Department of Mechanical and Aerospace Engineering

ELECTRIC VEHICLES CHARGING FROM SURPLUS WIND POWER IN NON-CONNECTED ISLANDS

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A thesis submitted in partial fulfillment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2012

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Signed: Carlos Ara Bellés Date: 7th September 2012

Abstract

The further development of wind energy depends strongly on the ability to accommodate its intermittent and undispatchable nature to the energy system. Likewise, the successful introduction of the Electric Vehicle (*EV*) as an effective means of transport requires overcoming its limitations and minimizing the effect of its drawbacks. This dissertation explores the integration of both technologies together in a favourable context. This context is a Non-Connected Island (*NCI*) where the surplus wind generation, which cannot be exported, can be used to meet part of the energy requirements of an *EV* fleet. The benefits for the energy system are examined if wind power and EVs are introduced together in a combined strategy to an NCI. In order to analyse this, a model of the transportation and electrical energy system of a generic *NCI* is created. To do so, data is extracted from available sources and literature on the topic. Then a calculation method is applied to obtain certain parameters which reflect the performance of the wind and *EV* combined strategy in a *NCI*. The total energy savings, and their related cost and CO_2 emissions savings, are increased remarkably when both technologies are applied together. The results obtained demonstrate that a technological symbiosis exists. In the *NCI* model without wind power generation, the primary energy savings for electricity generation and transport achieved with a 100% EV penetration has been calculated as an 8.51% for a typical August month. Considering the models with existing wind farms in the *NCI*, these savings have been calculated as 11.72%, 14.10% and 16.16% for three different wind availability cases. This trend is also found for the typical December month. Also, the calculated payback time of installing extra wind capacity is reduced by 2.8, 2 and 3.8 years for these three models if the vehicle fleet in the *NCI* is considered fully electric. The existence of wind power favours the introduction of *EV's* and, reciprocally, new investments in wind power benefit from the existence of an *EV* fleet. This dissertation describes a method that can be used with specific data to estimate the benefits of this symbiosis in a real *NCI* and support the decision of promoting both technologies together instead of individually.

Acknowledgments

This dissertation is the culmination of my academic experience in the University of Strathclyde. I would like to express my gratitude to everyone who has helped and supported me in the successful completion of it.

My supervisor and MSc coordinator, Dr. Paul Strachan, for his advice and support during my individual research and also for his approachability during the course.

Katalin, for giving me an insight into the electricity demand profiles and helping me to find some of the data required.

Luke, for facilitating the access to electricity demand data and helping me to interpret it.

Fundacion Iberdrola, for the support offered by its scholarship initiative which has allowed me to successfully complete my master studies.

My master colleagues, for not limiting our relationship to the class or lab rooms and for having shared great moments together.

The friends I have met during this year in Glasgow, which in one way or another have made me feel positive and motivated towards my studies.

My family and friends back home, which have shown me that the distance in human relationships should not be measured in kilometres, but in affection.

Table of contents

Abbreviations

CC	Percentage of *EVs* following the Controlled Charging schedule
D	Electrical power demand
DL	Dynamic Limit to the wind power penetration
EV	Electric Vehicle
E_{EV}	Daily Energy consumed by *EVs*
ICE	Internal Combustion Engine
L_{EV}	*EV* charging load
NCI	Non-Connected Islands
P	Wind power penetration limit
PHEV	Plug-in Hybrid Electric Vehicle
SRL	Spinning Reserve Limit to the wind power penetration
Wabs	Wind power absorbed
Wgen	Wind power generated
Wsur	Wind power surplus
$\%_C$	Distribution of the controlled *EV* charging profile
$\%_U$	Distribution of the uncontrolled *EV* charging profile

List of figures

List of tables

ELECTRIC VEHICLES CHARGING FROM SURPLUS WIND POWER IN NON-CONNECTED ISLANDS

Chapter 1: Introduction

One of the greatest challenges for most renewable energy systems is to find a way to handle its unpredictability and intermittency and integrate them into power grids. Acting directly on the renewable energy supply to balance the energy demand is not an option as most of the renewable energy sources are uncontrollable. The options left are acting on the demand side or using energy storage to buffer the imbalances. In this dissertation the renewable source analysed is wind and the chose way to integrate it is a fleet of Electric Vehicles (*EV's*). The *EV* fleet requires a charging load which acts as a kind of energy storage and also as an extra electricity demand load. This solution has been considered by several researches in the last years. Bruno Soares et al (2012) discuss the potential of Plug-in Hybrid Electric Vehicles (*PHEV's*) as a way to integrate the renewable wind generation in north-eastern Brazil. The results show that the entrance of a higher number of *PHEV's* with high controllability increases the capacity factor of the wind farms. In another paper the synergisms between plug-in hybrid electric vehicles and wind energy are assessed (Short and Denholm, 2006a) and they found them as an effective way to fight climate change and provide energy security. Wang et al (2011) also analyze the interactions between wind power and *PHEV's* including a scenario where demand side management is also considered. According to it, considering these interactions is fundamental to determine if the integration of large amounts of wind generation is technically feasible and economically reasonable.

The EDISON project (EDISON, 2012) is one of the most ambitious applications of those researches. It is a consortium of 12 partners from 8 countries including energy utilities and scientific bodies. In this project questions as what impacts on the grid can be caused by a large number of *EV's*, how will it affect the generation mix or how could different charging strategies look like are addressed. They propose a "Grid for Vehicles" strategy, where a controlled EV charging load is used as a flexible way to better integrate the inflexible renewable generation (Fig.1). By that, reductions on CO_2 emissions from the transport sector and a better integration of the renewable energy into

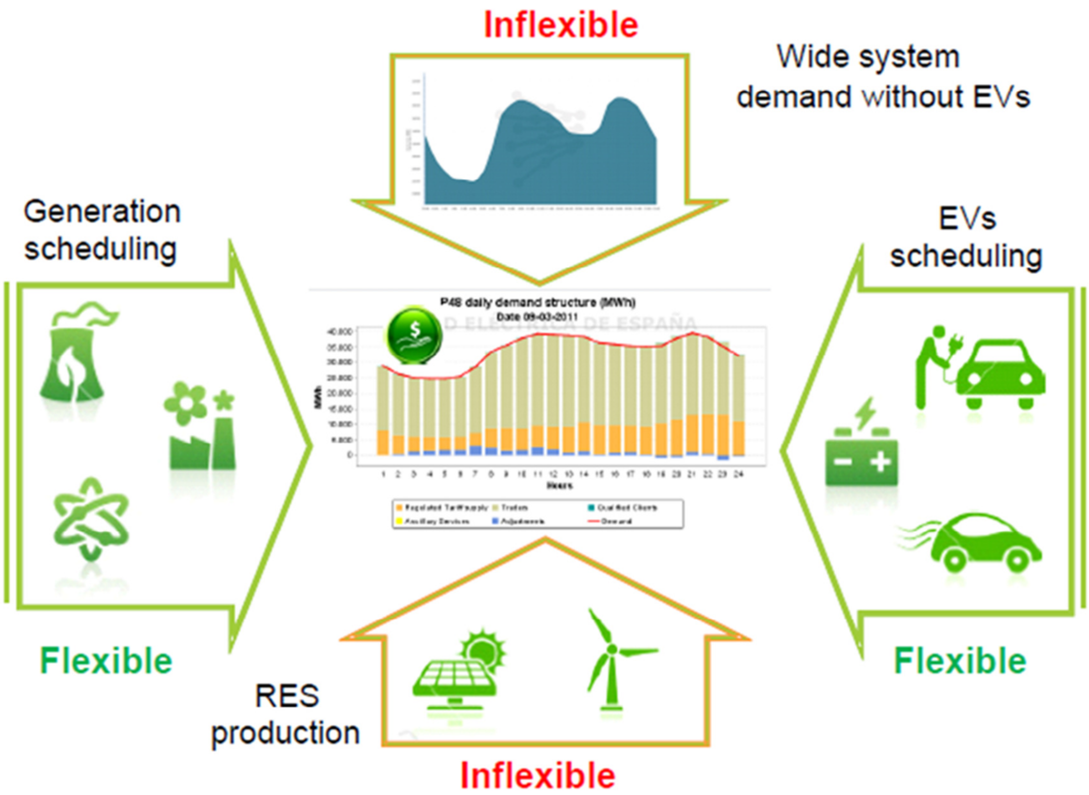


Figure 1: Diagram of the Grid for Vehicle strategy (EDISON, 2012)

the electricity system are achieved. Another project in line with this topic is being developed in El Hierro Island, part of the Canarian Archipelago (Spain). The island is planning to substitute all its 6,400 conventional vehicles by *EV's*. A consortium between an energy utility and a cars manufacturer has undertaken a study concluding that the average daily distance driven by a car in the island is 25 km at an average speed of 40 km/h. That makes that the EV solution adapts perfectly to the necessities of the island. In addition, it has been found that the surplus from a planned hydro-wind power plant can be used to make the EV charging more efficient (ENDESA, 2012).

The objectives of this dissertation are aligned to the research context described above. In this paper the interaction between the wind power generation and an EV fleet is analyzed for a particular case which is a Non Connected Island (*NCI*). The results intend to demonstrate the benefits and suitability of this strategy which combines wind and *EV's*. A model of an island with a number of relevant parameters is created for this purpose. Due to the time scale of this dissertation and the limited available data, not all the parameters have been obtained from a single real island. Data from different sources has been merged to generate a generic island model. Therefore, the results obtained from this model cannot be related to any specific island. However, the steps described can be used as a guidance to apply a similar methodology in case that all the data from a particular island is available.

The assumptions taken are based on a research and literature review explained in Chapters 2 to 5. Chapter 2 discusses the electricity demand profile of different islands and their general characteristics. In Chapter 3 the wind turbine model used to calculate the wind power generation is detailed. The limits for the wind power penetration in *NCI's* are discussed in Chapter 4. Chapter 5 is on *EV's* and the characteristics of the charging load required by a fleet of them. After this review the parameters for the calculations are chosen and it is set a methodology to model the island, being all this explained in Chapter 6. The results obtained for different wind scenarios are shown and discussed in Chapter 7. Finally, some important conclusions are presented in Chapter 8.

Chapter 2: Electricity demand profile in islands

The electricity demand profile is the graphic representation of the instant electricity demand in a certain system during a period of time. It represents power versus time with a data resolution of a certain time step, which is normally an hour, half hour or a number of minutes. The electricity demand is the sum of all the individual load consumptions plus the distribution and transmission losses. This electricity demand has to be instantly balanced with the net generation including power exchanges with other interconnected systems.

These profiles offer the electricity energy consumption, which can be obtained by integrating the demand profile for a given period. They not only offer the amount of energy consumed but also the rate it is consumed at in different instants. Despite the power demand is stochastic, for large nationwide systems it usually follows certain patterns during certain time scales. The first one is the daily variation (Fig.2). It depends on the commercial, residential and industrial activity at different times of the day and it is characterized by a low demand overnight. This demand increases during the labour hours. The peak on demand usually takes place during the evening due to the absence of

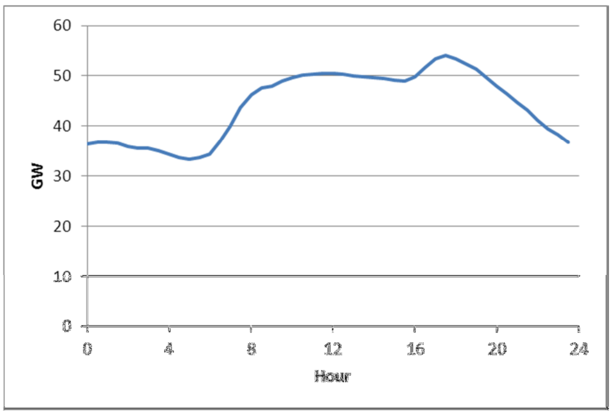


Figure 2: Electricity demand profile, day (National Grid 2011)

daylight and the heating demand, but in warm days it can take place during the afternoon because the heating requirements are low and, in some climates, the high demand for air conditioning. Another identifiable pattern common to most electrical systems is the weekly variation (Fig. 3). The commercial and industrial sector requirements are higher during the weekdays than during the weekends. Generally, during Sundays and public holidays the demand is slightly lower than during Saturdays.

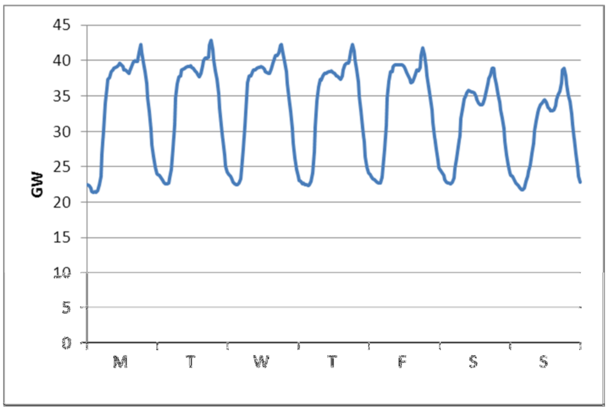


Figure 3: Electricity demand profile, week (National Grid 2011)

The last variation pattern, common to most electricity systems northern or southern the tropical geographic area, is the seasonal (Fig 4). During the winter the demand is higher than during the rest of the year due to heating requirements. During spring and autumn the demand respectively decreases to and increases from the summer demand levels.

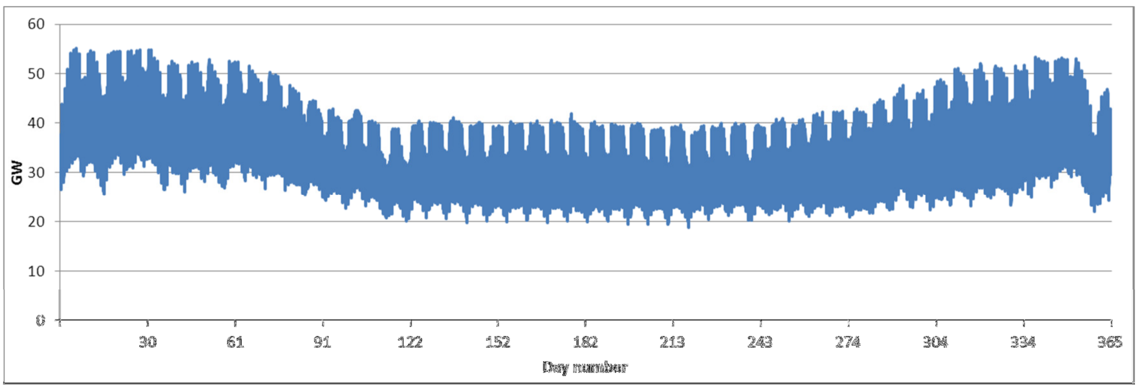


Figure 4: Electricity demand profile, year (National Grid 2011)

The electricity demand profile in islands is somehow affected by these general patterns for nationwide systems. However, one of the characteristics of the electrical system in islands is that usually they are not connected to the main grid or their interconnectivity with it is constrained. That makes that its shape is particularly affected by its own commercial, residential and industrial activities and its local climate. Below it is presented a case where the demand profile is strongly affected by these particular circumstances. The profile is an example of a day demand for an island in northern Scotland with a small population. If the demand profile of UK is scaled down to the population of the island and compared to the actual island demand there are found big differences (Fig. 5). The peak demand and the energy consumption are smaller, probably due to the rural profile of the island and the absence of significant industrial and commercial activities. There is a peak demand overnight, which is caused by the high percentage of electric storage heaters used during off-peak tariff hours. This is probably due to the lack of gas supply for heating in that particular island.

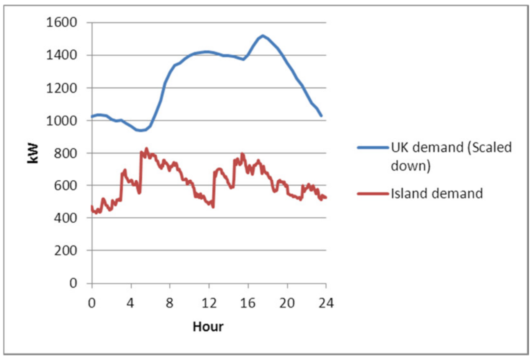


Figure 5: Comparison between the electricity demand profile in a small island and the national electricity demand scaled down to the population of the island (own elaboration)

Another difference is the random short term variability, which occurs when there are a relatively small number of individual loads. Larger systems present a lower variability in load demand because the changes in individual loads are not represented in the total load as a huge number of individual loads are added together and, statistically, increases and decreases of load are balanced. However, these fluctuations in the range of minutes existing in small islands are smothered in medium and big size islands.

For example in the Canarian Islands (Spain), the variability of the electricity demand in 'El Hierro' (Fig. 6, left) is considerably greater than it is in larger systems. This is caused by its small population of 10,000 inhabitants and consequently its low number of individual loads. As the island is more populated, the fluctuations in electricity demand are smothered. This reduction in fluctuations can be observed in the demand profile of 'La Gomera' (Fig. 6, centre) and 'La Palma' (Fig. 6, right) with 23,000 and 83,000 inhabitants respectively (INE 2012).

