales), a share that is clearly lower than in the rest of Spain (0.27%) and far lower than in leading countries such as the UK (1.1%), the Netherlands (3%) and Norway (22.9%).

covered and range required by car drivers. We find that WTP correlates positively with income, age and education level, and those early adopters tend to be ICT- friendly and environmentally conscious.

Section 3.2 presents the empirical application (the CV experiment) and describes the survey structure and the sample. Section 3.3 presents the descriptive results of the survey and an estimation of potential EV sales. Section 3.4 details and discusses the outcomes of the logistic and continuous regressions. Finally, section 3.5 concludes.

3.2 Contingent Valuation Experiment

According to Carson (Carson, 2000), contingent valuation (CV) is a widely-used technique for the measurement of WTP and the valuation of public goods and services. The method consists in using interviews to create a realistic (although hypothetical) market scenario, that starts by describing the good or service and ends by getting respondent to directly state their WTP (and also WTC) for it. This CV methodology has been used for market valuation of non–market or new-to-market products and/or services (Carson & Hanemann, 2005). Governmental agencies and international organizations have applied this same technique to assess the potential market (Mitchell & Carson, 1989) and WTP for solutions in energy (Bollino, 2008; Carlsson et al., 2004; Hao, Ou, Du, Wang, & Ouyang, 2014), pollution (Wang, Sun, Yang, & Yuan, 2016) and transport (David A. Hensher and Truong P. Truong, 2007).

Focusing on the EV studies, Thiel et al. (Thiel et al., 2012) led a CV experiment to determine the intention to buy an EV in a set of European countries, and found that in Spain, 50% of car drivers would be willing to buy an EV. Italy is just ahead at 54%, while France is at 30%, Germany 31%, and the UK at 27%. Other studies assessing WTP for EVs highlight the value of improving knowledge on EVs and find that the most important common features that explain EV purchases are levels of emissions, individual incomes, environmental awareness and educational attainments (Erdem, Şentürk, & Şimşek, 2010; Larson, Viáfara, Parsons, & Elias, 2014).

Here we use a CV experiment to assess two important issues: i) WTC from a conventional car to an EV; ii) WTP for an EV. WTC is assessed using a dichotomous- choice question (Yes/No). This concept is defined by the respondent's readiness to pay more for an EV instead of their preferred conventional vehicle. This definition does not mean the consumer is immediately going to buy an EV, but that they are a candidate buyer of this new technology. WTP is assessed using an open-ended question and the payment card elicitation. First, we ask for the WTP for a new conventional car (open-ended format). If the respondent is willing to change to an EV, we ask for how much more money they would be willing to pay it (open-ended format). If the respondent is willing to pay less for an EV, we then ask for the discount rate (via payment card format) on the amount of money previously stated in the WTP for a new conventional car.

Oerlemans et al. (Oerlemans, Chan, & Volschenk, 2016) analyze different CV formats and found that the open-ended question is easy and convenient for respondents to answer with complete freedom. The payment card format then offers a simple ranged response and greater efficiency than the dichotomous choice. The structure of our CV experiment is described below.

3.2.1 The survey structure

To develop the CV survey, we considered the use of an iterative face-to-face pilot questionnaire designed by an expert focus group.[3] The questionnaire is described in full in Appendix A. Following Carson (Carson, 2000), the CV survey design is structured as follows: a) presentation of the purpose of the survey; b) detailed description of the good and its purchase conditions to be valued; c) elicitation section to ask about WTC and WTP; d) socio-demographic characteristics of the respondents. Building on this structure, we propose an original CV survey with five main steps. First, respondents are briefed on the survey (step 1). Next, respondents are asked about their mobility characteristics (step 2). In this step, they answer with their average distance travelled per day, distinguishing between weekdays and weekends, after which we ask them about the minimum range that would prompt them to buy a vehicle (Franke & Krems, 2013).

In step 3, we obtain the WTC and WTP for an EV (Figure 3.1). First, we give an open-ended question on the WTP for a new conventional vehicle (question 4 in the questionnaire). Then we describe hypothetical scenarios on EV infrastructure location on the island and the purchasing conditions in order to start the CV experiment. Respondents are then given two assumptions: i) there is a charging infrastructure distributed around the island and the user has a charging station at home; ii) the EV purchasing conditions include owning the battery instead of renting it. The people surveyed then answer a dichotomous question on whether they would be willing to pay more for an EV to replace their preferred conventional vehicle (question 5). For question 6, the interviewees are given additional information on the features of EVs (pollution, consumption, range, charge and acceleration), and then re-polled on question 5 (Hidrue, Parsons, Kempton, & Gardner, 2011).[4,5]

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[3] The survey design process was conducted by an expert focus group that comprises academics, researchers and experts from private companies. Two different rounds of 10 in-depth interviews using a preliminary questionnaire were executed to an initial group of respondents in order to check the internal validity of the survey. The suggestions provided by these respondents and the expertise of the members of the focus group helped in the design of the final questionnaire.

[4] This information is provided as follows: *"The electric vehicle pollutes 95% less locally, and fuel costs (recharge) are 85% less. The EV is silent and has 25% more acceleration. Moreover, the EV needs 60%*

Depending on the response to question 6, the respondent then completes the WTP questionnaire. If the respondent answer "yes" (willing to pay for an EV to replace their preferred conventional vehicle), then we ask how much more money they would be willing to put into an EV (question 7). Given the information previously provided, and by analogy with conventional cars, they should have an idea about the amount of money they would be willing to pay. The effects of "protests zeros" and the "scope effect" caused by the use of the open-ended format are thus mitigated.[6] However, if the respondent answers "No", the interviewer jumps to question 8, which is related to the price differential reduction needed in order to buy an EV.

