DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING

University of Strathclyde Engineering

Solutions for electricity provision in the off-grid autonomous city of Ceuta (Spain)

Author: Carlos Javier Cortés Montero

Supervisor: Dr. Daniel Cóstola

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

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2018

REF UK TOP 20 RESEARCH-INTENSIVE UNIVERSITY

THE UK UNIVERSITY OF THE YEAR WINNER

THE UK ENTREPRENEURIAL UNIVERSITY OF THE YEAR WINNER

The place of useful learning

The University of Strathclyde is a charitable body, registered in Scotland, number SC015263

COPYRIGHT DECLARATION

This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Signed: Carlos Javier Cortes Montero Date: 24 August 2018

EXECUTIVE SUMMARY

The city of Ceuta is a Spanish small and isolated thermal-based electricity system located in Africa, which has no electricity connection with either the Spanish Peninsula, or with Morocco, because of energy security reasons related with its sovereignty. The cost of electricity generation in Ceuta is five times higher than in the Spanish Peninsular System and generates almost 3 times more carbon dioxide emissions per unit of electricity produced. Moreover, the city suffers blackouts, providing a poor-quality electricity service. This project aims to find an optimal combination of the different electricity generation technologies available to improve the current electricity provision in Ceuta.

Five different scenarios have been modelled, using the software HOMER PRO for the simulations. The Scenario 0 represents the current situation, with all the electricity produced by a 97 MW diesel power plant. The Scenario 1 combines an electricity interconnector which connects Ceuta with the Spanish Electricity System and a minimum use of the power plant. In the Scenario 2, all the electricity is provided by the interconnector. The Scenario 3 combines the installation of 21 MW onshore wind, 13 MW solar rooftop photovoltaics and a 60 MWh pump hydro energy storage with the diesel power plant. The last one, Scenario 4, combines the Spanish interconnector plus 25 MW of onshore wind, 5 MW of solar and a minimum use of the power plant. All the scenarios are compared using a Multicriteria Decision Analysis, using the electricity costs, the carbon footprint and the energy security as comparison criterions. The Scenario 4 was selected as the optimal solution, due to its 68 Million € reduction in the net present cost, a high level of energy security which can assure the energy security and the quality of the electricity service provided, and its 51 % reduction in the carbon dioxide emissions with respect the current situation. Also, a pathway for the future electricity generation in Ceuta is provided, giving some guidance related to the appropriate time to install the different electricity generation technologies. As conclusions, the optimal solution would need to minimize the electricity produced by the power plant (the most expensive and polluting technology) while maintaining its maximum operational capacity (increases the system energy security) and including the interconnector, as it assures a high quality of the electricity service provided, eliminating the necessity of additional energy storage and making feasible the maximum installation of onshore wind power capacity, proven to be the most economical electricity generation technology. A gradual installation of solar rooftop photovoltaics is recommended, and a future integration of offshore wind power could be feasible, once its levelized costs have reached the grid parity.

ACKNOWLEDGEMENT

I would like to thank Dr. Daniel Costola for his great guidance as the mentor for this project, to Dr. Paul Tuohy for his support as the Course Director and to the University of Strathclyde for giving me the opportunity to study here and live this marvellous experience.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Problem definition

In response to the climate change and with the aim to hold global warming well below 2ºC on preindustrial levels, 196 countries all over the world adopted the Paris Agreement in the 2015 United Nations Climate Change Conference, to foster low greenhouse gas emission development [1]. In turn the European Commission, to comply with the Paris Agreement and in its ambition for world leadership in renewable energy, established different targets in the "Clean Energy for All Europeans" Package [2]: cut in greenhouse gas emissions, increase the share of total energy consumption from renewable energy [3] and increase the percentage in energy efficiency [4], stablishing goals for years 2020 and 2030 to be achieved collectively between its Member States.

Spain has different goals to comply with the target stablished by the European Union: 22.7% of share of energy generated from renewable sources in gross final energy consumption and 40% of electricity demand met by electricity generated from renewable energy sources in 2020 [5]. So far, the objectives proposed in the Spain´s National Renewable Energy Action Plan 2011-2020 [6] are in good track to comply with Europe´s climate and energy targets [7]. However, this renewable energy promotion and greenhouse gas reduction that could be seen in Spain, the European Union and all around the word, has paradoxically some exceptions that can be found in the Spanish territory: its non-peninsular systems [8]. The Spanish non-peninsular systems are two island systems, the Balearic and the Canary Islands, and two autonomous cities, Ceuta and Melilla. Renewable energy sources cover only around the 7 % of the electricity demand in the Balearic and the Canary Islands, which is very far away from the 40 % goals projected for Spain in 2020. Nevertheless, the percentage of electricity demand covered by renewables is even lower (4 %) in the case of Melilla and no renewables are used in the electricity production in Ceuta [9], the autonomous city selected to be the object of study for this master thesis.

Ceuta is an autonomous city neighbouring to Morocco and, along with Melilla, constitutes the only European land border with Africa. Ceuta and Melilla are currently part of the Spanish territory, but Morocco claims the sovereignty over them, so there exists a geopolitical dispute which has not been resolved yet [10]. Until date, there are neither electricity connection between these cities and the Spain peninsula, nor interconnection with Morocco, because creating a dependency on Moroccan electricity imports would increase the vulnerability and risks for the electricity supply on this territories. Thus, these cities are small and isolated thermal-based electricity systems which needs to be self-sufficient, and due to is lack of electricity transport grid, they suffer from grid instability and blackouts [11], offering a poor quality in the electricity service provided [12].

In the case of Ceuta, the city has a 97 MW diesel power plant [13] for a population of around 85,000 people [14] and the combustion of fuel oil is the only source used for electricity generation. Ceuta lacks indigenous oil reserves, so all fuel consumed in the electricity production needs to be imported, which increases the costs of this service. Furthermore, the system needs a significant redundant capacity to match demand peaks, which combined with the fuel cost and the interrupted 24 hours service, makes the electricity generation is Ceuta the second highest in the Spanish Territory [15]. Using fossil fuels for the combustion in the electricity generation has not only impacts on the costs, but also in the carbon dioxide emissions produced, being the greenhouse gas emissions in Ceuta between 2 to 3 times higher than in the electricity produced in the Spanish Peninsular Electricity System [16].

The geopolitical complexity has been added to the international and domestic economic considerations, making the electricity generation in Ceuta a difficult issue to be solved for the Spanish Government, whose solution has been postponed until now [11]. On the one hand, the way of approaching the problem by the Spanish Government has been planning to install an electricity interconnector between Spanish peninsula and Ceuta [17], which would solve, at least, Ceuta electricity isolation [18]. On the other hand, due to its geographic location, Ceuta has elevated levels of solar radiation [19] and high wind resources due to its proximity to the Gibraltar Strait [20], which opens the possibility of integrating renewable technologies in the electricity generation. It was necessary to revise the existing literature to explore which measures have been taken in other energy isolated territories for integrating renewables in the electricity generation ([21]-[22]).

This project thesis analyses the different solutions available for the electricity provision in Ceuta, comparing and combining the different electricity generation technologies available to find the most suitable combination of systems for Ceuta´s electricity supply.

1.2 Aim

The aim of this project is finding the optimal combination of the different electricity generation technologies available to improve the current electricity provision in Ceuta. This solution should reduce considerably the cost of the electricity production, increase the energy security and the quality of the electricity service provided, and achieve a substantial reduction in the carbon dioxide emissions during the electricity generation.

1.3 Objectives

This thesis has three main objectives:

- Analyse the different solutions available for the electricity provision in Ceuta.
- Determine the optimal combination of the technologies available for the electricity provision in Ceuta and quantify its improvements in terms of electricity costs, energy security and carbon footprint with respect to the current situation by the horizon year 2033.
- Provide a pathway for the future electricity generation in Ceuta.

1.4 Methodology

The first part of the project will be the literature review, where is described mainly the geopolitical complexity of Ceuta´s territory and conducted a high-level research of different energy strategies applied in other electricity isolated systems.

In the boundary conditions analysis, it will be illustrated the current Ceuta´s electricity generation system situation and why it could be beneficial to include new ways of electricity provision like an interconnector or renewable energies, where it is quantified the maximum capacity potential that can be installed for each renewable technology.

In the modelling part, it will be explained: the suitability of HOMER PRO as the software to carry out the simulations, the main inputs to be introduced in the model, which would be the scenarios simulated, and the main assumptions taken while creating the model.

The result section will be divided in three main parts. The first one is the explanation of each of the different scenarios modelled (its objective, the data inputted, and its main outcomes). In the second part, all the scenarios will be compared using a Multicriteria Decision Analysis, using the electricity costs, the carbon footprint and the energy security as criterions to make this comparison, obtaining after this analysis the optimal solution for the electricity generation in Ceuta. In the third part of the results, a pathway for the future electricity generation in Ceuta is provided, the role of the different technologies in future Ceuta´s electricity generation system is analysed and some recommendations about the appropriate time to install them are given.

The last part of the project is the “Final Remarks”, which contains the main conclusions of the project, a discussion of the results and the direction for future investigations.

2 LITERATURE REVIEW

The key literature to be covered has been divided into these blocks: project location, geopolitics between Spain and Morocco, assessment of renewable energy potential, energy strategies in isolated islands and issues which appears with a high integration of renewables in the system, providing conclusions at the end of the section.

2.1 Project Location

Ceuta is a Spanish autonomous city located in the north part of the African continent, neighbouring to Morocco and, along with the city of Melilla, constitutes the only European land border with Africa. The city presents a strategic situation, just in the edge of the Strait of Gibraltar, one of the busiest areas in the world related to the marine traffic and commodity flows, which communicates the Atlantic Ocean with the Mediterranean Sea and links the European and African continents (See Figure 1).

Figure 1. Location of Ceuta Autonomous City within Spanish Territory. Source [23]

Ceuta has an extension of 18 square kilometres, separated by the closest point of the Spanish Peninsula by 21 kilometres, constituting a continental island delimited by the Moroccan territory and the Mediterranean Sea.

Due to its geographical location, this enclave suffers a dramatic migratory pressure, where thousands of persons each year, mostly from Sub-Saharan Africa, try to climb a double six-meter high fence which surrounds Ceuta´s city perimeter, to enter illegally into the city and therefore, to Spain and the European Union (See Figure 2).

Figure 2. Satellite image of Ceuta autonomous city. Source [23]

The city of Ceuta has around 85,000 habitants and all its electricity produced by a 97 MW diesel power plant.

The cost for water and electricity is the second highest in all the Spanish territory [24], so the Spanish Government subsidizes partially its costs in order to have a similar price for electricity and water consumption in all its territory.

2.2 Geopolitics between Morocco and Spain

A geopolitical dispute exists between Morocco and Spain about the sovereignty of Ceuta, which is currently part of the Spanish territory, but Morocco claim it.

The city of Ceuta is part of the Spanish Kingdom from the XVII century. Since the moment that Morocco obtained its independence in 1956, it has claimed its jurisdiction over Ceuta, but the United Nations does not consider Ceuta as Moroccan colony since it has been part of the Spanish territory before the foundation of Morocco as a country [25].

Despite these geopolitical disputes about Ceuta, there are already two electricity interconnectors which link the electricity systems of two both countries [26], and it has been recently a negotiation to build a third one of 900 MW of electrical capacity.

Until date, there is neither electricity connection between Ceuta and the Spain peninsula, nor interconnection with Morocco, because creating a dependency on Moroccan electricity imports would increase the vulnerability and risks of for the electricity supply. Ceuta is a small and isolated thermal-based electricity system which needs to be self-sufficient, and due to is lack of electricity transport grid, it suffers from grid instability and blackouts [11], offering a poor quality in the electricity service provided [12].

While Morocco is demanding the third electricity interconnector, the city of Ceuta has a similar petition for the Spanish Government, to link its electricity system to the Spanish Peninsular with aim of reducing the electricity generation costs and improving the quality of the electricity service provided (the project would be fully funded by the Spanish National Government.). This is a difficult political decision for the Spanish Government, which cannot justify a negative answer for the interconnector in Ceuta in relation with the costs of the project and the increase in the average national price of electricity, if there is a similar project, which much higher electrical capacity and costs, that would be projected to link again with Morocco [11].

Within an economic point of view, it would be much more efficient to connect Ceuta to the Moroccan electricity grid, which already receives electricity exports from Spain, instead of producing all its electricity with the power plant or planning to connect through an interconnector with the Spanish Peninsular System, but the geostrategic implications have more weight than the economics one for this case, being the most important value the security of the electrical supply.

The situation could end up in building two different interconnectors, one with Ceuta and another one with Morocco, but its high cost would be reflected in the already high price of electricity of the average consumer. A midway solution could be an indirect interconnector which links first with Morocco and from there to Ceuta. Ceuta would refuse it because of the vulnerability of its electrical supply, but it would be unacceptable also for Morocco because it would mean legitimizing the Spanish sovereignty over Ceuta. The other option of linking the Spanish Peninsular System with Ceuta and from there with Morocco would be unacceptable as well for Morocco [11].

The usual way of proceeding associated with the relations between Morocco and Spain is leaving the Ceuta sovereignty aside and progress with normal economic and political bilateral relations in other important matters. Nevertheless, this is a live conflictive topic, so frictions reappear from time to time, making too hazardous the electricity interdependence between Morocco and Ceuta for the security of the electrical supply [11].

2.3 Assessment of renewable energy potential

- Solar

The state of the art for calculating photovoltaic roof potential has been analysed in this section [27] and several examples cases for different city sizes are studied ([28] - [29]).

The most important article analysed for this part was the "The role of Photovoltaics towards 100% Renewable energy systems" [30]. In this academic paper, a balance between the wind power and the solar photovoltaics installed in the system is recommended, providing an estimated ratio for wind/solar as 80/20 for systems with high renewable penetration. On the one hand, first photovoltaic panels installed in the system have a higher value for the system than the following ones installed later, because they can replace more electricity produced by fossil fuels. On the other hand, the later the photovoltaics are installed, the more its installing cost would have decreased if the current trend in its price is maintained. Using Geographical information systems, it could be quantified the solar radiation for each part of the building roof, taking into account the shadows from different objects or building as well as its geographical location, orientation and inclination [27]. The solar radiation per each meter square for every building in the city could be quantified, providing a much more accurate number about the maximum potential capacity of photovoltaics which can be installed and which buildings would receive higher solar radiation and would provide a better output [30].

- Wind

The report related with the Spanish Renewable Energy Strategy for 2020 [31], published by The Spanish Agency for Energy Diversification and Saving (IDAE), was the main reference used in the process of estimating the maximum potential of onshore wind power capacity which could be installed in Ceuta. This report contains information related with the estimated maximum available onshore wind potential for the area of Ceuta. To provide this data, IDAE used a combination of weather and wind resources data with Geographical Information Systems to assess the suitable areas for installing the wind technology, using variables like natural protected areas, built environment or the elevation of the terrain.

- Pump Hydro Energy Storage

Storing the excess of the electricity produced can be one of the most powerful tools for a successful integration of renewable energies.

Two interesting articles were found about the way to assess the hydro pump potential through in the territory through using GIS ([32] to [33]). To quantify the maximum pump hydro available potential in Ceuta, it will be used the results obtained in this report [34], where the pump hydro energy potential in Ceuta was analysed in detail, using GIS for quantifying the maximum water volume capacity in the head water reservoir.

2.4 **Energy Strategies in isolated systems**

Three cases in the literature were selected to be representative of the energy strategies in isolated places, because its similarities with Ceuta case.

The first one is Malta, which has been chosen due to its high population (approx. 4 times bigger than Ceuta) and its objectives to increase the percentage of renewables in its electricity generation [21].

The second case is a small canary Island whose name is “La Gomera”. Its population is around three times lower than Ceuta, but it has been selected because of its aim to propose of a sustainable energy system configuration, proposing several scenarios for a 100 % renewables integration in the island [22].

The third case, is Tenerife, an Spanish island located in the Canary Islands System where the parity grid has been reached for wind and photovoltaic technologies [35].

These three cases will be used not only as a source of inspiration, but also as reference models for methodology to study the potential renewable integration in isolated regions.

- Energy Scenarios for Malta [21]

Malta is an isolated island without any electrical connection with another region, so it needs to be self-sufficient, and currently all its electricity is produced by fossil fuels. Its most important consumers for electricity are domestic sector, commercial and water production and the fossil fuel consumed for energy production is the biggest export costs for this country. Its carbon emission accounted 0.873 tonnes of carbon dioxide emissions per MWh of electricity produced. The renewable energy potential is assed, obtaining average wind speeds around 6.9 m/s, considering this value as encouraging to implement this technology for electricity generation. It is mentioned as well than if the power produced by renewables is not higher than 30% of the demand, it would not disturb or affect the synchronous operation of the generating system. A financial analysis is carried out, calculating the levelized cost of each technology until the horizon year defined. To make a comparison between the several electricity generation technologies in the different scenarios, all the costs were levelized to the present. The replacement cost of the different technologies is also a relevant parameter for the model. Results shows that net present costs of producing electricity with onshore wind in the island are lower than producing it with fossil fuels. Challenges of implementing renewables due to the reduced land area available are acknowledged, which limit the maximum capacity and the type of renewables that can be installed. The conclusions show that the introduction of renewable energies in the system needs to be in combination with the use of the power plant to secure the electrical supply, but renewables would create a positive effect in Malta´s electricity generation system, reducing the elevated exportation costs of fuel import.

- Assessment of sustainable energy system configuration for “La Gomera” [22]

La Gomera is a small off-grid Canary Island with around 20,000 habitants. This article analyses the current electricity generation in the island, which is full covered by a diesel power plant and analyses the different issues which come up while trying to convert the system in 100 % renewable.

Projects with the aim to achieve a renewable energy penetration higher than 80 % are mainly designed for small communities with less than 10,000 habitants, where the demand-driven control is challenging due to the intermittency of renewables.

The benefits of using energy storage like Li-ion batteries or pump hydro if available is mentioned, and its contribution to balancing the frequency and voltage of the electricity grid, apart from storing the electrical excess.

The integration of renewable energies can provide, not only environmental benefits, but also economic ones, reducing the dependency of fossil fuel imports and providing electricity at lower levelized costs, providing the integration of wind turbines and photovoltaics an improvement in the whole electricity trade balance.

Different sustainable scenarios are proposed and in all of them lower annual costs than with operating the system in the current situation are obtained. In all of them, the power plant is still used as the component for balancing the system electric load but using biofuels instead.

The choice of installing a technology or for determining which is the most suitable scenario should not depend only in the energy costs, being the environmental considerations like the carbon footprint or the security of the electrical supply, as important as the cost depending on the features of the system analysed.

- Grid parity on PV an wind power energy in a Spanish Insular System [35]

This paper analyses the current Spanish legislation, and its part relative to the stimulation of renewable energy technologies integration in the insular systems to reduce the cost of the electricity generation. The case of the Island of Tenerife is shown, where the grid parity with wind power and photovoltaics has been reached, despite its most electricity generation relies on thermal power plants. It is also mentioned the increase in the levelized cost of electricity provided by renewables due to the curtailments for not having enough energy storage capacity or an interconnector to export the excess of electricity, as well as how the levelized cost of the electricity produced with the power plant increase where the generator operates at suboptimal conditions. The necessity to couple the price between the electricity produced by renewables and the defined by the electricity market (Spanish Pool) is remarked as well, to make economically feasible the electricity generation without being subsidized by the Government.

2.5 Issues related with high integration of renewables in isolated energy systems

When there is a high percentage of renewable energies integration in an electricity generation system, certain issues affect the grid system such as voltage fluctuation, voltage rise, voltage balance, and harmonics ([36] and [37]). Specific problems related with photovoltaics are analysed [38], and specific problems for wind power generation are described in the documentation used [39].

It will be also covered which is the optimal generation for insular systems with high percentages of renewable integration [40].

- Photovoltaic penetration issues and impacts in distribution network [38]

In this paper three different types of photovoltaics are defined: utility scale (connected to the transmission grid), and small and medium scale (connected to the distribution grid) which goes to photovoltaic installations from 0 to 10 kW, and from 10 to 1000 kw respectively. The main impacts relative with a high photovoltaics penetration in the system are studied in detail, and are relative with harmonics of current and voltage, the unbalance and voltage variations, the protected related with grid islanding and some quality issues.

- Technical impacts of high penetration levels of wind power on power system stability [39]

When the electricity production by wind turbines is higher than the electricity load, if no energy storage is available, the excess of electricity system would create a system stress, where wind power curtailment is one the possible options to maintain the stability of the system. This curtailment option should be used as the last option, being more frequent to happen in small isolated systems. If there is a high penetration of wind power in the system, it would probably be needed some upgrades in the electrical network (transmission and distribution), especially in this installation of offshore wind power.

Four main issues relative with the system stability are described related to transient stability, voltage stability, frequency stability and small signal stability, which will depend on the size of the system and the capacity of wind installed. These effects would be higher during the night, when the electricity demand is lower, so the wind power could reach a high instantaneous penetration, which would affect particularly small energy system because of its limited inertia.

- Optimal operation of insular electricity grids under high renewable penetration [40]

In this paper is analysed the case of Crete, a Greek Island, evaluating the impact of a high penetration of renewables in the electricity system and how storage capacity like pump hydro can reduce its negative effects. The main challenges for the Electricity System Operator would be related with how to schedule and operate the system with the intermittency of renewables. It is mentioned that for the for Crete, it could be reached 20 % of the generation with solar and another 20 % of the generation with wind, which would have a dramatic reduction in the operational costs of the system. At the same time, it would not affect the reliability and security of the electrical supply if it is installed enough pump hydro capacity for energy storage to accommodate this increase in the renewable penetration.

2.6 Conclusions of the Literature Review

The main conclusions obtained in the literature review have been summarized:

- The electricity connection of Ceuta and the Moroccan electricity grid is not feasible due to geopolitics conflicts between Spain and Morocco relative to the sovereignty of the city, which could affect to the security of the electrical supply.

- A certain balance between the solar and wind capacity installed is recommended, being provided a ratio of 80/20 for the installation of wind and solar in energy systems with high renewable penetration.
- A gradual installation of photovoltaic could reduce the installation costs due to the decrease of its prices over time.
- Importance of GIS as a method to quantify the maximum renewable potential.
- In Malta case, the levelized cost of onshore wind for electricity generation is lower than producing it with fossil fuels, although renewables needs to operate in combination with the use of the power plant to secure the electrical supply. The levelized cost of the electricity produced with the power plant increases when the generator operates at suboptimal conditions.
- With high percentage of renewable energies integration in an electricity generation system, certain issues affect the grid system such as voltage fluctuation, voltage rise, voltage balance, and harmonics. If the power produced by renewables is not higher than 30% of the instantaneous demand penetration, it would not disturb, in theory, the synchronous operation of the generating system.
- The levelized cost of electricity provided by renewables increases due the curtailments for not having enough energy storage capacity or an interconnector to export the excess of electricity. The curtailment option in systems with high wind integration should be used as the last option, being more frequent to happen in small isolated systems.
- Couple the price between the electricity produced by renewables and the electricity market, would make economically feasible to introduce renewables in the electricity generation without being subsidized by the Government.
- Enough pump hydro storage capacity can open the door to a high renewable integration in the system, mitigating the negative effects relative with renewables intermittency.
- When determining the most suitable scenario in isolated energy systems, it should be considered not only the energy costs, but also the environmental considerations and the security of the electrical supply.

3 BOUNDARY CONDITIONS ANALYSIS

This section will be used to connect the literature review with the modelling section

3.1 Electric System. Electricity Demand, Generation and Costs

3.1.1 Electric System

All the electricity consumed in Ceuta is provided by its diesel power plant, so the electricity production needs to adapt instantaneously to the electricity demand. Thus, electricity generation and demand graphs match perfectly in each time of the year except for the back-up generation reserves, to be able to cover limited variations in the demand.

Once the electricity is produced in the power plant, it is distributed through eight medium voltage lines at 15 kV in the integrated electricity substation along the city.The power plant is operated by the company "Endesa", the city system operator is "Alumbrado Ceuta" and all the electrical data is managed by the Spanish National System Operator "Red Eléctrica".

In relation with how the electricity consumption is distributed by sectors, the 80 % of the total electricity demand belongs to three sectors: business and services (35%), domestic sector (29 %) and the desalination plant (16 %) (See Figure 3). The hospitality sector (tourism) accounts for the 10 % of the electrical demand, which is important for Ceuta´s city, but not big enough to drive its entire economy. This aspect will be represented when analysing the monthly electrical demand, where in the summer Ceuta experiences an increase in the electricity demand (due to a higher tourism as well as higher temperatures) but not enough to modify the electrical demand pattern accounted during the year.

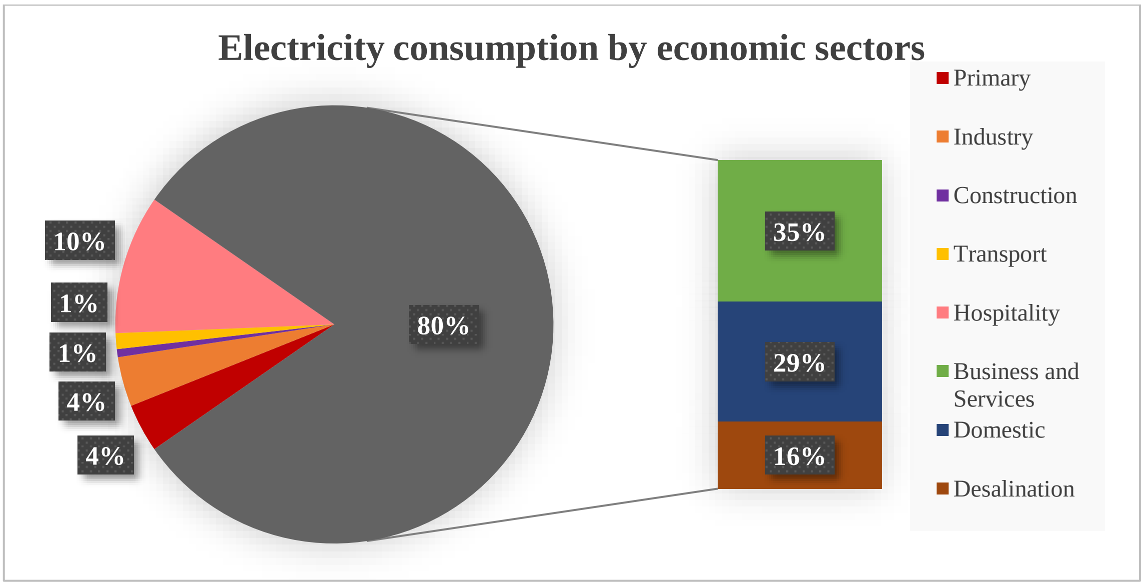


Figure 3. Electricity consumption in Ceuta by economic sectors. Source [41]

3.1.2 Electricity Demand Analysis

In this section it will be analysed the average temperature in Ceuta and how it affects the electricity demand during the year, how the electricity demand varies along the week and when are the peaks during a typical day in the winter and in the summer season. The last part will be related with which has been the evolution in the electricity demand and generation capacity installed in Ceuta during the last fifteen years and if it is forecasted to change in the future.

- Dry bulb Temperature

The temperature will have effects in the electricity demand. The following graph shows how the dry bulb temperature in Ceuta varies by hourly data (See Figure 4). The figure shows that climate is very stable during the year, where the minimum temperature does not go below 5 degrees and the maximum temperature above 35 degrees. This stable climate influences the electricity demand, where the electricity load does not vary considerably in the different periods of the year but experiences a limited increase during July and August.

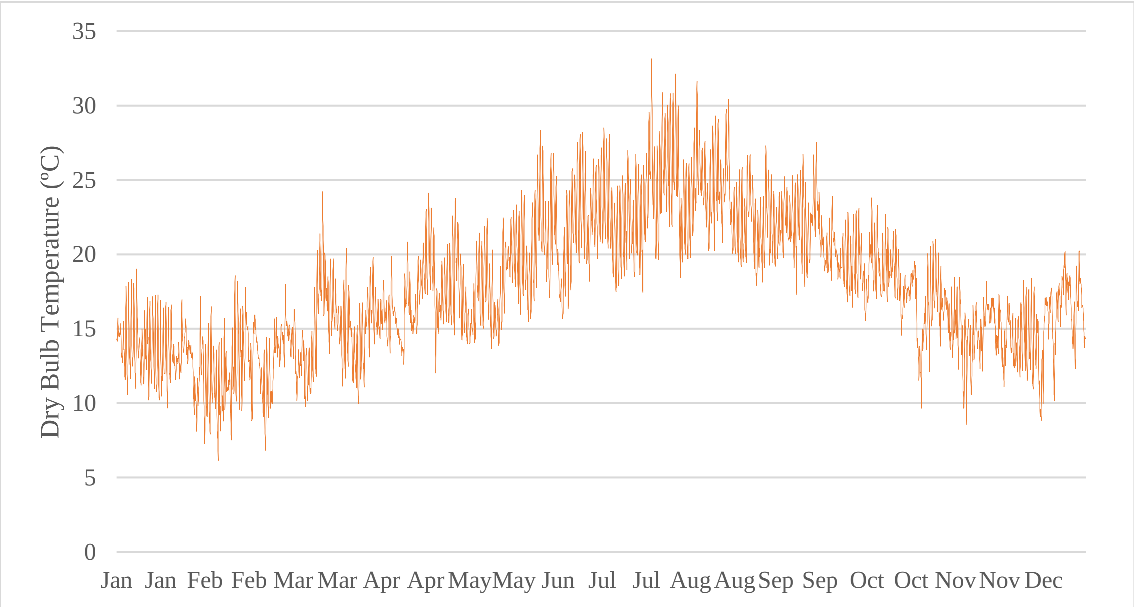


Figure 4. Hourly dry bulb temperature over the year in Ceuta. Source [19]

- Hourly Electricity Demand

The electricity demand in a typical winter day (3 February) and in a typical summer day (12 July) the year 2016 was analysed (See Figure 5). During the winter, the electrical demand has two peaks, the first one happens around 2pm (during the lunch time) and the other one, which has a bigger intensity, around 9 pm (dinner time) when the heating is working. During the summer time, there is only one peak demand during the day, which happens around 1 pm (probably in real time is the same as 2pm in the winter due to the variation in the hour time along the year) which is higher than the winter peak demand in the afternoon. Overall, the electricity demand in a typical summer day is higher than in winter, probably due to the combination of higher temperatures (that requires air conditioning) and the increase in the hospitality activity in the region.