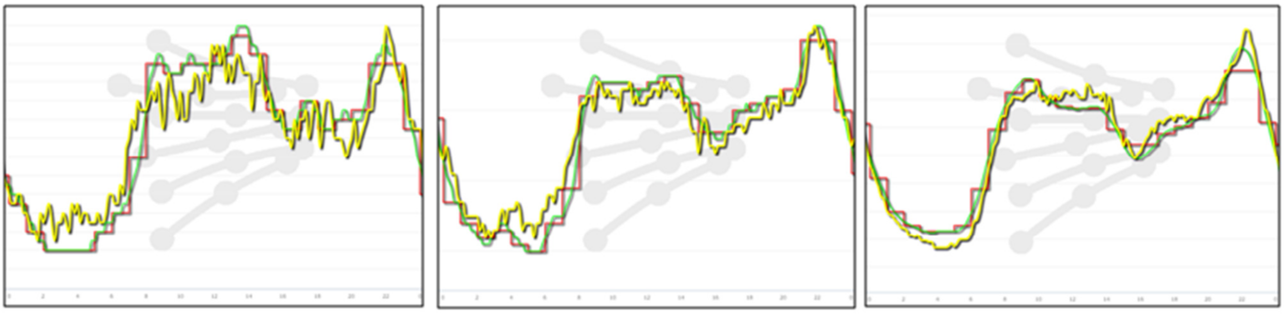


Figure 6: Electricity demand profile, real (yellow) and predicted (green) and generation schedule (red) in El Hierro (left), La Palma (centre) and Lanzarote-Fuerteventura (right) electrical systems (REE 2012)

Even for medium and big islands where the demand profile has no big differences with the one of mainland interconnected systems, the operation of an insular system presents additional difficulties. One advantage of grid connected systems is that when there is a mismatch between supply and demand locally, the electricity can be exported to or imported from other areas. Even if the load change trend is common to all the areas and consequently there is no possibility to trade the surplus or deficit, the frequency load response of a large number of generators and the sum of all the storage systems connected to the grid can help to balance the system.

This interconnectivity advantage does not exist in Non-Connected Islands (*NCI's*). Therefore, the electricity demand has to be met instantly only by the generation facilities existing in the island. Also the regulation provided by frequency load response is limited to the offered by the generation plants located in the island, and the same applies to the energy storage systems.

Taking this into account, an analysis of the electricity demand profile is the starting point to evaluate the effect of the *EVs* charging load and the accommodation of the wind production on it. The demand profile is affected by many factors as climate, daylight hours, economic and industrial activity, inhabitants' lifestyle or utilization of electric appliances. For a given island, the complex and sometimes random nature of all these factors makes the modeling of the electrical demand profile difficult and inaccurate. However, the power demand data can be easily metered in the electrical system substations. The future demand profile will probably change due to an increasing or decreasing trend in population and economic activities or other uncontrollable factors as the climate. Predicting future demand profiles can be done for individual islands, taking into account all the factors that may affect it. This forecast will include a high level of uncertainty. The conclusions of this dissertation do not intend to be valid for a particular island. They apply for islands in general as it is an approach based on the common characteristics of most islands. So that, using existing measured profiles is accurate enough to obtain a vision of how the thermal and wind generation and the EVs charging load interact in islands, and it is not necessary to predict a future demand profile.

The electricity demand profiles used have been obtained from information obtained in literature, published data and own sources. For the profiles, the time resolution chosen is half hourly. The dynamics of the electrical demand in the range of seconds and minutes are especially important to be considered in *NCI's*. The operation of the *NCI's* electrical systems is highly affected by these dynamics. In the models used the generation system is constrained by certain conditions which are discussed in Chapter 4. Under these conditions, it can be assumed that the system is able to handle the dynamics both in generation and demand. This assumption does not change significantly the results obtained as these dynamics do not have an important effect on the total energy consumption. Assuming that the dynamics are correctly handled due to the wind penetration dynamic limit discussed in Chapter 4, using a half hourly resolution of the demand profile is enough for the purposes of this dissertation. Some of the profiles used in this dissertation are discussed below.

The first demand data to be presented is based on the Crete (Greece) load profile offered in Tsakiris (2011) report (Fig.7). Its population is approximately 600,000 so its electricity system can be considered a large one. A profile is obtained for summer and another for winter. Due to the warm climate two demand peaks can be observed during the day, one in the afternoon and another in the evening. As the economy in Aegean islands is based on tourism it can also be observed that the power demand is higher in the summer day than in the winter day. The peak demand both in winter and summer is about twice the minimum demand.

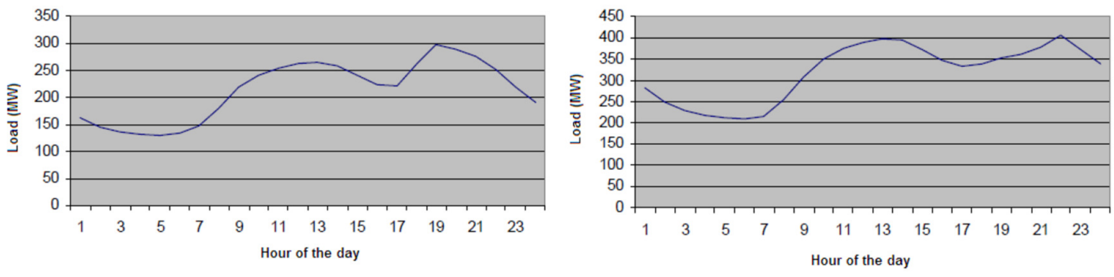


Figure 7: Typical Daily Profile for the Island of Crete. Winter season (left) and summer season (right) (Markoulakis,2009)

Another profile for an island, the Sao Miguel Island in Azores archipelago (Portugal), is obtained from Camus and Farias (2012) paper (Fig.8). There it is found data for weekdays, Saturdays and Sundays for spring and summer seasons. This data can be used for a week analysis as it allows incorporating the demand change experienced during weekends. The main difference between winter and spring demand is found in the evening peak demand. During the winter week, a peak demand occurs in the evening probably due to the heating and lighting demand. In the spring week there is also a peak in the evening, but in this case it is lower that the peak demand registered during the morning and afternoon of the working days, when the economic activity demands more energy. The peak demand in winter is approximately a 10% lower in Saturday and a 14% lower in Sunday than during the weekdays. In spring the peak demand is around 12% lower in Saturday and 23% lower in Sunday. There is no big seasonal difference in the minimum demand which occurs overnight and is around 33,000 kW both in winter and spring.

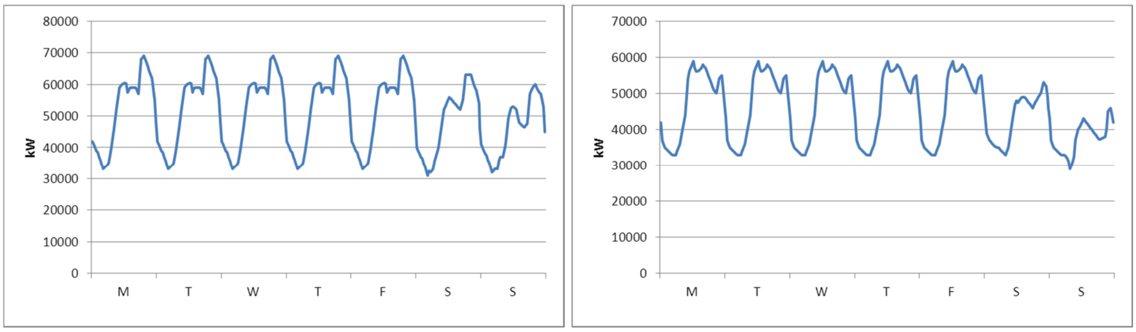


Figure 8: Electricity demand profile for a week in Sao Miguel for a typical winter (left) and spring week (right). (Camus and Farias, 2012)

The electricity demand profile used for the calculations in Chapter 6 is obtained from measures in Anglesey Island. It represents the electrical demand for the months of December and August, which are a good representation of the seasonal extremes of the year. Data from both months is plotted in Fig.9. In August the demand is lower and the

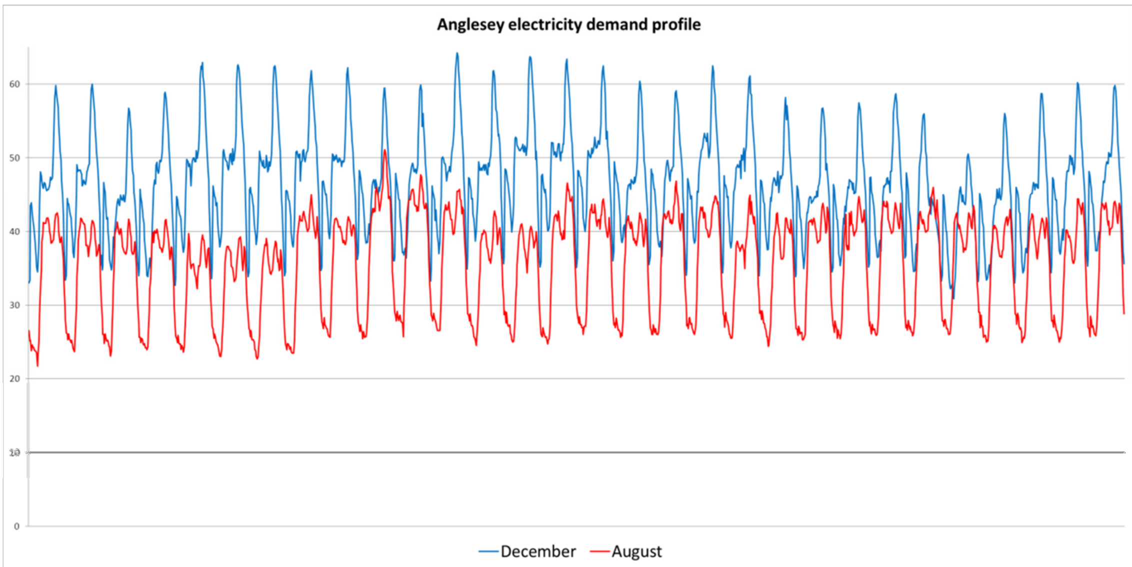


Figure 9: Electricity demand profile for the months of December and September in the Anglesey Island (own elaboration from SP substation data).

evening peak is less pronounced than it is in December. This system has a big difference between the annual maximum and minimum demand. In contrast with the previous profiles, which are all obtained from islands in warm climates, it can be seen the effect of the electric heating in winter. In addition to this increased demand, it can be observed that the valley hours during December are filled with the load of the electric storage heaters. The use of electric heating is common in islands located in cold climates. The absence of an infrastructure for gas supply in most of these islands makes electric heating an extended alternative.

Chapter 3: Wind power generation

Wind power is one of the most developed and effective renewable energy sources. The technical and economic suitability of it depends strongly on the existing wind resource in the location where a wind farm is installed. Generally islands and coasts are well fitted locations to accommodate wind projects. The existence of coastal winds makes the average wind speed high and consequently the capacity factor of the wind farms located in such areas. Many researches have been done to find the wind power potential in different islands. Yue and Yang (2009) have explored the wind potential in different locations in Taiwan finding the best one in the small island of Chontun which is away from the Taiwan main island. A great potential for wind power has been also found in the islands surrounding Hong-Kong (Lu et al, 2002) and many of the islands all over the world also present good wind resource, as the case of Prince Edward island in Canada (PEI, 2010). These are only a few examples, but many more can be found in literature.

A wind power system transforms the kinetic energy carried by the wind in rotating energy which moves a generator to obtain electrical energy. The most common wind turbine design consists on a three blade rotor aerodynamically designed to capture the maximum energy from the wind blowing through the area swept. The speed of the rotor and the power output can be controlled by mechanisms as the pitch regulation which consists on turning the blades into different angles to achieve an optimum operation. As a result every wind turbine has a fixed electrical output for a given wind speed. This relationship between wind speed and electrical power output can be really complex to model, but it can be easily obtained from a power curve which is usually offered by manufactures. These curves are based on the real performance of the turbine and one of these curves is the base for the wind turbine model used in this dissertation.

The model chosen is the Vestas V-80 whose technical sheet is publicly available (VESTAS, 2012). It has a diameter of 80 metres which offers an area swept of 5,027 m^2. It is regulated with pitch control to control the rotation speed and power output. The

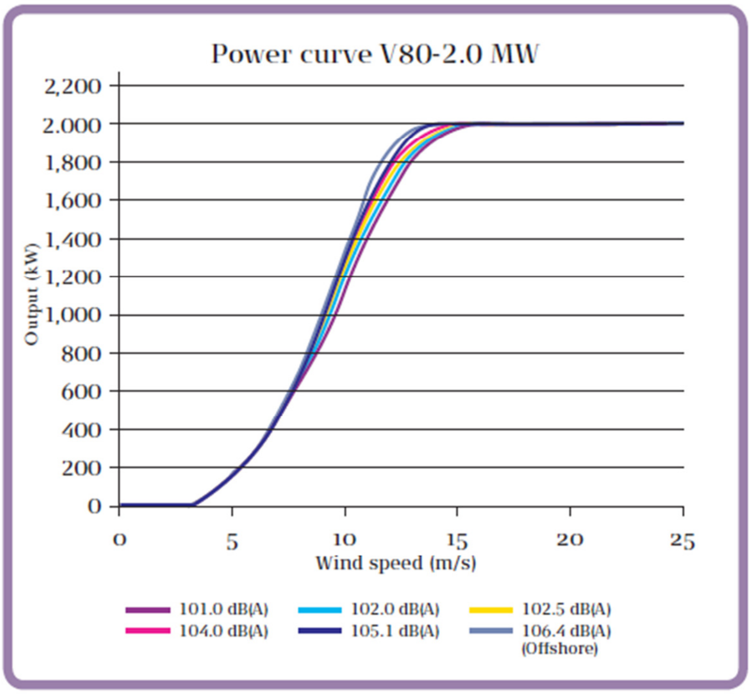


Figure 10: Power curve at different sound levels for the V-80 2MW wind turbine (VESTAS, 2012)

data used to create this model is the power curve in Fig. 10. The version with the lowest sound level is chosen in this case. The cut-in speed is 4 m/s, the cut-out speed is 25 m/s and the rated speed is 15 m/s. It is equipped with an asynchronous generator which offers a nominal output of 2,000 kW. MERIT software from the University of Strathclyde is used to calculate the electrical power output result of different wind speed profiles. These profiles are obtained from the US Department of Energy (DOE, 2012). The profiles are chosen to represent low, medium and high wind conditions and their selection is detailed in Chapter 6. The parameters of the wind turbine are entered in MERIT according to the brochure. The wind system is considered to be in an open terrain with smooth surface. Finally, the resulting wind generation profile is exported to be used in the calculations.

This initial wind generation profile will not represent the wind power absorbed by the system. In grid connected systems all the production from the wind farm is absorbed as the electricity produced from intermittent sources is prioritized in the energy market. The motivation of this prioritizing system is clear. It is logic that the dispatchable generation which requires fuel is reduced when uncontrollable systems are producing energy from free renewable resources. By that, this reduction in dispatchable generation is covered by the free undispatchable sources and therefore fuel savings are achieved. On the other hand, in the case of a NCI not all this generation can be absorbed. In grid isolated systems there are some other limits which need to be taken into account in calculating the energy yield from a wind farm. Those are explained in Chapter 4.

Chapter 4: Limits for wind power generation in grid isolated systems

Ideally, the only limit to the wind power generation in an isolated system would be its instantaneous power demand. As long as the electricity system had enough demand to absorb it, the production would not be limited. However, the connection of wind turbines to an electricity grid can potentially affect supply reliability and power quality, due to the unpredictable fluctuations in wind power output (Weisser and Garcia, 2005), and therefore some limitations apply to the wind penetration. The wind penetration is defined in two ways. Firstly the wind power penetration, which is the ratio of instantaneous wind power generation to the instantaneous power demand of the electricity system. The wind energy penetration is the ratio of electrical energy produced by wind to the electrical energy requirements during a certain period of time. A wind power penetration limit applied during a period of time results in a wind energy penetration limit which is always lower. In conclusion, the limits established to protect the grid system are defined for the instantaneous wind power penetration, and that has directly an effect on the wind energy penetration.