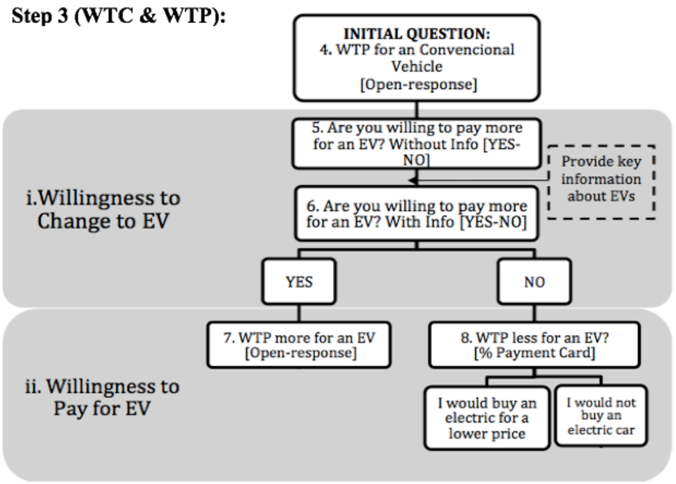

Figure 3.1. WTC and WTP questionnaire design (step 3)

In step 4, respondents complete a socioeconomic questionnaire in which we ask for age, gender, income, education, area of residence, number of cars in the household, and age of these cars. Finally, in step 5, we include questions addressing degree of environmental concern and frequency of use of technologies (see below for details).

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less maintenance compared to a conventional-fuel car. However, EV range reaches about 100–150 kilometers, depending on the route, and changing takes a long time (more than 30 min))"

[5] This elicitation format could cause some common problems such as "yea-saying". To offer a solution to this problem, the expert focus group suggested adding the possibility of acquiring an EV for a lower price. To guarantee a set of choices in which all respondents are represented, the option *I prefer the conventional car, but I would acquire an EV if it was cheaper to buy* is also included.

[6] The "protest zeros" effect occurs when the respondents fail to answer the open-ended question chiefly because they to valuate the product. The "scope effect" is caused by important pitfalls in questionnaire design or survey data collection procedure, or when the respondents struggle to understand the questions.

3.2.2 Indexes of environmental concern and ICT use

Our analysis considers two further aspects, environmental concern and familiarity with ICTs, for which we constructed two synthetic indexes (Appendix A). Both these index metrics are scaled from 0-10 (EC, 2008). Figure 3.2 shows the components and the weights selected for each component in the composite indexes.

The environmental concern index (ECI) is based on the response to four questions. The first one is level of awareness about the source of greenhouse gases emissions from electricity generation, the second is level of commitment to purchase low-energy-consumption appliances, and the third measures the rational use and saving of energy both in the home and in the car. The fourth and final item valuates the WTP for 100% renewable energy (Amador, Gonz??lez, & Ramos-Real, 2013).

The ICT index (ICTI) measures the respondent's daily use of ICT via their response to two questions. The first one captures ownership of ICT devices (desktop, laptop, or smartphone with Internet connection) and the second captures daily use of Internet (WEF, 2016).

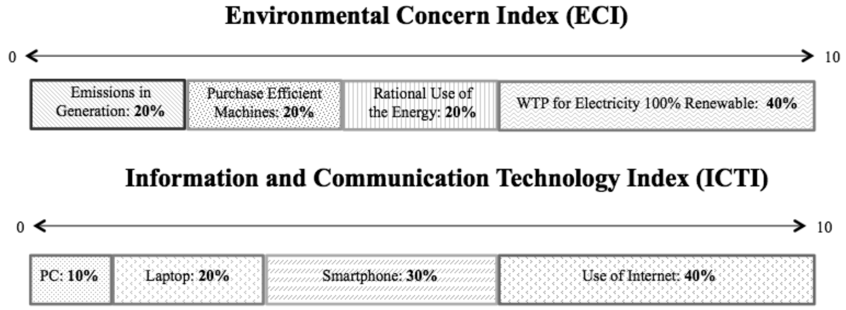

Figure 3.2. Synthetic Indexes–composition and component weightings

3.2.3 Description of the sample

The questionnaire survey was conducted in Tenerife, which is the largest of the Canary Islands in surface area (2,034 km^2) and population (891,111 inhabitants and 6.4 million tourists per year). The island comprises 31 municipalities in which every variety of populated areas in the archipelago is represented, from large cities (such as Santa Cruz de Tenerife) to small rural municipalities (such as Vilaflor). The island also counts a large diversity of driver profiles in terms of mobility routines. This means that in the same island, there is a representation of individuals who usually drive long-distances trips, such as motorway routes, and individuals who drive short-distances trips, such as urban and suburban routes. This is an important factor for checking whether there is a specific island-driver profile and whether there is a relationship between driver profiles and the limited range offered by the EVs.

Pollsters scattered around different areas in Tenerife conducted the survey from April to September of 2014. The sample of respondents was 250 private vehicle drivers in the island of Tenerife, which assures a small sampling error of 6.2%.[7] The questionnaire was delivered through face-to-face interviews to regular drivers (holders of driving license and owners of a vehicle). Table 3.1 charts the socio-demographic characteristics of the sample. Note that the characteristics of the sample resemble the general population in terms of age, gender, and population by geographic area, which gives reliability to our sample. [8]

Table 3.1. Description of the sample

Categories	**Total driving licenses in Tenerife (%)**	**Sample (%)**
Total	359,200 (100%)	250 (100%)
By Gender		
Male	163,485 (45.5%)	123 (49.2%)
Female	195,715 (54.5%)	127 (50.8%)
By Age		
18–29	59,739 (16.6%)	37 (15%)
30–39	84,834 (23.6%)	71 (28%)
40–49	91,172 (25.4%)	88 (35%)
50–59	65,329 (18.2%)	39 (16%)
60-plus	55,293 (15.4%)	15 (6%)
By Residence area		
Capital	160,087 (44.6%)	119 (47.6%)
North	94,242 (26.2%)	64 (25.6%)
South	104,871 (29.2%)	67 (26.8%)