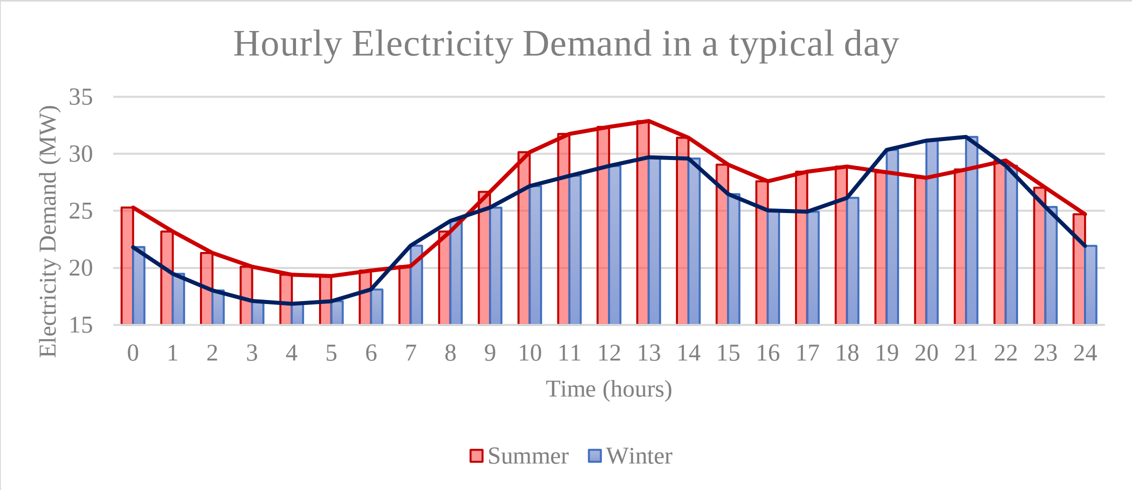


Figure 5. Ceuta hourly electricity demand in a typical winter and summer day

- Electricity demand comparison in a typical winter or summer week

The electricity demand in a typical winter week (1 to 7 February of 2016), and in a typical a summer week (11 to 17 July of 2016) was analysed (See Figure 6). Both simulations follow a similar pattern where there is a reduction in the electrical demand during the weekends due to interruption of business and services. It can be seen again the trend described in the daily demand profile, with one big peak in the electrical demand during the lunch time in the summer, and two peaks in the demand in the winter, being higher the one which occurs at night, where the overall electricity demand is higher in summer.

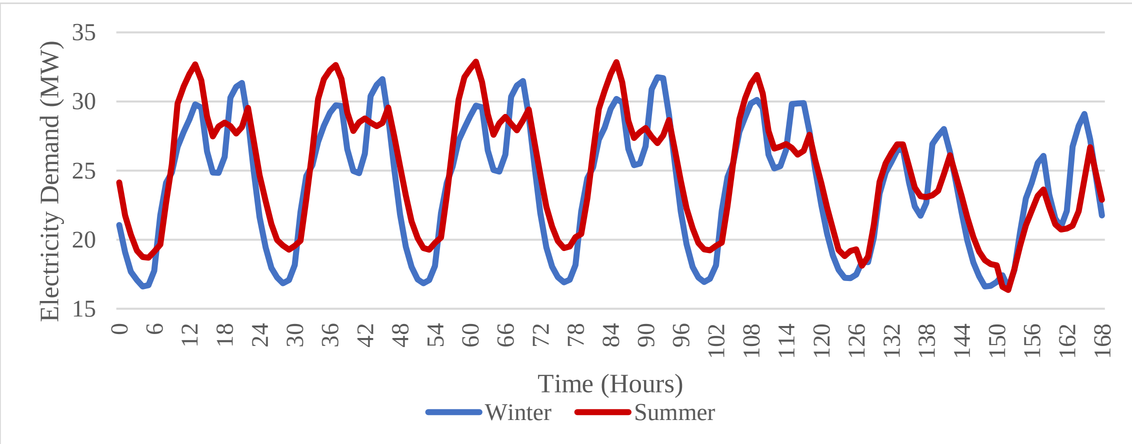


Figure 6. Electricity demand comparison in a typical winter and summer week

- Annual electricity Demand

The daily demand is quite stable during the year, experiencing a limited increase during July and August due to the higher temperatures and more tourism activity (See Figure 7).

The peak demand in the system is around 35 MW, while the lowest demand accounts for 15 MW, having an average electrical output of 25 MW. The total annual electricity demand is 210 GWh, so this is the electricity necessary to produce each year to meet the electricity demand requirements.

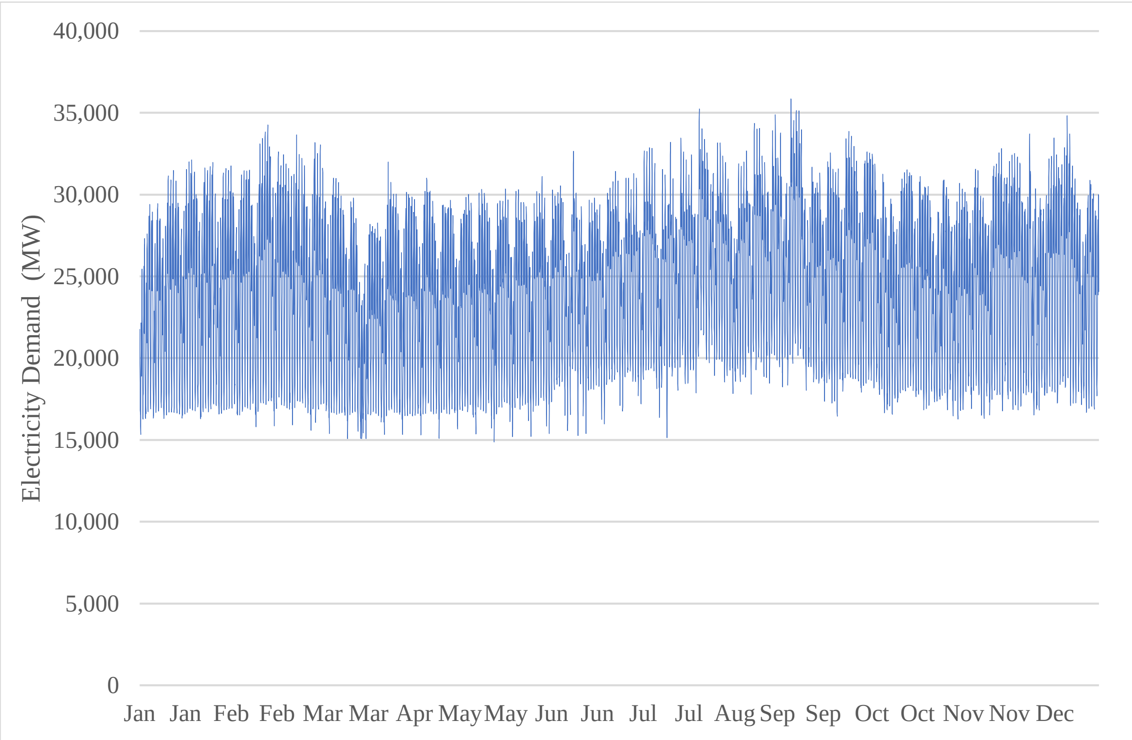


Figure 7. Hourly electricity demand over the year in Ceuta. Source [42]

- Evolution of the electricity demand and generation capacity installed

The increase in the electric demand and generation capacity over the last 15 years has been analysed (See Figure 8). It can be seen that the electric demand during the last seven years has been stable, with up and downs around the values 200 and 215 GWh per year. In relation with the generation capacity installed, from the year 2002 to the year 2010 it doubled the capacity, moving from 49 MW to 97.7 MW of generation capacity installed in the power plant. Since 2010, both, the generation capacity installed and the electricity demand have been roughly constant until the present.

Several documents have been checked to see different forecasts about how Ceuta´s electricity demand will increase in the future [9]. Most of them forecasted a very high increased in the electrical demand from 2015 to 2020, but these predictions have not been met at all, being the demand stable since the year 2010 [16].

The project lifetime has been defined as 15 years, so the horizon time when the results are compared will be the year 2033. As in the last seven years, the generation capacity and the electricity demand has been stable, it was decided to maintain this trend and use the current electricity demand of 2016 as the electricity demand in horizon year 2033.

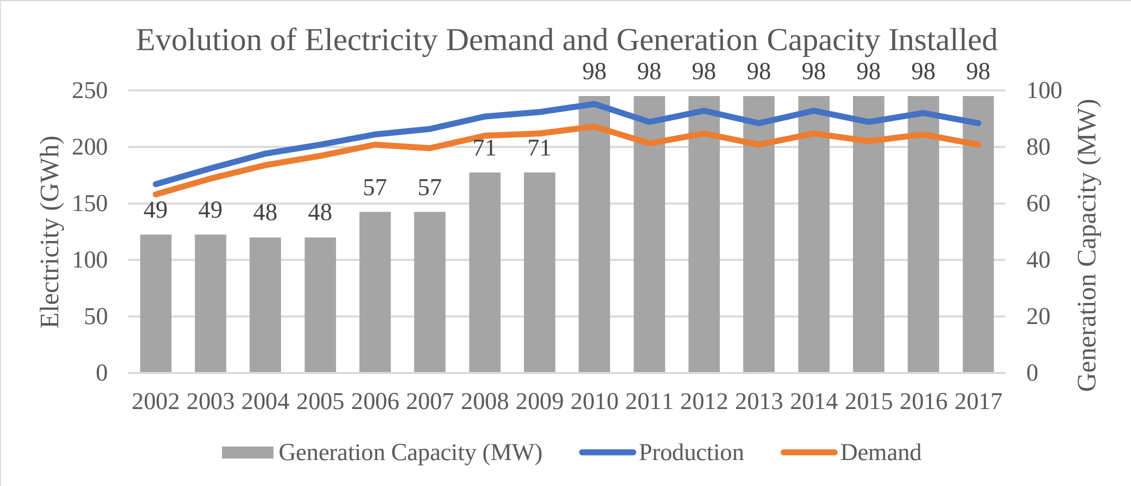


Figure 8. Electricity demand and generation capacity in Ceuta over the last 15 years

3.1.3 Electricity Generation. Diesel power plant

The diesel power plant is the installation in charge of suppling the electricity consumed in Ceuta. Its electricity production depends almost instantaneously of the demand necessary to cover, being the starting point in the electricity distribution process.

The power plant has a capacity of 97.7 MW and it is composed by 9 diesel generators, which accounts for 84 MW, and 1 gas turbine of 13,7 MW.

The Diesel Power plant use mainly low sulphur fuel oil for the electricity production, using diesel oil for the start-up and shut-down of the diesel generation and gasoil for the gas turbine generation [13]. The fuel oil accounts for the 99% of the fuel consumption (520 GWh/year of fuel oil, 9 GWh of diesel and 1GWh of gas oil consumption).

The power plant has five fuel oil storage tanks, four of them with 30 m^3 each for gross product and one with 150 m^3 for fuel oil ready to be used. For diesel oil storage the plant has two tanks of 30 m^3 each and for the gas oil supply, two storage tanks of 150 m^3 each, where in these processes all tanks are feed regularly by road tankers.

The Carbon dioxide emissions associated with the combustion process of the power plant to produce electricity accounts for 144,000 tonnes per year.

The summary of the most important parameters relative to the operation of the power plant can be seen in Table 1.

Table 1. Electricity generation covered by the diesel power plan. Source [13]

Electricity Demand (GWh/year)	Gross Electricity Production (GWh/year)	Fuel Consumption (GWh/year)	Carbon Dioxide Emissions (ton/year)
210	230	520	144,000

3.1.4 Electricity Generation Prices and Electricity Supply Vulnerability

The electricity generation price in Ceuta was analysed from the last year until the present, which can be seen in Figure 9. Generation prices goes from 200 to 300 €/MWh in normal conditions, except in the last part of November and the entire December (green oval in Figure 9), when the generation price goes from 100 to 150 €/MWh. From time to time, there is a sharply rising in the generation price, which could reach almost 900 €/MWh. This increase in the price reflects that generation has not covered the electricity demand needed, normally due to problems with some generators in the diesel-power plant or issues in electricity distribution network substations. The result is some areas of the city [43] or even the whole city [44] suffers a blackout (red ovals in Figure 9), and there is no electricity during 30 minutes to 1 hour (average time needed to restart the system again). This aspect reflects the poor quality of the electricity service provided in Ceuta.

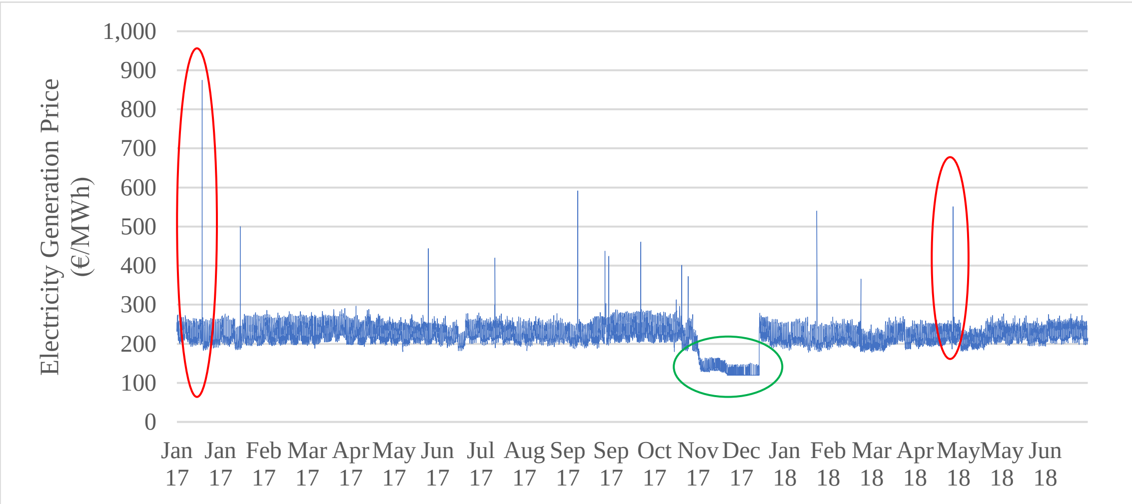


Figure 9. Electricity generation prices in Ceuta from 2017 to 2018. Source [42]**.**

As it can be seen in Figure 10, electricity generation price for the year 2016 goes from 350 to 200 €/MWh, obtaining and average of 263 € per MWh of electricity produced, which will be used as an input for the economic part of the model.

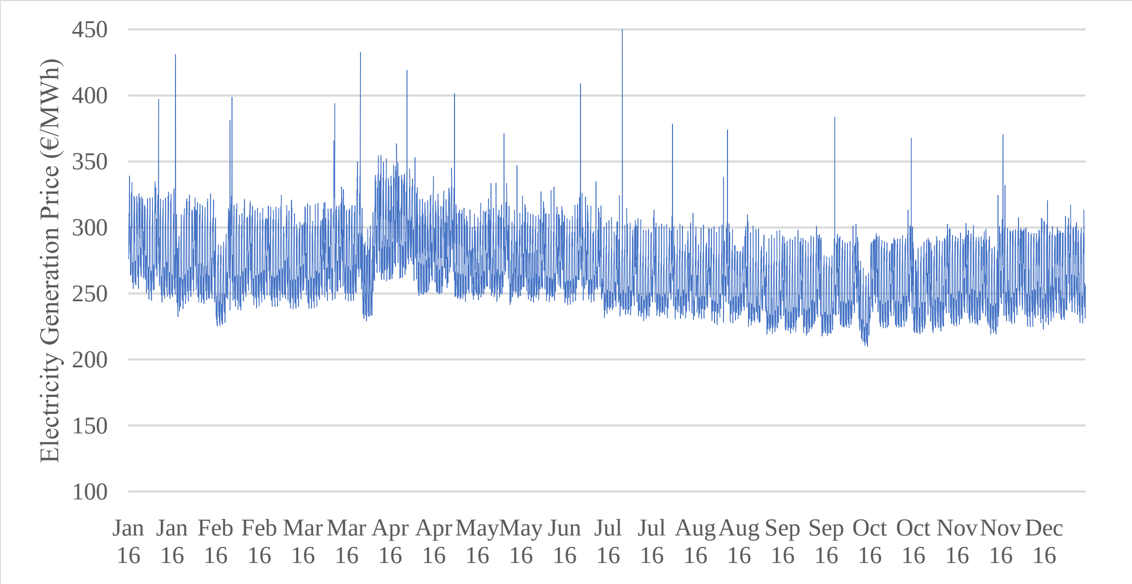


Figure 10. Electricity generation prices in Ceuta (year 2016). Source [45]**.**

The generation price in Ceuta was compared with the other non-peninsular systems of the Spanish territory in 2016. The average price in the majority of them goes from 90 to 120 €/MWh, being only close to Ceuta´s price islands of La Gomera and La Palma (located in the Canary Islands) and Melilla (the other Spanish autonomous city in the African Continent) with average prices from 170 to 190 €/MWh [46]. This analysis shows that Ceuta is the second most expensive region in the Spain for the electricity generation, surpassed only by "El Hierro" (which aims to be a 100 % Renewable Energy Island [47] and it achieved recently to produce all its energy by renewables during 18 days in a row).

If the comparison is made with the Spanish Peninsular system, the difference is even higher, being the national average price of electricity generation 48.4 € per MWh [16].

It is vital for this project to understand why electricity production is so expensive in Ceuta compared with the rest of the territory. The different cost components of the electricity generation to obtain an average price of 263 € per MWh can be seen in Table 2.

In the Modelling part (Section 4.4.2), it will be done a detail analysis of these costs in order to create an accurate simulation of the current Ceuta´s electricity generation system.

Table 2. Ceuta electricity generation cost components in 2016. Source [15]

Electricity Production (MWh)	Fixed Costs (M€)	Variable Costs (M€)	Total Costs (M€)	Unit Costs (€/MWh)
210,068	27.41	27.78	55.19	262,7

3.1.5 Electricity Demand Price

The electricity demand price in Ceuta was analysed from the last year until the present, which can be seen in Figure 11. Electricity demand prices goes from 40 to 80€/MWh in normal conditions, although the price could reach up to 120 €/MWh.

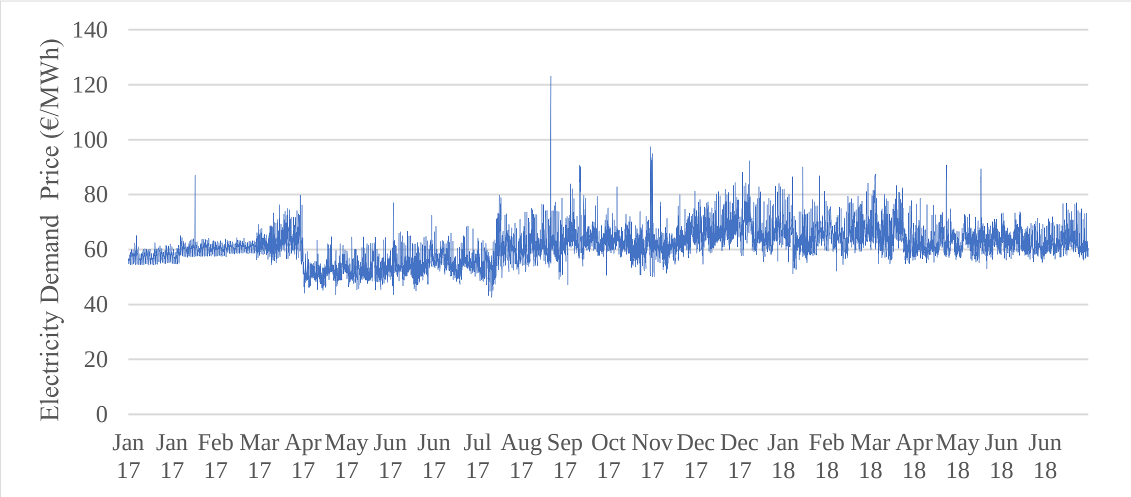


Figure 11. Electricity demand prices in Ceuta from 2017 to 2018. Source [42]

The average price of for the electricity demand in 2016 is around 55 €/kWh, although it fluctuates between 10 and 120 €/MWh consumed (See Figure 12).

Comparing this result with the average price of the electricity production of 263 €/kWh, it is acknowledged that 80 % of the total price of the electricity consumption is subsided by the Spanish National Government, in order to maintain a similar price for the electricity consumption in all the territory.

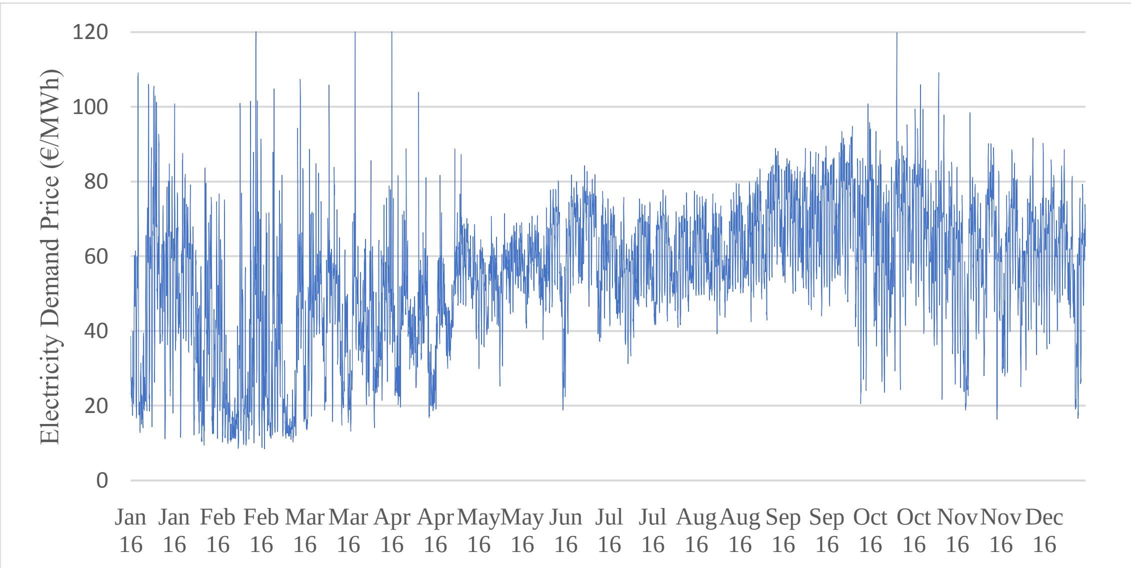


Figure 12. Electricity demand Prices in Ceuta (year 2016). Source [45].

3.2 Rationale for the project

The main features of the current Ceuta´s electric system were discussed in previous sections, giving a poor picture on how its electricity generation system works.

Firstly, the cost of electricity generation in Ceuta is the second highest in Spain, and accounts for more than five times the average cost of generating electricity in the Spanish Peninsular Electricity System.

Secondly, the electricity demand in Ceuta has similar price than in the rest of Spain with the aim of having a similar price for the electricity consumption in all the Spanish territories. This leads to a situation in which the electricity demand price cannot cover the electricity generation costs, so the Spanish Government needs to subsidise the 80% of the electricity produced (and consumed) in Ceuta.

Thirdly, there is only once source for providing the electricity, one diesel power plant, which covers the whole electric load. When there is a problem in some generators of the power plant and the electricity produced cannot reach the electricity demand needed, part of the city of even the whole city suffers a blackout until the power plant is re-started again (which takes normally between 30 minutes to 1 hour). This shows the poor quality of the electricity service provided in Ceuta.

Furthermore, the power plant consumes mainly fuel oil, which is not only costly (accounts for almost the 50% of the costs of generating electricity), but also generates much more carbon dioxide emissions per each unit of electricity produced than the average Spanish Electricity System.

To sum up, all these aspects show why the city of Ceuta could benefit from investigating different solutions for the electricity provision which could reduce the cost of the electricity generated, increase the energy security and the quality of the electricity service provided and reduce the carbon dioxide emissions produced during the electricity generation.

Several solutions are going to be investigated in this report to improve the current Ceuta´s electricity generation system: the installation of an electricity interconnector to connect Ceuta with the Spanish Electricity System, the integration of different renewable technologies to take advantage of the natural resources available in Ceuta´s territory and different combinations of these two with the existing diesel power plant.

3.3 Electricity Interconnector Ceuta-Iberian Peninsula

The Spanish Government is planning to build an electricity interconnector to connect electricity systems of the Iberian Peninsula and the Autonomous city of Ceuta, as it its reflected in the "National Planning Network Electricity and Gas Transmission 2015-2020" [48]. This project is also included in the European Continental South West Regional Investment as a project with regional significance for Spain, whose main driver is the market integration of Ceuta in the Spanish Electricity Market [17].

The electricity interconnector would be a high voltage alternative current line (HVAC) of 132 kilovolts (kV), an approximate length of 45 km (35 submarine and 10 in land), and its cost would be 129 million Euros (M €) [18]. The electrical capacity of the interconnector has not yet been defined (or at least published), but it could be from 40 MW up to 100 MW (2 pipes of 50 MW each).

The interconnector project was supposed to be finished by 2020, but it is still on its early planning stage, so it is more likely to not be finished before December 2022 [49].

The south part of the Iberian Peninsula and Ceuta borders are surrounded by archaeological and natural protected areas as well as areas related with the fishing industry. Different alternatives have been proposed and have been analysed to detect which one is the solution which has less impact in the environment for the project which connects the Peninsula with Ceuta. All of them depends on the territorial factors which determine the pathway which follows the interconnector. See Figure 13.

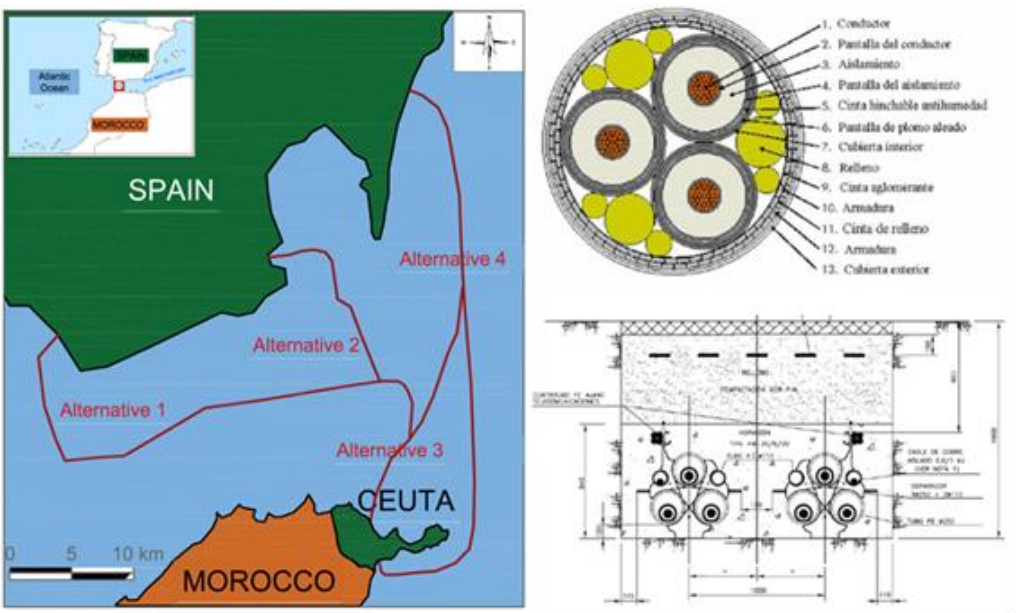


Figure 13. Alternatives pathways for the interconnector Ceuta-Iberian Peninsula (left). Interconnector pipe and double line cross section (right). Source [18]

The construction of the electricity interconnector is supported by four main facts:

- It would reduce the costs associated with electricity production in Ceuta (currently the city has special monetary retribution for the electricity production due to be an isolated electricity system).
- It would solve the electricity supply problems which appears when two of the main generators are being maintained at the same time.
- It would reduce the number of blackouts, which normally happens with the automatic load shedding when the frequency in the electricity distribution is altered due to incidents in the generation. The frequency of the electricity grid in Ceuta is altered when in the generation there are loses above 4 MW.
- In small isolated systems like Ceuta, there is a recommendation of installing generators with a maximum capacity of 8 MW to avoid frequency stability problems. When there is lack of generation above 4 MW, there is variation in the system frequency strong enough to activate the lad shedding units and producing an interruption in the electricity supply. This recommendation has not been followed in Ceuta´s power plant case, where there are at least five generators higher than 11.5 MW capacity. If the peak demand is around 40 MW, it is normally covered by four of these big size generators, which implies as well, a bigger generation investment to maintain the backup reserves stipulated.

The cost of this project will not affect directly the price Ceuta citizens pay for the electricity because is totally funded by the Spanish National Government.

The information related with the interconnector will be used while creating different scenarios for the electricity production and comparing its result with the current situation, where all the energy consumed comes from the diesel generator power plant.

3.4 **Renewables Potential.**

3.4.1 Solar

Ceuta territory has very limited space available. South, North and East city borders are restricted to the Mediterranean Sea and its West-side by the Moroccan border fence. Most of the urban space has been occupied by the city urban expansion and there is only available space in the mountain located before the border fence, which avoids the possibility of installing a Concentrated Solar Power Plant [50] due to the multiple shadow projections. This urban environment configuration opens the possibility of taking advantage of the solar potential over roof [51]. Using GIS, it will be analysed how many buildings in Ceuta could be suitable for installing photovoltaic panels, in order to quantify the maximum solar photovoltaic capacity that can be installed.