There are two main factors affecting the selection of the wind power penetration limits (Kaldellis, 2007):

The first one has to do with the technical minima of the dispatchable generation facilities in the grid system. With no wind conditions the electricity system has to be able to provide the electrical demand in any instant. So that, the power capacity of the dispatchable generation has to be, at least, equal to the estimated peak load. By this, it is guaranteed that the peak demand is covered even in the event of no wind production. Usually the dispatchable generators in islands are based on diesel or heavy oil engines, gas or steam turbines and, in the case of big islands, gas combined cycles. In order to respond against an instantaneous loss of all the non dispatchable generators, a number of dispatchable generators able to cover the instant demand if they were operating at full capacity have to be switched on. It is regulated that these generators have to be already spinning, even if it is at minimum load. If they were not, due to the start-up time, the response time to reach full capacity of these systems could be too long and produced power failures on the network. This response time, also known as ramping duty, is considerably reduced when the generators are already spinning, so these generators switched on at partial load are known as the spinning reserve. These generators have a technical minimum load under which they should not operate as it will increase the wear and consequently the maintenance works on the equipment. As a guidance, for heavy oil powered engines this minimum load is between 30-50% and for diesel fired engines and gas turbines it is between 20-35% (Tab. 1). For a given isolated system, the maximum power which can be covered by wind generation will be the difference between the power demand and the sum of all the technical minimum power generation of the instantaneous spinning reserve. This is the first limit to the wind power penetration which is set by the need of maintaining a spinning reserve. For practical purposes, it will be called from now ‘Spinning Reserve Limit (SRL)’.

	Unit type	Location	Fuel used	Start up time	Rated power (MW)	Technical minimum (MW)
1	Steam turbine	L-H	Mazut	1965	6.2	4
2	Steam turbine	L-H	Mazut	1970	15.0	7
3	Steam turbine	L-H	Mazut	1970	15.0	7
4	Steam turbine	L-H	Mazut	1977	25.0	12
5	Steam turbine	L-H	Mazut	1981	25.0	18
6	Steam turbine	L-H	Mazut	1981	25.0	18
7	Diesel engine	L-H	Mazut	1989	12.3	3
8	Diesel engine	L-H	Mazut	1989	12.3	3
9	Diesel engine	L-H	Mazut	1990	12.3	3
10	Diesel engine	L-H	Mazut	1990	12.3	3
11	Gas turbine	L-H	Diesel	1973	16.3	3
12	Gas turbine	L-H	Diesel	1974	16.3	3
13	Gas turbine	Ch	Diesel	1969	16.2	3
14	Gas turbine	Ch	Diesel	1979/85	24.0	3
15	Gas turbine	Ch	Diesel	1979/87	36.0	3
16	Steam turbine	Ch	Diesel	1993	44.4	18
17	Gas turbine	Ch	Diesel	1992	45.0	7
18	Gas turbine	Ch	Diesel	1992	45.0	7
19	Gas turbine	Ch	Diesel	1998	59.40	8
20	Gas turbine	Ch	Diesel	1998	59.40	8
21	Gas turbine	L-H	Diesel	1982/01	15.50	3
22	Gas turbine	L-H	Diesel	2002	43.30	5
23	Gas turbine	L-H	Diesel	2003	30.00	4
24	Gas turbine	Ch	Diesel	2003	30.00	4
25	Diesel engine	A	Diesel	2004	51.00	12.3
26	Diesel engine	A	Diesel	2004	51.00	12.3

Table 1: Crete island thermal generation system, end of 2004 (Kaldellis, 2007)

A second limit is set by the dynamic requirements of the electricity system. The power quality has to be maintained during the short period fluctuations in generation typical of wind farms. Power quality is defined by the Danish Wind Industry Association (DWIA, 2004) as voltage and frequency stability, together with absence of various forms of electrical noise, such as flicker or harmonic distortion. The voltage and the frequency have to be kept in a small threshold around the rated value for the grid to guarantee the perfect operation of the electrical machines and elements connected to it. Regarding the frequency, for example, when the generation is lower than the demand the frequency of the system decreases. If this situation is not balanced quickly the frequency can fall below the legal established limits implying economic fines to the network operator and possible failures and wear in equipment connected to the network. The higher the wind power penetration the more complex it is to balance electrical supply and demand instantly. So that, a limit is selected by regulation or by the system operator to guarantee a correct dynamic control which is called 'Dynamic Limit (*DL*)'. This limit is influenced by subjective attitudes and there is no general consensus on which dynamic limit guarantees the long term perfect operation of the system. A good descriptive definition is given by Gonzalez et al (2004):

"The boundary between low and high penetration may be set at the wind energy capacity that can be assimilated without major problems. As the wind capacity rises, changes in operation [and design] of the electric system are necessary."

Historically, the penetration level has been empirically set in a range of 25-50% in grid isolated islands (Lundsager et al, 2005). The detailed dynamic control is not deeply studied in this dissertation. It is assumed that by keeping the wind power penetration under the Dynamic Limit the short period fluctuations are handled correctly. That is why under this assumption, as mentioned in Chapter 2, the 30 minutes time steps are considered short enough for our analysis.

Taken into account these limitations, the calculations of this dissertation are executed following the procedure explained below:

At every instant, the wind power penetration limit (*P*) will be either the *SRL* or the *DL*, depending on which one is the lowest. The maximum wind power that can be absorbed

($Wabs_{max}$ in kW) will be a percentage of the instantaneous electricity demand (D in kW),

$$Wabs_{max}(t) = D(t) * P(t)$$

$$P(t) = \min\{SRL(t), DL(t)\}$$

and using the instantaneous data of wind power generation ($Wgen$ in kW) and electricity demand (D) the wind power absorbed ($Wabs$ in kW) and surplus ($Wsur$ in kW) are calculated (Fig.11),

$$Wabs(t) = \begin{cases} Wgen(t) & if \quad Wgen(t) < Wabs_{max}(t) \\ Wabs_{max}(t) & if \quad Wgen(t) \geq Wabs_{max}(t) \end{cases}$$

$$Wsur(t) = \begin{cases} 0 & if \quad Wgen(t) < Wabs_{max}(t) \\ Wgen(t) - Wabs_{max}(t) & if \quad Wgen(t) \geq Wabs_{max}(t) \end{cases}$$

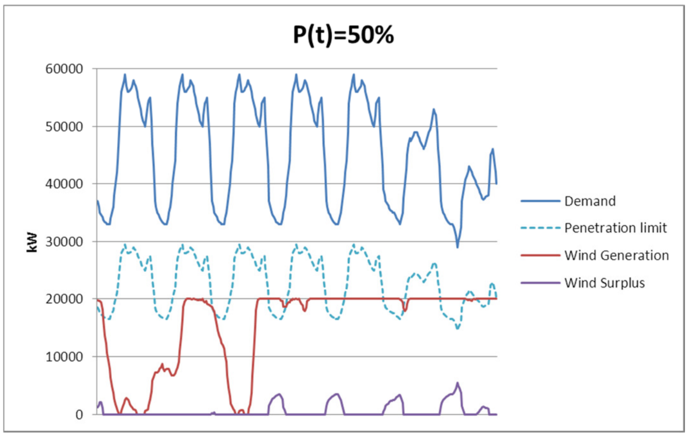


Figure 11: Example graph of the wind surplus calculation taking into account the wind power penetration limit, in this case 50% (own elaboration)

finally the required dispatchable generation (G in kW), which in islands is usually produced by conventional thermal systems (heavy oil or diesel engines, gas turbines,…), is calculated by subtracting the wind power absorbed ($Wabs$) from the electrical demand (D) (Fig.12).

$$G(t) = D(t) - Wabs(t)$$

After these calculations, the profiles obtained can be integrated for a certain period of time, say a day, a week or a year. By that, a measure of the fuel savings in electricity generation thanks to the installed wind can be obtained. As explained in Chapter 3, the evaluation of the energy yield from a wind farm in a grid connected system is a standard procedure. It depends basically upon the wind potential in the area, the characteristics of the wind turbines and the special distribution of those within the wind farm. In the case

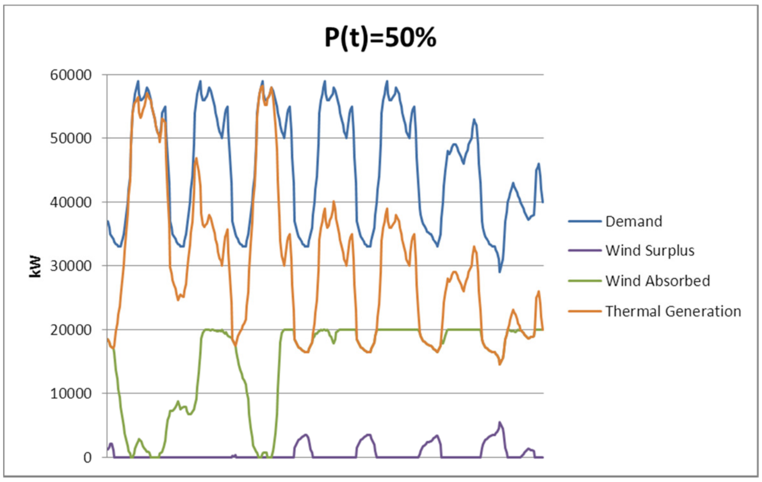


Figure 12: Continuation of the example graph showing the calculation of the thermal generation required (own elaboration)

of a Non Connected Island (*NCI)*, in addition to these factors, the power output limitations derived from the system operation are to be taken into account. Unlike the case of unconstrained operation, where wind speed is the only random variable, when a wind farm operates in a *NCI,* its output is determined both by the wind speed and the load demand, because the latter defines the imposed output power limitations (Papathanassiou and Boulaxis,2006).

Due to these additional limitations, the benefits of the wind generation in a *NCI* will be lower and the probabilities of experiencing wind surplus that has to be rejected are higher than in an interconnected system. That has to be carefully taken into account in the design of a wind farm of a certain capacity in a *NCI*. The large investment required for a big size wind farm would not be profitable if the production in good wind conditions, when it is generating at full capacity, would not be absorbed at any time. On the other hand, the wind farm could be designed to reduce the wind surplus virtually to zero. That would be achieved if the maximum power capacity is lower than the maximum wind power penetration at low demand periods. In that case, most of the time the wind absorption limit of the network would be higher than the wind generation, either in higher demand periods when the limit increases or in the case of wind generation at partial capacity. Consequently, by designing a wind farm small enough to avoid wind surplus, some of the wind potential is not used. That presents a compromise problem which consists on deciding the optimum power capacity for a wind farm.

To illustrate it, an example using the demand of the Sao Miguel Island in a spring week is presented. The peak demand load is almost 60 MW and in this case a 50% maximum wind power penetration is assumed. In a first approach 30 MW of wind capacity is considered (Fig.13, left). The blue line represents the total demand for the island, and the red line is obtained by taking the wind power absorbed away from the total demand. Therefore, this red line represents the thermal generation required to cover the demand after considering the instantaneous wind production and wind power penetration limits. The purple line represents the wind production rejected by the system also called wind surplus. The seven days of the week can be easily identified by observing the demand profile. As expected, the thermal generation is reduced in favorable windy conditions and in periods of low wind production (first and third days) it has to cover the demand almost completely. In the other days, an important wind surplus is shown which indicates an oversizing of the wind capacity since. Even though the wind generation rejected is ‘free’, the capital investment and the maintenance have a cost which will not be recovered if an important portion of the wind production is not absorbed. To avoid the wind surplus, a second solution with 15 MW of wind capacity is proposed (Fig.13, right). In this case, the wind surplus is practically zeroed, but the required thermal generation increases in comparison to the previous case.

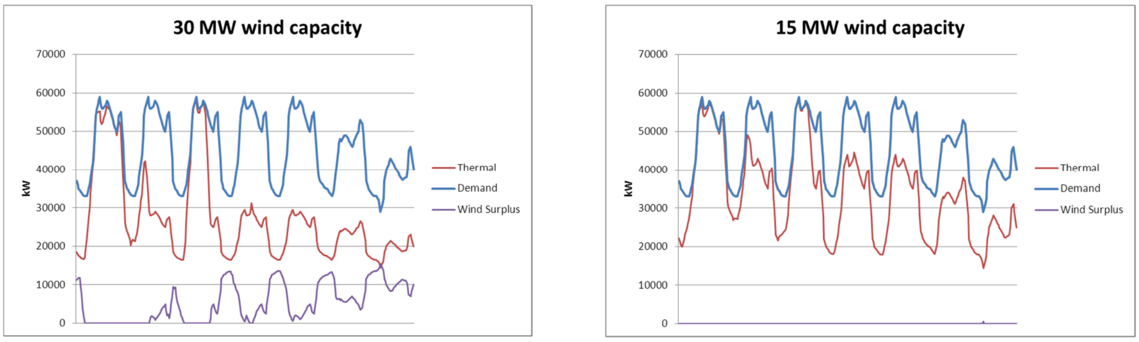


Figure 13: Effect of different wind capacities in an electrical system with a 50% wind power penetration limit

The optimum solution is somewhere between the first and the second case, and it depends on several factors as the characteristics of the thermal generation, the local wind resource, the wind farm costs, the fuel costs and so forth. It also depends strongly on the variability of the wind speed and the wind power penetration limit which is related to the variations in electrical demand. It is impossible to control the wind speed, but some action can be done over the second source of variation, the load demand. It would be much more effective to design the wind power capacity if the load demand would not have big variations, especially the ones between day and night, or winter and summer.

The wind capacity can be adapted to the high demand characteristic during the day or to the low demand characteristic during the night or 'valley' period, but not to both at the same time. Consequently, it would be of great interest to reduce the difference between minimum and maximum demand. This is known as the system cycling, calculated as the average difference between daily peak and daily minimum demand, normalized by the annual peak demand. Additionally, a reduction in cycling will translate into decreased power plant start-up and operations and maintenance (O&M) costs (Short and Denholm, 2006b). This reduction could be achieved by various strategies. One is by demand side management which implies adapting the system to analyze real time data and connect and disconnect loads consequently. These systems, known as smart grids, would be able to handle some variability but it will not be enough to balance the big difference between peak and valley electricity demand. Another strategy would be using some form of energy storage. Operating the plants in a way to produce a constant generation profile, the storage would be able to provide extra power required during peak hours with energy stored during the valley period.

The solution proposed in this dissertation is a combination of those two strategies. Electric Vehicles are introduced and their charging is displaced to the valley period. That increases the electricity demand overnight with a useful load that reduces the wind surplus and also the fossil fuel consumption in transport.

Chapter 5: Electric vehicles charging profile in islands

Initially, the electricity demanded to charge Electric Vehicles (*EVs*) in Non Connected Islands (*NCI*) can represent a double benefit. Firstly, the use of *EVs* can reduce the importation of fossil fuels required by petrol and diesel cars, and its CO_2 related emissions, in the island. Secondly, the aggregated electricity demand profile can become easier to manage by reducing its variation between high and low demand periods. Those benefits will only be achieved if the EVs are introduced following a well-designed planning.

The reduction in fossil fuels requirements will become a fact as long as the electricity generated in the island has a generation mix low in conventional thermal generation. Otherwise, the emissions saved in the car engines can be lower than the produced in the electricity generation required by the EVs in power plants. Most of the *NCI's* have a generation structure based in diesel and heavy oil generators. Therefore, the expected savings in fuel consumption may actually become increases as the demand for electricity generation will increase. So that, the presence of wind farms or other renewable generation systems is fundamental to achieve a fossil fuel consumption reduction when introducing *EVs*.

Obtaining a flatter demand profile will only be possible if the charging is done mainly during low demand hours. If the user has absolute freedom to choose when to charge the *EV*, most of the charging load will occur during the evening time. At that time most of the electricity systems are already experiencing peak load, so the additional increase will create a higher peak demand. That has fatal implications, as the network would need to be redesigned including new generation systems and new transmission and distribution lines. The main objective of introducing a controlled charging scheme is avoiding this increase of the peak demand.

The requirements to achieve the benefits explained above fit very well with the integration of wind generation and *EVs* together. It has been mentioned that the fossil fuel reduction by the use of *EVs* will only be achieved by a high wind energy penetration. At the same time, a high wind energy penetration is favored by the existence of a flat demand profile without big differences between day and night. With a flat demand it is easier to decide on the optimal wind power capacity. Flattening the demand profile can be achieved by controlling the charging schedule of the *EVs*. Therefore, a beneficial symbiosis relationship between wind power and *EVs* in *NCI* is clear.

In islands, there are other favorable factors for this strategy. One of the main concerns about *EVs* is the range anxiety. The impossibility of charging the *EVs* as fast as filling the tank of a conventional car, together with the limited range offered by them, is one of the main disadvantages of the *EVs*. In many islands this problem does not exist. The daily distance that a car would need to travel is geographically limited. Also, the price of petrol or diesel is generally higher in islands as the refineries are in mainland and the cost in the island includes the transport of the oil products to the island.