3.3 Descriptive results and estimation of market penetration

In this section we report the descriptive results of the survey and analyze the market penetration of the EVs in Tenerife. Table 3.2 summarizes results on the WTP and WTC questions. The first important result is that 44.0% of respondents are willing to pay more for an EV to replace their preferred conventional car, base on their own knowledge of EVs technology (first row, Table 2). After we gave them information on key EV features, 21.2% of respondents

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[7] Total number of individuals holding a driving license in Tenerife was 359,200 in 2014. In order to match our sample to the population, we consider the driving license as our main condition. We decide to segment the sample by area of residence, to balance gender but give more relevance to the 30–49 age-bracket as potential new car buyers, instead of younger and older consumers.

[8] A set of chi-squared tests was performed and, in all cases, there is not enough evidence to reject the null hypothesis, that the sample and the population characteristics are not different.

(53 individuals) changed their opinion in favor of the EV, while only 2% of respondents (5 individuals) changed their initial answer from *yes* to *no*. Hence, providing relevant information on EVs is a crucial factor in shaping the decision whether or not to purchase an EV. Thus, a total of 63.2% of individuals are willing to change a conventional car for an EV (second row, Table 3.2), while 18.8% of people surveyed would consider buying an EV if its price was lower than their preferred conventional vehicle (third row, Table 3.2) (Thiel et al., 2012). The remaining 18.0% are simply not willing to pay for an EV (fourth row, Table 3.2), always choosing their preferred conventional vehicle.

Table 3.2. WTC results

Categories	**YES/NO (% YES)**
Without providing any information on EVs (question 5)	
WTP more for an EV than your preferred conventional car	110/140 (44.0%)
After providing information on EVs (question 6)	
WTP more for an EV than your preferred conventional car	158/92 (63.2%)
WTP less for an EV than the preferred conventional car	47/203 (18.8%)
Never WTC to an EVs (question 8, option a)	45/205 (18.0%)

Table 3.3 (top-panel) gives the WTP results. The first row shows the WTP for a new conventional car, priced at a mean of around €14,315 but with a high dispersion (with a std. deviation of €6,953) [9]. The second row shows the WTP for an EV, priced at a mean of €18,144 (with a std. deviation of €9,040). These data only take into account the individuals who would pay more for an EV (i.e. WTC equal to 1), and so the value represents the most positive attitude of the respondents regarding WTP. The third row shows the WTP for the whole set of respondents who would pay some amount for an EV (excluding the 18% of respondent who prefer a conventional car), resulting €15,935 for the mean and a std. deviation of €9,107.

Furthermore, Table 3.3 (bottom-panel) shows the mobility characteristic results. First, average daily distance travelled is one of the most important parameters to considered. As Table 3.3 shows, the mean distance covered during weekdays is 34.3 km, increasing to 40.68 km on weekend days. The second mobility-factor issue is the minimum range required in order to acquire an EV. In our survey, the sample mean is around 252.36 km. Comparing the results detailed above from island regions with the results of continental zones, there are significant differences between island and mainland drivers. Indeed, according to Perez et al., (2013), certain mobility characteristics could be particularly relevant in island territories to limit the *range anxiety* issue due to territory characteristics.

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[9] According to Facoauto (association of Spanish car dealerships) the average car price in Spain in 2014 was 19,723€ after taxes and aids. The gap between the real price in Spain and the WTP obtained in our study in Tenerife (14,315€) could be mainly caused by lower taxes on car purchases in the Canary Islands, 3% instead of 21% in the mainland.

Table 3.3. Descriptive statistics for WTP and mobility characteristics

Categories	**Mean**	**Std. Deviation**
WTP questions		
WTP to purchase a new car (all sample)	€14,315	€6,953
WTP to purchase an EV (only WTP more for EV than conventional, 63.3% of sample)	€18,144	€9,040
WTP to purchase an EV (all sample excluding individuals who would never buy an EV, 82.0% of sample)	€15,935	€9,107
Mobility characteristics of Drivers		
Average daily distance travelled weekdays (km)	34.30	35.90
Average daily distance travelled weekend days (km)	40.68	35.76
Minimum range required (km)	252.36	137.29

In order to estimate the potential market penetration of the EV, the WTP distribution of the sample is compared with the real average market price of EVs in Tenerife (DGT, 2016). Using the prices of total sales in the Canary Islands market during the years 2010–2016, the average real market price is €33,841 with a standard deviation of €7,997. A potential EV buyer in Tenerife (or early adopter) can be defined as those individuals whose WTP is this average price of €33,841. Accordingly, we find that only 4.4% of people in our sample would be willing to acquire an EV, which would equate to 619 EV sales per year (DGT, 2016).[10] Taking into account the Spanish government aid provided to subsidize the acquisition of an EV (€5,500), the percentage of people in our sample that would willing to acquire an EV reaches 7.2%, which would equate to 1,013 EV sales per year (Instituto Tecnológico de Canarias S.A, 2013).[11] However, the current sales figures show that just 46 EV were sold in 2016 in Tenerife. This gap between current sales and ideal market scenario could be attributed to two main reasons: (i) the narrow market offer of EV models, which excludes a majority of possible buyers; (ii) the assumptions of the hypothetical scenario on availability of charging points around the island. [12]

3.4 Estimation results: determinants of the WTC and the WTP

In this section we report the estimation results for the WTC and WTP models. Explanatory variables are classified by groups: a) socio-economic variables (gender, age, income and educational attainments); b) individual car ownership (number of cars in the household and age of the cars); c) mobility characteristics of drivers; d) synthetic indexes (ECI and ICTI).