- Analysis of photovoltaic potential to be installed

A photovoltaic panel of 250 W was selected to be installed in the rooftop of the buildings in order to maximize the limited space available through a panel with high power output. Its main features can be seen in the following Table 3 and in APPENDIX.

Table 3. Size and power of the photovoltaic panel selected. Source [52]

Photovoltaic Panel parameters			
Width (m)	Length (m)	Area (m2)	Power (W)
0.958	1.64	1.63	250

The area available in the city of Ceuta to install photovoltaic panels in its rooftop was quantified. The surfaces available has been defined as residential buildings, public buildings and industrial buildings. The surfaces of them have been calculated using the software ARCGIS (See Figure 14).

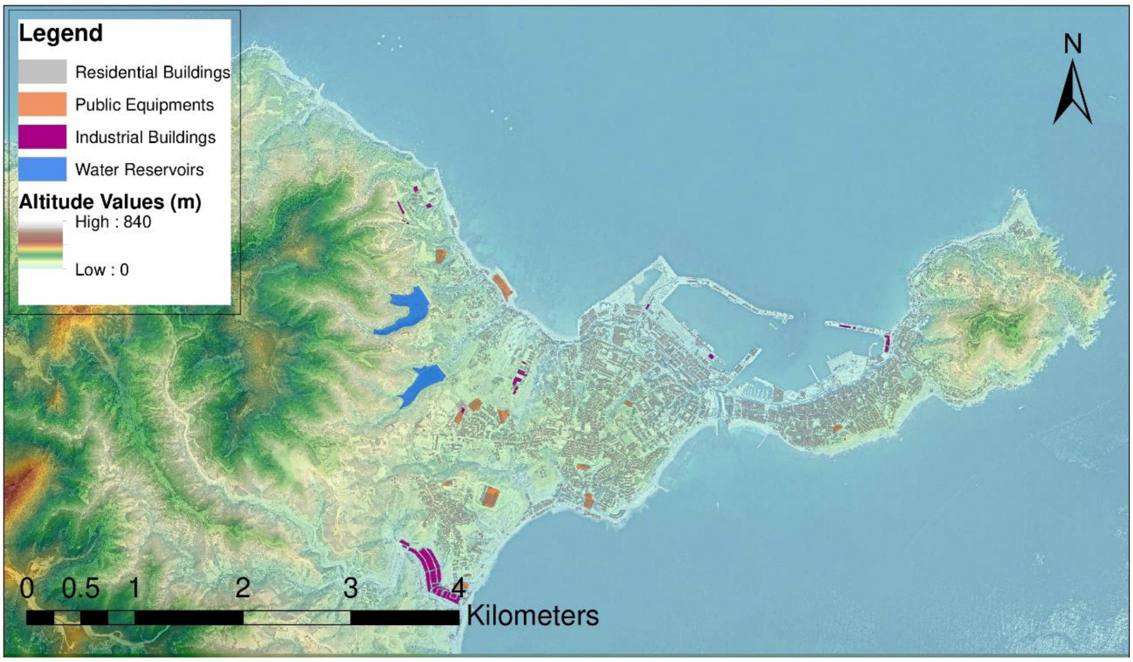


Figure 14. Analysis of buildings rooftop area available for pv installation in Ceuta

Once calculated the surfaces of the different building it has been established a percentage of how many of them would be in reality suitable for installing photovoltaics. This parameter was established as the 20 % of the space available (See Table 4). The available capacity for installing photovoltaics was calculated to be around 320,000 m^2.

Table 4. Available area for rooftop photovoltaics panel installation in Ceuta

Ceuta Surface Potential for PV Installation	**Area (m2)**
Residential Building Roof Top	1,393,587
Public Equipment Roof Top	105,256
Industrial Buildings Roof Top	84,696
Total	1,583,539
Estimated available space for rooftop pv installation (%)	20
Available Area for rooftop photovoltaics installation (m2)	320,000

If the photovoltaics panels of 250 W are installed in packages of four, they will form a photovoltaic potential of 1 kW per package. It has been compared the physical size of the panel with the available space in the city of Ceuta to install them (See Table 5). The result is that the maximum rooftop photovoltaics which can be installed is 40 MW.

Table 5. Maximum capacity of rooftop photovoltaics that can be installed in Ceuta

Power per panel (W)	PV 250 W size (m2)	Package 4 PV (W)	PV Package 1000 W size (m2)	Number of packages 1000 W which could be installed	Maximum PV Potential (MW)
250	1.63	1,000	8	40,000	40

3.4.2 Wind

- Onshore Wind

So far, it has been proposed four different projects for wind farms in Ceuta over the last 20 years, but all of them have been rejected due to environmental impact issues [53]. Reasons behind this discarded were the following: first two projects were projected inside the Natural Area for Birds Projection and last two projects were designed near to historic monuments, creating a high impact visual impact in the city.

This environmental aspect will affect the final wind power potential doable to be used in the region [54]. Wind potential needs to combine both requisites: enough wind power suitability and preservation of Ceuta nature and build environment.

- Wind Capacity

The Spanish Energy Agency developed an study in each autonomous community in Spain to quantify the available surface with higher wind speed than 6 m/s to discover the onshore wind potential for each region. For the city of Ceuta, the 100 % of its mainland territory has a wind velocity higher than 6 m/s at 80 meter high, but only the 33 % of this area could be available to install wind turbines (See Table 6).

Table 6. Available surface for onshore wind power installation in Ceuta. Source [31]

Ceuta Area (km^2)	Area with average wind velocity higher than 6 m/s at 80 m high	Area with average wind velocity higher than 6 m/s at 80 m high, removing Protected Natural Areas and technical challenges
18	100%	33 %

In the same study it was defined the onshore wind potential of Ceuta at different wind velocities (See Figure 15). The study found that there is 25 MW of wind power potential at the average wind velocity 6.5 m/se and 80 meters height. Therefore, the maximum onshore wind capacity which could be installed in Ceuta is 25 MW.

This value will have a great importance in the model, and it will establish a limitation which will influence the renewables capacity that can be integrated in the system. The limited space was already covered in the literature review (See Section 2.4) as one of the biggest limitations for the integration of renewables in isolated places.

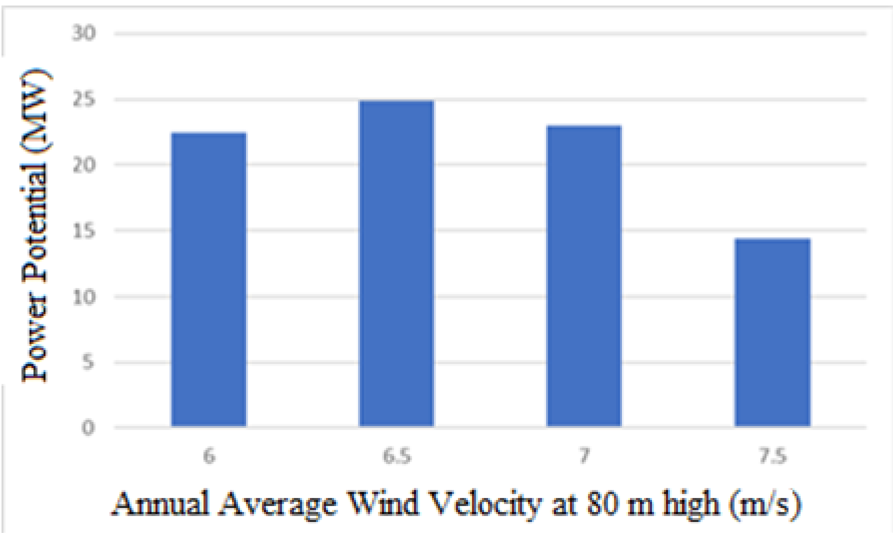


Figure 15. Estimated maximum onshore wind power potential in Ceuta. Source [31]

- Wind Technology

With average wind velocity of 6.5 m/seg defined previously and the wind density of 500 W/m^2 (See Figure 16), it was found the wind class [55] for Ceuta is III low wind class (average wind speed under 7,5 m/s) [56]. It was analysed different types of models available in the market for this wind class, and finally it was chosen a turbine a 2.1 MW, whose main features can be seen in the APPENDIX.

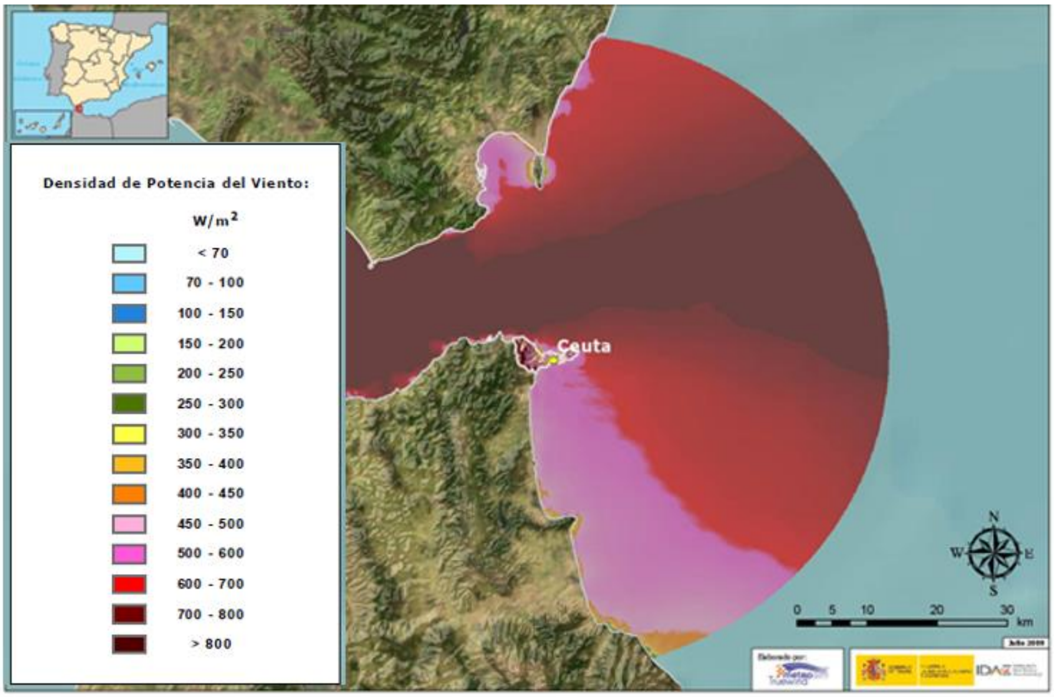


Figure 16. Wind density potential at 80 m high in Ceuta (W/m²). Source [20]

The power curve of the wind turbine selected could be seen in Figure 17. The wind turbine chosen needs winds speeds higher than 8 m/s to provide at least the 50 % of its power output, reaching its maximum value when the wind speed is 13 m/s or above.

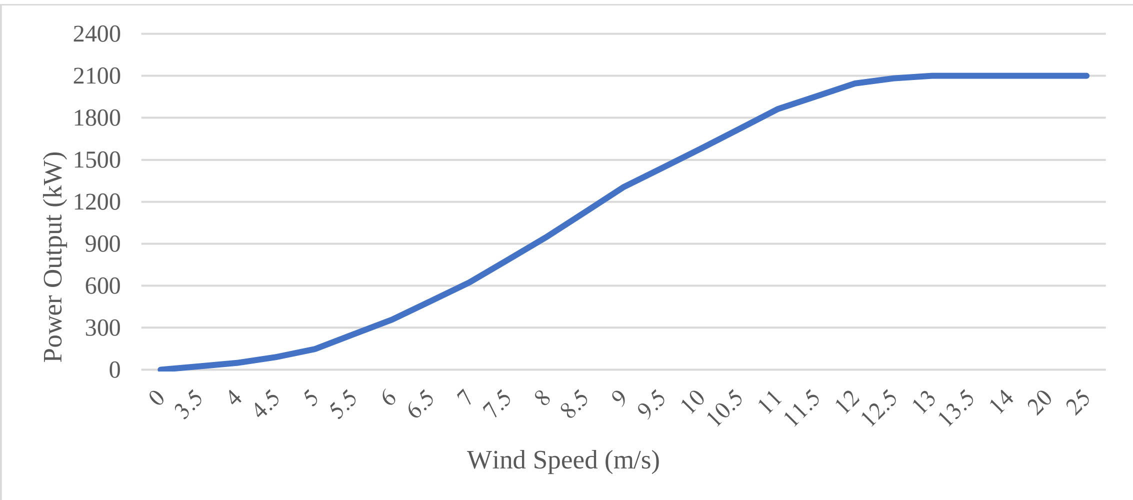


Figure 17. Power curve for the 2.1 MW onshore wind turbine selected. Source [57]

A summary of the most important features of the onshore wind power is provided (See Table 7)

Table 7. Maximum capacity of onshore wind power that can be installed in Ceuta

Average Wind Speed (m/seg)	Wind Class	Wind Turbine Capacity (MW)	Maximum Onshore Wind Capacity (MM)
6.5	III	2.1	25

- Offshore Wind

The offshore wind technology will not be included in the model simulations. It is decided to include only in the energy solutions for Ceuta the renewable technologies with the lowest levelized costs, which could compete with the cost of purchasing electricity from the interconnector. The levelized cost of the offshore wind now is almost three times higher than the onshore costs and therefore it was selected onshore instead of offshore for modelling wind in the simulation [58]. Despite not being modelled in the scenarios, the offshore wind technology has a great potential, and could be seen as a feasible solution to be integrated in the electricity system once its levelized cost reach the grid parity.

One aspect that could be a limitation for installing offshore wind in the future is the elevated Marine Traffic in the area. The Gibraltar Strait is one of the busiest areas related to the marine traffic, being the main entrance of ships in to the Mediterranen Sea. Approximately 120,000 vessels cross The Gibraltar Strait annually, appart from the thousands of marine species in the area and five international underwater data cables located in the region. Ceuta is in the edge of this area, so this could a limitation factor for the potential of installing off-shore turbines in the area, because of the risk collision that a offshore farm could generate (See Figure 18).

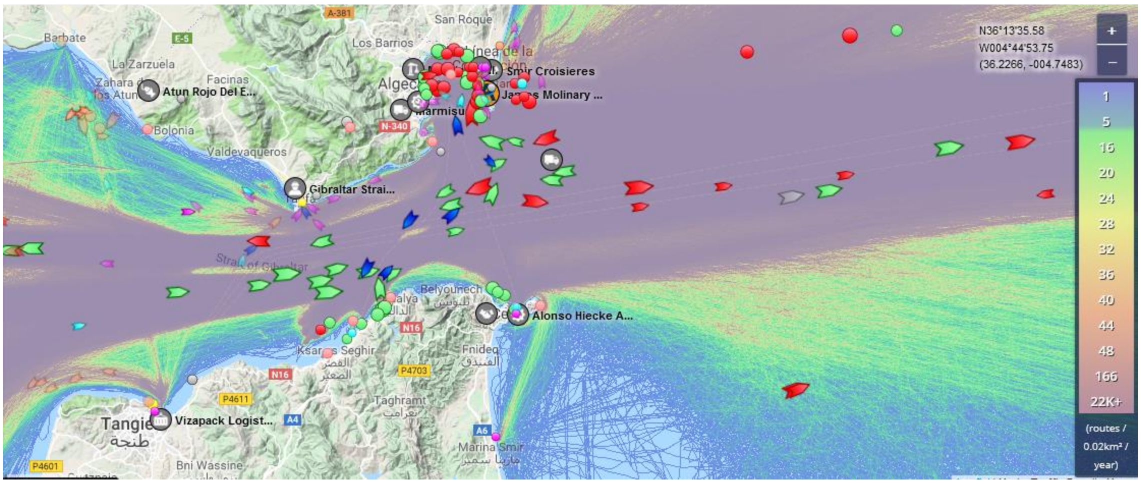


Figure 18. Marine traffic in The Gibraltar Strait. Source [59]

3.4.3 *Pump Hydro Storage*

Ceuta already has two water reservoirs which provides the city with drinkable water.

In 2014, there was conducted a report to assess the feasibility of installing a pump hydro for electricity storage in Ceuta [34]. The pump hydro plant would use the excess of electricity produced with renewables to pump water from a lower to a higher water reservoir during its charging process. When the electricity is needed again by the system, the water goes from the higher water reservoir to the lower one, taking advantage of the potential energy of the water to produce electricity (See Figure 19).

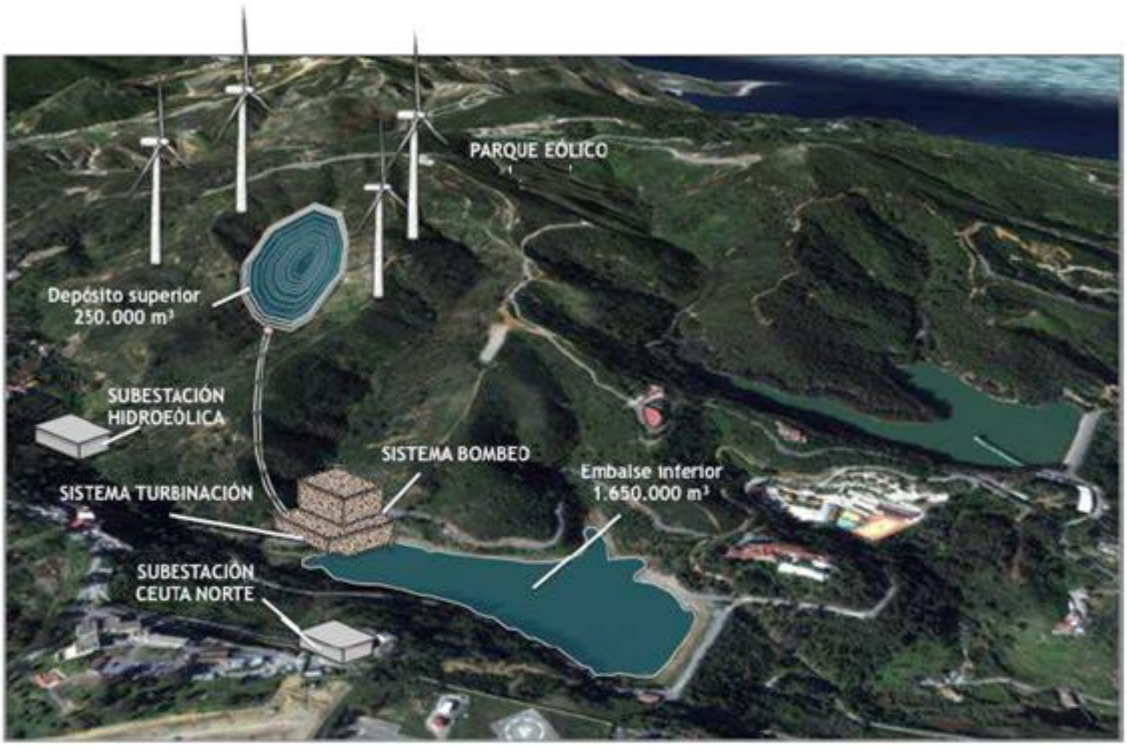


Figure 19. Schematic for Pump hydro plant installation in Ceuta. Source [34]

The available volume to build a water reservoir in Ceuta territory was found to be 250,000 m^3, located at high altitude difference of 105 meters with respect to the water reservoir from which the water would be pumped. To calculate the maximum pump hydro storage capacity was used the following equation:

$$Storage_{(MWh)} = \frac{gravity_{(m/seg)} \cdot \rho_{water\,(kg/m^3)} \cdot V_{OL\,RESERVOIR\,(m^3)} \cdot h_{head\,(m)} \cdot \eta_{(\%)}}{3.6 \cdot 10^3}$$

The efficiency for the pump hydro was defined as 85 %, obtaining a maximum storage capacity of 60 MWh. This parameter will have a great importance while modelling the scenarios which contains renewables because it will define the maximum renewable energy which can be stored in the system, having influence as well while sizing the renewable capacity in the system.

The pump hydro contains water turbines which determines its electrical power capacity. The following equation has been used to calculate the power capacity of the pump hydro:

$$Power_{(MW)} = \frac{gravity_{(m/seg)} \cdot \rho_{water\,(\frac{kg}{m^3})} \cdot h_{head\,(m)} \cdot \eta_{(\%)} \cdot Q_{\,(\frac{m}{seg})}}{10^6}$$

If the water flow is defined as 10 m/seg, the power capacity that needs to be installed in the pump hydro plant would be 8.8 MW. The capacity of 8.8 MW would be provided through 4 Francis turbines of 2.2 MW each. The power capacity of the pump hydro would be used to calculate the costs of this technology, which normally are defined as € per kW installed.

A summary of the most important features of the pump hydro storage plant is provided (See **Table** 8)

Table 8. Maximum pump hydro energy storage capacity available in Ceuta

Volume Reservoir (m3)	Head height (m)	Power capacity (MW)	Maximum Storage Capacity (MWh)
250,000	105	8.8	60

4 MODELLING

4.1 Software adopted

- Software Selection

After a review of all the software currently available to model hybrid energy systems [60] and their capabilities [61] (MERIT, ENERGY PLAN, H2RES…), HOMER PRO was assessed to be the most suitable one, so it was the software chosen for the simulation of this project.

HOMER provides an intuitive and user-friendly interface, which has already incorporated the required aspects for the fulfilment of the purposes of this report, (although it also has some limitations). It enables fast optimisation calculations, allowing an annual hourly analysis simulation of both off-grid and grid-connected microgrid systems

- Software Description

HOMER (Hybrid Multi-Resource Resource Optimization) analyses the operation of a system calculating the energy balance of 8,760 hours in a year.

For each hour, HOMER analyses the electric load demand and compares it with the electricity produced from different technologies, calculating the energy flow between the different components of the model. Additionally, in case that energy storage exists in the system, the software specifies the times that it will be charged and discharged. HOMER does an energy balance for each combination of different technologies which have been defined in the model, giving the possibility to experiment with different technology sizes with the aim to find the optimal solution.

Firstly, in order to simulate the system, the user defines a set of components, including their technical and financial details. Afterward, the software simulates the operation of the system resulting from the computation of the energy balance for every hour for the time period of a year, contrasting at the same time the demand with the electricity produced within the system. Ultimately, the software conducts sensitivity analysis on various aspects of the system like the radiation produced by the sun, the wind speed and the life expectancy of the system's components.

- Simulation algorithm

HOMER simulates, optimizes, and conducts a sensitivity analysis on micropower systems in three different stages as described below:

- Simulation

During this stage, the user defines the main parameters of the system which will be simulated. After configuring the loads, the resources (wind, solar, temperatures or the type of fuel consumed) and the system components (generators, wind turbines, photovoltaic panels) and the restrictions of the system upon which they rely, the software combines all of them in order to present a comparison between the electrical demand for every hour and the electricity produced for the system.

- Optimization

During this stage, HOMER finds the solution which can meet the requirements of the system at the lowest net present cost. In the optimization stage is also calculates the levelized cost of electricity for each system combination and the operating costs of it.

- Sensitivity Analysis

For the sensitivity analysis, an optimization is carried out to discover the sensitiveness of the input variables in the system. To sum up, the software estimates the most efficient size for of all the elements of the system and the energy flows between them.

4.2 Object

The purpose of this thesis is to analyse several feasible ways to produce electricity in Ceuta, creating an overview about how much would cost each pathway and the different benefits of each of them, so a HOMER model is created to represent the current electricity production in Ceuta and the multiple scenarios in which the electricity system can evolve.

In the Modelling section, it will be covered which are the most important variables that the software uses in the simulation, which data needed to be inputted to simulate the scenarios, which are the different scenarios proposed, and which assumptions taken while building the model.

4.3 Variables used in the model and Mathematical modelling behind them

To describe the main variables the software uses during the simulation, it will be used the definition provided by HOMER and the maths formulas provided in its user´s manual:

- Costs Variables

"The total net present cost of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.

HOMER calculates the total net present cost by summing the total discounted cash flows in each year of the project lifetime. It is the main economic output, the value by which it ranks all system configurations in the optimization results, and the basis from which it calculates the total annualized cost and the levelized cost of energy"[62].

The total annualized cost is the annualized value of the total net present cost.

$$Total\ annualized\ cost = Total\ Net\ present\ Cost\ (€) \cdot Capital\ Recovery\ Factor$$

The capital recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the capital recovery factor is:

$$Capital\ Recovery\ factor = \frac{Real\ discount\ rate}{(1-(1+Real\ discount\ rate)^{-Project\ lifetime})}$$

The project lifetime is the length of time over which the costs of the system occur and for this project is 15 years.

The real discount rate is used to calculate discount factors and annualized costs from net present costs.

$$Real\ discount\ rate = \frac{nominal\ discount\ rate - expected\ inflation\ rate}{1 + expected\ inflation\ rate}$$

The nominal rate is the rate at which the money is borrowed. After evaluating which was the average discount rate for different solar and wind projects in Spain during the year 2017 [63], the nominal rate of 7.5 % was defined for this project.

To define the expected inflation rate for the project it has been analysed the inflation value during the last 20 year in Spain [64], obtaining an average value of 2.2 % which has been selected as the expected inflation rate for this project.

The Levelized Cost of electricity, is the division between the annualized cost of producing electricity by the total electric load served.

$$Levelized\ Cost\ of\ Electricity = \frac{Total\ annualized\ Cost\ of\ the\ System\ (€/year)}{Total\ Electrical\ Load\ Served\ (kWh/year)}$$

The operating cost is the difference between the total annualized cost and the total annualized capital cost.

$$Operating\ Cost\ (€) = Total\ annualized\ Cost\ (€/year) - Total\ annualized\ Capital\ Cost\ (€/year)$$

"Salvage: is the value remaining in a component of the power system at the end of the project lifetime. HOMER assumes linear depreciation of components, meaning that the salvage value of a component is directly proportional to its remaining life. It also assumes that the salvage value depends on the replacement cost rather than the initial capital cost."[65]

The life time has its relevance in the salvage costs. The lifetime of the project defined is 15 years so, if the lifetime of the renewable technology is higher (20, 25 or 50 years), the renewable installation will still have some economic value in the horizon year 2033. This monetary value is considered through the salvage. In all renewable technologies proposed for the horizon year, the replacement cost would be zero because its lifetime has not been reached and will have some remaining value (salvage) which return as a result a negative value for the for the calculation "Replacement-Salvage Cost" and will decrease the overall cost of the renewable technology.

- Renewable Fraction

The renewable fraction for the model used is the fraction of the energy delivered to the load that originated from renewable power sources.

$$Renewable\ Fraction\ (\%) = 1 - \frac{Non\ renewable\ Production\ \left(\frac{kWh}{year}\right)}{Total\ electrical\ Load\ Served\ \left(\frac{kWh}{year}\right)}$$

- Carbon dioxide emissions

HOMER calculates the annual CO_2 emissions by multiplying the emissions factor (kg of CO_2 emitted per unit of fuel consumed) by the total annual fuel consumption.

To calculate the CO_2 emissions associated with the grid purchases, HOMER multiplies the net grid purchases (in kWh) by the CO_2 emission factor (in g/kWh).

4.4 Input Data and setting of simulations

The methodology followed for the creation of the model uses the Section 2.4 [21] of the literature review as a reference to revise which are the most important parameters in the simulation.

4.4.1 Electric Load and Constraints

- Electricity Demand

The annual electric demand can be seen in the following graph (See Figure 20). The seasonal demand is quite stable, experiencing a small increase in the demand during the summer period (especially in August).

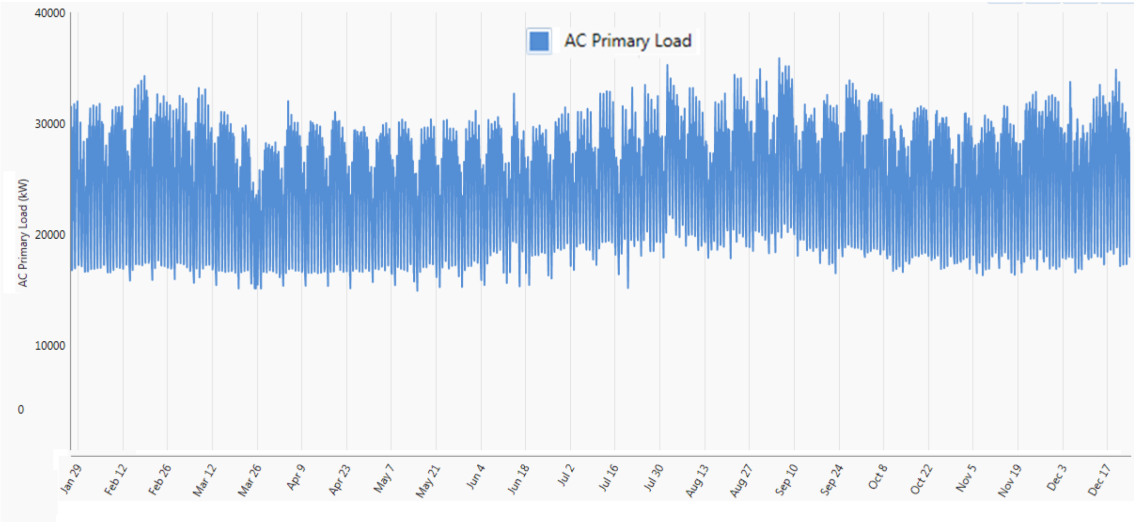


Figure 20. Hourly electricity demand over the year in Ceuta. Source [39]

The main important parameters relative to the electricity demand for the model can be seen in Table 9.

Table 9. Main parameters of the electrical demand in Ceuta

Electrical Demand Main Values			
Annual Electrical production (GWh)	Mean electrical output (MW)	Minimum electrical output (MW)	Maximum electrical output (MW)
210	24	15	36

- Project Constraints

The system needs to be prepared to assume some electrical variations, like an increase in the load or obtaining less output than expected from renewables. These aspects can be modelled in the operating reserve section in HOMER. The unexpected load variation was established at 10 % for the annual peak demandand the load, and 25 and 50 % for the solar and wind resources respectively.

An example of how the operating reserve works can be seen in the next graph (Figure 21), which represents the weekly variation of the electric load profile. In order to make a more realistic model, the system would be operating at higher electric values than the Alternative Current load, with the use of a generation reserve of 10 % to respond to a moderated increase in the expected demand.