The first step to calculate the *EVs* charging profile is to determine the total daily energy requirements (E_{EV} in kWh). It is a function of the total number of *EVs*, the distance travelled by each of them and their energy efficiency.

$$E_{EV} = \sum_{1}^{N_{EV}} (d[miles] * \eta[kWh/mile])$$

The number of *EVs* can be obtained directly or estimated from the population of the island, the cars per capita in the region or country and an assumed *EVs* penetration percentage. This penetration percentage and its evolution in future years could be estimated for each island considering multiple socioeconomic factors. However, this dissertation does not analyze the full process of renewing the old cars by *EVs* which is assumable that will not be instantaneous. It is focused in the operation of the system at the last stage, once the wind power capacity and *EVs* have been totally developed. So that, different scenarios of *EVs* penetration levels will be assumed in the analysis. The distribution of the driven distances will be strongly affected by the size of the island. This effect can be observed in the National Household Travel Survey (NHTS, 2011) from the United States. This data is particularly interesting as it is broken down by States, and one of the States, Hawai, is fully conformed by islands. This fact will help in differentiating the driving patterns in islands from the ones in the mainland. In Hawaii, a frequency distribution of the daily distance travelled shows that most of them are less than 40 miles (81.8%) and almost all of them are less than 100 miles (99.0%) (Fig.14). The mean daily distance driven in Hawaii is 24.53 miles. The difference with the national patterns is clear, for the whole US, the daily driven distances are higher. For the national data, the daily distance less than 40 miles accounts for the 68.2% and less than 100 miles for the 93%. The mean daily distance is 39.5 miles, around a 60% higher. It is also important to remark that, on average, only 61% of the existing vehicles are driven in a day (Van Haaren, 2011), while the others remain parked.

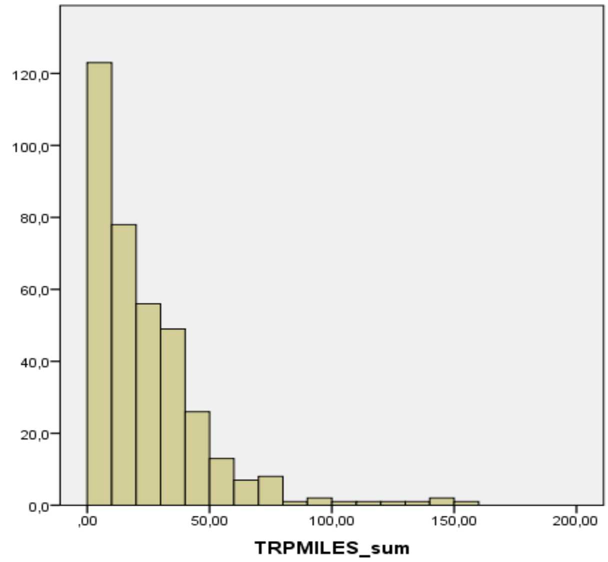


Figure 14: Frequency distribution of the daily distance travelled in Hawaii (own elaboration from NHTS survey)

This data confirm the good conditions for *EVs* introduction in islands, as the range requirements are not as exigent as in the mainland. Every island has its particular differences, but the Hawaii driving patterns are good enough to calculate the general distance requirements of the transport fleet in an island. To transform the distance requirements in energy requirements, the battery-to-wheel efficiency of the *EVs* has to be known. An accurate enough number for this efficiency is 0.24 kWh/mile. This is proposed by D. MacKay (2008) after an analysis of several current EV models (Tab.2).

MODEL	RANGE (miles)	Efficiency (kWh/mile)
Th!nk	125	0.32
Electric Smart Car	70	0.14
Berlingo Electrique 500E	63	0.40
i MiEV	100	0.16
EV1	75-150	0.18-0.36
Lightning	200	0.18
Aptera	-	0.10
Loremo EV	95	0.10
eBox	140-180	0.19
Ze-0	50	0.36
e500	75	-
MyCar	60	-
Mega City	54	0.18
Xebra	25	0.19
TREV	94	0.10
Venturi Fetish	100-156	0.18-0.27
Toyota RAV4 EV	81-118	0.22-0.34
Phoenix SUT	130	0.27

Table 2: Range and efficiency of various EV models (MacKay, 2008)

As it is impossible to predict which will be the *EVs* model distribution, and what will be the distances driven with them each day, the calculation of the daily energy requirements (E_{EV}) is simplified. Assuming that the efficiency of all the *EVs* is the same, using the mean value ($\bar{\eta}$), and adding a grid-to-battery charging efficiency (γ) of 88% (Short and Denholm, 2006a), the E_{EV} to be supplied by the grid is calculated as

$$E_{EV} = \frac{\sum_1^{N_{EV}}(d * \eta)}{\gamma} \approx \frac{\bar{\eta} * \sum_1^{N_{EV}}(d)}{\gamma}$$

Once the energy to be supplied by the grid for *EVs* charging is calculated, the supply profile has to be estimated to represent the power demand increase at every instant. This profile is called the *EVs* charging load.

Many different models to simulate the *EVs* charging load can be used. A good compilation of different models can be found in the Weiller (2011) paper. The models discussed are divided in groups depending on the assumptions taken. In the first group an uncontrolled charging is assumed, which means that the *EV* starts charging right after it is parked, generally when the car arrives home. A second group of models assume a time delay in the charging after the car is plugged. The third group is formed by the models assuming an off-peak charging which considers that the system operator has a direct or indirect control of the *EV* fleet charging in order to optimize it. Other groups are discussed in the paper as “fast charging”, “smart charging” and “charging controlled to minimize power losses”. Most of the models offer several charging scenarios which depend on certain parameters (Tab. 3).

Scenario name and number		Charging parameters				
		Charging location	Battery size (kW h)	Charge rate (A/V)	Blackout period	Last minute
Baseline	CH1	Home	10.4	12/120	None	No
Last minute	CH2	Home	10.4	12/120	None	Yes
Home and work	CH3	Home and Work	10.4	12/120	None	No
Blackout	CH4	Home	10.4	12/120	1–7 PM	No
Slow	CH5	Home	10.4	8/120	None	No
Fast	CH6	Home	10.4	16/240	None	No
Fast, H and W	CH7	Home and Work	10.4	16/240	None	No
1/2 Battery	CH8	Home	5.2	12/120	None	No

Table 3: Example of charging scenario inputs for Kelly et al (2012) model.

In this dissertation, a combination of two charging profiles is used. These two profiles are the ‘controlled’ and ‘uncontrolled’ charging, assuming that a certain percentage of *EVs* follow the controlled charging each day. This percentage is called the controlled charging percentage (*CC*). The total *EVs* charging load will be the result of adding both profiles up. Both profiles assume that the *EVs* are only charged at home. This assumption is based on the analysis of the driving patterns previously exposed in this chapter. As practically all the daily distances driven in island are below the range of most *EVs* it can be assumed that the cars can be charged at home and there is no need of charging it through the day commute or journey. The other assumptions are different for each of the two profiles.

The uncontrolled charging profile is based on the one obtained by Parks et al (2007) “Case 1: Uncontrolled Charging”. It assumes that the EV plugs in as soon as it reaches home and the charging is done at a constant rate (1.4kW) until the battery is fully charged. The arrival times after the last trip of the day are obtained from the NHTS survey and they are considered as the starting times of the charging. The profile has the shape illustrated below (Fig.15)

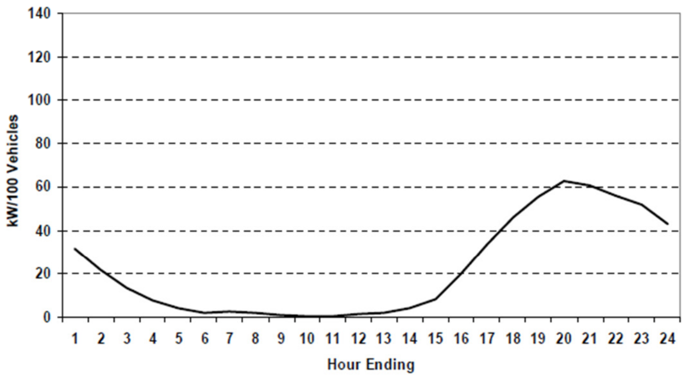


Figure 15: Fleet Average Charging Profile in the Uncontrolled Charging Case (Parks et al, 2007)

From this profile the percentage of cars that are being charged at every time of the day is obtained (Tab.4). Then, using this charging power distribution ($\%_U$), the profile is

0:00	4.06%	8:00	0.19%	16:00	1.89%
0:30	3.49%	8:30	0.19%	16:30	2.55%
1:00	3.02%	9:00	0.09%	17:00	3.21%
1:30	2.45%	9:30	0.09%	17:30	3.77%
2:00	1.98%	10:00	0.00%	18:00	4.34%
2:30	1.51%	10:30	0.09%	18:30	4.72%
3:00	1.13%	11:00	0.09%	19:00	5.19%
3:30	0.94%	11:30	0.19%	19:30	5.47%
4:00	0.75%	12:00	0.28%	20:00	5.85%
4:30	0.57%	12:30	0.28%	20:30	5.75%
5:00	0.47%	13:00	0.38%	21:00	5.66%
5:30	0.28%	13:30	0.47%	21:30	5.38%
6:00	0.19%	14:00	0.57%	22:00	5.19%
6:30	0.28%	14:30	0.66%	22:30	5.09%
7:00	0.28%	15:00	0.75%	23:00	4.91%
7:30	0.19%	15:30	1.32%	23:30	3.77%

Table 4: Distribution of the uncontrolled EV charging ($\%_U$) (Parks et al, 2007)

scaled to cover the energy requirements (E_{EV}) calculated by the procedure discussed previously in this chapter.

For the controlled charging, it is assumed that the network operator is able to control the charging schedule both by direct and indirect mechanisms. The target of this control is to displace the charging to the off-peak hours and fill the 'valley' of the electricity demand profile. An *EV* charging load result of an uncontrolled charging may increase the daily peak demand for a high level of *EV* penetration (Fig.16). This effect wants to be avoided by any means, as an increase of peak demand will entail an increase of the generation and transmission capacity which can offset the advantages of introducing *EVs.* The controlled charging is assumed to take part from 23pm to 10am. The user will set the time at what his car is required, and the network operator will use the information from all the charging points to schedule the charging of all the *EVs*. The users who select more flexibility for the charging will be rewarded as their vehicles will be charged in periods with a lower electricity cost. The users who set an early charging as they need the vehicle at certain time in the morning will still benefit from the lower price of the controlled charging schedule. In the case that the user needs to charge the

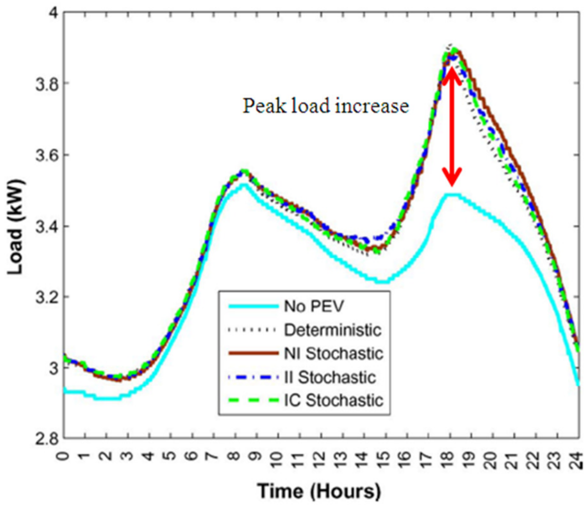


Figure 16: Average load profile per person with 100% EV penetration with different estimation methods (Ashtari et al, 2012)

vehicle as soon as possible, the charging will start immediately after the *EV* is plugged in and the cost of the charging may be higher. A detailed simulation of this control system is very complex and the mechanisms required to achieve this control are not studied deeply in this dissertation. At a high level, the flow diagram of the algorithm is illustrated in Fig.17.

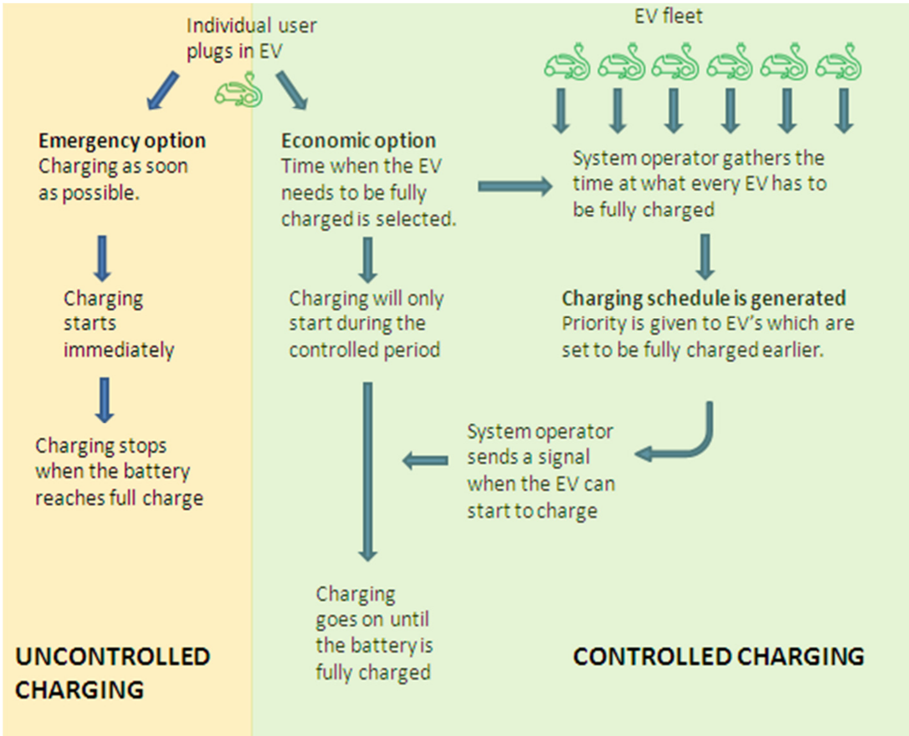


Figure 17: High level flow of the charging algorithm (own elaboration)

It is assumed that the control results in a charging load that is zero out of the charging period. During the charging period the charging load is higher when the electricity demand (excluding *EVs* load) is lower. To obtain this controlled charging profile, the difference between the instant demand and the peak demand is calculated. By this, the availability to accommodate the new load is measured at every instant, and the *EV* controlled charging load is distributed according to this availability. At a certain time, the lower the demand is, the higher EV charging load is assigned by the operator. Therefore, the controlled charging profile ($\%_C$) is obtained from a typical electricity demand profile of each period of the year. It pursues to adjust the EV charging to the reversed shape of the demand during the off peak hours in order to fill the valley.

As an example, using the Sao Miguel Island demand data for a spring week presented in Chapter 2 (Fig.8), a certain controlled charging distribution is obtained. The first step to calculate this charging distribution is obtaining the power availability during the charging period, which is the difference between the instant demand and the peak demand. This is represented by the grey area in Fig. 18. Representing the magnitude of

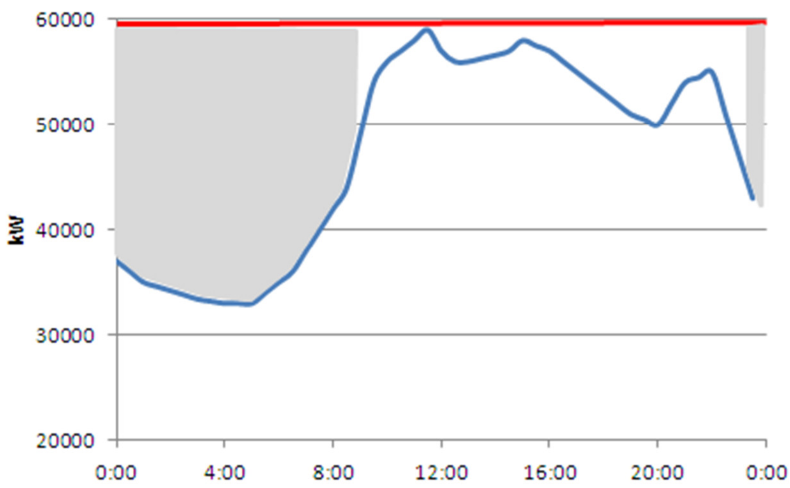


Figure 18: Power availability during the charging period for a typical spring day in Sao Miguel (own elaboration)

this difference the reversed shape of the demand during the charging period can be obtained (Fig.19) and from it the percentage distribution of the charging profile ($\%_C$) is created (Tab.5).