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[10] According to the data from DGT, an average of 14,065 cars were sold per year in Tenerife during the period of the study (2010-2016).

[11] This assessment is close to the predictions made in 2013 by the Canary Islands government about EV sales in Tenerife (566 electric cars in 2015 and 1,528 in 2016).

[12] Using as the reference the mean plus twice the standard deviation on the EV price (€44,335), instead of the average EV market price, the estimated EV sales would drop to 169 EVs per year, which is close to the current sales picture.

Table 3.4. Explanatory variables of the models

GROUP	CODE	NAME	DESCRIPTION	TYPE OF VARIABLE
SOCIO-ECONOMIC VARIABLES	Gender	Gender	Gender (male=0, female=1)	Dichotomous
	Age	Age	Age of the respondent	Continuous
	Dummy_inc_1	Income	Income level (€22,001–€35,000€=1, other=0)	Dummy var.
	Dummy_inc_2		Income level (more than €35,001€=1, other=0)	
	Dicho_university	Education	Education level (University=1, other=0)	Dichotomous
INDIVIDUAL CAR OWNERSHIP	Dicho_anti	Age of cars	Average age of the cars in the family unit (more than 12 years old =1, less than 12 years old=0)	Dichotomous
	Dummy_ncar	Number of cars in household	Number of vehicles in the household (One vehicle=1, more than one=0)	Dichotomous
MOBILITY CHARACTERISTICS VARIABLE	Min_range_req	Minimum range required	Describe the Minimum range required for the user in order to purchase an EV (in kilometres).	Continuous
	Av_dist_week	Average distance travelled per week	Describe the number of kilometres (on average) covered in a week using cars.	Continuous
SYNTHETIC INDEXES	ICTI	ICTI	Level of familiarity with and use of information and communication technologies, where 0 is the minimum and 10 is the maximum.	Continuous
	ECI	ECI	The level of environmental awareness, where 0 is the minimum and 10 is the maximum.	Continuous

The WTC model is estimated following a *logit* and a *probit* approach, whereas the WTP model, in which the variable is truncated at zero, uses a *tobit* regression model (Brooks, 2008). The estimated model is illustrated in (3.1):

$$y_t = \beta_1 + \beta_2 x_{2,t} + \beta_3 x_{3,t} + \cdots + \beta_k x_{k,t} + u_t, \qquad t = 1,2, \ldots T \tag{3.1}$$

where the variables $x_{2t}, x_{3t, \ldots,} x_{kt}$ are the explanatory variables, i.e. 11 individual variables here organized in the 4 different categories described in Table 3.4 (Harrell, 2015). These explanatory variables have an impact on the dependent variable (y_t) through the estimated coefficients $\beta_1,$ $\beta_2, \ldots, \beta_k$, which represent the partial effect of each explanatory variables on the endogenous variable, with all other variables held constant. The term u_t is the error term representing the part not explained by the model.

Although our sample size implies a sampling error of only 6.2% (as commented in section 3.2.3), we perform an intensive robustness analysis to address potential representativeness problems in our 250 observations.[13] Lack of representativeness would entail, among other things, inaccurate results and thus lack of robustness. Accordingly, in addition to the baseline

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[13] To reduce the number of regressors and thus increase the degree of freedom of the regression, we considered the possibility of employing principal component analysis (PCA). The PCA technique groups each set of variables in a synthetic index. However, PCA can only be applied if the groups of variables are correlated strongly enough (correlation matrix) and whether exist a sampling adequacy (KMO test among others), which is not the case in our model. Therefore, we discarded the PCA approach to reduce the number of regressors.

specification, we have also considered a backward stepwise approach, i.e. a fitting regression method in which in each step considers a variable to be added or subtracted from the set of original explanatory variables based on a F-tests or Akaike's information criterion (Harrell, 2015). We have also conducted estimations by blocks of variables, i.e. including only the set of socio-economic variables or individual car ownership or mobility characteristics of drivers or the synthetic indexes, or any combinations of these blocks. As a final robustness analysis, we have performed a bootstrapping exercise (using 300 replications, dropping 20% of the sample in each simulation,), concluding that sampling selection does not affect our main results either. In all cases, we find that the conclusions reached in the following section are strongly robust. Results about the backward stepwise approach will be showed in Appendix 3.B for WTC models and in Table 3.7 for the WTP model. Results for the estimation by blocks and bootstrapping are available upon request.

3.4.1 Willingness to change results

In the WTC model, '1' denotes that the individual is willing to change to an EV, while '0' indicates that the individual is not willing to change their preferred conventional vehicle for an EV. Table 3.5 shows estimated results for our baseline specification. Results are robust to the alternative specifications. In our application, the *logit* and *probit* models are applied twice: before (first and second columns) and after (third and fourth columns) the individuals were given extra information on the feature characteristics of EVs.[14] For extra information of the dichotomous estimations, appendix 3.B (Table 3.B.1.) contains the results for our best model under the backward stepwise approach.

Results of both logit and probit show that when respondents had not received extra information (first and second columns), the only significant socioeconomic characteristics are gender and age: women are more reluctant to change to an EV than men, and older people more likely to change to an EV than younger people. However, these socioeconomic characteristics are no longer significant once the respondents have been provided extra information on key EV (third and fourth columns). Thus, advertising campaigns on the properties of EV would take socioeconomic factors out of the equation explaining WTC decision. This is an important result, because it suggests that mass information to all individuals on the characteristics of the EV would make it possible to gain a larger market share without significant age and gender limitations.

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[14] All estimated models in this section have been evaluated through global significance tests (goodness-of-fit, R², and ANOVA), partial correlation verification tests, absence of multi-collinearity (F-test, using tolerance analysis) and forward likelihood-ratio testing to adjust the model. All models passed these tests.