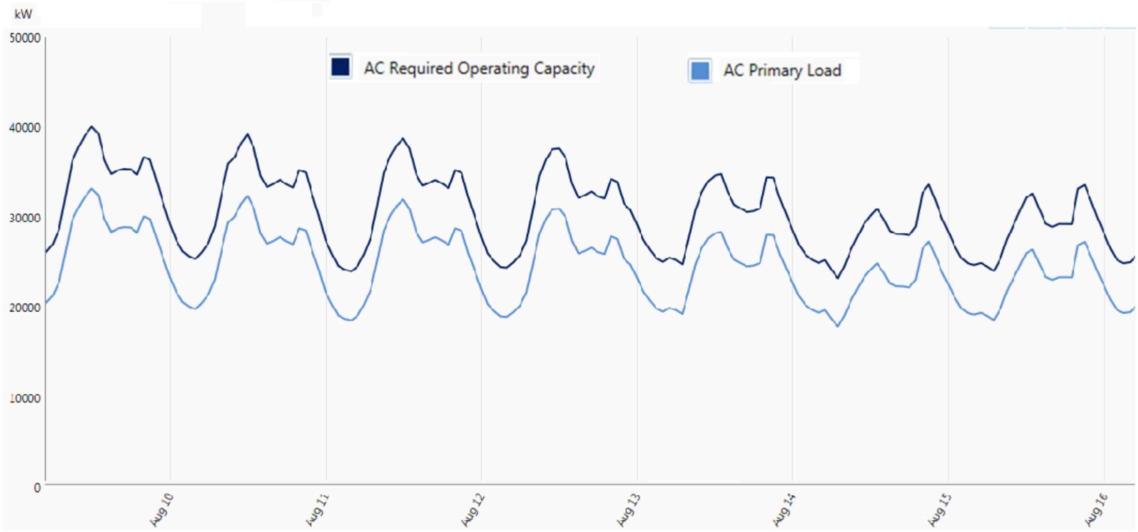


Figure 21. Operating reserve in the system to cover the variations in the demand

4.4.2 Diesel Power Plant

- Capacity

The power plant has a capacity of 97.7 MW, a capacity factor of 24.5 % and an electrical efficiency of 40.6 %. The capacity installed will be maintained in all the scenarios, but the capacity factor and electrical efficiency will vary according to the amount of electric load covered by the power plant.

- Power Plant Costs

The levelized cost of electricity generation in Ceuta is 0.263 € per kWh. This value has been taken from real values of electricity costs previously shown in Table 2 . The levelized cost of the electricity generated by the power plant will vary in the different scenarios according to the electric load covered by the power plant.

The levelized cost is built by the addition of different power plant cost components (fixed capital, operation and maintenance, fuel and replacement) which are explained below:

  - The System fixed Capital Cost

The amount of money that has been invested over the lifetime of the plant was more than 135 million Euros, and despite being amortised the cost of the first generators installed, there are still 95.8 million Euros which still needs to be covered [66]. This aspect has high relevance in all scenarios modelled, because it creates an additional 95.8 M€ cost which needs to be covered whether the existing diesel power plant is used or not, and it increases the overall net present cost and levelized cost of each scenario.

- Operation and Maintenance Cost

The operation and maintenance costs of running the plant for 24 hours, every day of the year are around 14.5 M€ per annum [66]. The plant cost operation per hour has been adjusted to match with the mentioned cost value, obtaining a cost of 17 €/h per each MW installed which, with a 97 MW plant, accounts for almost 40,000 € per day (1,660 €/hour). The operation and maintenance cost will be adjusted in al the scenarios according to the way the power plant is operated.

- Fuel Cost
    - Fuel Price

Due to its electricity isolation and the lack of renewables installed, the entire electricity generation in Ceuta is produced through fossil fuels. Ceuta lacks of own oil resources so the cost of the fuel depends completely on the price established by the oil market.

The Spanish Government established a price for compensating the amount of fuel consumed in its non-peninsula territories for the electricity generation, which varies in each semester of the year. The price for the fuel goes from 450 to 750 € per tonne of fuel consumed during the electricity production.

After analysing the price for different years, it has been selected the reference price for the year 2014, where the price is around 600 € per ton of fuel oil consumed [66].

The fuel used for the electricity production in the Diesel Power plant is **Fuel Oil.** Table 10 shows the main properties of the fuel oil consumed.

Table 10. Properties of the fuel oil used in the electricity generation. Source [13]

Price (€/ton)	Lower Heating Value (MJ/kg)	Density (kg/m3)	Carbon Content (%)	Sulphur Content (%)
600	40.19	960	86	0.93

- Fuel Consumption

The fuel price costs are 600 € per ton of fuel oil consumed (See Table 10). The specific fuel consumption has been established at 0.22 tonnes/MWh produced. The value for the specific fuel consumption will vary as well with the electric load covered by the power plant in the different scenarios, so the cost related to the fuel consumption will vary. The current fuel consumption costs of the plant are 27.8 Million Euros per year.

- Replacement and Salvage Cost

The Diesel Power Plant has nine diesel generators and one gas turbine. These generators were bought in the eighties the first ones until 2010 the last one. In 2033, the horizon year of the project, is forecasted to replace all generators installed before the year 2000, which accounts to be 30 MW of the total 97 MW of the Power Plant. The replacement cost has been determined around 1.25 M€ per MW installed, which provides a difference between the replacement and salvage cost for the horizon year of 37 M€ or 3,3 M€ cost per annum. The replacement cost will be adjusted in al the scenarios according to the way the power plant is operated.

- Summary of diesel power plant features

The main features relative to the current operation and costs of the diesel power plant can be seen in Table 11 and

Table 12. Except the capacity installed and the system fixed capital cost, all other parameters will vary in the different scenarios according to the electric load covered by the power plant.

Table 11. Current main operational values of the diesel power plant. Source [13]

Capacity (MW)	Capacity Factor (%)	Electrical Efficiency (%)	Specific Fuel Consumption (ton/MWh produced)
97.7	24.5	40.6	0.22

Table 12. Current levelized cost of electricity and power plant costs. Source [15]

Levelized Cost of electricity (€/MWh)	System Fixed Capital Cost (M€)	Operation and Maintenance Cost (M€/year)	Fuel Consumption Cost (M€/year)	Replacement Cost (M€/MW)
263	95.8	14.5	27.78	1.25

4.4.3 Interconnector

- Interconnector Costs

The interconnector has a capital cost of 129 Million Euros and an operation and maintenance cost of 1.8 Million Euros per year [67].

- Interconnector Capacity

Relative with the Interconnector, it is known the estimated cost of the project, but it has not been published (or decided) yet the electrical capacity of it. It has been checked by different regional, national and European sources, and this specific data is not provided. Different interconnector capacities are simulated to analyse which effects would have in the current Ceuta electricity system, starting with a minimum interconnector capacity of 15 MW and a maximum one of 40 MW, with different intermediates capacities which vary 5 MW each other. The interconnector real final capacity could be up to 100 MW, but this aspect would not alter the model results because with the maximum modelled value (40 MW) it is covered the maximum daily demand of the year (around 35 MW).

- Cost of purchasing electricity through the interconnector

The cost of purchasing electricity from the interconnector depends on the price of the electricity established by the Spanish Pool (Spanish Electricity Market), so the cost of purchasing or selling electricity was analysed and introduce in the model (See Figure 22). These values will determine the price at which the electricity will be purchased from the electricity interconnector, and the price that will be received when selling electricity exceed to the to the grid.

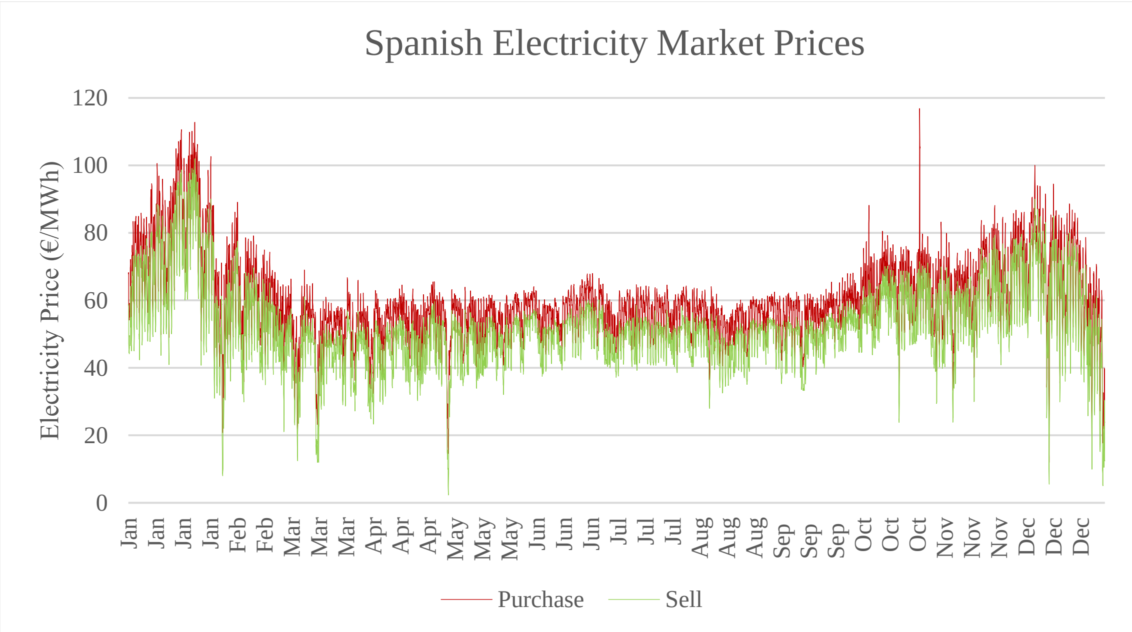


Figure 22. Hourly price for purchasing of selling electricity in the Spanish Electricity Market. Source [42]

The average price in 2017 of purchasing electricity from the grid in the Spanish Electricity Market is 59.33 €/MWh while the price for selling the electricity into the market is 52.24 €/MWh. The average value of purchasing electricity is around 60 €/MWh, but these values change substantially during the day and along the year, with maximum values around 120 €/MWh and minimum values of 25€/MWh.

These values will have a great importance in scenarios where there are different ways of generating electricity (diesel power plant, solar and wind), to determine which way of generating electricity is more economical, if this way of generating electricity is cheaper than purchasing it from the Spanish Electricity Market (through the interconnector) or for knowing the price that will be obtained when selling the electric excess to the grid.

The final cost of purchasing electricity from the interconnector in the different scenarios will depend on the amount of electricity purchased and sold to the grid.

- Spanish Electricity Market Carbon Dioxide Emissions

The CO_2 emission factor associated with national electricity generation in Spain is 0.28 tonnes of CO_2 per MWh produced, which have been used while modelling the emission in the electricity purchased from the grid.

- Summary of Interconnector features

A summary of the interconnector most important parameters is shown at **Table** 13.

Table 13. Cost, capacity and emission values for the electricity interconnector

Capital Cost (M€)	Operation and Maintenance (M€/year)	Electrical Capacity (MW)	Average Electricity Purchase Price (€/MWh)	Average Electricity Sell Price (€/MWh)	Carbon footprint (CO2 Emissions/MWh)
129	1.8	0-40	59.33	52.24	0.28

4.4.4 Wind Power

- Wind Resources

The wind power distribution will have effects on how much power could be produced by the wind turbine chosen for the electricity generation in Ceuta.

The wind does not follow a seasonal pattern like the solar case, and it is a more unpredictable resource. It has been chosen two months of the year to represent the variability of wind speed over time (See Figure 23). In July, for example, the wind speed rarely reaches values above 4 m/s. The power output of the wind turbine chosen at 4 m/s is very low, so the wind power would have a minimum contribution for the electricity generation for the month analysed. In the case of January, wind speeds over 8 m/s happen very often, reaching values of wind speed over 16 m/s. The wind turbine chosen for the project runs at more than 50 % of its power capacity with wind speeds over 8 m/s, reaching its maximum value of 2.1 MW when the wind speed is 13m/s or above.

Therefore, the wind power in the month analysed (January) would be enough to maintain the wind turbine running most of the time at least at 50 % of its power capacity.

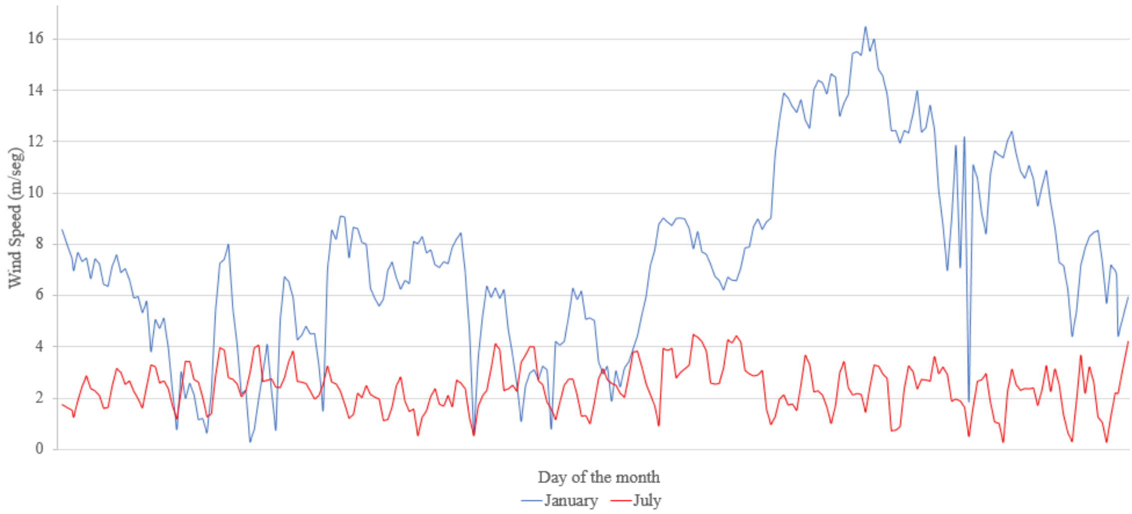


Figure 23. Hourly wind speed resources for each day of January and July in Ceuta. Source [19]

- Onshore Wind turbine

Each turbine installed has a capacity of 2.1 MW. It has been defined a capital cost of 1,275 €/kW (1.275 €/MW installed), with a replacement cost of 70% of the capital cost and an operation and annual maintenance cost of 11,000 € per MW installed [58]. The lifetime for the wind turbines is 20 years. The capacity factor obtained for the wind turbine installed is 23.5 %. The maximum onshore wind capacity that could be installed was quantified to be 25 MW. A summary of the most important parameters for the onshore wind power is provided (See Table 14).

Table 14. Main parameters for the onshore wind power

Capital Cost (€/kw)	Replacement Cost (€/kW)	Operation and Maintenance Cost (€ kW/year)	Life time	Capacity Factor (%)	Maximum Capacity (MW)
1,275	850	11,000	20	23.5	25

4.4.5 Solar Power

- Solar Resources

The factor which has a bigger contribution to the photovoltaics power output is the global horizontal radiation. The value of this parameters changes noticeably along the year, even in sunny places located in the African continent, like Ceuta. The next figure shows the daily global horizontal in January and July, which have been selected to represent the winter and summer season respectively (See Figure 24).

During the winter, the values for the global horizontal radiation rarely reach the 600 W/m^2 and have some variations in its magnitude, obtaining values even lower than 100W/m^2 when the sky is covered.

In the summer period, the global horizontal radiation is quite constant at 1000 W/m^2, taking advantage that is the period of the year when the sky is clearer.

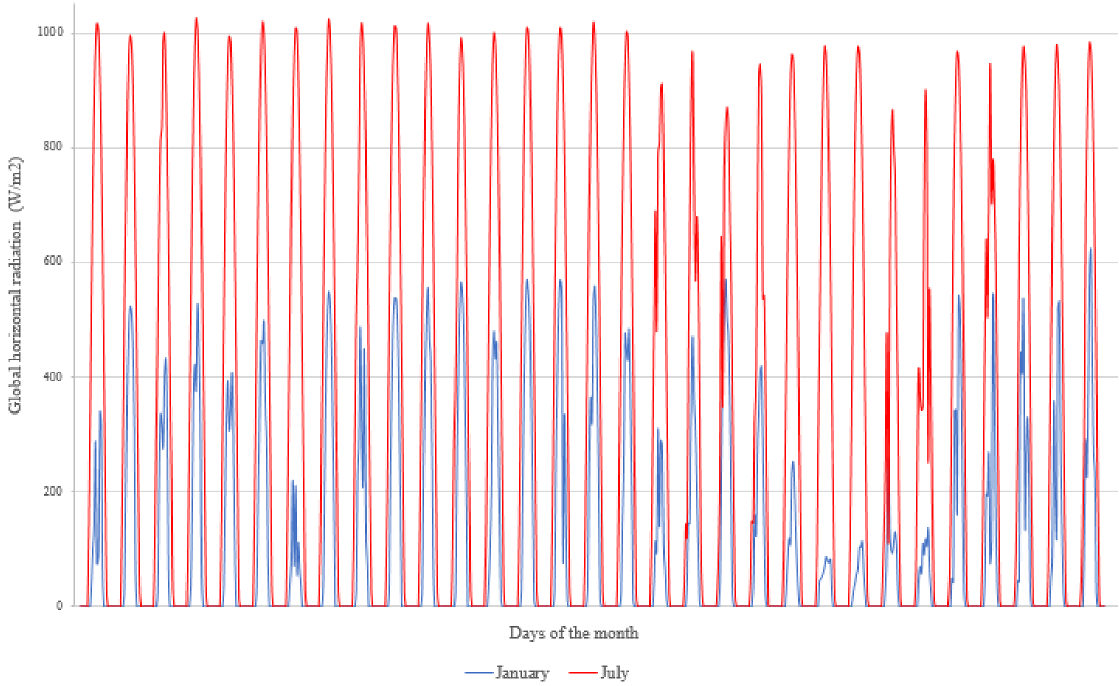


Figure 24. Hourly global horizontal radiation for each day of January and July in Ceuta. Source [19]

- Solar rooftop photovoltaic Panel

The photovoltaics panels simulated have a power output of 250 W, which installed in groups of four forms photovoltaic packages of 1 kW of capacity.

It has been defined a capital cost for photovoltaics of 1,500 €/kW, with a replacement cost of 1,000 €/kW, and operation and maintenance cost of 50 €//kW per year [68] and a lifetime of 25 years [69].

The capacity factor obtained for the photovoltaic panels installed is 17.3 %.

The maximum solar rooftop capacity that could be installed was quantified to be 40 MW.

A summary of the most important parameters for the solar photovoltaics is provided (See Table 15).

Table 15. Main parameters for the solar photovoltaics power

Capital Cost (€/kw)	Replacement Cost (€/kW)	Operation and Maintenance Cost (€ kW/year)	Life time	Capacity Factor (%)	Maximum Capacity (MW)
1,500	1,000	50	25	17.3	40

4.4.6 Pump hydro and Converter

- Pump hydro

The pump hydro plant designed would have an energy storage capacity of 60 MWh. The plant would be composed of four turbines of 2.2 MW for the pump hydro energy storage, which gives a capacity of 8.8 MW. It has been established a capital cost of 3,000 €/kW installed [70], so if the power to be installed is 8.8 MW it is obtained a capital cost of 26.4 Million Euros for the pump hydro energy storage installation.

It has been considered a lifetime of pump hydro of 50 years and a replacement cost of 30% of the capital cost of the plant and the operation and maintenance costs per year a 1 % of the capital cost.

In order to test the performance of different technologies for energy storage, it was simulated to obtain a similar storage capacity through 60 Li-ion batteries of 1 MWh. The economic results showed that is more feasible to install pump hydro energy storage, and this is why pump-hydro is the only storage technology considered in the model.

To simulate pump hydro storage, it was necessary to use rough hand calculations to integrate it properly in the model since it was not covered by the software. The pump hydro was added to the model through a modified battery with 80% round-trip efficiency, establishing a 60 MWh for its storage capacity and adding it to the Direct Current part of the model through a converter of 100 % efficiency[71]. It was detected that with the integration of a pump hydro energy storage, any other storage technology could be included in the model to work at the same time.

A summary of the most important parameters for the pump hydro plant is provided (See Table 16).

Table 16. Main parameters for a pump hydro energy storage plant

Capital Cost (€/kw)	Replacement Cost (€/kW)	Operation and Maintenance Cost (€ kW/year)	Life time	Maximum Storage Capacity (MWh)	Turbines Power Capacity (MW)
3,000	1,000	30,000	50	60	8.8

- Converter

The converter in the system is mainly used for the photovoltaics conversion from DC to AC and to help HOMER to transfer the energy stored in the pump hydro from DC to AC without any cost or efficiency lost. (Homer use Pump hydro as a DC storage by default, and this is the way to store to AC electricity in the pump hydro).

4.5 Scenarios modelled

4.5.1 Scenario 0-Business as Usual: Diesel Power Plant

The purpose of the "Scenario 0 – Business as usual" is to create a model which represents the most important features of Ceuta´s electricity generation current situation. Results obtained for this section will be used as the reference to compare the different scenarios. In the Scenario 0 all electricity generated in Ceuta comes from an only Diesel Power Plant which has a capacity of 97.7 MW.

4.5.2 Scenario 1: Diesel Power Plant + Interconnector

In Scenario 1, it is proposed to minimise the use of the diesel power, providing only enough electricity to maintain operative its current capacity. The rest of the electricity demand will be covered through the interconnector which connects with the Spanish Peninsular Electricity Market.

4.5.3 Scenario 2: All electricity is supplied by the electricity interconnector

In Scenario 2, all the electricity demand will be covered through the interconnector which connects with the Spanish Peninsular Electricity Market.

4.5.4 Scenario 3: Diesel Power Plant + Renewables + Pump Hydro Storage

In Scenario 3, the diesel power plant is used in collaboration with wind and solar technologies and a pump hydro energy storage to cover the system electricity demand.

4.5.5 Scenario 4: Diesel Power Plant + Renewables +Interconnector

In Scenario 4, the interconnector is used in collaboration with wind and solar technologies and the diesel power plant to cover the system electricity demand.

4.6 HOMER Software Validation

It was created a HOMER model to represent how the electricity is currently generated in Ceuta and how it would vary depending on the energy provision solution adopted.

The Ceuta´s electricity generation model created in HOMER was proven to be reasonably accurate. The behaviour of the diesel power plant was compared to real-life data to demonstrate this accuracy. This methodology allowed for the validation of the model; thus, validating the accuracy of the algorithms behind the HOMER software.

In conclusion, HOMER was a robust and reasonably accurate modelling tool for many aspects of this report. It did not, however, provide a ‘complete package’ and this had to be accommodated for by hand calculations when investigating certain renewable technologies (like pump hydro).

4.7 Assumptions and simplifications adopted

- Electricity Demand Increase

Probably, if the interconnector is installed, it will provide a higher quality of the electricity service provided, so it is probable that the electricity demand would increase in the future. For the model created, it has been used the electricity demand of the year 2016, with no increases in the electricity demand in the future, based on the fact that the yearly electrical demand has not experienced any variation during the last ten years.

- Fuel prices and technologies degradation

Parameters like the fuel price or electricity price will, for sure, vary over time, but it has not been considered in the model created. The same would happen with the maintenance costs of the generation technologies, which normally increases over time, or with the effect of time on the performance and the power output of the renewable technologies (like in the case of photovoltaics degradation with time) which have not been taken into consideration. These aspects were not included in the calculation, but these aspects would only have enough relevance to change the results if they experience a drastic change over its contemporary values (for example if the fuel oil price reduces its price in 90 %, the generation with the power plant would change to be the most expensive option to the cheapest one).

- Fuel used

It has been assumed that all generation is produced with fuel oil, which in the real case accounts for the 99 % of the fuel consumed in the power plant. This assumption appears to be feasible, due to the huge difference in the quantities of fuels used in the generation with respect to the fuel oil and the other fuel used in the electricity generation in Ceuta.

5 RESULTS

5.1 SCENARIO 0-Business as Usual: Diesel Power Plant

5.1.1 Objective

The purpose of the "Scenario 0 – Business as usual" is to create a model which represents the most important features of Ceuta´s electricity generation current situation. Results obtained for this section will be used as the reference to compare the different scenarios.

As it has been explained in previous sections, all electricity generated in Ceuta comes from an only Diesel Power Plant which has a capacity of 97.7 MW (See Figure 25).

Figure 25. Scenario 0-Business as usual Schematic.

5.1.2 Input data

- Diesel Power Plant

The electric demand profile showed previously match with the generation profile, so all values for this parameter have already been explained in previous sections.

The generation plant has an electrical capacity of 97.7 MW and runs for 24 hours in every day in the year, obtaining a capacity factor of 24.5 % with its production.

The default fuel curved provided by the software was modified to match with real fuel consumption values and efficiency provided in Ceuta Diesel Generator 2016 Report [13].

The fuel consumption per year is 46,000 tonnes, which accounts for fuel energy input of 516 GWh. If the total generation is 210 GWh, the above-mentioned fuel energy input, the mean electrical efficiency of the generation plan is 40.6 % and the specific fuel consumption of 0.22 ton/MWh produced (See Table 17)

Table 17. Scenario 0. Main operational values of the diesel power plant. Source [13]

Capacity (MW)	Capacity Factor (%)	Electrical Efficiency (%)	Specific Fuel Consumption (ton/MWh produced)
97.7	24.5	40.6	0.22

The system has a fixed capital Cost relative the repayment of the previous inversion in the generators installed in the power plant, which will the same for all the scenarios. The fuel consumption accounts for the 50 % of the annual costs while the operation and maintenance is the 26% of all the annual cost of producing electricity in the power plant (See Table 18).

Table 18 Scenario 0. Levelized cost and power plant cost components. Source [15]

Levelized Cost of electricity (€/MWh)	System Fixed Capital Cost (M€)	Operation and Maintenance Cost (M€/year)	Fuel Consumption Cost (M€/year)	Replacement Cost (M€/MW)
263	95.8	14.5	27.78	1.25

5.1.3 Modelling Results

- Electrical Results

All the electricity demand is provided by the diesel power plant (210 GWh).

- Emissions

The business as usual scenario produces 146,000 tonnes of carbon dioxide each year. If the annual electricity production is 210 GWh, the average would be 0.695 tonnes of $C0_2$ per MWh of electricity produced.

- Energy Cost

In this case, the diesel power plant is the only way to produce electricity in the system, so the cost of the diesel power plant is equal to the cost of the system.

The biggest cost component corresponds to fuel costs (See Table 19), where the price is given by the external factors and the operator has no power to control over it. The second biggest cost is the operation and maintenance, which has suffered almost no variations during the last ten years and the third biggest cost is the cost of the capital cost which was invested to acquire the different generators in the power plant. Adding all the expenses, the system will have a net present cost of 565 Million Euros for the year horizon 2033 (15 years lifetime project).

Table 19. Scenario 0. Net present cost

SCENARIO 0: BUSINESS AS USUAL		
NET PRESENT COST (Million €)		
Cost Type	**Power Plant**	**Electricity System**
System Fixed Capital Cost	95.80	95.80
Operation and Maintenance Cost	149.14	149.14
Fuel Cost	284.71	284.71
Replacement Cost-Salvage Cost	36.05	36.05
TOTAL (Million €)	**565.70**	**565.70**

In order to make it easy to understand the cost result, the annualized cost has also been provided, which shows which would be the cost of the system on an annual basis (See Table 20). This annualized cost result is not the same as the net present cost divided by the project lifetime (15 years) because of the effects of the inflation and the discount rate that has been defined (2.2 and 7.5 % respectively).

Table 20. Scenario 0. Annualized cost

SCENARIO 0: BUSINESS AS USUAL		
ANNUALIZED COST (Million €)		
Cost Type	**Power Plant**	**Electricity System**
System Fixed Capital Cost	9.35	9.35
Operation and Maintenance Cost	14.55	14.55
Fuel Cost	27.78	27.78
Replacement Cost-Salvage Cost	3.52	3.52
TOTAL (Million €)	**55.19**	**55.19**

The amount of electricity generated per year is 210 GWh and the annualized cost of electricity is 55.19 Million Euros, thus, the levelized cost of electricity for the Scenario 0 is 263 €/MWh.

5.1.4 Results Evaluation

All the results will be analysed in three different areas: electricity costs, carbon footprint and energy security.

- Electricity Costs

The main values of the electricity costs for this scenario can be seen in Table 21.

Table 21. Scenario 0. Costs summary

SCENARIO 0: BUSINESS AS USUAL			
Fixed Capital Cost (M€)	Operating Cost (M€/year)	Levelized Cost of Electricity (€/MWh)	Net Present Cost (M€)
95.8	45.8	263	565.7

The main value which will be used for the cost comparison of the system will be the net present cost and the levelized cost of electricity.

The levelized cost electricity in Ceuta 263 €/ MWh, which is very high compared to the price of producing electricity in the Spanish Peninsula which goes from 90 to 120 €/MWh. The main reasons for this situation are the high operating cost per year (due to the imported fuel prices and the operation and maintenance of the system, which needs to be always prepared the provide the electricity needs without any other backup system) and the repayment of the different generators that have been acquired during its lifetime.

The net present cost of the project is 565.7 Million Euros, which would be the reference value to compare the cost of the different scenarios proposed.

- Carbon footprint

It has been obtained for this scenario an average value of 0.695 tonnes $C0_2$ per MWh produced. According to other resources, this data could be even higher, reaching up to 0.770 $C0_2$ per MWh. In the Peninsular Spanish electricity system, the average value is 0.28 tonnes of carbon dioxide emissions per MWh of electricity produced. This value reflects that the value $C0_2$ emissions values in Ceuta are around 2.5 to 3 times higher than producing it in the peninsular Spanish territory.

This system has a renewable fraction of 0 % because all the electricity is produced by fossil fuel.

It has been verified that the emission values obtained in the model are almost the same as the plant real values emission (see Section 4.4.3).