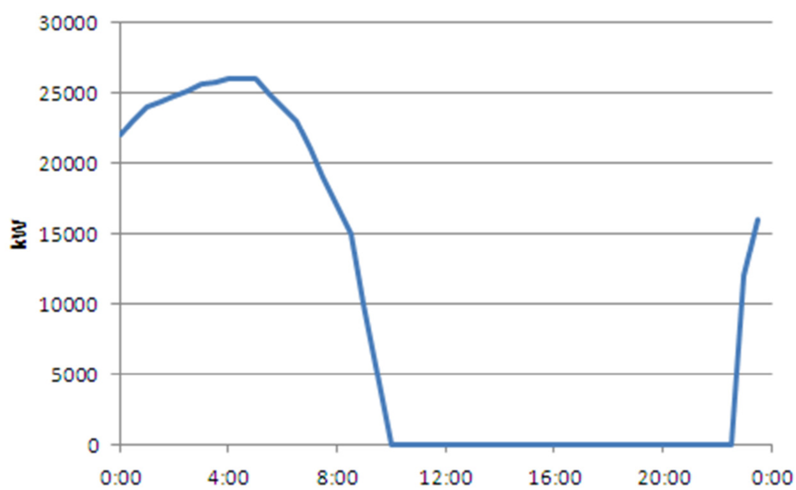


Figure 19: Difference between peak and instant demand during the controlled charging period in Sao Miguel island (own elaboration)

Different assumptions can be taken for the percentage of *EVs* following the controlled charging scheme (*CC*), resulting in different *EV* charging loads. For every time step, using the *EV* load distribution percentage in the controlled ($\%_C$) and uncontrolled ($\%_U$) case, the *EV* charging load (L_{EV} in kWh) is calculated as:

$$L_{EV}(t) = E_{EV} * \{CC * \%_C(t) + (1 - CC) * \%_U(t)\}$$

0:00	4.82%	8:00	3.56%	16:00	0.00%
0:30	5.08%	8:30	3.05%	16:30	0.00%
1:00	5.33%	9:00	1.78%	17:00	0.00%
1:30	5.43%	9:30	0.51%	17:30	0.00%
2:00	5.54%	10:00	0.00%	18:00	0.00%
2:30	5.64%	10:30	0.00%	18:30	0.00%
3:00	5.74%	11:00	0.00%	19:00	0.00%
3:30	5.79%	11:30	0.00%	19:30	0.00%
4:00	5.84%	12:00	0.00%	20:00	0.00%
4:30	5.84%	12:30	0.00%	20:30	0.00%
5:00	5.84%	13:00	0.00%	21:00	0.00%
5:30	5.59%	13:30	0.00%	21:30	0.00%
6:00	5.33%	14:00	0.00%	22:00	0.00%
6:30	5.08%	14:30	0.00%	22:30	0.00%
7:00	4.57%	15:00	0.00%	23:00	2.29%
7:30	4.06%	15:30	0.00%	23:30	3.30%

Table 5: Distribution of the controlled EV charging ($\%_C$), adapted to the electricity typical spring demand profile of the Sao Miguel Island (own elaboration)

The EV charging load (L_{EV}) shape, will be affected by the shape of the controlled EV load distribution ($\%_C$) which is directly affected by the electricity demand profile overnight. As the *CC* increases, there is a displacement of the charging load to off-peak hours (Fig.20).

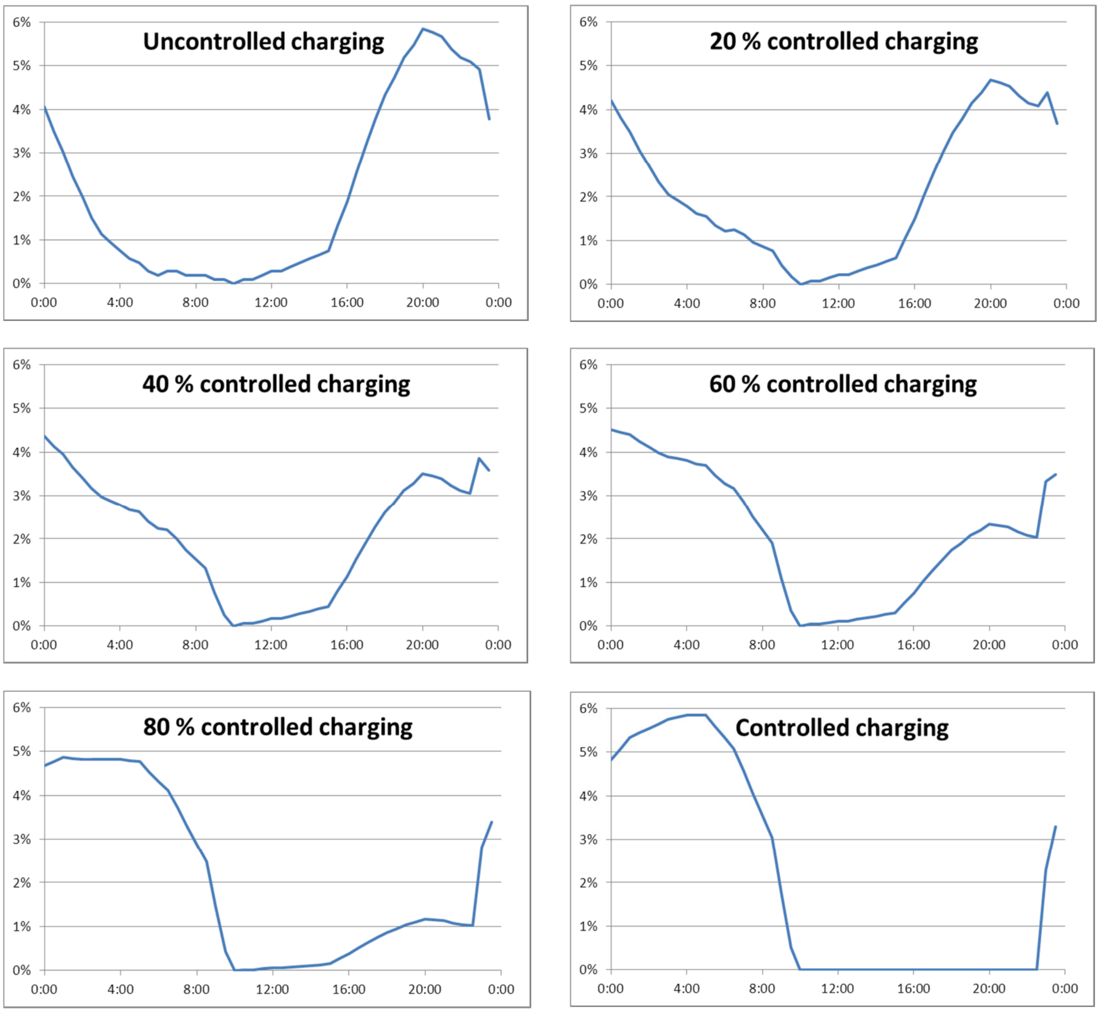


Figure 20: Distribution of the *EVs* charging load depending on the percentage of *EVs* following the controlled charging (*CC*) (own elaboration).

Chapter 6: Methodology

In the previous chapters some of the assumptions used to obtain the results presented have been explained. A hypothetical island is analysed in this Chapter. The results obtained do not have the intention of representing an existing island. The objective is to obtain a general idea of the consequences of introducing an *EV* fleet in a Non Connected Island (*NCI*), and how it can improve the profitability of increasing the installed wind capacity. Once the calculation procedure is described, it can be applied for a particular island to predict the best wind power capacity to be installed for a certain level of *EVs* penetration. Some parameters of the hypothetical island consist of the most characteristic factors for *NCI's*, which have been described in the previous chapters. Some other parameters are not fixed and different scenarios are used to cover different possibilities. All them are summarize in Tab.8 in the end of the Chapter.

Size

The size of the island has a direct effect on the driving patterns and the desired distance range for the cars. The driving patterns will affect the energy needs for the *EV* fleet charging (E_{EV}). The larger dimensions an island has the more likely that there is a higher distribution percentage of long daily trips. Of course this is just an approach, as the road networks can be very different in islands with similar dimensions. If there are a high percentage of daily trips over the range of most *EVs* (75 to 100 miles) the assumed advantage of islands for the introduction of *EVs* will not be justified. Therefore, the hypothetical island dimensions and road network is considered similar to the ones of Hawaii, as the driving patterns have been obtained from them. Especially, to the dimension of the most populated island, Ohau, as statistically most of the survey data comes from it (Tab.6).

Island	Population	Largest Dimension
Kauai	66,921	30
Oahu	953,207	35
Maui	144,444	40
Molokai	7,345	35
Lanai	3,135	15
Hawaii Island	185,079	70
TOTAL	1,360,301	

Table 6: Hawaiian islands population and approximated largest dimension (Hawaii DBEDT, 2010)

Population

The number of vehicles in the island is directly related to the population of it. It can be obtained multiplying it by the vehicles per capita in the region. The total energy demand in the island also depends strongly on its population, so a realistic relation between the number of cars and the electricity demand needs to be achieved. By that, the total energy requirements for electricity generation and for transport will make sense. As the electricity demand profile used is based on data from Anglesey (Fig.9), the hypothetical island is assumed to have its population, which in 2001 was 66,828 (ONS, 2002). Using this figure, and the 0.525 vehicles per capita in UK (Eurostat, 2010), the total number of vehicles in the hypothetical island is assumed to be 35,084.

Climate

The climate of an island has a big importance on its residential and economic activity, and influences strongly the energy demand in it. The electricity demand profile is built using the Anglesey data (Fig.9). The implication of using this profile is that the conclusions will only be applicable to islands in a cold climate, with an important presence of electric heating which create a large yearly system cycling (Tab.7), defined as the difference between the peak and minimum demand for a year, and normalized by the peak demand. However, there are a multitude of islands whose electricity demand profile is similar to the used in this dissertation, including the ones in the UK, so an important portion of islands is covered by this study. In addition, reducing the system cycling is one of the expected results of introducing *EVs*. Therefore, it makes sense that a system with a problematic large system cycling is analysed in this dissertation. The time resolution of the data is half-hourly which, as explained in Chapter 4, is suitable for this analysis, and the December and August months are representative of the seasonal variation extremes, so analysing both months provide information of the system in its limit situations. This system cycling is also high in warm islands, but interchanging summer for winter as the highest demand limit. This is caused by the use of air conditioning and the touristic economy that those islands present normally, which increases the population and economic activity during the summer. The peak demand in warm islands occurs in the midday instead of in the evening, but this peak is still outside the *EV* charging period, so the reduction achieved in the system cycling of cold islands will be similar to the one in warm islands.

SYSTEM CYCLING			
Crete	Sao Miguel	UK	Anglesey
0.65	0.57	0.65	0.66

Table 7: Yearly system cycling for different electricity demand profiles (own elaboration)

However, to make it more accurate, the climate of the hypothetical island is assumed to be cold, as the characteristics of the load demand profile affect the shape of the *EVs* controlled charging. In order to estimate the power distribution of the controlled

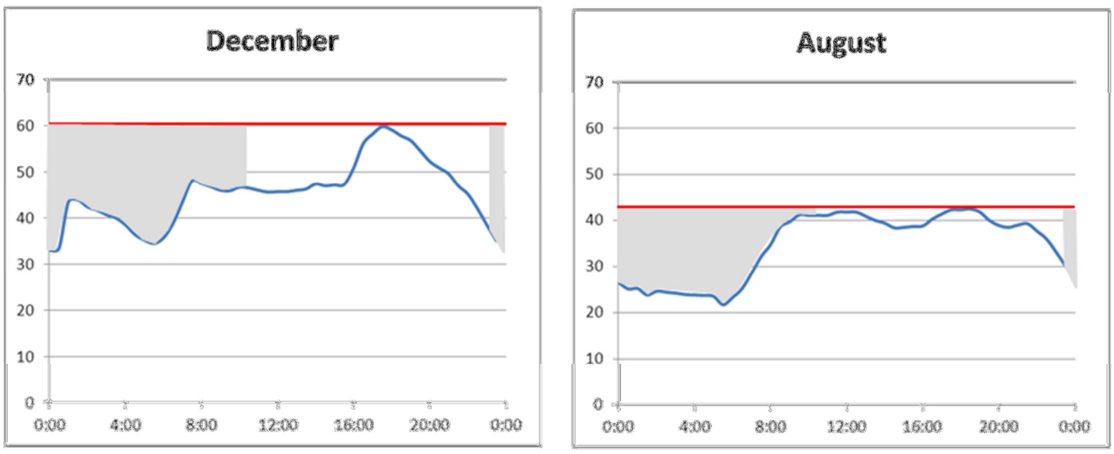


Figure 21: Electricity demand profile for a characteristic day in December and August. The area marked represents the power availability during the controlled charging period. (own elaboration)

charging a representative day is chosen for each month (Fig.21). Its electricity demand profile will be the base to estimate the controlled *EV* charging load distribution ($\%_c$).

The *EV* controlled charging schedule will be programmed according to the power availability during the charging period to avoid overpassing the system peak demand as discussed in Chapter 5. The resulting charging load distribution varies for the two different months (Fig.22), as they do the electricity demand profiles, in particular due to the overnight charging of the electric storage heaters.

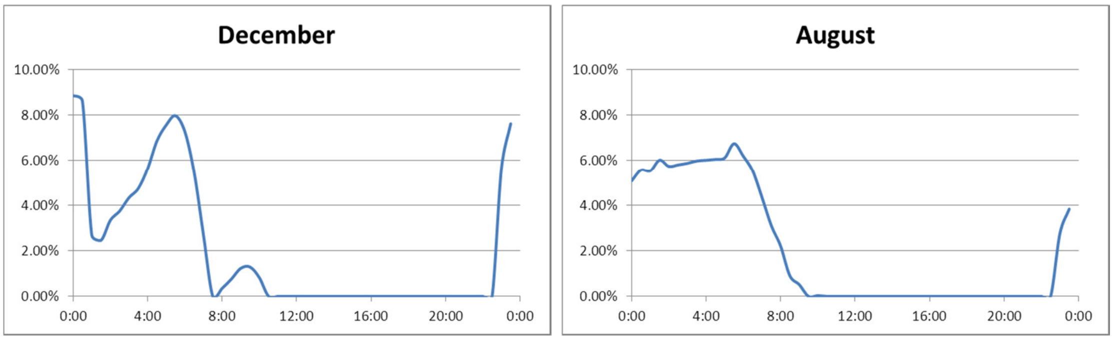
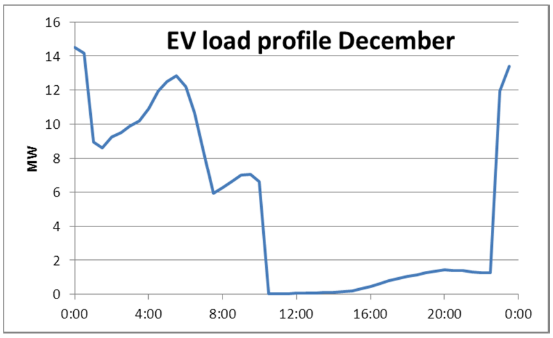


Figure 22: Controlled *EV* charging load distribution ($\%_c$) for December and August

Charging scheme

It is uncertain which will be the number of *EV* users that will choose to charge their vehicle following the controlled charging scheme each day. That will depend on the incentives offered, probably economic, and the restrictions imposed by the system operator. It can be assumed that the right mechanisms are applied in the hypothetical island, and therefore the total number of users will try to follow the controlled charging scheme. However, due to different circumstances, it is assumed that every day a 10% of the users will need to charge their vehicle outside the controlled charging scheme. Under the assumptions presented above, the resulting *EV* charging load (L_{EV}) can be now calculated (Fig.23).

In December the *EV* charging load is adapted to the simultaneous existing load for electric storage heaters. The period programmed for the charging electric storage heaters seems to be from 00:30 to 5:30, so during this period the EV charging load is lower to avoid overpassing the system peak. Due to the pronounced evening peak in December,



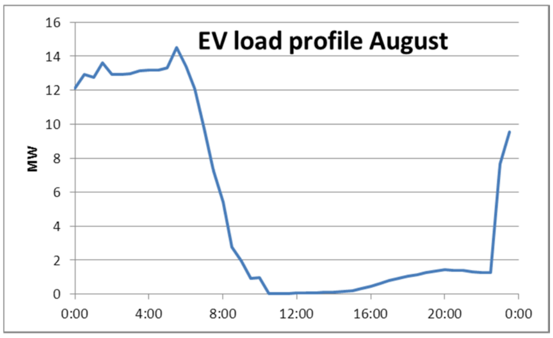


Figure 23: Resulting *EV* charging load for the two months analyzed for a 100% EV penetration (own elaboration)

there is power availability after 8:00 to finish charging the last *EVs* without increasing the operating requirements to cover the seasonal peak. However, in August, the evening peak is inexistent, so the *EV* charging load after 8:00 would generate an increase of the daily peak demand, and that would increase the thermal generation units operating during the season, which would have negative consequences. Therefore, the *EV* charging load after 8:00 in August is very low.

Grid connectivity

Some islands are grid connected, either among them, as is the case of the Lanzarote-Fuerteventura system in Canarian Islands, or with the mainland, as is the case of Anglesey. This ability to import and export electricity makes the operation of the network much different to Non Connected Islands (*NCI*). The hypothetical island is considered an *NCI*, and the main effect of this will be on the wind power penetration limit. As discussed in Chapter 4, this limit is normally set in a range from 25 to 50%. It will depend on which is the lowest value between the spinning reserve limit (*SRL*) and the dynamic limit (*DL*). Both the *SRL* and the *DL* depend on the nature of the generation and distribution system and in the evaluation and decision of the system operator. For the hypothetical island analysed in this dissertation, an optimistic limit of 50% wind power penetration is chosen.