Table 3.5. WTC estimated results

Endogenous Variable	**WTC an conventional vehicle for an EV (Own knowledge on EVs)**		**WTC an conventional vehicle for an EV (Given extra info on EVs)**	
	Logit	Probit	Logit	Probit
Explanatory variables	B (Std. error)	B (Std. error)	B (Std. error)	B (Std. error)
Gender	-.648 (.303)**	-.387 (.181)**	-.426 (.304)	-.240 (.180)
Age	.029 (.015)*	.017 (.008)*	.016 (.015)	.009 (.008)
Dummy_income_1	.350 (.362)	.211 (.220)	-.201 (.367)	-.091 (.221)
Dummy_income_2	.291 (.521)	.179 (.311)	-.301 (.530)	-.165 (.317)
Dicho_university	.215 (322)	.117 (.193)	.328 (.330)	.175 (.197)
Dicho_anti	.530 (342)	.317 (.207)	.479 (.363)	.274 (.213)
Dicho_ncar	.258 (.292)	.155 (.175)	.277 (.297)	.155 (.177)
Av_dist_travelled_week /10	-.015 (.007)**	-.009 (.004)**	-.013 (.007)*	-.007 (.004)*
Min_range_required /10	-.013 (.011)	-.007 (.006)	-.031 (.011)***	-.018 (.006)***
ICTI	.049 (.071)	.027 (.043)	.014 (.074)	.013 (.042)
ECI	.551 (.107)***	.331 (.062)***	.433 (.995)***	.259 (.058)***
Constant	-4.501 (1.195)***	-2.646 (.683)***	-1.650 (1.087)	-1.019 (.064)
Number of observations	250	250	250	250
Pseudo R^2	0.164	0.164	0.138	0.136
LR chi^2	56.52	56.53	45.52	44.84
Classification table	69.60%	68.80%	73.20%	74.00%

* Significance 10%, ** Significance 5%, *** Significance 1%

Note that level of education and income variables are not significant for the WTC decision in all estimated models. The question here focuses on whether an individual would be willing to change to an EV, without any reference to whether the change would be financially feasible (as we will see below, these variables are significant for the WTP models).

The second set of variables related to individual car ownership (i.e. number of vehicles in the household and age of the cars) showed no determinant for the WTC decision either. For the third set of explanatory variables (mobility characteristics), average distance travelled per week is negatively related and significant in all estimated models, which shows that drivers have some negative preconceptions on the EV range anxiety. Another important result is that the "vehicle range requirement" turns highly significant, with negative coefficient, once extra information is provided (third and fourth columns). Once again, providing relevant information on the EVs is crucial factor in shaping the WTC decision.

Finally, note that ICTI is not significant in any of the WTC models, whereas ECI is positive and highly significant in all models, at similar levels of significance and magnitude. Thus, the WTC decision is strongly correlated with an individual's level of environmental concern. In other words, improving the environmental awareness of the population would help improve market penetration of EV in the islands.

Based on the estimations from Table 3.5, Table 3.6 next shows a set of conditional probabilities to illustrate the magnitude of the impact of most significant variables in explaining the WTC decision. First, an "average" driver (i.e. setting the average level of all explanatory variables) has a 41.9% probability of being ready to pay more for an EV. [15] However, once extra information on EVs is provided, the average driver probability of being ready to pay more for an EV rises to 65.4%. Thus, information campaigns on EV features are key to boosting consumer interest in these vehicles.

Table 3.6. Probabilities of the WTC

Nomenclature	Description	Extra info on EVs	Probability (% 'yes')
$WTC_{without\ info}^{Average}$	WTC to an EV if the respondent is average on all variables.	NO	41.9%
$WTC_{without\ info}^{gender=0}$	WTC to an EV if the respondent is male.	NO	50.0%
$WTC_{without\ info}^{gender=1}$	WTC to an EV if the respondent is female.	NO	34.3%
$WTC_{without\ info}^{ECI=10}$	WTC to an EV if the respondent has a top ECI	NO	88.0%
$WTC_{with\ info}^{Average}$	WTC to an EV if the respondent is average after receiving information	YES	65.4%
$WTC_{with\ info}^{Min\ ran\_req=25.72-13.72}$	WTC to an EV if the driver requires the 'average minimum range required' minus the standard deviation (120 km)	YES	74.5%
$WTC_{with\ info}^{Min\ ran\ req=25.72+13.72}$	WTC to an EV if the driver requires the 'average minimum range required' plus the standard deviation (394 km)	YES	54.9%
$WTC_{with\ info}^{ECI=10}$	WTC to an EV if the driver has the top-level ECI	YES	92.0%

If we take a closer look at certain attributes, males have 15.7% more probability of switching to an EV than females. Note too that the mobility characteristics only start to become relevant once people are given extra information on key EV properties. In this situation, if we change the driver's minimum range required within their standard deviation, the probability of switching to an EV lies between 74.5% (at least 120 km of autonomy) and 54.9% (for 394 km). Finally, comparing an average driver with average environmental concern to an alternative driver with the top-level environmental concern, the probability to change to an EV would rise to about 88%. This figure remains essentially unchanged after providing information on key EV properties.

3.4.2 Willingness to pay results

Next, we discuss the estimation results of the *tobit* model (Table 3.7), which analyzes the determinants of WTP for an EV. The model is estimated using the sample of individuals who responded *'yes, willing to pay more for an EV'* after receiving information about the properties of the EV (158 surveyed, 63.2% of the total sample). The first column shows the estimated

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[15] All the attributes considered in the model for the average individual are represented by the mean. For dummies or dummy variables take the average rather than median or mode.

results when including all explanatory variables, while the second column gives the results for the stepwise regression method. As with the WTC analysis, results are strongly robust to alternative specification models.