- Energy Security

The energy security factor will be determined through the number of back up layers of the system to provide the electricity required. In the Scenario 0, all the electricity is provided by the power plant, so if there is a problem with the generators, the security of the electricity supply could be compromised. It has been explained in previous sections the different electricity black-outs that the city suffers which affects part or the whole electricity supply in Ceuta electricity system. It is also true that this plant has been operating for at least the last 40 years, and even though there are some back-outs, the time to solve the problem in the generator which causes it and re-start the system again is around one hour. The fuel oil is provided through the Sea, and it is an international commodity, so there is no evidence which supports a high risk of interrupting the fuel oil supply in the short term. The problem in Ceuta electricity grid is more related with the quality of the electricity service provided, rather than the energy security of it. This scenario will be assigned a Level 1 on the Energy Security Scale.

- Results Summary

Table 22 shows the results of the Scenario 0 relative to the electricity cots, carbon footprint and energy security, which will be used as a reference to compare with the rest of the scenarios.

Table 22. Scenario 0. Electricity costs, carbon footprint and energy security

SCENARIO 0: BUSINESS AS USUAL					
Electricity Costs		**Carbon footprint**		**Energy Security**	
Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (tonnes/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
565.7	263	146,000	0	0	1

5.2 SCENARIO 1: Diesel Power Plant + Interconnector

5.2.1 Objective

In the previous scenario it has been shown that generating electricity with the diesel power plant implies a high cost for the electricity produced. In this scenario, it is proposed to minimise the use of the diesel power in order to reduce costs, providing only enough electricity to maintain operative the full power plant current capacity. The rest of the electricity demand will be covered through the interconnector which connects with the Spanish Peninsular Electricity Market (See Figure 26). Generating electricity with Ceuta power plant is more expensive than the price that will be obtained for the electricity generated in the Spanish Electricity Market, thus, it has been established that no electricity can be sold to Spain mainland through the interconnector.

Figure 26. Scenario 1 Diesel Power Plant + Interconnector Schematic

5.2.2 Input Data

- Interconnector

The interconnector has a capital cost of 129 Million Euros and an operation and maintenance cost of 1.8 Million Euros per year. The average value of purchasing electricity is around 60 €/MWh, although this price varies considerably (from 120 €/MWh to 25€/MWh). The final cost of this parameter will depend on the amount of electricity purchased from the grid.

Different interconnector capacities are simulated to analyse which effects would have in the current Ceuta electricity system, starting with a minimum interconnector capacity of 15 MW and a maximum one of 40 MW, with different intermediates capacities which vary 5 MW each other. It cannot be taken advantage of the excess in the electricity capacity for selling electricity to the grid because selling electricity is not allowed for this scenario.

- Diesel Power Plant

Regardless of whether the diesel power plant is used or not, there are system fixed capital costs related to the past inversion on the generators used in the power plant which needs to be repaid. This value accounts for 95.8 Million Euros.

In this scenario, the diesel power plant will operate at minimum values with the objective to maintain operative its current capacity be prepared to cover the whole electricity demand in case it is necessary. It has been made the assumption that the replacement cost in this scenario will be the half than in scenario 0 because the number of hours that each generator is operating will decrease considerably, giving the possibility to extend the lifetime of some of these components.

A similar assumption has been made with the operation and maintenance costs. The power plant will run for 24 hours every day, but the demand which needs to be met is much lower than in the current situation, so with an efficient operation and maintenance design, the cost of this parameter could be reduced substantially. It has been considered that its annual operation and maintenance value will decrease to 1/3 of its current value.

5.2.3 Sizing the system

To determine the optimum capacity of the interconnector, it needs to be taking into account not only the the levelized cost of energy, but also how variable is the capacity to be provided capacity (if it is a fixed number is more easy to the system andd more easy to manage by the system operator), the number of greenhouse gas emissions produced or if the number of hours working and the power required is enough for an appropriate maintenance of the installation of the power plant.

After analysing the different alternatives, two configurations have been found to be more feasible than the others.

- Option 1: Stable 20 MW Interconnector Capacity with Variable Diesel Generation

The first option is based in providing a stable electrical amount through the interconnector (20 MW) and covers the rest of the electrical demand with the diesel generator, which due to the fluctuations would be variable and would involve the different generators of the power plant in the generation process (See Figure 27).

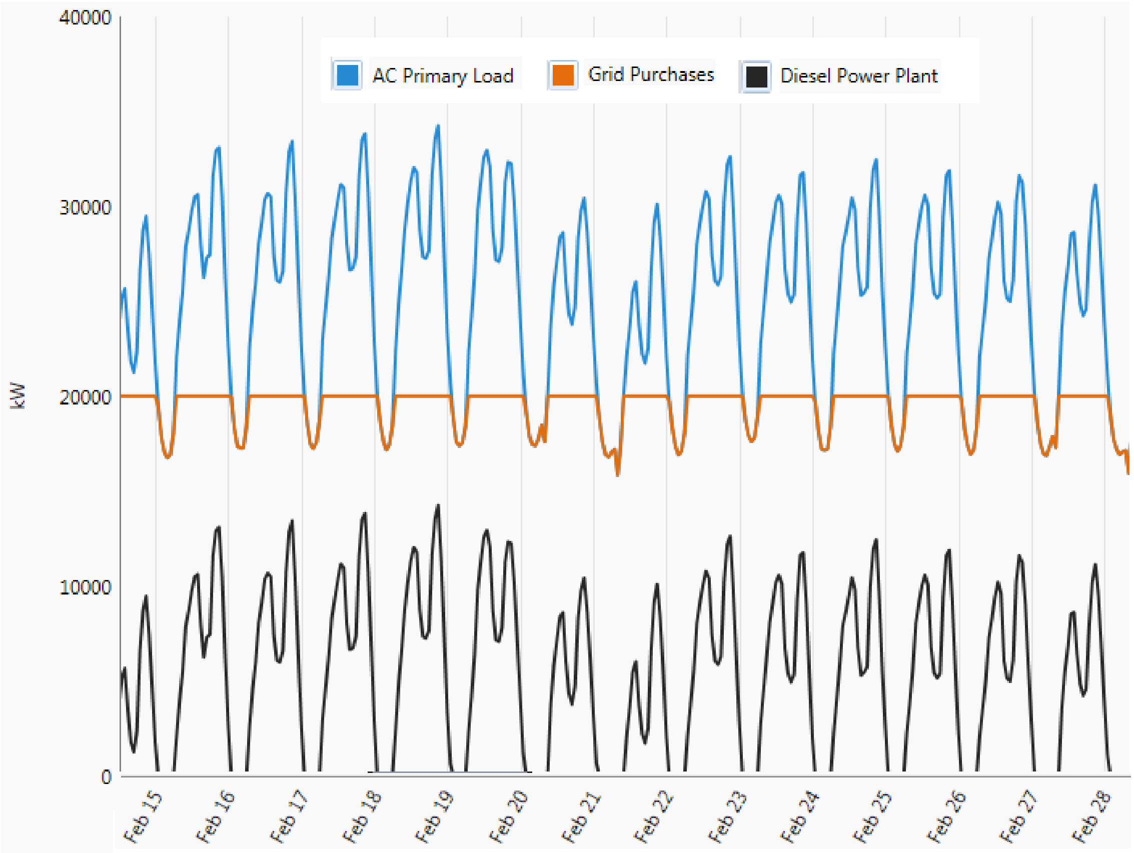


Figure 27. Configuration where the interconnector provides a stable load and the power plant covers the electric peak demand in Scenario 1

The advantages of this option are that the power provided by the interconnector is quite stable for the whole year, thus it could even be fixed an unique price for purchasing the electricity from it. In addition, the electricity load covered by the diesel power plant is high enough (15 MW) for the bigger generator in the diesel plant (11 MW) to work at full capacity while trying to cover the electrical demand, which could help in the operation and maintenance process.

The negative aspect is the fact that the diesel generator is covering the peak demand each day, thus the demand fluctuates substantially and the system is more difficult to operate and maintain.

- Option 2: Variable 25 MW Interconnector Capacity with Stable Diesel Generation

This option is based in providing a stable load with the diesel generator at around 5 MW and the rest of the electricity demand, which varies considerably, is provided by the interconnector (See Figure 28).

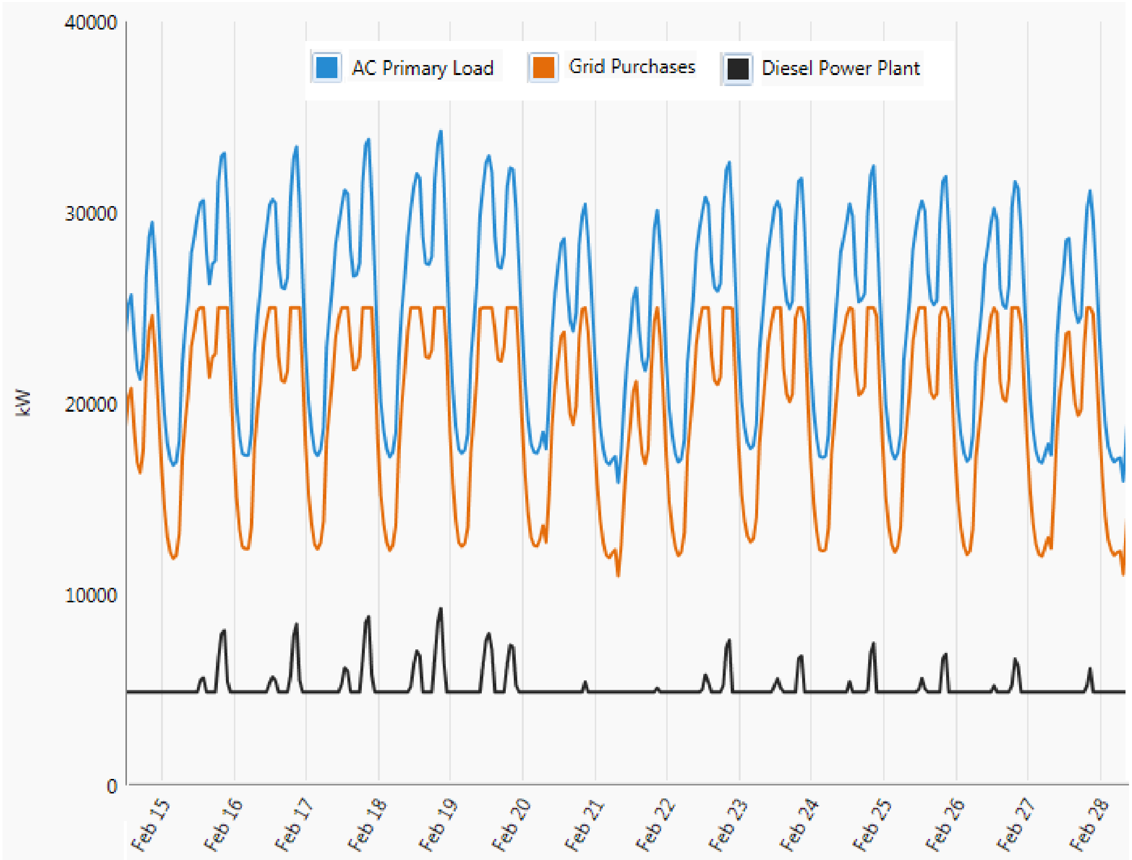


Figure 28. Configuration where the power plant provides a stable load and the interconnector covers the electric peak demand in Scenario 1

The main advantage of this option is the easiness to maintain and operate a power plant if it is known in advance the amount of electric load that needs to be covered. The fluctuations would be beneficial to challenge the most powerful generators inside the power plant, allowing them to work at full capacity.

- System size selection

Probably, in real life operations, the final solution would be a combination of these two cases, having a minimum electrical daily load to maintain the generators working and from time to time, make a test with the diesel power station and its full capacity, to assure that the plant will be ready to cover the full electrical demand in case it is necessary.

Both options have a similar cost around 230 €/MWh produced, and despite having a slightly higher fuel consumption, the option chosen to represent this scenario is the second one, with a variable 25 MW interconnector and a stable load of 5 MW covered by the diesel power plant, which increases occasionally while there is a peak in the electric demand. The main aspect of choosing this option is because it is easier to maintain and operate the diesel power plant.

5.2.4 Modelling Results

- Electrical results

From the 210 GWh of the electricity demand, the diesel power plant only covers the 21 % (44 GWh), while the electricity interconnector covers the other 79 % (166 GWh).

- Emissions

The values of the carbon dioxide emissions per year are 87,000 ton. Giving an average of 0.414 tonnes of CO_2 per MWh in the electricity supply.

- Energy Costs

Despite being the proportion of the electricity covered by the interconnector and the diesel power plant (79 vs 21 %), the net present cost of both technologies for the horizon year 2033 is quite similar (250 vs 246 Million Euros) (See Table 23).

Table 23. Scenario 1. Net present cost

SCENARIO 1: Interconnector + Power Plant			
NET PRESENT COST (Million €)			
Cost Type	**Interconnector**	**Power Plant**	**Electricity System**
System Fixed Capital Cost	-	95.8	95.8
Capital Cost	*129*	-	129
Operation and Maintenance Cost	*18.45*	52.64	71.09
Grid Energy Charge (Purchase -Sell)	*102.85*	-	102.85
Fuel Cost	-	80.31	80.31
Replacement Cost-Salvage Cost	-	18.02	18.02
TOTAL (Million €)	**250.3**	**246.77**	**497.07**

The parity in the cost of these components can be explained easily with the annualized cost table (See Table 24). Comparing these results with the current situation explained in detail in the business as usual the fuel costs have decreased 70 % of its value, the operation and maintenance a 65 % and the replacement cost a 50 % and the system fixed capital cost per year is the same as in the Scenario 0. The real difference comes with the fact that the electric demand covered has been reduced a 79 % of its previous value. This makes the levelized cost of electricity provided by the power plant increase from 263 €/MWh in the previous scenario to 548 €/MWh, with the objective of maintaining the full capacity operative of the power plant for security reasons.

This cost is compensated by the cost of electricity provided by the interconnector, with an average cost of 147 €/MWh, from which approximately the 40 % of these costs come from purchasing electricity from the grid and the other 60 % from the capital cost and the operation and maintenance of the interconnector.

Table 24. Scenario 1. Annualized cost

SCENARIO 1: Interconnector + Power Plant			
ANNUALIZED COST (Million €)			
Cost Type	**Interconnector**	**Power Plant**	**Electricity System**
System Fixed Capital Cost	-	9.35	9.35
Capital Cost	*12.58*	-	12.58
Operation and Maintenance Cost	*1.8*	5.14	6.94
Grid Energy Charge (Purchase -Sell)	*10.03*	-	10.03
Fuel Cost	-	7.83	7.83
Replacement Cost-Salvage Cost	-	1.76	1.76
TOTAL (Million €)	**24.41**	**24.08**	**48.49**

The amount of electricity generated per year is 210 GWh and the annualized cost of electricity is 48.49 Million Euros, thus, the levelized cost of electricity for the Scenario 1 is 231 €/MWh.

5.2.5 Results evaluation

All the results of this scenario will be analysed in three different areas: electricity costs, carbon footprint and energy security.

- Electricity Costs

In this scenario the capital cost has increased with respect the Scenario 0 due to the construction of the interconnector, but the operating cost has been reduced a 45 % from its original base on decreasing the operation of the power plant (See Table 25). The levelized cost of electricity has decreased in 32 € per MWh produced with respect the Scenario 0 and the net present cost of the project is 497 Million Euros, saving 68 Million Euros from the Scenario which represents the current situation.

Table 25. Scenario 1. Costs summary

SCENARIO 1: Interconnector + Power Plant				
Fixed Capital Cost (M€)	Capital Cost (M€)	Operating Cost (M€/year)	Levelized Cost of Electricity (€/MWh)	Net Present Cost (M€)
95.8	129	26.56	231	497.07

- Carbon footprint

Comparing the average of 0.414 tonnes of CO_2 per MWh in the electricity supplied in this scenario with the values from Scenario 0, it has been a decrease of 40% with respect the Scenario 0, but it is still 32% higher than the average emissions produced in the Spanish Peninsular Electricity Market.

This Scenario would save 59,000 tonnes of $C0_2$ to be released into the atmosphere.

This system has a renewable fraction of 0 % because all the electricity is produced by fossil fuel through the diesel power plant or imported from interconnector.

- Energy Security

The energy security factor will be determined through the number of back up layers of the system to provide the electricity required. This Scenario has an additional level of security than the Scenario 0 because it maintains the full operational capacity of the diesel power plant and there is also an electricity interconnector which transfers electricity generated in the Spanish Territory. With this system configuration it would be solved as well, the problems with the black-outs that the city of Ceuta experiences from time to time. If there is a problem with the diesel generator and cannot provide enough electricity as expected, the interconnector has enough capacity to cover it. And if there is a problem with the interconnector, the diesel power plant would cover the whole electricity demand. This is why it is important to maintain the diesel power plant and design an appropriate operation and maintenance schedule for the plant which could cover part of the daily electricity demand, to have the plant available to be used in its full power in case it is necessary

It has been assigned a level of 3 in the energy security for this model.

- Results Summary

Table 26 shows the results of the Scenario 1 relative to the electricity cots, carbon footprint and energy security.

Table 26. Scenario 1. Electricity costs, carbon footprint and energy security

SCENARIO 1: Interconnector + Power Plant					
Electricity Costs		**Carbon footprint**		**Energy Security**	
Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (tonnes/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
497.07	231	87,000	0	1	3

The Scenario 1 shows a system which has improved the overall quality in all the aspects analysed compared with Scenario 0. It has decreased its net present costs and therefore its levelized cost of electricity, it has been reduced the carbon dioxide emissions despite not using any renewables for the energy supply and it builds a system with a strong energy security which improves as well the quality of the electricity provided.

Despite these improvements, the levelized cost of electricity of 231 €/MWh is high compared with the price of producing electricity in the Spanish Peninsula which goes from 90 to 120 €/MWh. In the following scenario it will be analysed what would happen if it is decided that it is not worthy to maintain the diesel power plant and all the electric load is covered by the interconnector.

5.3 SCENARIO 2: All electricity is supplied by the electricity interconnector

5.3.1 Objective

To minimise the costs, it is proposed a scenario where all electricity demand will be covered through the interconnector which connects with the Spanish Peninsular Electricity Market (See Figure 29). It has been shown previously that generating electricity with the diesel power plant implies a high cost for the electricity produced, so no electricity will be produced in this scenario with the diesel power plant.

Figure 29. Scenario 2 All electricity is supplied by the interconnector Schematic

5.3.2 Input Data

- Interconnector Costs and Capacity

The interconnector costs are the same than in the Scenario 1, a capital cost of 129 Million Euros and an operation and maintenance cost of 1.8 Million Euros per year and an average value of purchasing electricity is around 60 €/MWh.

The capacity of the interconnector in this scenario goes from 40 MW to 100 MW, to assure that the maximum daily demand of the year (around 35 MW) can be covered.

- Diesel Power Plant

Despite not using the diesel power plant in this scenario, there are system fixed capital costs related to the past inversion on the generators used in the power plant which needs to be repaid. This value accounts for 95.8 Million Euros.

5.3.3 Modelling Results

- Electrical results

The whole electricity demand (210 GWh) is covered by the electricity interconnector.

- Emissions

The values of the carbon dioxide emissions per year are 58,800 ton. Giving an average of 0.280 tonnes of CO_2 per MWh in the electricity supply.

- Energy Costs

The net present cost of the system is 372.88 Million Euros. The capital cost (the interconnector plus the fixed capital costs of the power plant) accounts for the 60 % of the total costs (See Table 27).

Table 27. Scenario 2 Net present cost

SCENARIO 2: All electricity is supplied by the electricity interconnector		
NET PRESENT COST (Million €)		
Cost Type	**Interconnector**	**Electricity System**
System Fixed Capital Cost	95.8	95.8
Capital Cost	129	129
Operation and Maintenance Cost	18.45	18.45
Grid Energy Charge (Purchase -Sell)	129.63	129.63
TOTAL (Million €)	**372.88**	**372.88**

The amount of electricity generated per year is 210 GWh and the annualized cost of electricity is 36.38 Million Euros, thus, the levelized cost of electricity for the Scenario 2 is 173 €/MWh (See Table 28).

Table 28. Scenario 2 Annualized cost

SCENARIO 2: All electricity is supplied by the electricity interconnector		
ANNUALIZED COST (Million €)		
Cost Type	**Interconnector**	**Electricity System**
System Fixed Capital Cost	9.35	9.35
Capital Cost	12.58	12.58
Operation and Maintenance Cost	1.8	1.8
Grid Energy Charge (Purchase -Sell)	12.65	12.65
TOTAL (Million €)	**36.38**	**36.38**

5.3.4 Results Evaluation

It has been simulated as well, which would be the electricity costs, carbon footprint and energy security if it would be decided to provide all the electricity with the electricity interconnector and the power plant is not used anymore.

- Electricity Costs

The fixed and capital cost of the system are maintained with respect the Scenario 1 (Interconnector + Power plant). The operating cost is mainly composed by the electricity that is purchased from the grid and it has decreased in 45% its value from the Scenario 1 and in 68 % from Scenario 0 (Business as usual) (See Table 29).

The net present cost of the project has decreased to 125 Million € with respect to the Scenario 1 and in 193 Million € with respect the Scenario 0 for the horizon year 2033.

Table 29. Scenario 2 Costs summary

SCENARIO 2: All electricity is supplied by the electricity interconnector				
Fixed Capital Cost (M€)	Capital Cost (M€)	Operating Cost (M€/year)	Levelized Cost of Electricity (€/MWh)	Net Present Cost (M€)
95.8	129	14.45	173	372.86

- Carbon footprint

The values of the carbon dioxide emissions per year are 58,800 ton. Giving an average of 0.280 tonnes of CO_2 per MWh in the electricity supply. Obviously, the average emissions of this scenario are the same than in the Spanish Peninsular Electricity Market because all the electricity purchased come from there. There would be a 32 % reduction compared with the current value of CO_2 provided in Scenario 1 and 60 % from the Scenario 0. The renewable fraction would still be zero, because there is no local electricity generation in Ceuta.

- Energy Security

This is the weakest aspect by far in this scenario. This system has only one-way to supply electricity and no back-up systems. The interconnector has enough capacity to cover the peak demand, but what would happen if there is a problem with the interconnector? The whole system will suffer a black-out. Until this point, apparently, the energy security of this scenario could be compared with the Scenario 0 because of the number of back-up systems and the problems where the main system fails, but it is not the same. If there is a fail in the system in Scenario 0, the electricity production will stop, and normally in less than an hour, the electricity is supplied again once the whole system has been re-started. In the case of providing electricity only with the interconnector, what would happen then if there is a problem with the interconnector and no electricity can be transferred from the Iberian Peninsula to Ceuta? Normally if there is a problem with the cable and needs to be repaired, it could take several months to do so. What would happen with the whole electricity supply in Ceuta? The power plant has not been maintained to act in case a problem of this magnitude happens, so the whole energy security of the system will be compromised. It will be assigned the minimum level of energy security (Level 0).

- Results summary

The net present cost of this scenario is the lowest one so far, with 372 Million € for the whole project, obtaining cost reduction of 193 Million € with respect to the current situation. Relative the carbon footprint, this scenario obtains the minimum emissions value so far, obtaining a reduction of around 60% with respect of the current carbon dioxide emissions. There has not been included renewables in this solution, so the renewable fraction is zero. Relative to the energy security, this scenario has the weakest level of it, proposing a solution where if there is a problem in the supply, all the energy security all the system could be compromised (See Table 30).

Table 30. Scenario 2. Electricity costs, carbon footprint and energy security

SCENARIO 2: All electricity is supplied by the electricity interconnector					
Electricity Costs		Carbon footprint		Energy Security	
Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (tonnes/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
372.86	173	58,800	0	0	0

5.4 SCENARIO 3: Diesel Power Plant + Renewables + Pump Hydro Storage

5.4.1 Objective

Having been analysed the maximum renewable potential that could be installed for solar photovoltaics, wind power and pump hydro energy storage in Ceuta territory, it will be simulated which is the best combination of these systems for the electricity generation. As it will be shown later, the renewable potential is not enough to cover all the electricity demand, so the diesel power plant is used in collaboration with the renewable technologies in all the combination proposed. There is no electricity interconnector in this scenario (See Figure 30).

Figure 30. Scenario 3 Power Plant + Renewables + Pump Hydro Storage Schematic

5.4.2 Input data

- Diesel Power Plant

The Cost for the diesel power plant will be the same as the one described in Scenario 0 (See Table 19), with the exception of the fuel costs, where the final costs will change depending on the amount of electricity provided by the power plant.

- Renewables

The maximum renewable potential which could be installed for each renewable technology is:

-40 MW for Solar Rooftop photovoltaics due to the limited space available.

-25 MW for On-shore Wind turbines.

-60 MWh for pump hydro energy storage, which depends on the volume of water which can be stored in the head water reservoir.

The costs and main features of wind turbines, photovoltaic panels and pump hydro plant has been explained in Section 4.4.4, Section 4.4.5 respectively, but Table 31 and Table 32 with all the main features are provided.

Table 31. Main parameters for the onshore wind and solar photovoltaics power

Renewable Technology	Capital Cost (€/kw)	Replacement Cost (€/kW)	O &M Cost (€ kW/year)	Lifetime	Capacity Factor (%)	Maximum Capacity (MW)
Photovoltaics	1,500	1,000	50	25	17.3	40
Wind Turbines	1,275	850	11000	20	23.5	25

Table 32. Main parameters for a pump hydro energy storage plant

Renewable Technology	Capital Cost (€/kw)	Replacement Cost (€/kW)	O &M Cost (€ kW/year)	Lifetime	Storage Capacity (MWh)	Maximum Capacity (MW)
Pump Hydro	3,000	1000	30000	50	60	8.8

5.4.3 Sizing the system

The objective behind this scenario is integrating renewables in the electricity generation in Ceuta but creating a stable system which avoids troubles of frequency and voltage in the electricity grid, which will be done through managing the excess of electricity generated.

The limiting factors in this simulation are the energy storage capacity available (60 MWh), suitable areas in the building roof-top where photovoltaic panels could be installed (40 MW) and the maximum on-shore wind potential and the energy storage available (25 MW). In order to provide a feasible solution which did not compromise the stability of the electricity grid, one of the priorities of this simulation is to make the excess of the electricity generated the closest as possible to zero.

- Simulations

It has been simulated a rooftop solar photovoltaic capacity from 0 to 40 MW to see which would be the maximum feasible capacity to be installed. The maximum theoretical capacity for onshore wind is around 25 MW (according to data provided by the Spanish Energy Agency). It has been done different simulations from 0 to 25 MW of potential wind to be installed.

Once the simulation is done, it has been detected that maximum capacity for solar and wind which match with the storage capacity and the objective of minimize the excess of electricity generated at minimum rates.

- First Approach for sizing the system
  - Maximum Solar Capacity without the need of Energy Storage

It has been found that the maximum integration of solar without energy storage is 13 MW, which provides slightly less of 10 % of Renewable Integration in the system. Higher values of renewable integration without storage would create problems in the frequency and voltage in the electricity grid.

  - Maximum Wind Capacity without the need of Energy Storage

Wind is more variable than solar, so if there is only wind as renewables in the grid, problems with frequency and voltage in the grid can appear when the renewable integration is higher than 8 %, and always storage is needed when integrating wind power into the grid.

  - Maximum Capacity of Solar, Wind and Energy Storage

It has been analysed the maximum feasible capacity of solar and wind, individually, that is feasible to install according to the energy storage capacity available. If both maximum capacities (40 MW of solar and 25 MW of wind) are combined with the predicted energy storage capacity (60 MWh of pump hydro), it can be seen a widespread excess of electrical production during the year, which would create several instability problems in the electricity grid of the system, so it is not a feasible solution.

The energy storage available should be six times higher (360 MWh) to be able to manage the electrical excess production and it would be reached a renewable penetration of 51 %.

- Feasible combinations for solar, wind, pump-hydro and the diesel power plant

The purpose of this section is to create a combination of wind and solar technologies, which could introduce as many renewables as possible, but matching at the same time with the storage capacity available, creating a solution which would not cause troubles to the current electricity system.

During the simulation, it has been found several combinations of wind and solar which would provide a high percentage of renewable penetration at a moderated levelized cost of electricity, which can be seen in Table 33:

Table 33. Scenario 3. Feasible combinations for wind and solar power

PV (MW)	Wind (MW)	Net Present Cost (M€)	Initial Capital Cost (M€	Levelized Cost of Electricity (€/MWh)	Renew. Fraction (%)	Excess of Electricity (%)	Widespread excess of electricity
5	21	560	155	260	27.9	0	-
13	21	561	167	260	31.3	0.0207	NO
20	21	561	178	261	36	0.111	YES
20	17	567	173	263	31.7	0.006	NO
5	25	555	160	258	30	0.27	YES

With all the options proposed, the results are quite similar of around 30 % renewable fraction and 560 M€ of net present cost. To decide which one is the best option it has been taken into consideration the percentage of excess of electricity generated and if this value happens sporadically or it is widespread all over the year, being more benecitial to happens sporadically. After this value, the balance between the net present cost and the percentage of renewable penetration is analysed.

From all of these options, the combination of 13 MW of photovoltaics with 21 MW of on-shore wind power, plus the pump hydro energy storage of 60 MWh has been selected as the best one, because it offers a minimum electric excess (0.0207 %) which is sporadical and is balanced between its net present cost (560 M €) and the renewable penetration obtained (31.3 %).

It can be noted that solar power provides a more consistent power while wind power in more cost effective related to the price per MW installed.

Despite a high renewable integration, the excess of the electricity production is minimum and it only happens in four days during the whole year (See Figure 31). One of the solutions to avoid the excess of electricity production is to turn off the turbines when the pump hydro storage is full and can not accept more energy for storage.