Power generation mix

In order to evaluate the fuel savings related to the reduction in thermal generation substituted by wind generation, or to compare the increase in fuel consumption to generate the *EVs* charging load with the petrol savings obtained by the use of those *EVs*, the power generation mix of the island must be taken into account. Firstly, it will be assumed that the only no thermal generation source in the hypothetical island is the wind power. Secondly, the thermal generation mix is based on the Crete island data (Tab.1). The main fuel used is heavy oil (Mazut) and diesel in engines and turbines. However, since 1990 all the new plants installed use diesel as a fuel, so it is reasonable to assume that in Crete the future thermal power generation mix will be 100% diesel power plants. That is the case chosen for the hypothetical island, whose diesel power plants are assumed to have an overall thermal to electrical efficiency of 40%, which is in the upper range for diesel generators (Mahon, 1992). The primary energy required by these plants is proportioned by diesel fuel, and its emissions per unit of energy are considered to be 0.25 $kgCO_2/kWh$ (AECOM, 2009). The investment cost of this power plants is 1,000 US$/kW, its O&M cost are 7.99 US$/MWh (Bruno et al,2012) and the diesel fuel cost 94.44 US$/MWh (EIA, 2012).

Wind generation profile

There exist wind speed data from several locations around the world offered by the US Department of Energy (DOE, 2012). The performance of the installed wind capacity depends on the wind resource, which can vary a lot in different islands. The better the wind resource is, the higher the capacity factor of the wind farms in the location. The model to obtain the wind power generation is based on the Vestas V80-2MW turbine (Fig.10). Using MERIT software and the V80 power curve, the wind generation profile can be calculated for a full year in different locations.

In order to evaluate the wind resource in these locations, the estimated capacity factor of the wind production is obtained. Different wind conditions are assumed in the hypothetical island, so that, three different scenarios are chosen: low, medium and high wind resource. For the low wind case (Island L) the January month from Oban data is chosen which gives a 22% capacity factor. The medium (Island M) and high (Island H) wind scenarios are chosen from Lerwick data for the months of June and March respectively. Their estimated capacity factor is 36% and 50% respectively. The

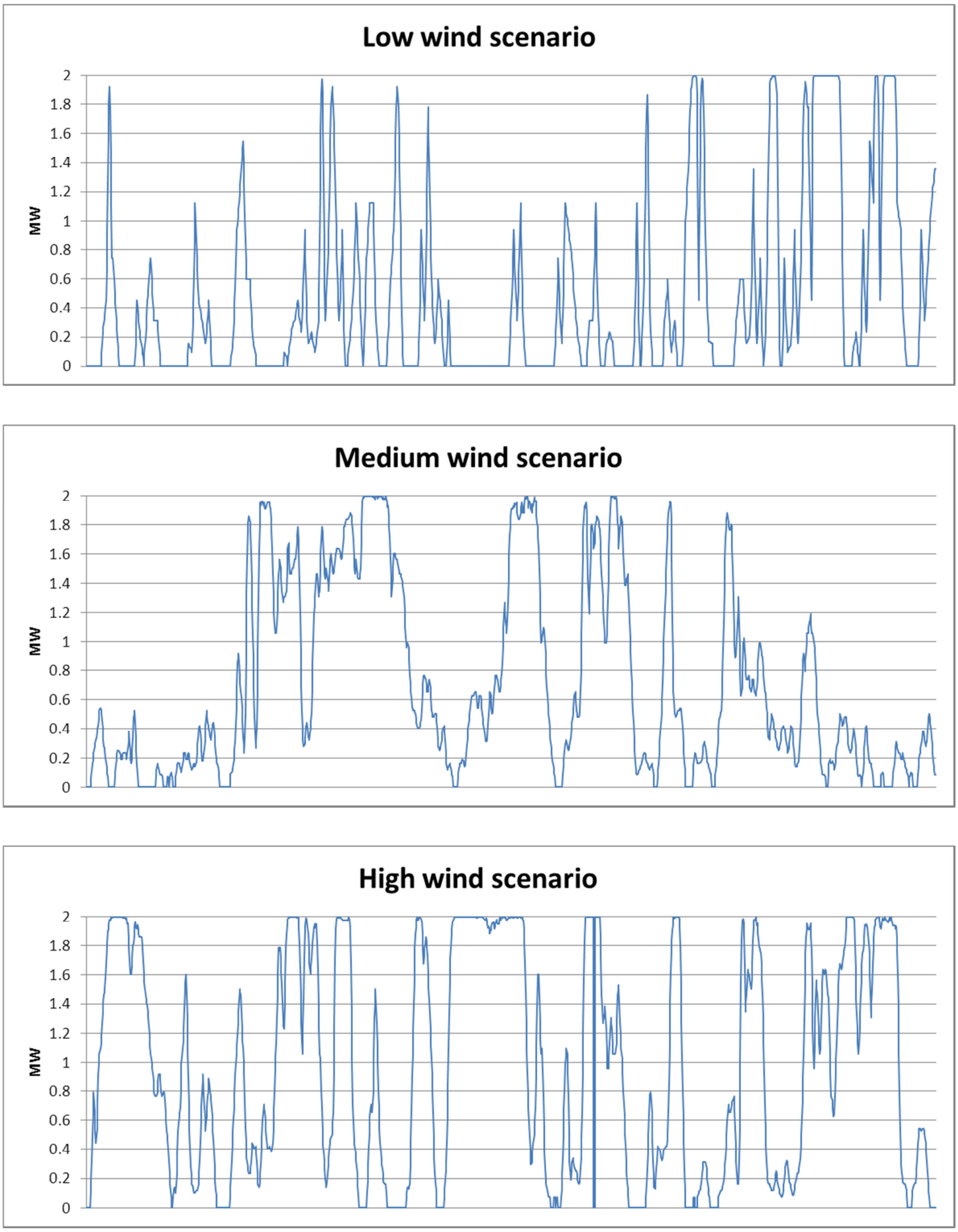


Figure 24: Wind power generation of a V80-2MW turbine during a month in the three posible scenarios analysed. (own elaboration)

generation profile of the V80-2MW turbine on the three chosen scenarios during the month is illustrated in Fig.24.

Wind capacity installed

The wind capacity installed is assumed to be 46 MW which is the real capacity of the wind farms in Anglesey Island. A hypothetical 10 MW increase of this capacity is also analysed. The variation on wind capacity installed will affect the wind generation surplus and the fuel savings in generation. The wind production reduces the primary energy requirements of the diesel generation plants. In terms of cost, the investment cost for a wind farm is considered of 1,810 US$/kW and its fixed O&M cost of 41.62 US$/kW per year (Bruno et al, 2012).

EV penetration

This is a variable parameter analysed. The effect of different *EV* penetration levels is examined. A high *EV* penetration will reduce the fuel consumption for vehicles but increase the diesel consumption for electricity generation. In order to calculate the fuel consumption savings in transport the total primary energy consumption of the substituted Internal Combustion Engine (*ICE*) vehicles has to be calculated, and then compared to the increased diesel requirements for electricity generation. The primary energy consumption is also directly related with the CO_2 emissions and with the operating cost of the vehicles and the diesel generation plants. In order to compare it is obtained in kWh both for generation and transport, and its calculation follows certain assumptions. Considering an equal distribution of petrol and diesel cars, the estimated mean consumption of the existing vehicle fleet is 7 litres/100km, which represents 1.12 kWh/mile with an emission factor of 0.24 $kgCO_2/kWh$ (AECOM, 2009). The price for petrol and diesel is 87.20 and 94.44 US$/MWh respectively (EIA, 2012), so for the assumed equal distribution of petrol and diesel cars the mean fuel price is 90.8 US$/MWh. For the investment calculations, an arbitrary 15 years life cycle for the vehicles is assumed.

SUMMARY OF ASSUMPTIONS		
PARAMETER	**EFFECT**	**HYPOTHETICAL ISLAND**
Size	Driving distances Vehicles range Energy consumption per EV	**Hawaii Islands** Driving patterns NHTS survey
Population	Energy demand Demand profile variability Number of EVs	**Anglesey** 66,828 people 0.525 vehicles per capita Electrical demand profile
Climate	Energy demand Demand profile shape	**Anglesey** August and December from electrical demand profile
Charging scheme	EV charging load profile	**Controlled charging period from 23:00 to 10:00** 10% Uncontrolled 90% Off-peak
Grid Connectivity	Export and import capacity Wind energy penetration	**Non Connected Island** Wind power penetration limit 50%
Power generation mix	Emissions and cost of primary energy	**Diesel generators** 40% efficiency 0.25 $kgCO_2$/kWh emissions 102.43 US$/MWh O&M costs
Wind speed profile	Wind power profile	**Oban and Lerwick** Island L: 22% CF Island M: 36% CF Island H: 50% CF
Wind capacity installed	Wind energy Wind power surplus Cost of wind generation	**Anglesey** 46 MW 1819 US$/kW investement cost 41.62 US$/kW fixed O&M cost
EV penetration	EV charging load Reduction of fuel for vehicles	**Variable % of EVs** EV: 0.27 kWhe/mile ICE: 1.12 kWh/mile 0.24 $kgCO_2$/kWh 90.8 US$/MWh Vehicles lifecycle: 15 years

Table 8: Summary of the assumptions taken in the calculations (own elaboration)

Chapter 7: Results and discussion

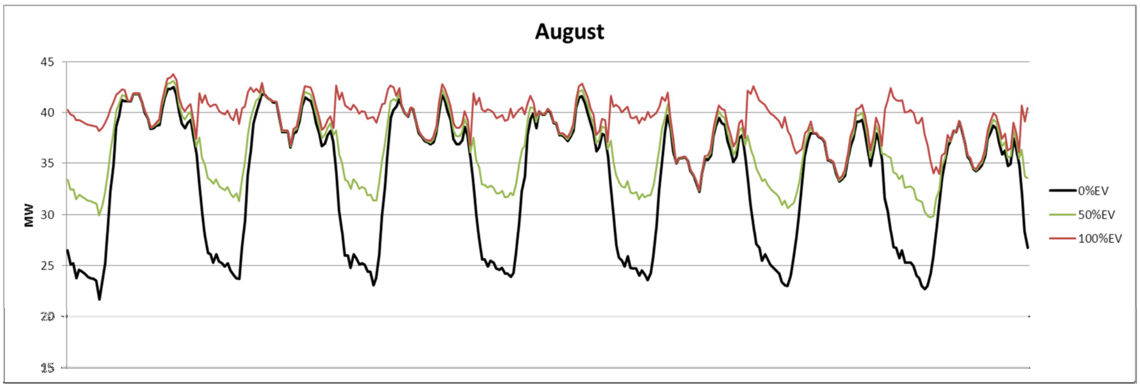
The results are presented for four island scenarios. In case of considering that there is no wind capacity installed at all, the effect of the introduction of *EVs* is independent of the wind resource. This situation is analysed in a scenario which is referred to as Island 0. In this case, the benefits from introducing *EV's* to an island with no wind power are calculated and can then be compared to the benefits in the islands where there is some wind power installed, which are the next three scenarios.

According to their low, medium and high wind speed profile, the islands with installed wind power are called Island L, Island M and Island H respectively. All the islands share the same characteristics except the wind speed profile, so they have the same electricity demand profile and *EV* charging load.

Island 0

The expected increase in the demand profile load due to the *EV* charging load depends on the *EV* penetration level. The higher the penetration level, the higher impact on the electricity demand profile it will have. The controlled charging profile is designed for the two different months. They are designed to share the *EV* charging load during the charging period in a way the existing valley in the demand profile is filled. By that, it is avoided an increase in the seasonal peak demand at high *EV* penetration levels.

The resulting electricity demand profile becomes flatter as the EV penetration increases. Both in August and in December the variation between the peak and the minimum seasonal demand is visibly reduced. Fig.25 illustrates an example week for each month where the resulting electricity load demands for a 0%, 50% and 100% *EV* penetration are displayed. It is also confirmed that the shape of the EV charging profile does not increase significantly the peak demand if the *EV* penetration increases (Tab.9), which is the objective of the controlled charging scheme.



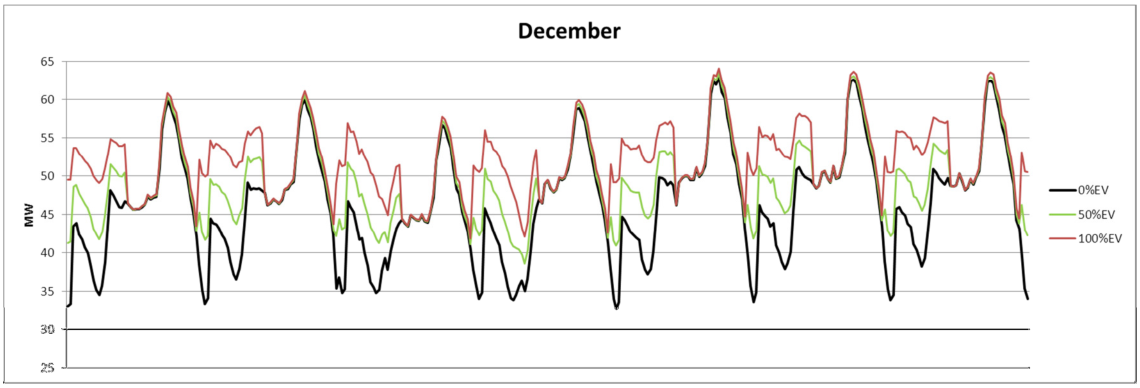


Figure 25: Electricity demand profile for a sample week in the two different months analyzed for 0%, 50% and 100% *EV* penetration levels.(own elaboration)

PEAK DEMAND		
% EV PENETRATION	AUGUST	DECEMBER
0	51.10 MW	64.20 MW
25	51.40 MW	64.46 MW
50	51.71 MW	64.73 MW
75	52.01 MW	64.99 MW
100	52.31 MW	65.26 MW

Table 9: Increase on the month peak electricity demand due to different *EV* penetration levels.(own elaboration)

With the introduction of the *EV* fleet it is observed that there is a reduction in primary energy consumption, CO_2 emissions and cost of fuel imports. For the Island 0 case, the reduction is equal in magnitude for August and December, as the driving patterns are considered to be the same in both months. However, in relative terms the reduction is more significant in August as the primary energy consumption is lower during this month. For August, a 100% EV penetration produces a reduction of the 8.51% in the primary energy consumption, the 7.73% in CO_2 emissions and the 7.02% in the cost of fuel imports (Tab.10).

ISLAND 0: August	NO EV's	25% EV's	50% EV's	75% EV's	100% EV's
Electrical energy demand (MWh)	25602	26653	27704	28756	29807
Primary energy for generation (MWh)	64005	66632.5	69260	71890	74518
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**81453**	**79719**	**77984**	**76252**	**74518**
CO_2 emissions from generation (tCO2)	16001	16658	17315	17973	18629
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**20189**	**19799**	**19409**	**19019**	**18629**
Cost of fuel for generation (millions of US$)	6.25	6.51	6.76	7.02	7.28
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of fuel imports (millions of US$)	**7.83**	**7.69**	**7.55**	**7.42**	**7.28**

Table 10: Results for the August month in the Island 0 case

For December, a 100% EV penetration produces a reduction of the 6.85% in the primary energy consumption, the 6.21% in CO_2 emissions and the 5.75% in the cost of fuel imports (Tab.11).

ISLAND 0: December	NO EV's	25% EV's	50% EV's	75% EV's	100% EV's
Electrical energy demand (MWh)	33464	34551	35567	36619	37670
Primary energy for generation (MWh)	83660	86378	88918	91548	94175
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**101108**	**99464**	**97642**	**95910**	**94175**
CO_2 emissions from generation (tCO2)	20915	21594	22229	22887	23544
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**25103**	**24735**	**24323**	**23934**	**23544**
Cost of fuel for generation (millions of US$)	8.17	8.43	8.68	8.94	9.19
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of fuel imports (millions of US$)	**9.75**	**9.62**	**9.47**	**9.33**	**9.19**

Table 11: Results for the December month in the Island 0 case

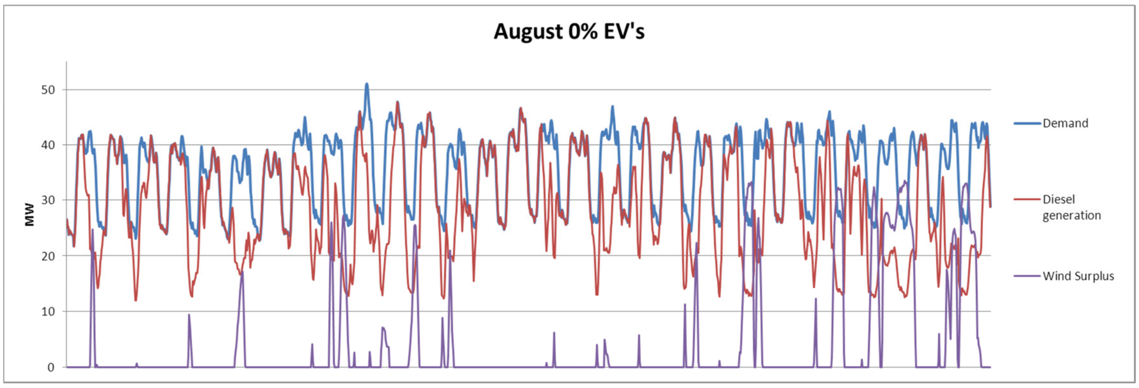
The resulting savings obtained with the *EV* implementation are positive. Obviously, to achieve them a certain investment has to be done, as the *EVs* are generally more expensive than *ICE* vehicles. According to the results for a 100% *EV* penetration, the monthly cost savings on fuel imports are 0.55 million US$. In the assumed 15 years lifecycle of the vehicles this represents savings of 99 million of US$. If the 35,085 vehicles in the island are to be substituted, this quantity represents savings of 2,822 US$ per vehicle during the 15 lifecycle years. Under these assumptions, the investment of substituting the vehicle fleet will be economically beneficial if the price difference between an EV and its equivalent ICE become less than this quantity.