Table 3.7. WTP model results

Endogenous variable	**WTP for a new EV**	**WTP for a new EV**
Explanatory variables	Tobit B (Std. error) ^{sig}	Stepwise regression-Tobit B (Std. error) ^{sig}
Gender	-3045.3 (1148.6)***	-2889.9 (1127.1)**
Age	204.6 (54.9)***	210.01 (54.5)***
Dummy_income_1	3895.9 (1405.5)***	3532.2 (1393.2)**
Dummy_income_2	10701.5 (1975.38)***	10090.6 (1928.3)***
Dicho_university	2512.5 (1212.5)**	2641.6 (1192.9)**
Dicho_anti	945.73 (1257.7)	-
Dicho_ncar	-1438.4 (1108.7)	-
Av_dist_travelled_week /10	73.96 (29.79)**	64.8 (29.4)**
Min_range_required /10	-55.5 (45.5)	-
ICTI	782.4 (255.5)***	757.7 (253.9)***
ECI	1101.2 (396.6)***	1085.2 (393.8)***
Constant	-4077.6 (4155.9)	-5658.5 (3908.5)
Number of objects	158	158
R^2	.489	.476
F (11, 146)	12.71	16.93

* Significance 10%, ** Significance 5%, *** Significance 1%

First, all socioeconomic variables are significant in the WTP for an EV. Females reduce their willingness to pay for an EV in €3,045 in comparison with males. Conversely, age, education and income levels increase the WTP. As expected, the most important socioeconomic variable for the WTP is the individual's level of income, the WTP for an EV increases by up to €10,701 for highest-income-level individuals compared to the lowest-income-level individuals.[16] These results concur with Erdem et al. (2012), who stated that high levels of salary and education attainments are important variables to explain the WTP for an EV.

Individual car ownership variables do not have a significant impact on WTP. Nevertheless, as expected, one of the mobility characteristics is significant. This variable is the average distance travelled per week, which is positively related with the WTP for an EV, and increases by around €73.9 per 10 additional kilometers covered per week. This positive relationship between the kilometers travelled and WTP could be explained by the fact that potential EV drivers believe that using an EV will allow them to save both fuel and euros per kilometer driven.

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[16] We could highlight that the island (15,995€ per year) inhabitant has poor salaries in comparison with the mainland regions in Spain (18,429€ per year). Thus, the WTP of island drivers is expected to be lower than in the rest of the Spanish territory.

Finally, the WTP is positively and strongly correlated with ICTI and ECI. Thus, as discussed earlier, one option to increase the WTP for the EV (and thus increase market penetration of EVs) is to improve the environmental concern of the population. Indeed, according to one study, environmental concern is one of the most important factors influencing WTP for hybrid vehicles (Erdem et al., 2012). Thus, if information campaigns on the environmental impacts associated to fossil-fuel consumption brought a 50% increase in average ECI, then the WTP for the EV would rise by €3,000. Even though the ICTI has 30% less impact on WTP than the ECI, greater use of ICTs nevertheless increases the amount willing to be paid for an EV by €782 per index point. In order to boost sales, advisory campaigns by automotive sellers are advised to target their campaigns around the enhanced technological experience and environmental advantages tied to the acquisition of an EV in comparison to conventional vehicles.

3.5 Conclusions and policy implications

This chapter set out to analyze the EV market of Tenerife by characterizing the early-adopters profile and quantifying potential EV sales. We estimated WTC from a conventional car to an EV and WTP for an EV via a contingent valuation experiment using a survey to collect data from 250 private car drivers. Binary logistic and a continuous regression models were then used to analyze the impact of sets of explanatory variables on WTC and WTP for an EV, respectively. This work brings an important empirical contribution to the literature by identifying the potential EV early adopters within an isolated island of the EU.

These are the main findings obtained from the descriptive analysis of the survey:

- The profile of the island car-drivers differs from mainland car-drivers on certain characteristics. Island car-drivers are less exposed to the effects of range anxiety due to natural territorial limitations.
- 44% of respondents would be willing to change their preferred conventional car for an EV. Moreover, when relevant technical information on EV is provided, 21.2% of respondents changed opinion towards acquiring an EV. The island drivers thus show a high level of readiness to buy EVs (more than the average in Spain, which is 50%).
- Considering the current EV prices, 4.4% of people surveyed are willing to buy an EV without any government-subsidized support. This figure would reach 7.2% with the Spanish government support schemes in place from 2010 to 2016.

Regarding the characterization of early adopters, the main findings of the econometric application are as follows:

- According to our analysis of determinants of WTC, those who would be likely to change for an EV are middle-aged men who use their cars regularly (covering many kilometers) but without strong requirements in terms of vehicle range. Moreover, WTC is strongly correlated with the individual's level of environmental concern.

- Increasing age, educational attainment and income levels increase the WTP. As expected, the most important socioeconomic variable is the vehicle driver's income level. Finally, WTP is positively correlated with education level, regular use of ICT devices, and strong environmental concern.

Taking into account the special conditions of Tenerife, replacing conventional cars by EVs could bring significant socioeconomic benefits. More information on EVs is needed to boost the EV market. Information campaigns should focus mainly on two key points: (i) the environmental advantages of using EVs over conventional cars; (ii) the technical characteristics of EVs and their implications for energy and economic efficiency in the mid-to-long term. At the same time, as seen in this empirical work, reducing EV prices through State subsidies would increase EV sales.