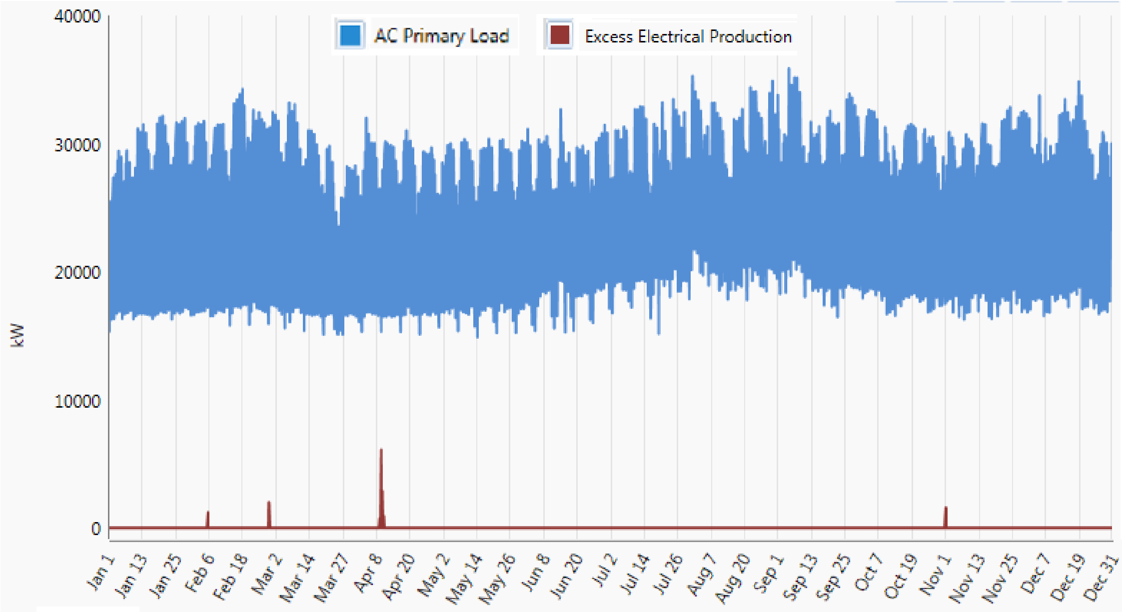


Figure 31. Excess of electricity produced with the combination of 13 MW Solar, 21 MW Wind, 60 MWh Pump hydro energy storage and the power plant in Scenario 3

In this next section, it will be covered in detailed the most relevant aspects of the solution composed of 13 MW Solar, 21 MW Wind, 60 MWh and Diesel Power Plant chosen for this scenario.

5.4.4 Modelling Results

- Electrical Results

From the 210 GWh of the electricity demand, the diesel power plant only covers the 68 % (144 GWh), the wind turbines cover the 22 % (47 GWh) and the rooftop photovoltaics the 9.3 % (19 GWh). The way in which the different technologies operates can be seen in Figure 32.

When there is no renewable power, the diesel power plant covers all the electric load needed and provides no power when there is an excess in renewables. It can be observed a difference in variability between solar and wind, while the solar power produces power every day during the hours of sun, the wind power is much more variable and some days can provide power at full capacity and in others provide no power. Solar power produces its power during the same time at the first of the two electric peaks demands occur, so it provides energy when it is needed, avoiding the excess of it.

When the renewable output (the combination of solar and wind) exceed the electric demand is when the pump hydro storage begins its charging operation. The pump hydro plant stores electricity until there is no more renewable output exceedance or until it reaches its maximum storage capacity. When renewables reach again the point of not being able to cover the whole electric demand is when the pump hydro discharge its power that had been stored.

The system has been designed to minimize the excess of electricity. The power provided by photovoltaics will never cover exceed the electric demand because the minimum demand in 15 MW and it has been installed 13 MW of photovoltaics. The electricity excess will be produced in a moment with high wind and solar or when the wind power available is higher than the electric demand and last enough time for exceeding the storage capacity of the pump hydro.

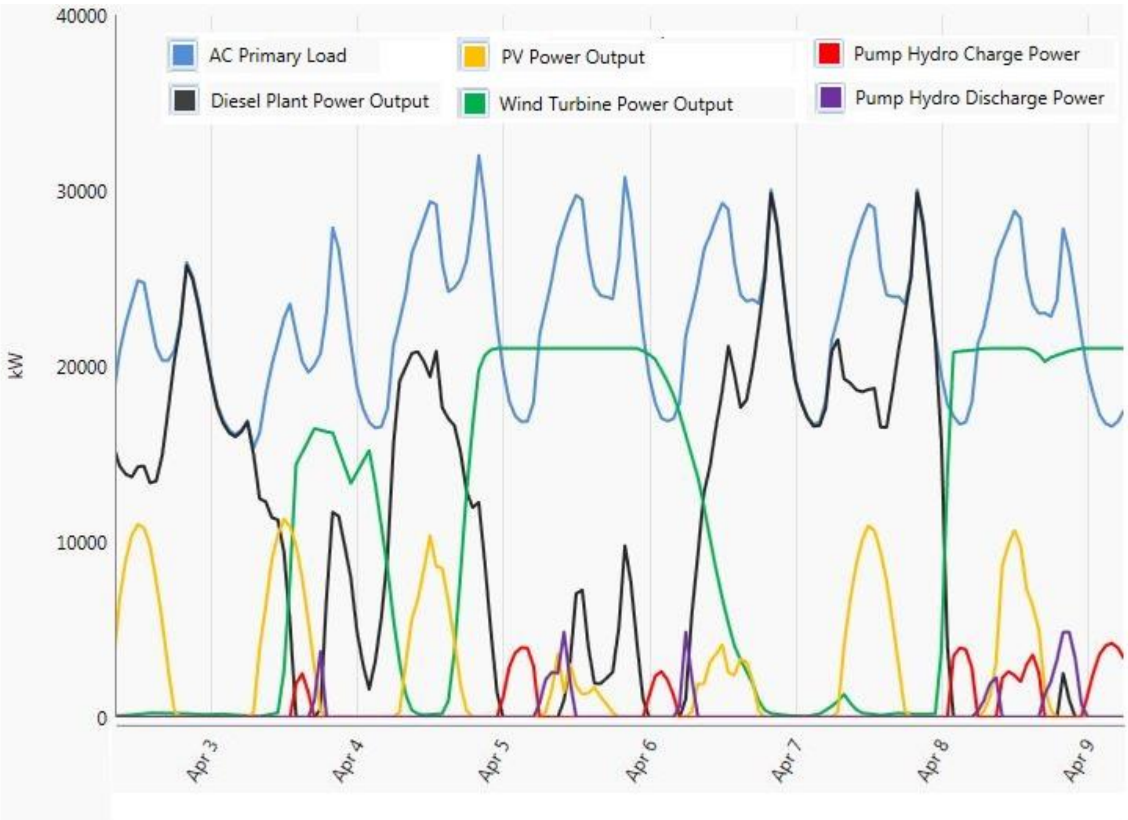


Figure 32. Interaction of the different technologies installed in Scenario 3 during the electricity generation depending of the renewable resources available

- Emissions

The values of the carbon dioxide emissions per year are 104,000 ton. Giving an average of 0.495 tonnes of CO_2 per MWh in the electricity supply.

- Energy Costs

Despite the diesel power plant covers the 69 % of the electricity and renewables the 31 % percent remaining, the difference in the net present cost of both technologies for the horizon year 2033 does not reflect this proportion (485 M€ for the power plant and 76 M€ for the renewables including the pump-hydro storage) (See Table 34).

Table 34. Scenario 3. Net present cost

SCENARIO 3: Wind Turbines + Rooftop PV+ Pump Hydro Storage + Power Plant					
NET PRESENT COST (Million €)					
Cost Type	**Power Plant**	**Pump Hydro**	**Wind Power**	**PV**	**Electricity System**
System Fixed Capital Cost	95.80	-	-	-	95.80
Capital Cost	-	26.40	25.50	19.50	71.40
Operation and Maintenance Cost	149.14	2.76	2.26	6.66	160.82
Fuel Cost	203.73	-	-	-	203.73
Replacement Cost-Salvage Cost	36.05	-2.57	-2.10	-2.43	28.95
TOTAL (Million €)	**484.72**	**26.59**	**25.66**	**23.73**	**560.70**

The difference in the cost of these components can be explained easily with the annualized cost table (See Table 35).

The power plant in this scenario provides 144 GWh per year, and its annualized cost is 47.29 M€, which provides a levelized cost of electricity of 328 €/MWh. In the Scenario 0, which simulates the current situation of providing electricity only with the diesel power plant, the levelized cost was 263 €/MWh. Why has it increased so much the cost of this component?

The explanation for this situation is that the only power plant cost component which has been reduced for this scenario is the fuel cost, while the others (operation and maintenance, capital cost or replacement) are still the same because the energy needs to be prepared to provide hourly the full electric demand load due to the intermittency of renewables. However, the electricity generated in each scenario differs greatly (210 GWh in Scenario 0 and 144 GWh in this scenario), so if the costs are quite similar but the difference in the electricity generated is 45 %, the levelized cost of electricity reflects this situation.

This cost is compensated by the cost of electricity provided by the renewables, where the wind power has a levelized cost of electricity of 53 €/MWh, and solar rooftop photovoltaics, whose levelized cost is 117 €/MWh produced.

Table 35. Scenario 3. Annualized cost

SCENARIO 3: Wind Turbines + Rooftop PV+ Pump Hydro Storage + Power Plant					
ANNUALIZED COST (Million €)					
Cost Type	**Power Plant**	**Pump Hydro**	**Wind Power**	**PV**	**Electricity System**
System Fixed Capital Cost	9.35	-	-	-	9.35
Capital Cost	-	2.58	2.49	1.90	6.97
Operation and Maintenance Cost	14.55	0.27	0.22	0.65	15.69
Fuel Cost	19.87	-	-	-	19.87
Replacement Cost-Salvage Cost	3.52	-0.26	-0.21	-0.23	2.82
TOTAL (Million €)	**47.29**	**2.59**	**2.50**	**2.32**	**54.70**

The amount of electricity generated per year is 210 GWh and the annualized cost of electricity is 54.70 Million Euros so, the levelized cost of electricity for the Scenario 3 is 260 €/MWh.

5.4.5 Results Evaluation

All the results of this scenario will be analysed in three different areas: electricity costs, carbon footprint and energy security.

- Electricity Costs

Despite increasing the capital cost in 167 M€ due to the installation of the different renewables technologies and the pump hydro, the reduction in the operating cost (due to the electricity generated with renewables installed instead of the power plant) gives a net present cost of the project of 560.69 M€, saving only 5 M€ from the current situation of generating electricity in Ceuta (See Table 36).

Table 36. Scenario 3. Costs summary

SCENARIO 3: Wind Turbines + Rooftop PV+ Pump Hydro Storage + Power Plant				
Fixed Capital Cost (M€)	Capital Cost (M€)	Operating Cost (M€/year)	Levelized Cost of Electricity (€/MWh)	Net Present Cost (M€)
95.8	167	38.4	260	560.69

- Carbon footprint

Comparing the average of 0.495 tonnes of CO_2 per MWh in the electricity supplied in this scenario with the values from Scenario 0, it has been a decrease of 29% with respect the Scenario 0, but it is still 43% higher than the average emissions produced in the Spanish Peninsular Electricity Market. This Scenario would save 42,000 tonnes of $C0_2$ to be released into the atmosphere per year. This system has a renewable fraction of 31.3 % due to the electricity generated by wind turbines and solar photovoltaics and using pump hydro as energy storage.

- Energy Security

The energy security factor will be determined through the number of back up layers of the system to provide the electricity required. This Scenario has an additional level of security than the Scenario 0 because it maintains the full operational capacity of the diesel power plant and there is also a 31 % of the demand covered by renewable technologies. With this system configuration, it is not sure to be solved the problems with the black-outs that the city of Ceuta experiences from time to time. If there is a problem in the diesel generator and cannot provide enough electricity as expected, depending on the hour of the day and the wind, solar and energy stored in the pump hydro installation, the could provide the electricity, but this cannot be taken for granted.

In this system, the back-up layer is not as reliable as in other scenarios (like in Scenario 1 with the interconnector) because the amount of electricity that could be generated depending on the wind, solar and storage resources, so it has been assigned a level of 2 for the energy security of this model.

- Results Summary

Table 37 shows the results of the Scenario 1 relative to the electricity cots, carbon footprint and energy security.

Table 37. Scenario 3. Electricity costs, carbon footprint and energy security

SCENARIO 3: Wind Turbines + Rooftop PV+ Pump Hydro Storage + Power Plant					
Electricity Costs		**Carbon footprint**		**Energy Security**	
Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (tonnes/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
560.69	260	104,000	31.3	1	2

The Scenario 3 does not improve so much the current situation of producing electricity in Ceuta. The net cost of the project is very similar compared with the Scenario 0, and the level of security has increased, but not enough to assure that black-outs that the city suffers from time to time will disappear. On the other side, the renewable fraction has increased from 0 to 31 % and the carbon dioxide emissions have been reduced by almost a 30 %, but similar or even higher values of CO_2 emissions decrease have been obtained in the other scenarios. This scenario has its biggest limitation in the storage capacity which can be obtained with the pump-hydro. The pump hydro storage capacity is a limitation for the maximum amount of solar and wind which can be installed in the system. Despite being cheaper generate the electricity with renewables rather than the diesel power plant, a higher renewable penetration will imply a higher excess of electricity in the system because there is not enough capacity to store it, and it may cause instabilities in the whole electricity system.

The results obtained for Scenario 3 are in line with the information provided in literature review (See Section 2.6) which states that enough pump hydro storage capacity can open the door to a high renewable integration in the system, mitigating the negative effects relative with renewables intermittency.

5.5 **SCENARIO 4: Diesel Power Plant + Renewables +Interconnector**

5.5.1 Objective

The objective of this scenario is creating a system which integrates the different solutions described for providing electricity to Ceuta, with the aim to create a more robust system which would take advantage of the benefits of each individual technology used (See Figure 33)

5.5.2 Input Data

- Electricity Generation

The system would be a combination of wind turbines, solar rooftop photovoltaics, the electricity interconnector and the diesel power plant.

The interconnector would have an operative capacity of 25 MW, whose power would vary from 0 to 25 MW in relation with the electricity demand that needs to cover. The total installed capacity of the interconnector would be higher (at least 40 MW), so if it is needed, the interconnector could increase its operative capacity until reaching this value.

The system would have also a stable load of 5 MW covered by the diesel power plant, which increases occasionally while there is a peak in the electric demand and there is no.

renewable energy to cover it. In this scenario, the diesel power plant will operate again at minimum values with the objective to maintain operative its current capacity and be prepared to cover the whole electricity demand in case it is necessary.

The main difference with respect to the Scenario 1, will be the integration of renewables (wind and solar) for the electricity generation. This would help to reduce the electricity purchased from the grid through the interconnector, would reduce the number of times that the diesel generator does not operate at its stable load and would permit to export the exceed of renewables to the Spanish Electricity market through the interconnector.

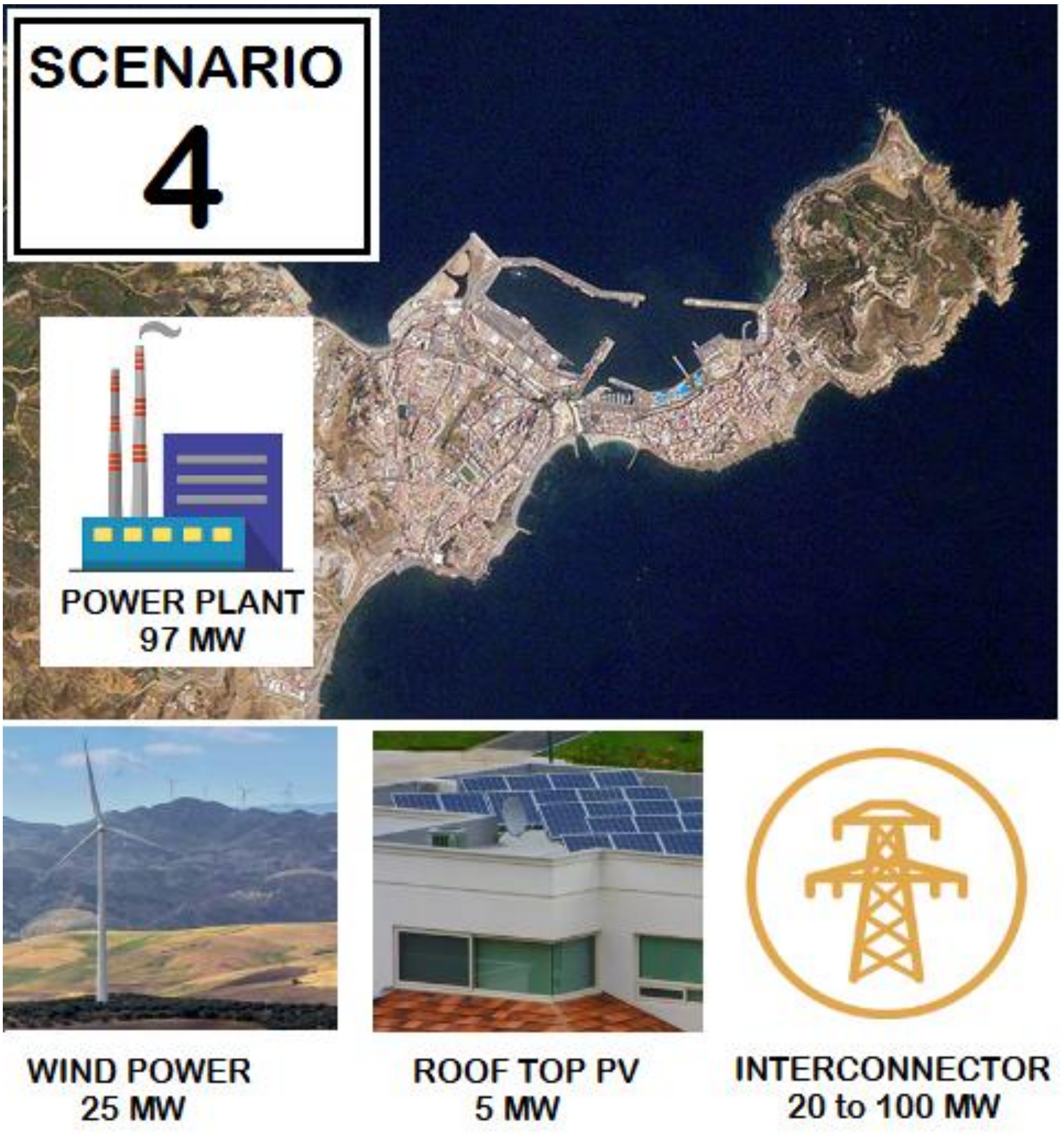


Figure 33. Scenario 4 Diesel Power Plant + Renewables +Interconnector Schematics

- Energy Costs
  - Interconnector

The interconnector cost is the same as in the other scenarios, a capital cost of 129 Million Euros and an operation and maintenance cost of 1.8 Million Euros per year.

In this scenario, due to the inclusion of renewable energies in the generation, it has been given the possibility not only to purchase electricity from the grid, but also to sell the electricity back to the grid. The prices for the electricity transaction are shown in Figure 22, with an average price of 59.33 €/MWh for purchasing electricity, while the average price for selling the electricity into the market is 52.24 €/MWh

  - Diesel Power Plant

The costs of the diesel power plant are the same as the costs of the diesel power plant detailed in Scenario 1, where the annual operation and maintenance cost and the replacement cost were reduced by 2/3 and ½ respectively compared with the current situation. There would be only a small variation in the fuel consumption costs (which depends on the amount of electricity generated) with respect to the costs in Scenario 1.

  - Renewables (Wind turbines and Solar photovoltaics)

The cost of and main features of the renewable technologies used (photovoltaic panels and wind turbines) will be the same that in previous scenarios (See Table 38).

Table 38. Main parameters for the onshore wind and solar photovoltaics power

Renewable Technology	Capital Cost (€/kw)	Replacement Cost (€/kW)	O &M Cost (€ kW/year)	Lifetime	Capacity Factor (%)	Maximum Capacity (MW)
Photovoltaics	1,500	1,000	50	25	17.3	40
Wind Turbines	1,275	850	11000	20	23.5	25

5.5.3 Sizing the system

- Why not including pump hydro as energy storage for this scenario?

In this case, it will be combined all the different technologies available to provide the best solution for the electricity production in Ceuta. Why not using the pump hydro energy storage as well? The first answer would be: with the existence of the electricity interconnector, all the excess electrical production could be sold to the grid, obtaining an economic reward for it. Consequently, the first question is reformulated as: is it worthy to build a costly energy storage infrastructure if it could be obtained an economic benefit for the electricity excess?

There is, at least, two different points of view to answer it.

-In terms of costs, if the pump hydro is not built, it would decrease the whole system net present cost due to the profits of selling the excess of electricity and the savings for not building the infrastructure (only its capital cost would be 26.4 M€).

-In terms of security of supply, building this infrastructure would include a new level of security of the system.

It has been analysed in Scenario 3 how the pump hydro storage capacity was the limitation factor for the renewable potential that could installed in the system, and the limited improvements that a system working with renewables, the power plant and the pump-hydro would provide with respect to the current situation when all the electricity is generated with the power plant.

Therefore, due to its limited improvements relative with the energy provision and the high energy costs that installing a pump hydro would imply for the electricity system of Ceuta, it has been decided not to include pump hydro in the simulations of this scenario.

- Main Considerations

Due to its reduced levelized costs, the wind power appears to be a promising option for the electricity generation. In Scenario 3, there was a limitation of the maximum installed capacity of wind that could be installed due to electric excess that the pump hydro could handle, but in this scenario this limitation does not exist anymore, so it will be used the full onshore wind potential available in Ceuta (25 MW).

Based on the energy security reasons, if it is planned to design a system with high renewable penetration, it is necessary to have an alternative solution in case the electricity interconnector fails.

If there is a problem with the interconnector and no electricity can be purchased or sold, what should be done with the electricity produced by renewables?

Wind turbines at least can be turned off if the system works without the interconnector but what would happen with the solar provided by photovoltaics? How can be turned off thousands of photovoltaics panels displaced in every roof building of the city if the photovoltaic potential installed is higher than the one that grid can cope with?

In Scenario 3 it has been defined that the maximum photovoltaic potential that could be installed in Ceuta electricity system without an energy storage is 13 MW. A higher value of photovoltaics installed in the system without energy storage could cause instability problems in the grid. Therefore, 13 MW will be the maximum installed photovoltaic capacity to assure that in case the interconnector fails, the system could cope easily with the amount of solar power installed.

- Feasible combinations for solar, wind, interconnector and the diesel power plant

Having fixed the values for the interconnector (25 MW), the stable load covered by the power plant (5MW), and the wind power prior to being installed (25 MW), it is only required to find the optimum rooftop photovoltaic potential to be installed.

Two options have been found to be the best, 5 MW and 13 MW of photovoltaics (See Table 39).

Table 39. Scenario 4. Two optimal combinations found for Scenario 4

PV (MW)	Wind (MW)	Net Present Cost (M€)	Operating Cost (M€)	Initial Capital Cost (M€)	Levelized Cost of Electricity (€/MWh)	Renew. Fraction (%)	CO_2 Emissions (tonnes)
5	25	497	22.8	167	224	29.6	71,676
13	25	505	22.4	179	225	34.6	68,577

It will be chosen the option with 5 MW of PV due to it its lower levelized cost of the project, but the other option with 13 MW provides also very promising results, having the possibility of implementing this option in the future when the levelized cost of electricity for photovoltaics decreases as it is expected.

In this next section, it will be covered in detailed the most relevant aspects of the solution composed of 5 MW Solar, 25 MW Wind, 25 MW interconnector and Diesel Power Plant, chosen for this scenario.

5.5.4 Modelling Results

- Electrical Results

There is an electrical demand of 210 GWh but the total electricity generated has reached the value of 217 GWh, of which 6.6 GWh has been sold to the Spanish Electricity Market through the interconnector. Approximately half of the electricity supplied (50.5%) is purchased from the grid (109 GWh), the diesel power plant covers the 19.8 % (43 GWh), the wind turbines cover the 26.2 % (57 GWh) and the rooftop photovoltaics only the 3.5 % (8 GWh). The different technologies operate as it is show in Figure 34.

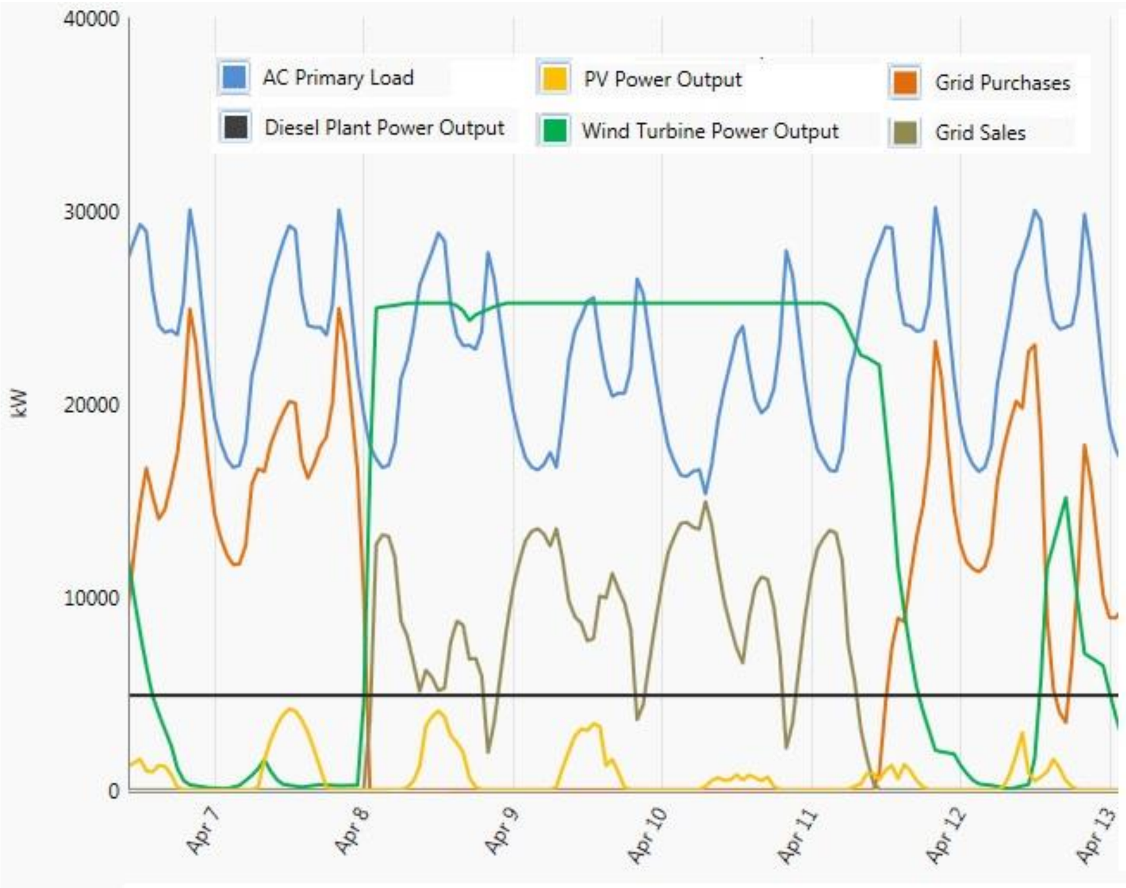


Figure 34. Interaction of 5 MW of Solar, 25 MW of wind, the interconnector and the power plant during the electricity generation in Scenario 4

The diesel power plant covers a stable load of 5 MW. When there is not enough renewable power, electricity is purchased from the grid to cover all the electric load needed.

When the renewable output (the combination of solar and wind) exceed the electric demand, the electricity produced is sold to the grid through the interconnector.

When there is not much renewable production, the grid purchases follow a similar trend than the electric load and the difference between both values is the energy covered by the diesel plant.

As it has been mentioned in the previous scenario, it can be seen a different variability between solar and wind, where solar power produces its power during the same time at the first of the two electric peaks demands occur, thus, it provides energy when required.

Only a 3.5 % of the total energy produced comes from photovoltaic power in this scenario. If in the future is decided to increase the amount of photovoltaics installed from 5 to 13 MW, this would be how the electricity supply-demand matching would change (See Figure 35).

In sunny days, when there is not enough wind, a higher photovoltaic capacity would reduce dramatically the electricity purchased from the grid during the first peak demand on the day (at the noon), when electricity is more expensive. A similar phenomenon would happen during the periods of high winds, when the electricity produced by photovoltaics would be sold to the grid a higher price because it happens during the peak demand time. It is also acknowledged that during no sunny days, there is not a big production of electricity with solar photovoltaics, independently of its capacity installed.