From these results, the positive effects of a 100% *EV* penetration are clear, and under the controlled charging scheme, it has been shown that it does not increase the system peak power. Despite the important economic investment required for the substitution of the vehicle fleet in the island, the long term objective has to be the 100% *EV* penetration, as the maximum savings and the flatter electricity demand profile are achieved by this option.

Island L

A low wind speed characterizes this island. Despite the low wind resource, the 46 MW of installed wind capacity supply an important part of the energy. When the wind is blowing the generation requirements of the diesel power plants are reduced. With certain frequency this wind power generation is higher than the *NCI* system is able to absorb resulting in a wind surplus. A higher amount of wind power is absorbed in December than in August, as a result of the higher demand during winter season. That makes the wind surplus more problematic during the August month. As it is illustrated in Fig.26 the *EV* introduction produces an increase of the electricity demand. This increase is covered by an increase on diesel generation, but also by a decrease of wind surplus in the periods when it is absorbed by the *EV* charging load.

By integrating the power profiles, the energy figures for the month of August are obtained. That is used to compare the results for different levels of *EV* penetration. As



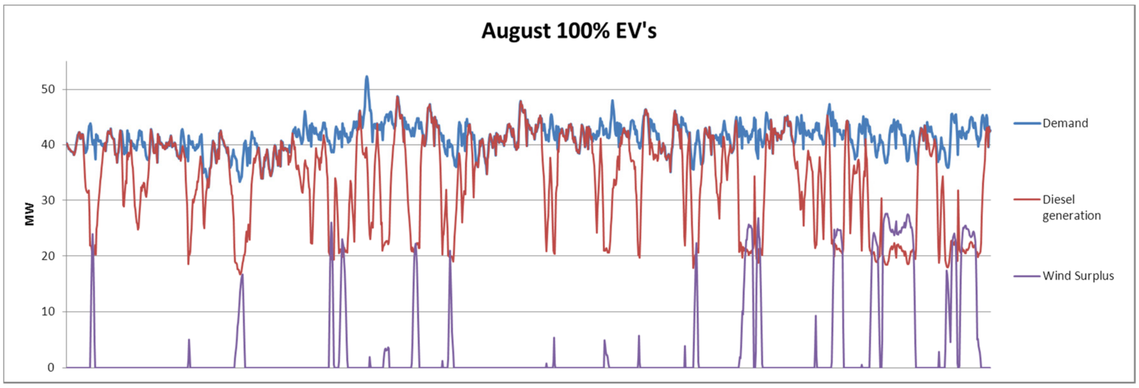


Figure 26: Total electricity demand profile, electricity demand covered by diesel generation and wind surplus in Island L for the August month with a 0 and 100% *EV* penetration. (own elaboration)

ISLAND L: August	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	7791	7791	7791	7791	7791
Wind energy surplus (MWh)	2660	2536	2422	2317	2217
Wind energy absorbed (MWh)	5131	5255	5369	5474	5574
Electrical energy demand (MWh)	25602	26653	27704	28756	29807
Electrical energy demand minus wind (MWh)	20471	21398	22335	23282	24233
Primary energy for diesel generation (MWh)	51178	53495	55838	58205	60583
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**68626**	**66581**	**64562**	**62567**	**60583**
CO_2 emissions from generation (tCO2)	12794	13374	13959	14551	15146
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**16982**	**16514**	**16053**	**15598**	**15146**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	5.04	5.27	5.49	5.73	5.96
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**6.78**	**6.61**	**6.45**	**6.28**	**6.12**

Table 12: Results for the August month in the Island L (own elaboration)

in the Island 0 case, where there was no wind generation, a primary energy reduction is achieved with high EV penetration levels. This reduction also entails a reduction in CO2 emissions and energy cost. In this case, the total and relative reduction is higher than in the previous case. Compared to the island without EVs, a 100% EV penetration produces a reduction of the 11.72% in the primary energy consumption, the 10.81% in CO2 emissions and the 9.73% in the cost of energy (Tab.12).

During December, as a result of the higher profile demand, wind surplus is lower than in August. Nevertheless the reduction in the primary energy consumption entailed with the increase of the *EV* fleet is also important. This reduction is also relatively higher than the achieved in the no wind Island 0, where the advantage of wind surplus absorbed by EVs does not apply. For December, the change of a 0% *EV* penetration level to a 100% entails a 9.07% reduction in the primary energy consumption, a 8.33% reduction in CO_2 emissions and a 7.6% reduction in the cost of energy (Tab.13).

ISLAND L: December	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	7791	7791	7791	7791	7791
Wind energy surplus (MWh)	2004	1905	1810	1720	1633
Wind energy absorbed (MWh)	5787	5886	5981	6071	6158
Electrical energy demand (MWh)	33464	34515	35567	36619	37670
Electrical energy demand minus wind (MWh)	27677	28629	29586	30548	31512
Primary energy for diesel generation (MWh)	69193	71573	73965	76370	78780
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**86641**	**84659**	**82689**	**80732**	**78780**
CO_2 emissions from generation (tCO2)	17298	17893	18491	19093	19695
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**21486**	**21034**	**20585**	**20139**	**19695**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	6.80	7.04	7.27	7.50	7.74
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**8.55**	**8.38**	**8.22**	**8.06**	**7.90**

Table 13: Results for the December month in the Island L. (own elaboration)

To calculate the economic implications of increasing the *EV* penetration level, the same calculation done for the Island 0 is repeated. Now the reduction in of the cost of energy in millions of US$ is different for August and December. The average is considered as the mean reduction in the monthly energy cost, which is 655,000 US$ for a 100% EV penetration. During 15 years, this represents savings of 3,361 US$ per vehicle, so if a vehicle is assumed to last at least 15 years, a price difference of less than this quantity would make an EV a better option than a normal ICE vehicle from an economical point of view.

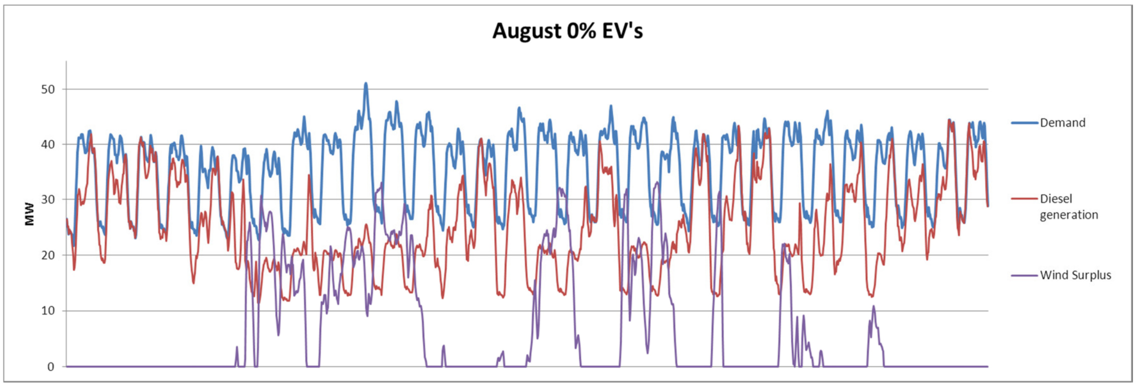
Even with the low wind resource existing in the island, an increase on the wind power capacity could be planned. The electricity generation with diesel in *NCI's* has a higher cost than the generation in a normal mainland grid system. That is why, even in not the best wind conditions, a wind farm project is interesting from an economical and environmental point of view. The effect of a 10 MW increase of the wind capacity has been analyzed. The cost of this investment is calculated as 18.10 US$ millions. The results vary depending on the *EV* penetration that the island has. The results show that the investment benefits from a high *EV* wind penetration, as it makes the payback period shorter (Tab.14). This is because a higher amount of wind is absorbed during the high wind generation periods due to the EV charging load increasing the electricity demand and, consequently, the wind power penetration limit.

	0%EV	25%EV	50%EV	75%EV	100%EV
Savings August (millions of US$)	0.069	0.074	0.079	0.084	0.088
Savings December (millions of US$)	0.103	0.107	0.110	0.113	0.116
Savings Year (millions of US$)	1.029	1.083	1.132	1.179	1.221
Estimated payback (years)	**17.6**	**16.7**	**16.0**	**15.4**	**14.8**

Table 14: Savings in energy costs with the installation of new 10MW of wind capacity in the Island L and estimated simple payback of the investment. (own elaboration)

Island M

A medium wind speed characterizes this island. The 46 MW of installed wind capacity reduce considerably the diesel power plants generation requirements. Frequently the wind power generation is too high resulting in wind surplus. When this surplus occurs it means that the wind is providing a power equal to the power limit set by the maximum penetration allowed for the system. As in Island L, a higher amount of wind power is absorbed in December than in August. Therefore there is also a higher wind surplus during August. Comparing the graphical results for the August month, it can be observed that in Island M (Fig.27) the wind surplus is more important and frequent that in Island L (Fig.26). This higher wind surplus in Island M is not necessarily negative. It means that some potential wind production is wasted, but also that there is a higher wind resource which provides more energy to the system, and that reduces further the requirements for diesel generation. It can also be observed that the wind surplus is reduced with the introduction of *EVs*. A 100% *EV* penetration makes the gap between total demand and demand covered by diesel generation wider. This gap represents the amount of wind power absorbed by the system.



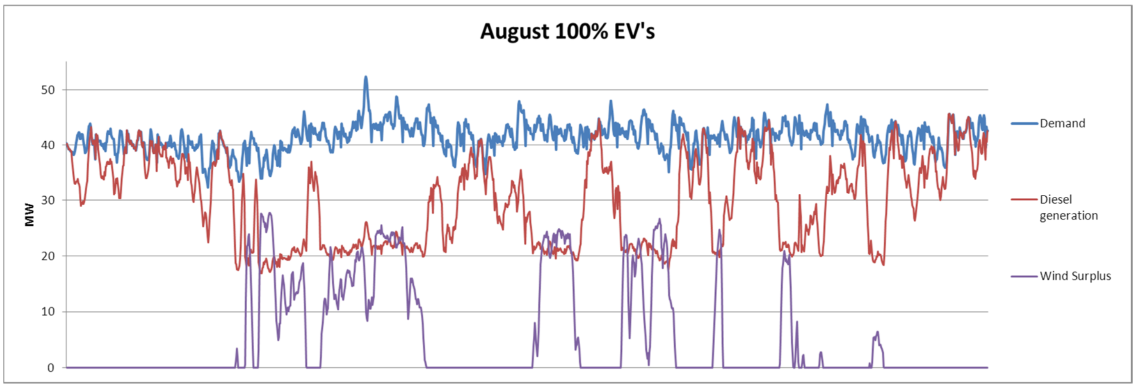


Figure 27: Total electricity demand profile, electricity demand covered by diesel generation and wind surplus in Island M for the August month with a 0 and 100% *EV* penetration. (own elaboration)

In order to get the energy results for the month of August, the power profiles are integrated. By that, the results for the island with different levels of *EV* penetration are compared. The primary energy reduction which is achieved with a high *EV* penetration levels in Island M is even higher than in the Island L. This proves the better result of the *EVs* and wind power combined strategy in a location with a higher wind resource.

Logically, the higher wind generation in Island M results in a lower primary energy consumption if no *EVs* are considered (62,403 MWh in Island M to 68,626 MWh in Island L). But the interesting result here is that when introducing a 100% *EV* penetration, the reduction achieved in primary energy consumption is also larger for the Island M (-8,798 MWh in Island M to -8,043 MWh in Island L).

Comparing the island without *EVs* to it with a 100% *EV* penetration, the relative reductions in percentage for this case are a 14.1% in the primary energy consumption, a 13.13% in CO_2 emissions and a 11.79% in the cost of energy (Tab.15).

ISLAND M: August	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	12156	12156	12156	12156	12156
Wind energy surplus (MWh)	4536	4325	4135	3960	3791
Wind energy absorbed (MWh)	7620	7831	8021	8196	8365
Electrical energy demand (MWh)	25602	26653	27704	28756	29807
Electrical energy demand minus wind (MWh)	17982	18822	19683	20560	21442
Primary energy for diesel generation (MWh)	44955	47055	49208	51400	53605
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**62403**	**60141**	**57932**	**55762**	**53605**
CO_2 emissions from generation (tCO2)	11239	11764	12302	12850	13401
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**15426**	**14904**	**14396**	**13897**	**13401**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	4.45	4.66	4.87	5.08	5.30
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**6.19**	**6.00**	**5.82**	**5.64**	**5.46**

Table 15: Results for August month in the Island M (own elaboration)

For December and in the case of no EVs in the island, the primary energy consumption is also lower for Island M than for Island L (78,683MWh in Island M to 86,651MWh in Island L). Also in December the primary energy reduction achieved by implementing a 100% *EV* penetration is greater in Island M than in Island L (-8,510MWh in Island M to -7,861MWh in Island L). Comparing the results for 0% and 100% *EVs* the reductions achieved by the *EV* introduction are of a 10.82% in the primary energy consumption, a 10.02% in CO_2 emissions and a 8.99% in the cost of energy (Tab.16).

ISLAND M: December	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	12156	12156	12156	12156	12156
Wind energy surplus (MWh)	3186	3019	2858	2705	2555
Wind energy absorbed (MWh)	8970	9137	9298	9451	9601
Electrical energy demand (MWh)	33464	34515	35567	36619	37670
Electrical energy demand minus wind (MWh)	24494	25378	26269	27168	28069
Primary energy for diesel generation (MWh)	61235	63445	65673	67920	70173
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**78683**	**76531**	**74397**	**72282**	**70173**
CO_2 emissions from generation (tCO2)	15309	15861	16418	16980	17543
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**19496**	**19002**	**18512**	**18027**	**17543**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	6.05	6.27	6.49	6.71	6.93
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**7.79**	**7.62**	**7.44**	**7.26**	**7.09**

Table 16: Results for December month in the Island M (own elaboration)

In this case also the calculations to unveil which extra cost for an EV in comparison to an ICE is acceptable for making the substitution of the vehicle fleet a cost profitable investment. The average value for August and December is considered to estimate the reduction in millions of US$ cost of energy per month. For a 100% EV penetration, the monthly reduction is 715,000US$. These represents savings of 3,668 US$ per vehicle during its 15 years lifecycle. Consequently, that figure is the assumable price difference that would make an EV a better option than a normal ICE vehicle from a purely economic point of view.

Also in this island the results for a possible increase on wind capacity are examined. It is calculated for an expansion of 10 MW in the installed wind capacity. Due to a higher wind resource than in Island L, the calculated economic savings per year are also higher, which results in a shorter payback period for the investment (Tab.17). The payback period in a scenario of no *EVs* for Island M is 13.1 years, which is much shorter than the 17.6 years for Island L. In the 100% *EV* scenario the estimated payback is reduced further, to 11.1 years, which is 2 years less than in the 0% *EV* scenario. In the Island L this difference between both scenarios was higher (2.8 years). That means that the effect of the EV penetration on a new 10MW wind power investment is a little bit more noticeable in Island L than in Island M.