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Appendix 3.A. Questionnaire summary

Table 3.A.1 Questionnaire

	Questions	**Format**
	Step 1: Introduction on the survey	
	"This survey aims to collect information about the respondent's perception and willingness to pay for alternative vehicles and their attributes. Moreover, the survey collects information on the respondent's current mobility characteristics. This survey is totally anonymous, and the data collected will be used by the University of La Laguna for scientific purposes only, ruling out any commercial use. If you should have any questions of your own during the course of the survey, the person leading the interview should help clarify them for you. We thank you for your helpful collaboration".	Information
	Step 2: Mobility characteristics of the drivers	
1	*"How many kilometers do you cover on average during a working day?"*	*Bounded response*
2	*"How many kilometers do you cover on average during a weekend day?"*	*Bounded response*
3	*"How many kilometers should be offered by electric vehicles? Give the number of kilometers that you would like to have at your disposal when the car indicates a 100% charge.*	*Open response*
	Step 3: WTC and WTP questionnaire	
4	*"If you were to buy a new conventional vehicle, how much would you be willing to pay?"*	*Open-ended question*
	"Purchasing conditions of an EV include buying a battery (no-leasing) and charging station" and "When you are willing to pay for an EV, it should be assumed that the infrastructure is developed and a charging station is available at home".	Information
5	*"If you were to acquire a new vehicle, would you be willing to pay more for an EV to replace your preferred conventional vehicle?"*	*(Yes-No) single-dichotomous question*
	Information: *"The electric vehicle pollutes 95% less locally, and fuel costs (recharge) are 85% less. The EV is silent and has 25% more acceleration. Moreover, the EV needs 60% less maintenance compared to a conventional-fuel car. However, EV range reaches about 100–150 kilometers, depending on the route, and changing takes a long time (more than 30 min)".*	Information
6	*"If you were to acquire a new vehicle, would you be willing to pay more for an EV to replace your preferred conventional vehicle?"*	*(Yes-No) dichotomous question*
7	*"What is the most you would be willing to pay for an electric vehicle in comparison with the price of your preferred conventional vehicle?"*	*Open-ended question*
8	*"Would you purchase an electric vehicle for a lower price than your preferred conventional vehicle?": a) I'd never buy one; b) I would buy one for 10% less; c) I would buy one for 20% less; d) I would buy one for 30% less; e) I would buy one for 40% less; f) I would buy one for 50% less.*	*Payment card question ("No"-"No, but I would buy at less"*
	Step 4: Socioeconomic questionnaire	
9	*"Age"*	*Open-ended question*
10	*"Gender"*	*Male/Female*
11	*"Income"*	*Bounded response*
12	*"Education"*	*Bounded response*
13	*"Residence area"*	*Multiple options*
14	*"Number of cars in household"*	*Open-ended*

		question
15	*“Age of these cars”*	*Open-ended question*
	Step 5: Key EV user characteristics	
16	*“Awareness of the sources of greenhouse gas emissions from electricity production”*	*Open response [0-10]*
17	*“Commitment to purchase low-energy-consumption appliances”*	*Open response [0-10]*
18	*“Rational use and saving of energy both in the home and in your car”*	*Open response [0-10]*
19	*“WTP for 100% renewable electricity”*	*Bounded response*
20	*“Ownership of technologies (desktop, laptop, or smartphone with internet)”*	*Multiple-choice response*
21	*“Hours of daily use of internet connection”*	*Open response*

Appendix 3.B: Robustness of the dichotomous models

Table 3.B.1 Robustness of the WTC logistic models

Endogenous Variable	**WTC an conventional vehicle for an EV (Own knowledge about EVs)**		**WTC an conventional vehicle for an EV (Providing information about EVs)**	
Explanatory Variables	Logit B (Std. error)	Back. Stepwise B (Std. error)	Logit B (Std. error)	Back. Stepwise B (Std. error)
Gender	-.648 (.303)**	-.599 (.290)**	-.426 (.304)	-
Age	.029 (.015)*	.028 (.013)**	.016 (.015)	-
Dummy_income_1	.350 (.362)	-	-.201 (.367)	-
Dummy_income_2	.291 (.521)	-	-.301 (.530)	-
Dicho_university	.215 (322)	-	.328 (.330)	-
Dicho_anti	.530 (342)	-	.479 (.363)	-
Dicho_ncar	.258 (.292)	-	.277 (.297)	-
Av_dist_travelled_week /10	-.015 (.007)**	-.016 (.006)**	-.013 (.007)*	-.012 (.006)*
Min_range_required /10	-.013 (.011)	-	-.031 (.011)***	-.028 (.010)***
ICTI	.049 (.071)	-	.014 (.074)	-
ECI	.551 (.107)***	.578 (.101)***	.433 (.995)***	.469 (.091)***
Constant	-4.501 (1.195)***	-4.131 (.934)***	-1.650 (1.087)	-1.068 (.560)*
Number of observations	250	250	250	250
Pseudo R2	0.164	0.145	0.138	0.117
LR chi2	56.52	41.49	45.52	34.36

Conclusions

This chapter summarizes the main conclusions of the doctoral thesis and proposes further research.

The contribution of the first chapter has been the assessment of the impact of a managed Electric Vehicle (EV) fleet in an isolated power system with high renewable penetration quote. Apart from the smart charging strategies thought Grid-for-Vehicle (G4V), the Vehicle-to-Grid (V2G) system is also included introducing electricity into the system to compensate the renewable intermittencies and flattening the demand in peak hours.