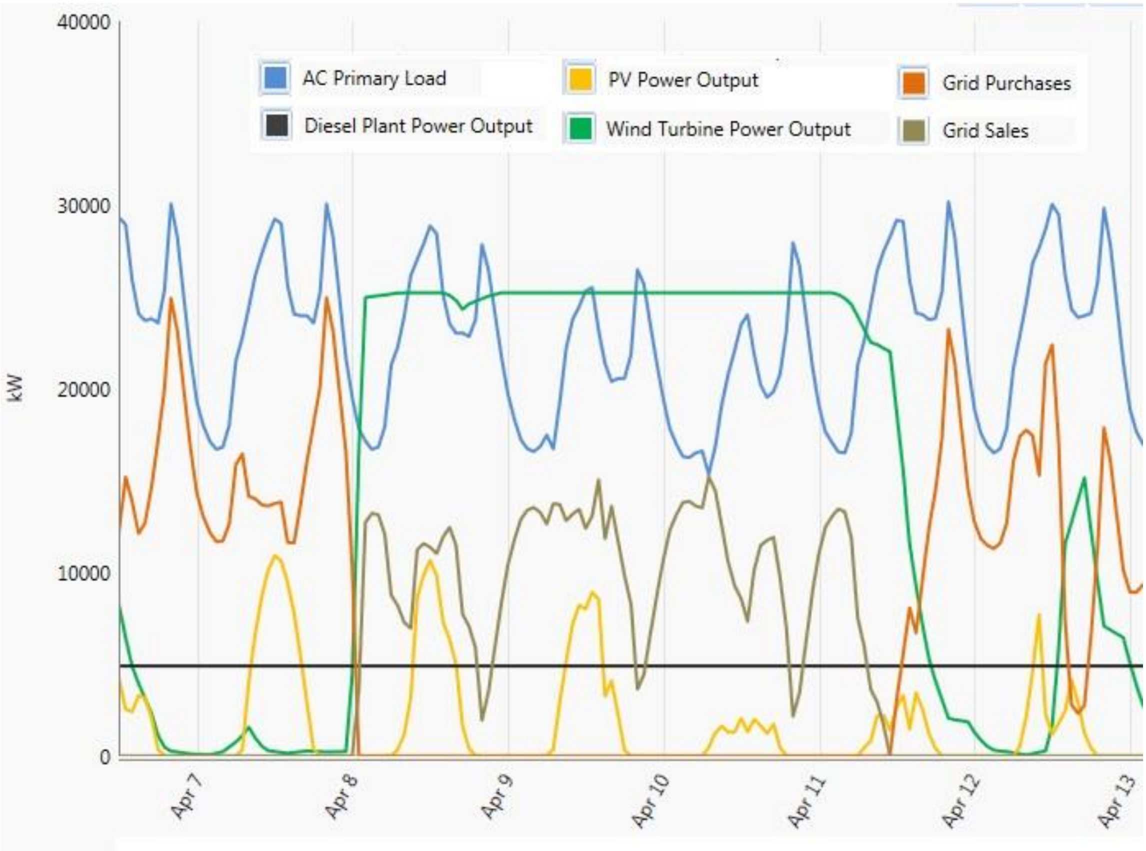


Figure 35 Interaction of 13 MW of Solar, 25 MW of wind, the interconnector and the power plant during the electricity generation for a future possible scenario

- Emissions

The values of the carbon dioxide emissions per year are 71,616 ton. Giving an average of 0.330 tonnes of CO_2 per MWh in the electricity supply.

- Energy Costs

The highest net present cost in this scenario belongs to the diesel power plant, which accounts for almost the half of the costs, despite providing only around the 20 % of all the electricity generated (See Table 40). The second largest cost is the interconnector, which accounts for the 42 % of the costs, but provides a half of the electricity supplied.

The wind power is the technology which gives the best balance of costs and energy supply, providing the 26 % of the electricity produced with only a 6 % of the total costs. The solar photovoltaics cover the 3.5 % of the electricity produced and accounts for the 1.8 % of the total costs of the project.

Table 40. Scenario 4. Net present cost

SCENARIO 4: Wind Turbines + Rooftop PV+ Interconnector + Power Plant					
NET PRESENT COST (Million €)					
Cost Type	**Interconnector**	**Power Plant**	**Wind Power**	**PV**	**Electricity System**
System Fixed Capital Cost	-	95.80	-	-	95.80
Capital Cost	129.00	-	30.60	7.50	167.10
Operation and Maintenance Cost	18.45	52.64	2.71	2.56	76.36
Grid Energy Charge (Purchase -Sell)	63.95	-	-	-	63.95
Fuel Cost	-	79.22	-	-	79.22
Replacement Cost-Salvage Cost	-	18.02	-2.51	-0.94	14.57
TOTAL (Million €)	**211.40**	**245.68**	**30.80**	**9.12**	**497.00**

The power plant in this scenario provides 43 GWh per year, and its annualized cost is 20.62 M€, which provides a levelized cost of electricity of 557€/MWh (See Table 41). In the Scenario 0, which simulates the current situation of providing electricity only with the diesel power plant, the levelized cost was 263 €/MWh. This increase in the cost is explained with the fact that, for this scenario, the plant is oversized (has a capacity factor of 5% for this scenario) with the objective of maintaining the full capacity operative of the power plant for security reasons.

This cost is compensated by the cost of electricity provided by the renewables, where the wind power has a levelized cost of electricity of 53 €/MWh, the solar rooftop photovoltaics has a levelized cost of 117 €/MWh, and the electricity purchased from the interconnector a levelized cost of 189 €/MWh.

Table 41. Scenario 4. Annualized cost

SCENARIO 4: Wind Turbines + Rooftop PV+ Interconnector + Power Plant					
ANNUALIZED COST (Million €)					
Cost Type	**Interconnector**	**Power Plant**	**Wind Power**	**PV**	**Electricity System**
System Fixed Capital Cost	-	9.35	-	-	9.35
Capital Cost	12.58	-	2.98	0.73	16.29
Operation and Maintenance Cost	1.80	5.14	0.26	0.25	7.45
Grid Energy Charge (Purchase -Sell)	6.24	-	-	-	6.24
Fuel Cost	-	7.73	-	-	7.73
Replacement Cost-Salvage Cost	-	1.75	-0.24	-0.09	1.42
TOTAL (Million €)	**20.62**	**23.97**	**3.00**	**0.89**	**48.48**

The amount of electricity generated per year is 217 GWh and the annualized cost of electricity is 48.48 Million Euros so, the levelized cost of electricity for the Scenario 4 is 224 €/MWh.

5.5.5 Results evaluation

All the results of this scenario will be analysed in three different areas: electricity costs, carbon footprint and energy security.

- Electricity Costs

In this scenario the capital cost has increased in 167 M€ with respect the Scenario 0 due to the installation of different renewables technologies and the electricity interconnector, but the annual operating cost of the system has been reduced a 50 % from its original value, based on decreasing the operation of the power plant (See Table 42).

The implementation of these changes in the system results in a net present cost of the project of 497 Million Euros, saving 68.7 Million Euros from the Scenario which represents the current situation and a levelized cost of electricity of 224 €/MWh, which has decreased in 39 € per MWh with respect to the Scenario 0 situation.

Table 42. Scenario 4. Costs summary

SCENARIO 4: Wind Turbines + Rooftop PV+ Interconnector + Power Plant				
Fixed Capital Cost (M€)	Capital Cost (M€)	Operating Cost (M€/year)	Levelized Cost of Electricity (€/MWh)	Net Present Cost (M€)
95.8	167	22.8	224	497.00

- Carbon footprint

Comparing the average of 0.330 tonnes of CO_2 per MWh in the electricity supplied in this scenario with the values from Scenario 0, it has been a decrease of 52%, and it is only 15% higher than the average emissions produced in the Spanish Peninsular Electricity Market.

This Scenario emits 71,600 tonnes but would save 59,000 tonnes of $C0_2$ to be released into the atmosphere per year with respect to the current situation.

This system proposed in this scenario has a renewable fraction of 29.6 % due to the electricity generated by wind turbines and solar photovoltaics (26.1 % from wind and 3.5 % from photovoltaics)

- Energy Security

The energy security factor will be determined through the number of back up layers of the system to provide the electricity required. This Scenario has an additional level of security than the Scenario 0 because it maintains the full operational capacity of the diesel power plant and there is also an electricity interconnector which transfers the electricity generated in the Spanish Territory.

The renewable capacity installed does not contribute enough to the security of the system. In case the interconnector fails, all the wind would be turned off to maintain the grid stability and solar only contributes to the 3.5% of all the electricity produced and it only operates while the hours of sun. The process of shutting down the turbines is instantaneous (there would be 12 turbines installed), and the grid could cope perfectly with the 5 MW of photovoltaics installed (the grid could handle until 13 MW), so the renewables energies installed would not generate any problem in the grid stability in case the interconnector fails, if the operation process is done correctly.

This system configuration would solve the current problem with the electricity black-outs in the city. If there is a problem with the diesel generator, the interconnector has enough capacity to cover it, and if there is a problem with the interconnector the diesel power plant would cover the whole electricity demand.

It has been assigned a level of 3 in the energy security for this model.

- Results Summary

Table 43 shows the results of the Scenario 4 relative to the electricity cots, carbon footprint and energy security.

Table 43. Scenario 4. Electricity costs, carbon footprint and energy security

SCENARIO 4: Wind Turbines + Rooftop PV+ Interconnector + Power Plant					
Electricity Costs		**Carbon footprint**		**Energy Security**	
Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (tonnes/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
497	224	71,676	29.6	1	3

The Scenario 4 shows a system which has improved the overall quality in all the aspects analysed compared with Scenario 0. It has decreased its net present costs in 68 M€ and therefore its levelized cost of electricity, it has been reduced the carbon dioxide emissions to half, and it has increased the renewable fraction from 0 to almost 30 %. The system has strong energy security because it is composed by two very reliable sources, which would improve also the quality of the electricity service provided.

5.6 SCENARIOS COMPARISON

Once it has been evaluated the results of each scenario, it is the moment to compare all of them to find the best solution for the electricity provision in Ceuta, which will be done using a multiple criteria decision analysis methodology, using the electricity cost, carbon footprint and energy security as comparison criterions.

5.6.1 Scenarios summary

It will be summarized the main features of each scenario to make it easy to understand the comparison between them.

- **Scenario 0**: **Business as usual**.

All the electricity generated in Ceuta is supplied by a diesel power plant of 97 MW.

- **Scenario 1**: **Interconnector + Power Plant**

Most of the electric demand in Ceuta is supplied through an electricity interconnector which connects with the Spanish Electricity Peninsular System, except for an average daily load of 5 MW which is covered with the existing diesel power plant to maintain its full operative capacity.

- **Scenario 2**: **All electricity is supplied by the electricity interconnector**

All the Ceuta electric demand is covered by the electricity interconnector and the diesel power plant is no longer used.

- **Scenario 3**: **Wind turbines + Rooftop photovoltaics+ Pump hydro storage + Power Plant**

The integration of 13 MW of solar, 21 MW of wind and a pump hydro energy storage plant of 60 MWh capacity are used in collaboration with the diesel power plant to cover Ceuta´s electric load.

- **Scenario 4**: **Wind turbines + Rooftop photovoltaics+ Interconnector + Power Plant**

The integration of 5 MW of solar and 25 MW of wind accounts for almost the 30 % of the electricity produced. Approximately the half of the electricity is supplied through the electricity interconnector, and it still maintains an average daily load of 5 MW which is covered with the existing diesel power plant to maintain its full operative capacity. This is the only scenario where the interconnector is used not only to purchase electricity but also to sell the excess of electricity that is generated with renewables.

Results will be compared according to the criterions which used to evaluate the results of the scenarios: electricity costs, carbon footprint and energy security. The criterion results per scenario are shown in Table 44.

Table 44. Electricity costs, carbon footprint and energy security per scenario

Scenarios	Electricity Costs		Carbon footprint		Energy Security	
	Net Present Cost (M€)	Levelized Cost of Electricity (€/MWh)	Carbon dioxide (ton/year)	Renewable Fraction (%)	Nº back-up generation systems	Level of Security
Scenario 0	565.7	263	146,000	0	0	1
Scenario 1	497.07	231	87,000	0	1	3
Scenario 2	372.86	173	58,800	0	0	0
Scenario 3	560.69	260	104,000	31.3	1	2
Scenario 4	497	224	71,676	29.6	1	3

5.6.2 *Electricity Costs*

The electricity cost of each scenario can be seen in Figure 36.

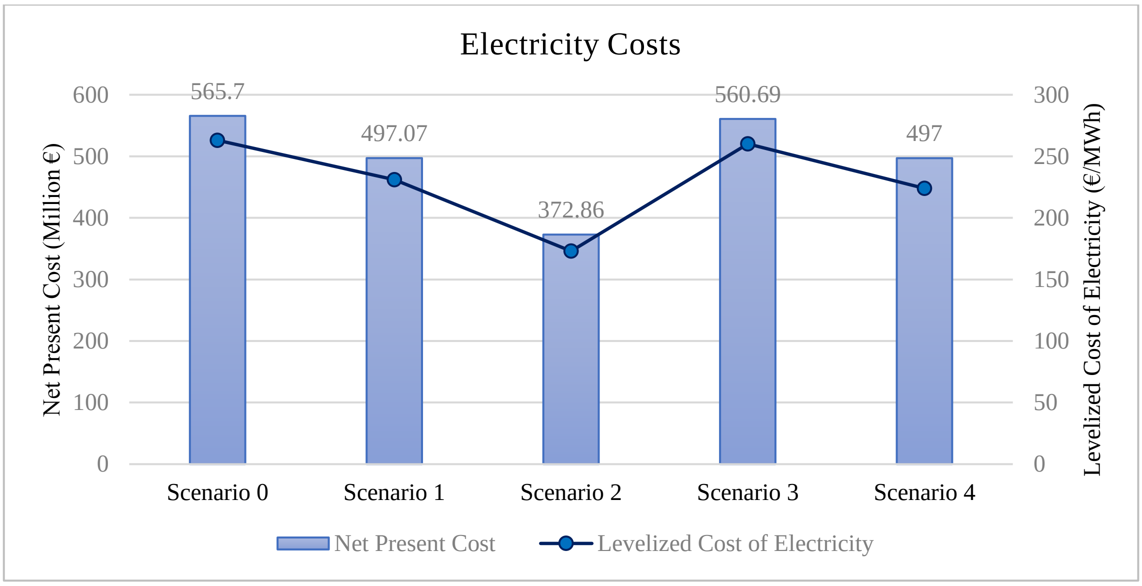


Figure 36. Comparison of the electricity costs per scenario

The levelized cost of electricity follows the same trend pattern than the net present costs, so it is not necessary to make a separate analysis of each indicator, being the results obtained for one valid as well for the other.

The net present cost of the Scenario 0 (power plant only) is the highest, although in Scenario 3 (renewables, pump hydro and power plant) is it obtained a very similar value, with a reduction in the net present costs of less than 1 %.

In Scenario 1 (interconnector and power plant) and Scenario 4 (renewables, interconnector and power plant) it is obtained almost the same cost value. Both options offer a 13 % reduction in the net present cost of the project compared with the current situation.

The lowest net present cost is obtained in Scenario 2 (only interconnector) which obtains a reduction of 34 % of the net present costs of the project compared with the current value.

Therefore, according to the electricity costs, the Scenario 2 would be the best option due to its high reduction in the net present cost, followed by the Scenarios 1 and 4, which obtain a limited reduction in the cost and being the less favourable option the Scenario 3, where the net present cost in almost the same than in the current situation.

5.6.3 Carbon footprint

The carbon footprint for each scenario can be seen in Figure 37

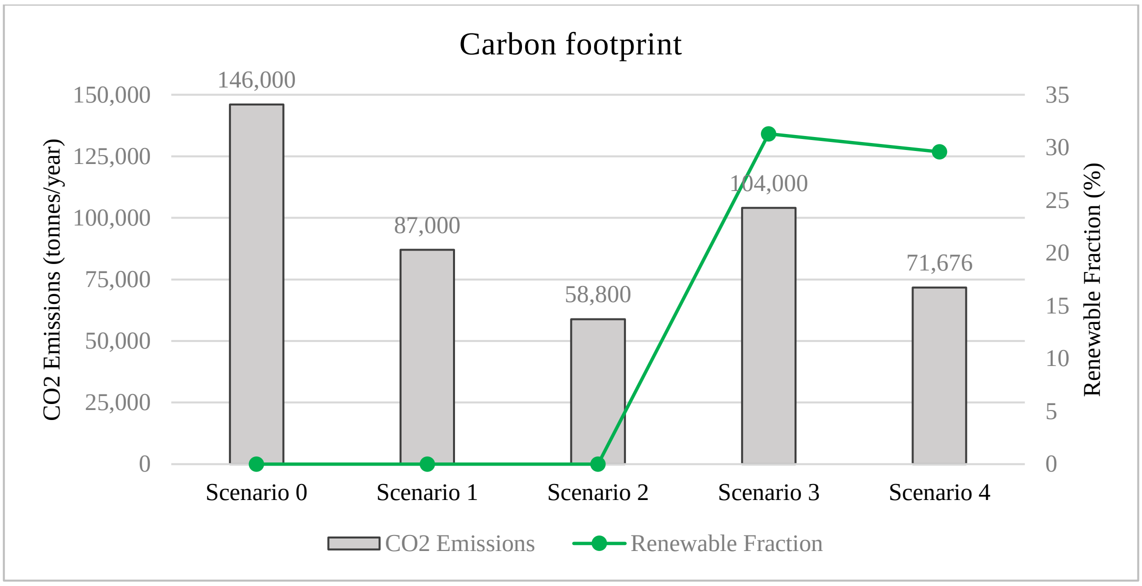


Figure 37. Comparison of the carbon footprint per scenario

A reduction in the carbon emissions not always is linked with the integration of renewables in the electricity system. In this case it will be compared the carbon dioxide emissions value between the scenarios and then it will be mentioned the renewable penetration in the scenario described.

The emissions value for the Scenario 0 (power plant only) is the highest one and all the scenarios proposed obtain a reduction with respect to the current value. In Scenario 0 all the electricity is generated by the diesel power plant so its renewable fraction is zero.

The highest reduction is obtained in Scenario 2 (only interconnector), where the average emissions are the same than in the Spanish Peninsular Electricity Market, with a reduction of almost 60 % with respect the current CO_2 emissions value. The renewable fraction for this scenario is zero, due to not generating any electricity in Ceuta´s territory.

The second biggest reduction is reached in Scenario 4 (renewables, interconnector and power plant), where it is achieved a reduction in CO_2 emissions of a bit more than 50 % with respect the current value. The renewable fraction for this scenario is almost 30 % due to the contribution of solar and wind power in the electricity generation.

In Scenario 1 (interconnector and power plant) the CO_2 emissions are reduced in a 40 % and in Scenario 3 (renewables, pump hydro and power plant) almost a 30 % with respect the Scenario 0 values. In Scenario 1 the renewable fraction is zero while in Scenario 3 it is obtained a 31 % due to the contribution of solar and wind power installed.

Therefore, according to the carbon footprint, the Scenario 2 would be the best option again for obtaining a reduction of 60 % with respect the current CO_2 emissions values, closely followed by the Scenario 4 which obtains a reduction of 51 %. The third and fourth option would be the Scenario 1 and the Scenario 3, with a reduction of 40 % and 30 % respectively with respect the current CO_2 emissions values.

5.6.4 Energy Security

Four levels of energy security have been defined:

Level 0: The energy security of the whole electricity system is compromised if there is a failure in the source in charge of supplying the electricity.

Level 1: It has a reasonable level of energy security, but it cannot always be guaranteed a high quality of the electricity service provided, so the electricity system suffers from blackouts occasionally.

Level 2: The system has more than one system to cover the electricity demand, which increases its energy security, but the back-up system is not reliable enough to assure that the system would always have a high quality in the electricity service provided.

Level 3: The energy security and the quality of the electricity service provided is assured.

The energy security of each scenario can be seen in Figure 38.

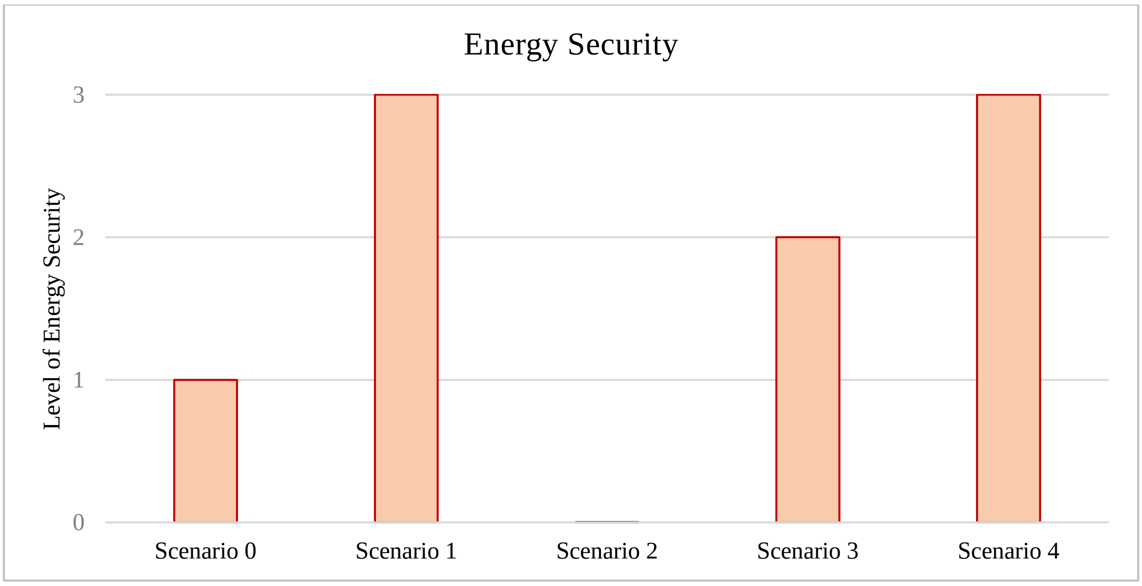


Figure 38. Comparison of energy security per scenario

The Scenario 0 (power plant only) represents a situation with a power plant which has been operating for the last 40 years, and even though the electricity system suffers back-outs from time to time due to the problems in the generation, it takes normally around one hour to solve the problem in the generator and re-start the system again. The problem in Ceuta electricity grid is more related with the quality of the electricity service provided, rather than the energy security of it. This scenario has a Level 1 in the Energy Security Scale.

The highest value of energy security is obtained in Scenario 4 (renewables, interconnector and power plant) and in Scenario 1 (interconnector and power plant), which have a Level 3 of energy security. A high energy security and high quality of the electricity service provided is assured. If there is a problem in the diesel generator, the interconnector has enough capacity to cover the electric demand and if there is a problem with the interconnector, the diesel power plant would be able to respond and cover the electric load.

The second highest level of energy security is obtained in Scenario 3 (renewables, pump hydro and power plant), which has a Level 2 in the energy security. This scenario has increased the energy security with respect to the current situation by adding renewables and pump hydro installation to store them, but due to its intermittency, it can not be assured that renewable technologies can be used as a back up in case of an electricity black-out, so there would not be an increase in the quality of the electricity service provided.

The Scenario 2 (only interconnector) has, by far, the weakest energy security of all the scenarios analysed. This system has only one-way to supply electricity and no back-up systems. There is no local electricity generation in Ceuta, where all the electricity comes from an electricity interconnector which connects with the Spanish Peninsular Electricity System, with all the risks that this situation could imply. If there is a problem with the interconnector cable, and no electricity can be supplied through it, the whole system will suffer a black-out that will last until the problem is fixed. Normally, if there is a problem with the interconnector cable and needs to be repaired, it could take even several months to do so, having disastrous consequences for the city of Ceuta, which would need to find other sources for providing electricity during that period (having in mind that is an isolated territory that belongs to Spain but is in the African continent). The power plant has not been maintained to act in case a problem of this magnitude happens, so the whole energy security of the system will be compromised if the interconnector fails. It will be assigned to this scenario the Level 0, the minimum level of in the Energy Security Scale.

Therefore, according to the energy security, Scenarios 4 and 1 have the highest level, assuring the energy security and the quality of the electricity service provided. The next one would be Scenario 3, which increases the level of security compared to the current situation but can not assure a higher level of quality in the electricity service provided. The following one would be The Scenario 0, which has a reasonable energy of security but a poor quality of the electricity service provided. The lowest level of energy security of all the scenarios analysed takes part in the Scenario 2, where the whole energy security is compromised if there is a problem with the electricity interconnector which supplies the electricity.

5.6.5 Overall assessment of the scenarios

Once it has it has been ranked the different scenarios inside each of the three main criteria used for the evaluation (electricity cots, carbon footprint and energy security), is the moment to implement the multicriteria decision analysis methodology to find the best solution for the electricity provision in Ceuta.

The best solution for the electricity provision in Ceuta will be the one which has the best balance for the three different criterions used for the evaluation, with the aim of building a robust system which provides an overall improvement over the current Ceuta´s electricity system.

The results of the different scenarios for each criterion evaluated can be seen in Figure 39, where in the vertical axis is represented the net present cost of the project and in the horizontal axes the carbon dioxide emissions and the level of security of the system.

The optimum system would be the one which has a higher level of energy security, minimizing the electricity costs and the carbon dioxide emissions at the same time.

The Scenario 2 (only interconnector) provides the lowest net present cost and the highest CO_2 emission reduction, but its energy security level is minimum. This scenario has not been selected as the best option due to its results unbalance in the criteria used for the evaluation. It is too risky to invest in a system which can reduce the CO_2 emissions and is cheaper if the energy security of the whole electricity system would be compromised.

The Scenario 3 (renewables, pump hydro and power plant) provides almost no reduction in the net present cost of the system, increases the level of energy security of the existing system but not enough to assure a high quality of the electricity service provided and, even though there is a 30 % decrease in the CO_2 emissions, this is the lower decrease of all scenarios analysed. This scenario offers an overall improvement with respect the current situation, but very limited, so it will not be chosen as the best solution possible, but it would partially improve the current situation for the electricity generation in Ceuta.

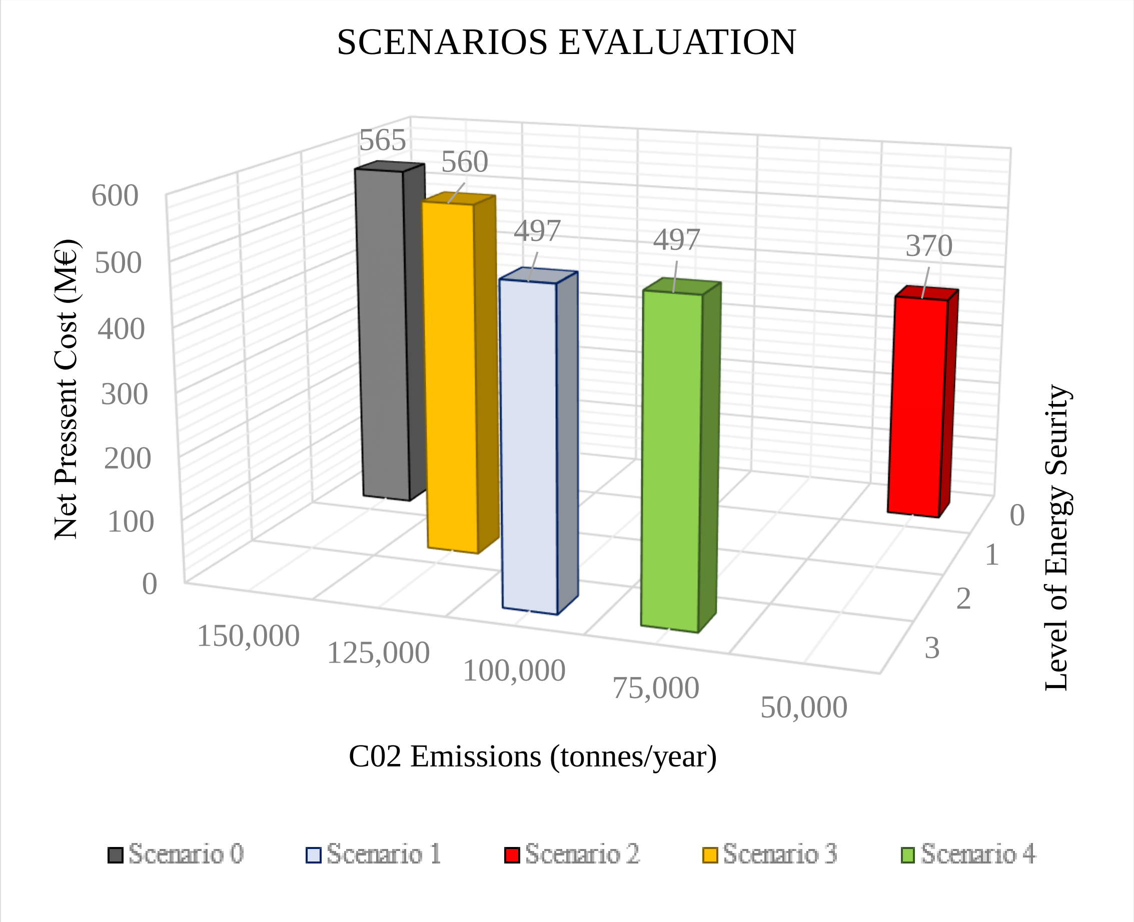


Figure 39. Scenarios evaluation using the multiple criteria decision analysis

The Scenario 1 (interconnector and power plant) and the Scenario 4 (renewables, interconnector and power plant) provides a solution which substantially improves the whole electricity generation system. Both scenarios are ranked in the second-best position relative to electricity costs for its 68 Million Euros reduction relative to the net present cost of the project with respect to the current situation. Furthermore, both of them have the highest level of energy security, where it can be assured not only the energy security but also the quality of the electricity service provided. To select the best solution from this two systems it was needed to go into the carbon dioxide emitted by each scenario. The Scenario 1 provides a reduction which is ranked as the third-best option for its 40 % reduction of carbon dioxide emissions while the Scenario 4 was ranked as the second-best option for its 51 % reduction with respect the current situation. The main difference between these two scenarios is that in Scenario 4, less energy is purchased from the grid due to the contribution of renewables in the electricity generation, so it is saved the amount of carbon dioxide that would be emitted in the Spanish Electricity System while it is produced the electricity that is supplied through the interconnector.

Therefore, the Scenario 4 provides the best solution for the electricity provision in Ceuta, due to its 68 Million € reduction in the net present cost, the highest level of energy security which can assure the energy security and the quality of the electricity service provided and its 51 % carbon dioxide emissions reduction with respect the scenario which represents the current situation.

5.6.6 Optimal solution summary

- Energy Capacity Installed

The scenario 4 is composed by 5 MW of solar rooftop photovoltaics, 25 MW of wind power delivered by 12 onshore wind turbines, a 97 MW diesel power plant and an electricity interconnector, whose maximum capacity would be from 40 to 100 MW but its normal operative capacity would be lower.

- System Operation

The interconnector would have an operative capacity that would vary from 0 to 25 MW in relation with the electricity demand that needs to cover. The system would have also a stable load of 5 MW covered by the diesel power plant, which will operate at minimum values with the objective to maintain operative its full current capacity to be prepared to cover the whole electricity demand in case it is necessary. The integration of renewables (wind and solar) in the electricity generation. would reduce the electricity purchased from the grid through the interconnector, would reduce the number of times that the diesel generator does not operate at its stable load and would permit to sell the exceed of renewables to the Spanish Electricity market through the interconnector.