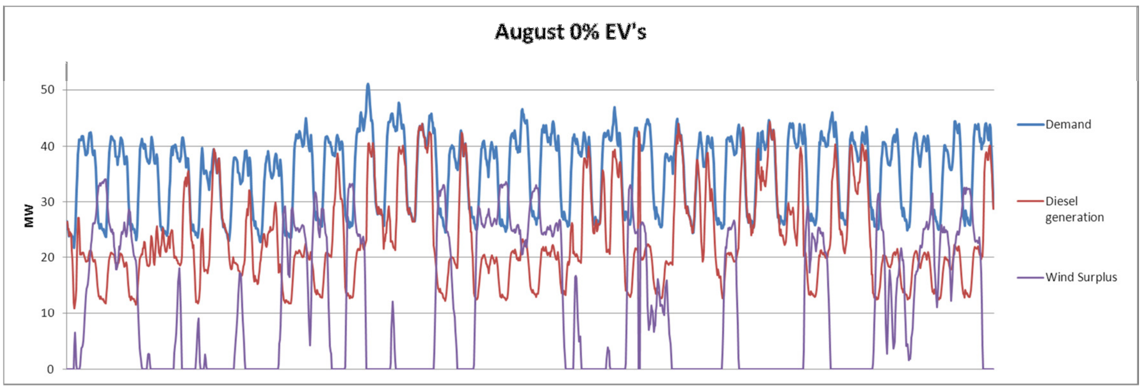
	0%EV	25%EV	50%EV	75%EV	100%EV
Savings August (millions of US$)	0.094	0.098	0.104	0.113	0.118
Savings December (millions of US$)	0.136	0.141	0.144	0.149	0.153
Savings Year (millions of US$)	1.379	1.428	1.492	1.567	1.624
Estimated payback (years)	**13.1**	**12.7**	**12.1**	**11.6**	**11.1**

Table 17: Savings in energy costs with the installation of new 10MW of wind capacity in the Island M and estimated simple payback of the investment.

Island H

The last case examined is an island with a very high wind resource. Periods or wind surplus are very frequent, and the 46 MW of installed wind capacity supply a very important part of the total energy demand. The wind production potential is very important in this island but it can be observed that during most than half of the time the wind power absorbed is limited by the wind penetration limit (Fig.28). As in the other islands, this situation is more evident during the August month, which has a lower demand. Also, a 100% *EV* penetration level results in a reduction of the wind surplus during the periods when this wind surplus coincides with the *EV* charging period. That increases the wind absorbed by the system, which as previously mentioned is not limited by the wind resource itself but by the demand load of the *NCI* electricity system.

The power profiles are integrated to obtain the monthly energy results. Island H benefits from its very high wind profile obtaining the lowest energy consumptions, CO_2 emissions and energy cost of all the cases. For the August month the primary energy



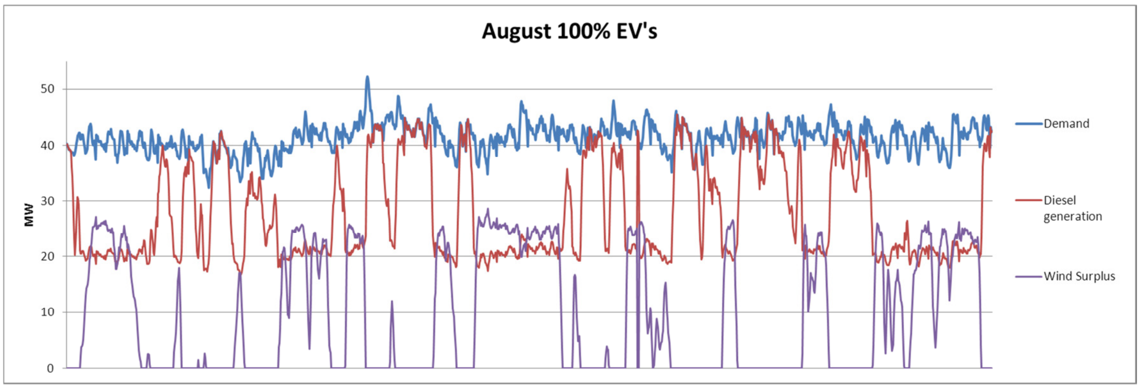


Figure 28: Total electricity demand profile, electricity demand covered by diesel generation and wind surplus in Island H for the August month with a 0 and 100% *EV* penetration (own elaboration)

consumption is in a range between 59,283 MWh in the no *EV* scenario and 49,703 MWh in the 100% EV scenario. That means a reduction of 9,580 MWh thanks to the full *EV* fleet introduction, higher than the 8,798 MWh reduction in Island M or the 8,043 MWh in Island L. In this case the relative reductions achieved by the 100% *EV* are a 16.16% in the primary energy consumption, a 15.16% in CO_2 emissions and a 13.73% in the cost of energy (Tab.18).

ISLAND H: August	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	16689	16689	16689	16689	16689
Wind energy surplus (MWh)	7821	7545	7278	7018	6763
Wind energy absorbed (MWh)	8868	9144	9411	9671	9926
Electrical energy demand (MWh)	25602	26653	27704	28756	29807
Electrical energy demand minus wind (MWh)	16734	17509	18293	19085	19881
Primary energy for diesel generation (MWh)	41835	43773	45733	47713	49703
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**59283**	**56859**	**54457**	**52075**	**49703**
CO_2 emissions from generation (tCO2)	10459	10943	11433	11928	12426
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**14646**	**14084**	**13527**	**12975**	**12426**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	4.16	4.35	4.54	4.74	4.93
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**5.90**	**5.69**	**5.49**	**5.29**	**5.09**

Table 18: Results for August month in the Island H (own elaboration)

In December also the reductions related to the EV introduction in Island H are the highest of the December month in the all the islands. Those are a 12.64% in the primary energy consumption, a 11.81% in CO_2 emissions and a 10.76% in the cost of energy (Tab.19).

The reduction in energy cost thanks to the 100% *EV* penetration for December is 0.79 millions of US$, higher than in any other island. The same applies for the August month, when 0.81 millions of US$ are saved. As a result of these savings being the largest, the investment for the vehicle fleet renovation is the most favourable. Using again the assumption of a 15 year vehicle lifecycle, the EV option will be cost effective if the unit price is less than 4,104 US$ more expensive than the price of an ICE vehicle.

ISLAND H: December	0%EV	25%EV	50%EV	75%EV	100%EV
Maximum wind potential production (MWh)	16689	16689	16689	16689	16689
Wind energy surplus (MWh)	5790	5549	5302	5061	4829
Wind energy absorbed (MWh)	10899	11140	11387	11628	11860
Electrical energy demand (MWh)	33464	34515	35567	36619	37670
Electrical energy demand minus wind (MWh)	22565	23375	24180	24991	25810
Primary energy for diesel generation (MWh)	56413	58438	60450	62478	64525
Primary energy for ICE vehicles (MWh)	17448	13086	8724	4362	0
Total primary energy consumption (MWh)	**73861**	**71524**	**69174**	**66840**	**64525**
CO_2 emissions from generation (tCO2)	14103	14609	15113	15619	16131
CO_2 emissions from ICE vehicles (tCO2)	4188	3141	2094	1047	0
Total CO_2 emissions (tCO2)	**18291**	**17750**	**17206**	**16666**	**16131**
Cost of wind generation (O&M) (millions of US$)	0.16	0.16	0.16	0.16	0.16
Cost of diesel generation (O&M)(millions of US$)	5.59	5.79	5.99	6.19	6.39
Cost of fuel for ICE vehicles (millions of US$)	1.58	1.19	0.79	0.40	0.00
Total cost of energy (millions of US$)	**7.34**	**7.14**	**6.94**	**6.75**	**6.55**

Table 19: Results for December month in the Island H (own elaboration)

The results presented above for Island H are the most positive of all the islands due to its high wind resource. That would make think that the best conditions for a new investment in wind capacity are found in this island. However, the results for the installation of the extra 10 MW wind capacity tell the opposite (Tab.20). The savings achieved for a year are the lowest, especially for August. That results in the longest payback period which in the 0% EV case is 3.7 years longer than in Island L and 8.2 years longer than in Island H.

	0%EV	25%EV	50%EV	75%EV	100%EV
Savings August (millions of US$)	0.055	0.057	0.060	0.064	0.067
Savings December (millions of US$)	0.087	0.093	0.097	0.100	0.105
Savings Year (millions of US$)	0.852	0.901	0.939	0.985	1.032
Estimated payback (years)	**21.3**	**20.1**	**19.3**	**18.4**	**17.5**

Table 20: Savings in energy costs with the installation of new 10MW of wind capacity in the Island H and estimated simple payback of the investment. (own elaboration)

This fact has a logical explanation. In the Island H, due to the 46 MW capacity the wind surplus is so high that the extra 10 MW mostly increase this surplus but do not increase the wind absorbed very much. In Island M, the wind surplus is important, but there is still an important available demand to be covered by wind production. With the extended capacity the wind surplus is also increased, but the new wind energy absorbed is very important. That makes Island M the best scenario for a new investment to install 10MW. In Island L there is also a lot of available demand to be covered by wind production. However, the wind resource is low and the increase on wind absorbed due to the extra added wind capacity is not as important as it is in Island M. That explains why the investment in Island L has a longer payback than in Island M.

Chapter 8: Conclusions

In this dissertation an energy wise strategy to be applied in Non Connected Islands (*NCI*) has been proposed. It is based on a combined strategy of introducing Electric Vehicles (*EVs*) as the main means of transport and producing as much electricity from wind as possible.

To check the results of this strategy, a model of the transport and energy system of the *NCI* has been designed. This model assumes some certain driving patterns, population, electricity demand profile, power generation system, energy network operation and other characteristics which affect the final performance of the solution. These parameters have been chosen according to available measured data or extracted from the literature on the topic. In order to represent islands with low, medium and high wind profiles, three different scenarios have been chosen and they are referenced to as Island L, Island M and Island H respectively.

Assuming 46 MW of wind capacity installed, the effects of an *EV* higher penetration in the vehicle fleet are positive. However, the reductions in primary energy, CO_2 emissions and energy costs obtained have to be taken carefully. They are based in assumptions and any change on these assumptions could have a great effect on the calculations. The target of this dissertation is not offering a detailed analysis of the wind generation neither it is a precise evaluation of *EVs*. The goal is to show the combined effect of wind generation and a high *EV* penetration in a *NCI*. A base scenario with no wind generation but the same other assumptions is created. This is the Island 0 scenario. It represents the results when the *EVs* are introduced in an island with no wind generation. Comparing with this scenario the extra advantages of introducing *EVs* in an island with a high wind energy production is checked. For example, the primary energy reductions when the ICE fleet is fully substituted by *EVs* are much more significant in the Islands L, M and H which have some wind generation than in Island 0 (Tab.21). The same applies for the CO_2 emissions and the energy cost.

Scenario	Month	Reduction achieved by the 100% EV penetration		
		Primary energy	CO_2 emissions	Energy cost
Island 0	August	8.51%	7.73%	7.02%
	December	6.85%	6.21%	5.75%
Island L	August	11.72%	10.81%	9.73%
	December	9.07%	8.33%	7.60%
Island M	August	14.10%	13.13%	11.79%
	December	10.82%	10.02%	8.99%
Island H	August	16.16%	15.16%	13.73%
	December	11.81%	11.81%	10.76%

Table 21: Reduction in percentage of different parameters when the *EV* penetration level is changed from 0 to 100% (own elaboration)

This effect makes the introduction of an EV fleet more assumable economically in islands with a high wind generation. If the total vehicle fleet in the island was to be substituted by *EVs,* the price difference per vehicle that would make the investment cost effective is higher when the wind resource is higher (Tab.22). That means that the EV penetration level in a *NCI* is favored if there is a high wind power production. In addition to this, another thing makes EVs suitable for islands. One of the most important drawbacks of *EVs* is their limited range. This will not be an impediment for its penetration in most of the small and medium sized islands. Assuming that the price difference becomes lower than these quantities (according to an AECOM report (2009) this will happen between 2020 and 2030) or economic incentives are placed, a 100% *EV* fleet could become real in a near future.

Island 0	Island L	Island M	Island H
2822 US$	3361 US$	3668 US$	4104 US$

Table 22: Minimum price difference between an EV and an ICE car that would make the investment on substituting the island's vehicle fleet cost effective. (own elaboration)

The results presented above come from scenarios created by merging data from different sources. Due to the difficulties in accessing to some of the data it has been no possible to generate a model of a real island. However, the methodology applied for the generic island models can be perfectly applied to a specific real case. The only requirement is to have all the required data from a real island and use it following the methodology applied in this dissertation. Normally, some of the data required is not publicly available. However, this data is not very complex and, in general, its access

DATA REQUIRED	PARAMETERS OBTAINED FROM THE DATA
Driving patterns	Total number of vehicles Percentage of vehicles driven in a day Daily driven distances Range required Energy consumption for transport
Electricity demand profile	Electrical energy consumption Peak demand Controlled charging period Controlled charging profile Limits to wind power penetration
Power generation mix	Electricity generation efficiency Emissions and cost of primary energy for electricity generation Spinning reserve and dynamic limit to the wind power penetration
Wind generation profile	Wind energy produced Cost of wind generation

Table 23: Summary of the data required to apply the methodology for an specific island case

will be relatively easy to a party interested in studying the wind and EV's development possibilities in a *NCI*. A summary of the required data is found in Table 23. The first are the driving patterns in the island which can be surveyed in case that there is no existing data. The electricity demand profile for a typical year can be obtained from substation data supplied by the network operator in the island. Also the power generation mix and other parameters of the power plant can be obtained from the utilities which operate the plants. The wind generation profile can be obtained directly from measures or calculated from the wind speed profile and the model of the existing or projected wind turbines.

Once all this data is gathered and the calculations detailed on this dissertation are applied to it, results similar to the ones detailed in Chapter 7 can be obtained for a real island. This can support the utilities and governments in the island to take the decision of promoting wind power and *EV* together to improve the performance of the energy system in the island.

Regarding the combined wind and *EV* strategy, not only an existing high wind generation level favours the *EV* penetration. In some cases, a high *EV* penetration level favours an increase of the installed wind power capacity. In the analysed scenarios, the payback period for an investment on new wind capacity is always higher when a higher

EV penetration level is considered. This is because in all the scenarios there is a wind surplus which becomes partially absorbed when the *EV* charging load is applied. A higher *EV* charging load increases the portion of the maximum wind potential generation which is absorbed (Fig.29). For a low wind capacity installed there is no difference on the energy absorbed in the different EV scenarios. All the wind generation is absorbed and there is no wind surplus. However, as the wind capacity increases and causes the occurrence of wind surplus, it can be observed that the EV penetration level has an effect on the total wind energy absorbed and improves the wind capacity factor.

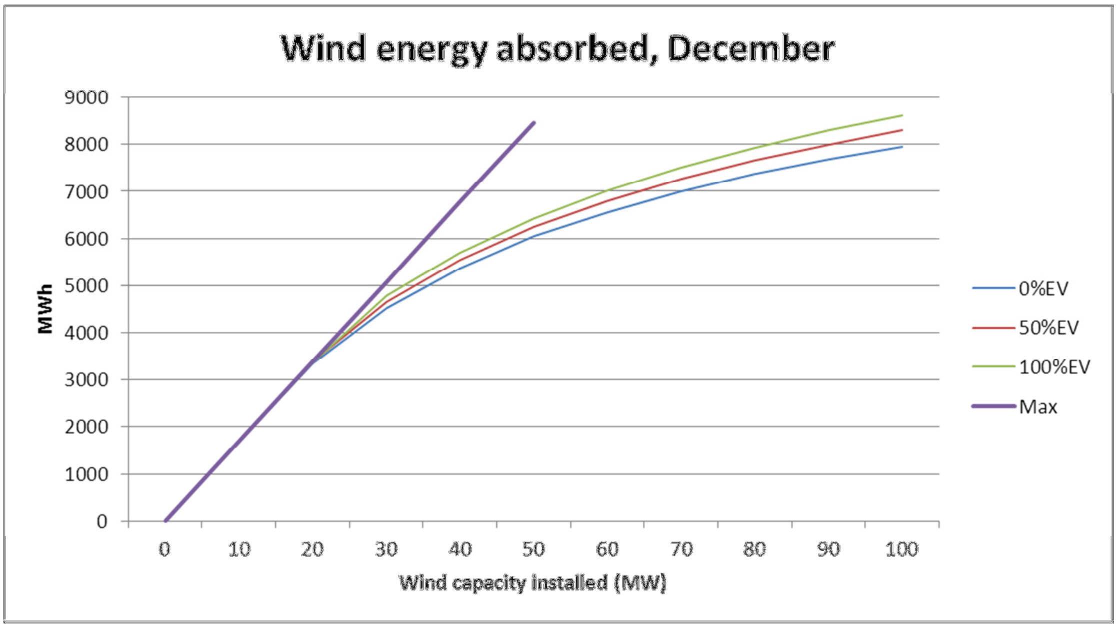


Figure 29: Total wind energy absorbed in relation to the wind power capacity installed for different EV penetration levels. December month in Island L. (own elaboration)

Therefore, the islands which present a wind surplus are the most indicated for introducing *EVs*. The *EV* charging profile is especially suitable to absorb the wind surplus, as this charging can be controlled to take place overnight while most of the vehicles are parked. In addition, it is precisely at night when the wind surplus is more likely to occur due to the lower electricity demand.

The *EV* fleet charged under these conditions reduces the energy required for transport in a *NCI*, and the derived CO_2, pollutant emissions and cost of fuel imports. At the same time, thanks to the *EV* charging load a portion of the wind surplus is absorbed reducing the energy required for conventional generation and, again, the derived emissions and costs. The most important conclusion of this work is that the benefits for the energy system in a *NCI* will be greater if wind power and *EVs* are introduced together in a combined strategy.

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