In order to perform this analysis, we have used the case study of Tenerife, which is the largest island in population and energy consumption from the Canary Islands archipelago. Through a model simulator, designed specifically for the case of isolated power systems, the impact of the EVs is analysed in five different outputs: (i) renewable share; (ii) renewable energy spilled; (iii) CO_2 emissions (both electric systems and road transport); (iv) levelised cost of electricity and (v) energy dependence of the island. Simulating a set of scenarios, we have concluded that the introduction renewable capacity should be accompanied by demand response or energy storage systems. These management systems take advantage of renewable energy spilled in periods when the renewable source is very high, and later inject this energy into the system. According to the results, substituting the 7% of the conventional automobile fleet by EVs (using V2G system) could increase the renewable share up to 6% in comparison with no storage situation in the island. Additionally, the use of V2G system could reduce also the CO_2 emissions in 124,830 Tonnes of CO_2 per year directly in road transport and help to reduce in a 26.6% the emission rate in the electric power system of Tenerife (compared to levels in 2013). From a technological point of view, the advantage of this system is that is fully scalable, the more EVs are connected, the more renewable share is achieved. Furthermore, the V2G system contributes in the reduction of energy dependence both in the road transport sector and in the electricity sector.

In order to response the unsolved questions from chapter 1, chapter 2 attempts to evaluate the impact of the EVs if there were no charging strategy of the EV fleet (a situation known as Plug&Charge). Besides, chapter 2 has assessed the compatibility of the EV fleet management strategies (V2G and G4V) with the introduction of a Pumped-hydro Energy Storage (PHES) system. These scenarios are modelled for the case of La Palma (Canary Islands), that it is a relative small island in comparison to Tenerife. This island has specific conditions in terms of energy vulnerabilities, because of their remoteness and the depth of the ocean does not allow the electrical interconnection with other islands in a long-term future.

In this chapter, the model simulator from chapter 1 is applied again, but completing it with two other new modules: plug&charge situation and pumped-hydro storage systems. According to the Canary Islands renewable energy plans and the estimations on the EV sales, a set of scenarios are analysed up to 2024.

The major insight of the chapter was that plug&charge situation is undesirable in small electric system, mainly due to the uncertainly and the impact numerous loads on the system concentrated on peak hours. These EV charges should be supplied by conventional power plants, and therefore providing an unclean charging for these vehicles. On contrast, the introduction of PHES mitigates the negative effects of the plug&charge situation in terms of emissions and instabilities generated by these unplanned loads. It is also important to mention that the best combination is to introduce both PHES and V2G system, because it allows to increase up to 50% the renewable share in La Palma by 2024, according to our simulations. Moreover, under this combined scenario (PHES plus V2G), the energy spilled from renewable is negligible, the cost is reduced fewer than 10% and the CO_2 emissions are cut off by 26%.

Summarizing the insight provided by the first two chapters, the PHES is a mature technology and good experienced in the Canary Island by REE (*Red Eléctrica de España*), such us in El Hierro island. This storage technology has large overnight cost but is necessary to implement in the near future. Moreover, the introduction of the EV charging management is essential in several key point: (i) to guarantee the security of the system; and (ii) to avoid the uncontrolled situation when the numbers of EVs start to be problematic for the grid in terms of electricity demand. Finally, to achieve a large penetration of renewables (for example over 50%), the EV should be used as distributed energy storage system (through V2G technology). This system is fully scalable as is mentioned previously. The rapid improvement in the EV battery technology is key for the potential of the EVs using these vehicles as distributed energy storage systems in these isolated regions.

Relying on the results from chapter 1 and 2, several conclusions are remarkable: (i) in the short-term, the energy policies should be focus on the promotion of the renewable capacities until achieve between 25% to 30%; (ii) to increase economically and sustainably the share of renewable in the medium-term –apart from increase the renewable capacity–, the energy storage systems must be implemented in the islands; (iii) PHES could be a solution for islands with potential characteristics (orography and environmental protection conditions) to increase the penetration of renewable share up to 50%; (iv) Additionally, the electromobility should be developed gradually and should be managed as soon as possible. First, incentivising the night charging and later promoting demand-side response services. Secondly, when the EVs represent around the 5% of the total fleet of the island, the development of V2G services could be applied in the region. These strategies could be previously implemented in living-labs projects in which the integration of the EV and distributed renewable sources (i.e. residential PV) within the insular electrical grids would be tested.

Chapter 3 has evaluated the demand-side perspective of the EVs in the island context, identifying the characteristics of the possible EV buyer to approach a near-market penetration in the islands. To perform the analysis an original survey has been designed. A total of 250 surveys were conducted during 2014 following a Contingent Valuation (CV) methodology where the Willingness-to-Change (WTC) and the Willingness-to-Pay (WTP) for the EVs were asked to the interviewed. The contribution of this chapter consist on the characterization of the potential buyer (i.e. early adopter) and check whether if the isolation condition –live on islands– could have an certain impact on the EV purchase decision.

The results show that the island drivers have different mobility routines respect the mainland one. They cover less average distance per day and also require less range in comparison to its continental namesake. These facts produce that the island driver is less exposed to the effects of range anxiety. Furthermore, facilitate information is crucial in order to promote an innovative product. According to our results, when information about EV is provided to the individuals 21.2% change their opinion toward acquiring an EV. After information a total of 63.2% of the interviewed would consider buying an EV paying more in substitution of their conventional preferred. The most important variables that determine the WTC are that the possible buyer is a middle-age man with high environmental concern and no large range requirement. Respect the WTP for the EVs, the socio-economic variables that results relevant are the age, high educational attainment and income levels. Furthermore, the intensive use of information and communication technologies and the environmental concerns are the most important variables that affect on the WTP for the EV. Taking the results from the analysis and comparing it with the real market prices, only a 4.4% of people surveyed would be willing to buy an EV (without subsides from government). However, including the current Spanish government aid, the market penetration could rise up to 7.2% of the market.

According to the results, chapter 3 has concluded with this set of policy recommendations: (i) more information on EVs is needed to boost the EV market. Information campaigns should focus not only promoting on the environmental advantages of using EVs, but also the technical characteristics of EVs and their implications for energy and economic efficiency in the mid-to-long term. (ii) It is also important to reduce the EV prices through State subsidies would allow us increase EV sales.