- Electricity Costs, Carbon footprint and Energy Security

Relative to the electricity cost, its net present cost is 497 Million € and it has a levelized cost of electricity of 224 €/ MWh. In relation to its carbon footprint, it would produce around 71,000 tonnes of carbon dioxide emissions per year and has a renewable penetration of 29.6 %. With respect to its energy security, the system has two reliable sources for the electricity production, which concedes the system a high energy security.

The methodology followed for the scenario comparison through different criterions, is in line with the literature review (See Section 2.6) which states that when determining the most suitable scenario, it should be considered not only the energy costs, but also the environmental considerations and the security of the electrical supply.

5.7 PATHWAY FOR CEUTA´S FUTURE ELECTRICITY GENERATION

While building the different scenarios for the electricity provision in Ceuta, each of the technologies involved in the electricity generation has been thoroughly analysed. In this section, it will be covered how each one of these technologies could contribute to the future electricity generation in Ceuta, providing some guidance about the optimal capacity and the proper time to install these technology in the system. Furthermore, it will be covered how the scenarios proposed can be used as a route for the evolution of the electricity generation system, providing at the end of this section a recommendation on the timeline to install the different technologies described.

The optimal solution for the electricity provision in Ceuta combines an electricity interconector, the diesel power plant, wind and solar power, so all of them will be covered.

5.7.1 Interconnector

The installation of the electricity interconnector proved to be an excellent solution for electricity provision of Ceuta, as long as it is combined with the diesel power plant. Its highest value of performance is reached when the interconnector and the diesel power plant are combined with the integration of renewable technologies (especially wind) in the electricity system.

Relative to the capacity of the interconnector, all the scenarios have been modelled with a maximum operative interconnector capacity of 25 MW and important reductions in the electricity costs and carbon dioxide emissions have been obtained.

The interconnector itself, has not been studied in detail enough to provide a recommendation relative to its optimum capacity necessary to be installed. Despite this limitation, it is worthy to be mentioned that an interconnector capacity of 40 MW could cover the maximum peak demand of the system 35 MW and still being able to cope with future increases in the electrical demand, apart from being able to receive the maximum load from the onshore wind potential in the area, which has been estimated to be 25 MW. In the case of deciding to build an offshore wind farm in Ceuta´s water in the future, depending on the scale of the project, an interconnector of 40 MW could be a limitation for the total installed capacity, having the possibility of building an electricity interconnector of up to 100 MW capacity for developing the installation of offshore wind power in the area

5.7.2 Diesel Power Plant

The electricity generated with the diesel power plant has the higher electricity cost of all technologies which has been analysed. Their levelized costs go from 263 €/MWh for the

Scenario 0 up to 557 €/MWh in the Scenario 4, where the power plant only covers a small portion of the electrical load to maintain its full operative capacity. These results match with the conclusions found in the literature review (See Section 2.6), which demonstrated that levelized cost of the electricity produced with the power plant increases when the generator operates at suboptimal conditions.

When the power plant is the only source of providing the electricity for the city, it is justified that the power plant had a capacity of 2.8 times the peak demand, as it currently happens, and that its operational costs are so high, in part, based on that it never stops working.

With the installation of the electricity interconnector, which would have enough capacity to cover the whole electric load of the system, the power plant would gain more flexibility to produce its power, so it would be the perfect moment to analyse how the cost of the electricity generated by the power plant can be reduced.

While modelling the scenarios where the diesel generator only covers a minimum part of the electric load with the purpose of maintaining its full operative capacity, it was simulated two options: one where the generator covers the fluctuations in the daily electricity demand and the other where the generator covers a stable load of 5 MW of the electricity demand. Probably, in real life operations, the final solution would be a combination of these two cases, having a minimum electrical daily load to maintain the generators working and from time to time, make a test with the diesel power station and its full capacity, to assure that the plant will be ready to cover the full electrical demand in case it is necessary. If it is designed a specific operative plan for the power plant, it could maintain its operative capacity while reducing its operation and maintenance cost and its fuel consumption. This situation would reduce the levelized cost of the electricity produced with the power plant and therefore the levelized costs of the scenarios which uses the power plant with a minimum load. For the optimal solution selected (Scenario 4), the variable costs (operation and maintenance, fuel and replacement costs) accounts for the 60 % of the costs of the diesel power plant, which in turn accounts for the 50 % of the total costs of the system, but the power plant only provides the 20 % of the electricity produced. If, for example, a 2/3 reduction in the variable costs is achieved in the power plant (due to improvements achieved after designing a new operative plan for the plant), while the amount of electricity covered by the plant remains constant, the total levelized cost of the solution would decrease from 224 €/MWh to 178 €/MWh for the electricity produced, very similar to the 173 €/MWh proposed by the Scenario 2 (only interconnector), which was the scenario with the lowest levelized costs. This cost reduction will only be known once the new operative plan for the power plant is designed and put in practice, and this is why a new operative plan is recommended.

A detailed analysis of the power plant capacity installed would be needed as well, to determine if the electric load could be covered even if the oldest generators (installed in the eighties) are decommissioned.

5.7.3 Wind Power

- Onshore Wind

Once the interconnector is installed an available to import and export electricity between Ceuta and the Spanish Electricity Market, is the correct time for the wind power to be installed.

In the Scenario 2, all the electricity demand was supplied through the interconnector. Its annualize cost was 36.38 M€, (See Table 28), but if it is only taking into account the cost of purchasing electricity from the grid (eliminating the other costs like the capital cost of building the interconnector or its operation and maintenance costs) the annualize cost would be 12.65 M€. If the electricity was 210 GWh, the levelized cost of purchasing electricity from the grid would be 60 €/ MWh. In the Scenario 4, the annualized cost for the onshore wind power installed was 3 M€ and the total wind production was 56.8 GWh, so the levelized cost of electricity of wind would be 53 €/MWh (See Table 41).

This means that the electricity produced by wind is cheaper than purchasing it from the interconnector, with an average difference of 7 €/MWh. This is why, once the interconnector is installed, it would be beneficial to take full advantage of the maximum onshore wind capacity of Ceuta (as it has been done in the Scenario 4), which is 25 MW, to cover the most part of the electrical demand with wind power and selling to the grid the electricity excess through the interconnector. It is important to notice that the wind power should be installed once the interconnector is fully operative, not only for the economic advantage of selling the electriciy excess but also to avoid creating stability problems that would be created with the excess of electricity produced.

Onshore wind has not only reached the grid parity, but it has improved it, thus, onshore wind power would be the most economical technology to be installed for Ceuta electricity system. These results match with the conclusions found in the literature review (See Section 2.6), which demonstrated that for some energy isolated places, the levelized cost of onshore wind for electricity generation is lower than producing it with fossil fuels.

- Offshore Wind

Due to the current high levelized cost offshore wind technology, it was decided to include only the onshore wind power in the scenario simulation, so the offshore wind does not appear in any of the scenarios. Despite this fact, it is considered interesting to provide some guidance related to this technology.

If the interconnector is finally built, it could be taken advantage of the extra capacity that this installation offers to sell electricity to the grid, but to make it economically feasible, it should be done at the appropriate time.

The current levelized cost of offshore wind projects is 119 €/MWh (140 $/MWh) which is almost the double of the average cost of purchasing electricity from the grid (60€/MWh). The International Renewable Energy Agency [58] estimates that offshore wind costs will decrease, and by 2020 the levelized cost for this technology would be 85 €/MWh. The average price for purchasing electricity in the Spanish Electricity Market has increased a 29 % from the year 2010 [72]. If this trend of increasing the electricity price and reducing the levelized cost of offshore wind is maintained, by 2030 it could be feasible to produce electricity with offshore wind farms at lower prices than purchasing electricity from the Spanish Electricity Market through the interconnector.

The moment when the levelized cost of offshore wind reachs the parity with the average price of purchasing electricity from the grid would be the ideal time to start installing offshore wind turbines in Ceuta seawater to take advantage of extra capacity that the interconnector provides, without being necessary any kind of subsidies by the Spanish Government to install this technology. This recommendation is in line with the literature review (See Section 2.6) which states that coupling the price between the electricity produced by renewables and the electricity market, would make economically feasible to introduce renewables in the electricity generation without being subsidized.

One of the main advantages in both, offshore and onshore wind power, is if there is a problem with the interconnector and its electricity cannot be exported or used in the electricity system, the turbines can be shut down instantaneously, without compromising the energy stability of the electric system. This way of operating is supported with the information covered in the literature review (See Section 2.6) which states that the curtailment option in systems with high wind integration should be used as the last option to be taken, but is more frequent to happen in small isolated systems.

5.7.4 Solar

Analysing the daily hourly demand and the hourly power output of the photovoltaics technology it could be seen that both graphs match perfectly, producing the PV panel its maximum output when it happens the first one of the two peaks in the daily electrical demand in Ceuta (See Figure 34).

The levelized cost of electricity produced by a rooftop photovoltaic panel in Ceuta for the Scenario 4 was 117 €/kWh, while the cost of purchasing electricity from the grid is 60 €/kWh and the levelized cost of generating electricity with the diesel power plant is 263 €/kWh (See Table 22). This means that electricity provided by photovoltaics doubles the cost from the one that is purchased from the grid, but its costs are less than a half of generating it with the diesel power plant.

Electricity produced by the photovoltaics would not be exported because it is available when it is more needed (during peak demand) and the earnings that would be obtained for selling it to the Electricity Market would be lower than its cost. On the one hand, purchasing electricity from the grid is cheaper than generating it with photovoltaics. On the other hand, if the electricity interconnector is not available, generating this electricity with the power plant would double the cost than with photovoltaics.

For the scenario 4, five MW of solar rooftop photovoltaics were proposed to be installed by 2033, which would account for the 3.5 % of the whole electricity produced. The rate of installing photovoltaics to reach 5 MW of power installed by 2033 should be around 1 kW installed per day. By the horizont year, the amount of wind and photovoltaics would be 25 MW and 5 MW respectively, which would give a wind/solar ratio of 83/17 from the total capacity of renewables integrated in the system. This value is in line with the ratio recommended in the literature review (See Section 2.6) of 80/20 for the energy systems with high renewable integration.

If the experience of installing this 5MW of photovoltaic capacity is successful, it could be proposed to install another 8 MW in the system by 2050. It would be reached then a solar capacity of 13 MW, which has been defined as the maximum solar capacity that the electricity system of Ceuta could handle without creating stability problems in the grid when there is not interconnector. This 13 MW would cover around the 10 % of the whole electricity demand, and it would operate independently if the electricity interconnector is working or not, thus, it would increase the energy security of the system.

This recommendation for installing photovoltaics progressively in the system matches with the conclusions found in the literature review (See Section 2.6), which demonstrated that a gradual installation of photovoltaic could reduce the system installation costs due to the decrease of its prices over time.

5.7.5 Scenarios Route

The five scenarios described in this report can contribute to creating a route map about how the electricity generation system in Ceuta could evolve from the current situation to the future planned scenario:

The timeline would be the following:

2018: Scenario 0 → **2025**: Scenario 1 → **2033**: Scenario 4

The Scenario 0 would be used to represent the current situation of Ceuta´s electricity system.

The Scenario 1 would represent the situation where the interconnector has been installed and it operates in combination with the diesel power plant (it will depend on the installation time of the interconnector but could be a reality from 2020 to 2025).

The Scenario 4 would represent the horizon year 2033, the interconnector and the diesel power plant are combined with the integration of renewable technologies for the electricity generation. By this year it would have been reached the maximum available onshore wind installed capacity (25 MW) and it would have been installed some solar rooftop photovoltaics (5 MW) to contribute to the Ceuta´s electricity generation.

The other two scenarios would not be part of the timeline, but can contribute as well in explaining the results that Ceuta´s electricity system would have it is decided to evolve in that direction:

The Scenario 2 would be useful for showing how the electricity system would operate with only the interconnector, reducing substantially all the costs and carbon dioxide emissions, but compromising the whole energy security of the system, providing an unfeasible solution.

The Scenario 3 would be useful for showing the results that the integration of renewable technologies and a pump hydro storage would have in Ceuta´s electricity, and why the improvements achieved with this option are lower than in the scenario which combines the interconnector and diesel power plant.

5.7.6 Recommended Pathway for the electricity provision in Ceuta

Year 2018: All the electricity demand in Ceuta is provided by the diesel power plant (Situation Simulated in the Scenario 0)

Year 2025: The electricity interconnector is installed and operative and works in combination with the diesel power plant (Situation Simulated in Scenario 1)

Once the interconnector is installed and operative:

- Create a new operation and maintenance plan for the diesel power plant to reduce its operational costs and evaluate if part of its electrical capacity could be decommissioned (older generators) without compromising the ability to cover the full electric demand if necessary.

- Beginning of the installation of the onshore wind power until reaching the 25 MW of capacity in 2033.

- Beginning with the installation of rooftop photovoltaics until reaching 5 MW for the year 2033.

Year 2033: The electricity supply in Ceuta is supplied by the diesel power plant, the electricity interconnector, 25 MW of onshore wind and 5 MW of solar. Excess of electricity is sold to the Spanish Electricity Market through the interconnector (Situation Simulated in Scenario 4)

- If the installation of solar rooftop photovoltaics has been successful, continue to the installation until reaching 13 MW of capacity by the year 2050.

- If the levelized cost of offshore wind has reach grid parity, begin the installation of an offshore wind farm with a capacity determined by the maximum electrical capacity that can be exported through the electricity interconnector.

Year 2050: The electricity supply in Ceuta is supplied by the diesel power plant, the electricity interconnector, 13 MW of solar, 25 MW of onshore wind and a certain capacity of offshore wind. Excess of electricity is sold to the Spanish Electricity Market through the interconnector (Future Situation which has not been simulated in any of the scenarios).

6 FINAL REMARKS

6.1 Discussion of the results

- Main outcomes against the aim and objectives

The aim of the project and the three main objectives have been fulfilled. The different solutions available for the electricity provision in Ceuta has been thoroughly analysed and an optimal combination of them was found. The optimal solution achieves a reduction 68 Million Euros with respect the current situation for the horizon year 2033, reducing in more than 50% the carbon dioxide emissions and assuring not only the energy security but also the quality of the electricity service provided in Ceuta. In addition, it was provided a pathway for the future electricity generation in Ceuta, which provides some recommendations on the different technologies and the appropriate timeline to install them.

- Assumptions and Limitations of the work

Despite using a discount rate and an expected inflation rate to represent the evolution of the economy, current prices for the different technologies installed, and for fuel oil and electricity consumed are fixed in the model and does not vary over time. This is one the simplifications made in the model. The current trend is to increase the electricity price and reduce the installation cost of the renewable technologies overtime [58], being more difficult to trace what will happen with the price of the fossil fuel consumed [73]. This tendency would make even more favourable to install renewables in the future Ceuta´s electric system, so its implications are in line with the results obtained.

During the last ten years the generation capacity and the electricity demand have been stable, so the current electrical demand has been established as the electricity demand for the horizon year 2033. This one of the main simplifications in the model, but the decision for this projection was made based in the last ten years of evolution in the demand.

While modelling the scenarios where the diesel generator covers only a minimum part of the electric load to maintain its full operative capacity, two options were simulated, but in real life operations, the solution would be a combination of both. An appropriate plan for the power plant operation would reduce the levelized cost of the electricity produced with it, and therefore the levelized costs of the scenarios which use the power plant with a minimum load, but this reduction in the cost would only be known once the measures designed for the power plant operational plan are implemented.

The maximum potential of solar rooftop photovoltaic and onshore wind potential that can be installed have been quantified, but it would be necessary to carry out an environmental impact analysis about the effects of installing them in Ceuta´s territory.

The results for the wind turbine modelled shows a capacity factor of 23.5 % (See Table 14), while the average capacity factor for the onshore wind turbines installed in Spain in 2016 is 31% [58]. These results show that the wind turbine does not reach the average performance expected, so it would be beneficial to carry out a detailed analysis to choose another model of a wind turbine which could obtain a higher electrical performance for the wind conditions analysed. As the cost of the technology is defined per kW of technology installed, a higher capacity factor for the wind turbine will produce more electricity per kW installed, so it would decrease its levelized costs of the electricity, confirming that is the technology which obtains better results, and supporting the recommendation of installing onshore wind power technologies until is fulfilled its maximum available capacity (25 MW), once the electricity interconnector is installed.

It was not modelled offshore wind turbines due to its current high levelized cost, but its cost is expected to decrease in the future, probably making feasible to install this technology. The model created could be upgraded in the future including this technology, although its purpose would be more related t with exporting electricity to Spain through the interconnector, rather than participating in the electricity provision of Ceuta.

It was defined that 13 MW was the maximum capacity of solar rooftop photovoltaics that could be installed in the system without creating stability problems in the electricity grid if there is neither energy storage nor the interconnector available, being the only renewable technology operating in the system. This value was selected because its renewable fraction is lower than 10 % and the instantaneous renewable penetration (the maximum part of the load that is cover by renewables at one specific moment is lower than 55 %). These results are in line with the values obtained in the literature review, but if Ceuta Council decides to follow the energy policy to install this capacity of photovoltaic in the system, it would be necessary to carry out a more detailed analysis of the electricity grid and the maximum renewable capacity that can be integrated without compromising the system´s stability.

Information relative to CO_2 emissions in the current situation and the reduction achieved by each Scenario is provided, but it was not possible to offer a wider vision on the results relative to other greenhouse gas emissions (like nitrogen oxides or particulates matters) due to the lack of reliable emissions data to be introduced in the model.

6.2 Conclusions

The project aim was finding the optimal combination of the different electricity generation technologies available to improve the current electricity provision for the off-grid autonomous city of Ceuta. The optimal solution was found, and it is composed by the interaction of these technologies in the following way:

- The diesel power plant was found to be the most expensive and most polluting way of producing electricity, but it offers a reasonable level of energy security. The optimal solution needs to minimize the electricity produced by the power plant while maintaining its maximum operational capacity, with the objective to cover the whole electricity demand with the power plant in case it is needed.
- The interconnector, used in combination with the power plant, increases the energy security and assures a high quality of the electricity service provided. It would provide the part of the electric load which is not covered by renewables or the power plant and would offer the possibility of selling the excess of electricity produced by renewables, eliminating the necessity of additional energy storage.
- Installing onshore wind turbines until it is fulfilled the maximum available capacity (25 MW). It is cheaper to produce electricity from onshore wind power than purchasing it from the grid, so onshore wind would be the most economical electricity generation technology that could be installed. This technology needs from the interconnector to export the electricity excess, having the possibility of instantaneously shutting down the wind turbines in case the interconnector is not operative, avoiding the creation of stability problems in the electricity grid.
- The installation of solar rooftop photovoltaics without surpassing the maximum available capacity that the grid can handle without the interconnector (13 MW). A gradual integration of photovoltaics would take advantage of the decrease in its installation price over time, being closer to reach the grid parity prices.
- A future integration of offshore wind power could be feasible, once its levelized costs have reached the grid parity. Its maximum capacity to install would depend on the interconnector capacity, which would export its electricity production.

Following these recommendations, the electricity provision in Ceuta would experience an overall improvement, with a reduction in the electricity generation costs, minimizing the carbon dioxide emissions, and creating a system with high energy security which assures a high quality in the electricity service provided.

6.3 Direction for future investigations

In order to implement some improvements in the solution provided, the direction for future work has been defined in four different fields: solar, wind, maximum renewable capacity in the system and environmental impact assessment.

- Solar

Use of Geographical Information systems to provide not only the available surface to install solar rooftop photovoltaics, but also to see which areas are more suitable for the installation of this technology, having the possibility of prioritising the installation of photovoltaics in the areas of the city where the photovoltaics have a better performance.

- Wind

Create a wind model using an appropriate software for an optimum selection of the type of wind turbines, to provide a more accurate number for the maximum capacity which can be installed and to discover the best places to install them for both, onshore and offshore wind turbines.

- Maximum Renewables Capacity in the System

Conduct a detailed analysis of the electricity grid to evaluate the maximum renewable capacity that can be integrated in the system without compromising the system stability.

- Environmental Impact Assessment

Perform an environmental study related with the impacts that the integration of this technologies (interconnector, solar rooftop photovoltaics and wind turbines) could have in Ceuta´s ecosystem and to detect which are the most suitable areas to install these technologies.

REFERENCES

[1] UNFCCC. *Paris Agreement*, https://ec.europa.eu/clima/policies/international/negotiations/paris_en (2015).

[2] European Commission. Clean Energy for All Europeans, https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans (2016, accessed 12 June 2018).

[3] European Commission. Proposal for a directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources (recast). *Off J Eur Union*; 0382, http://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC_1&format=PDF%0Ahttp://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016PC0767R%2801%29 (2017).

[4] European Commission. *Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency*. Epub ahead of print 2016. DOI: 10.1017/CBO9781107415324.004.

[5] IEA. Spain National Renewable Energy Action Plan 2011-2020, http://www.iea.org/policiesandmeasures/pams/spain/name-24876-en.php?s=dHlwZT1yZSZzdGF0dXM9T2s,&return=PGRpdiBjbGFzcz0ic3ViTWVudSI-PGRpdiBjbGFzcz0iYnJlYWRjcnVtYnMiPjxhIGhyZWY9Ii8iPkludGVybmF0aW9uYWwgRW5lcmd5IEFnZW5jeSZ6d25qOzwvYT4mbmJzcDsmZ3Q7Jm5ic3A7PGEga (2010, accessed 12 June 2018).

[6] IDAE(Instituto para la Diversificación y Ahorro de la Energía). Spain'S National Renewable Energy Action Plan 2011-2020. 2010; 1–163.

[7] Parkanyi T. Trends and projections in Spain 2017.

[8] CNMC. *Informe sobre la propuesta de planificación de la red de transporte de energía eléctrica 2015-2020*. 2015.

[9] Red Eléctrica. *The Spanish Electricity System*. 2017.

[10] Gallardo XF. Acrobacias fronterizas en Ceuta y Melilla. Explorando la gestión de los perímetros terrestres de la unión Europea en el continente Africano. *Doc d'Analisi Geogr* 2008; 129–149.

[11] Escribano G. The geopolitics of renewable and electricity cooperation between Morocco and Spain. *Mediterr Polit* 2018; 9395: 0.

[12] CNMC. *Informe Macro sobre la demanda de energía eléctrica y gas natural, y su cobertura. Horizonte -2013-2017*. 2014.

[13] Endesa. *Central Diesel Ceuta. Declaración Medioambiental 2016*. 2016.

[14] EURES-European Commission. Labour market information - Ciudad Autónoma de Ceuta, https://ec.europa.eu/eures/main.jsp?countryId=ES&acro=lmi&showRegion=true &lang=en&mode=text&regionId=ES0&nuts2Code= &nuts3Code=null&catId=456 (2018, accessed 12 June 2018).

[15] CNMC. *Acuerdo por el que se aprueba el informe sobre reconocimiento de los costes definitivos de las instalaciones de generación en los territories no peninsulares de Endesa S.A correspondientes al ejercicio 2014*. 2014.

[16] Red Eléctrica de España. *The Spanish Electricity System 2016*. 2017.

[17] ENTSOE. *Continental South West Regional Investment Plans 2017*. 2017.

[18] Red Eléctrica. *Interconexión Eléctrica Submarina Península-Ceuta*. 2016.

[19] EC. Photovoltaic Geographical Information System (PVGIS) - European Commission, https://ec.europa.eu/jrc/en/scientific-tool/pvgis (accessed 20 August 2018).

[20] Institute for the Diversification and Saving of Energy (IDAE). Spain Wind Atlas (Atlas Eólico de España), http://www.atlaseolico.idae.es/ (2011, accessed 7 June 2018).

[21] Busuttil A, Krajačić G, Duić N. Energy scenarios for Malta. *Int J Hydrogen Energy* 2008; 33: 4235–4246.

[22] Meschede H, Child M, Breyer C. Assessment of sustainable energy system configuration for a small Canary island in 2030. *Energy Convers Manag* 2018; 165: 363–372.

[23] CNIG. Centro de Descargas del CNIG (IGN), http://centrodedescargas.cnig.es/CentroDescargas/index.jsp (accessed 23 August 2018).

[24] Ministerio de Industria Energía y Turismo. *Estudio Ambiental Estratégico del Plan*

Hidrológico de la demarcación hidrográfica de Ceuta (ciclo 2015-2021) y Plan de Gestión del Riesgo de Inundación. 2014.

[25] Gonzáez Enríquez C. Ceuta and melilla: Clouds over the African Spanish towns. Muslim minorities, Spaniards' fears and Morocco-Spain Mutual dependence. *J North African Stud* 2007; 12: 219–234.

[26] REE. *2ª Interconexion eléctrica España- Marruecos Proyecto REMO*. 2007.

[27] Martín AM, Domínguez J, Amador J. Applying LIDAR datasets and GIS based model to evaluate solar potential over roofs : a review. 2015; 3: 326–343.

[28] Verso A, Martin A, Amador J, et al. GIS-based method to evaluate the photovoltaic potential in the urban environments : The particular case of Miraflores de la Sierra. *Sol Energy* 2015; 117: 236–245.

[29] Brito MC, Gomes N, Santos T, et al. Photovoltaic potential in a Lisbon suburb using LiDAR data. *Sol Energy* 2012; 86: 283–288.

[30] Mathiesen, Brian Vad; David, Andrei; Petersen, Silas; Sperling, Karl; Hansen K, Nielsen, Steffen; Lund, Henrik; Neves J. *The role of Photovoltaics towards 100% Renewable energy systems*, http://vbn.aau.dk/files/266332758/Main_Report_The_role_of_Photovoltaics_towards_100_percent_Renewable_Energy_Systems.pdf (2017).

[31] IDAE. *Análisis del recurso. Atlas eólico de España. Estudio Técnico PER 2011-2020*. 2011. Epub ahead of print 2011. DOI: 10.15713/ins.mmj.3.

[32] Rogeau A, Girard R, Kariniotakis G. A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale. *Appl Energy* 2017; 197: 241–253.

[33] Soha T, Munkácsy B, Harmat Á, et al. GIS-based assessment of the opportunities for small-scale pumped hydro energy storage in middle-mountain areas focusing on artificial landscape features. *Energy* 2017; 141: 1363–1373.

[34] Garcia EA, Nistal YF, Mérida ML, et al. *Prospectiva de Generación Eléctrica en la Ciudad Autónoma de Ceuta 2030*. 2014.

[35] Guerrero-Lemus R, González-Díaz B, Ríos G, et al. Study of the new Spanish legislation applied to an insular system that has achieved grid parity on PV and wind energy. *Renew Sustain Energy Rev* 2015; 49: 426–436.

[36] Ahmad S. Impact of Distributed Generation on the Reliability of Local Distribution System. 8.

[37] Waqfi RR, Nour M. Impact of PV and wind penetration into a distribution network using Etap. *2017 7th Int Conf Model Simulation, Appl Optim ICMSAO 2017*. Epub ahead of print 2017. DOI: 10.1109/ICMSAO.2017.7934892.

[38] Karimi M, Mokhlis H, Naidu K, et al. Photovoltaic penetration issues and impacts in distribution network – A review. *Renew Sustain Energy Rev* 2016; 53: 594–605.

[39] Flynn D, Rather Z, Ardal A, et al. Technical impacts of high penetration levels of wind power on power system stability. 2017; 6: 1–19.

[40] Simoglou CK, Bakirtzis EA, Biskas PN, et al. Optimal operation of insular electricity grids under high RES penetration. *Renew Energy* 2016; 86: 1308–1316.

[41] MINETUR. Informe De Sostenibilidad Ambiental De La Planificación Del Sector Eléctrico 2015-2020. 2020, http://www.minetur.gob.es/energia/planificacion/Planificacionelectricidadygas/desarrollo2015-2020/Informesostenibilidad/ISA_VERSIÓN_WEB_E.pdf (2015).

[42] REE. ESIOS Sistema de Información del Operador del Sistema. Red Eléctrica de España, https://www.esios.ree.es/es/generacion-y-consumo (accessed 29 July 2018).

[43] Rtvce. Un cortocircuito deja sin luz a gran parte de Ceuta | Radio Televisión Ceuta, http://www.rtvce.es/noticias/6446-un-cortocircuito-deja-sin-luz-a-gran-parte-de-ceuta (accessed 29 July 2018).

[44] Pablo Mates. Un apagón deja a buena parte de Ceuta a oscuras durante casi una hora - Administración - Ceuta al Día - diario digital de Ceuta, http://www.ceutaldia.com/articulo/administracion/apagon-deja-buena-parte-ceuta-oscuras-casi-hora/20170116205628155355.html (accessed 29 July 2018).

[45] REE. ESIOS electricidad. Precio medio de la generación en Ceuta, https://www.esios.ree.es/es/analisis/1337?vis=1&start_date=01-01-2016T00%3A00&end_date=31-12-2016T23%3A00&compare_start_date=31-12-2015T00%3A00&groupby=hour&geoids=8803 (accessed 29 July 2018).

[46] REE. ESIOS. Precio medio de la generación en los Sistemas No Peninsulares por subsistema, https://www.esios.ree.es/es/analisis/1337?vis=1&start_date=01-01-2016T00%3A00&end_date=31-12-2016T23%3A00&compare_start_date=31-

12-2015T00%3A00&groupby=hour (accessed 29 July 2018).

[47] Viento G del. El Hierro, 100% Energías Renovables, http://www.goronadelviento.es/index.php?accion=articulo&IdArticulo=167&IdSeccion=89 (accessed 29 July 2018).

[48] Ministerio de Industria Energía y Turismo. Planificación Energética. Plan de Desarrollo de la Red de Transporte de Energía Eléctrica 2015-2020. 2015; 549.

[49] 4C Offshore. Andalucia-Ceuta Interconnector, https://www.4coffshore.com/windfarms/interconnector-andalucia-ceuta-icid122.html (accessed 25 July 2018).

[50] Yushchenko A, de Bono A, Chatenoux B, et al. GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa. *Renew Sustain Energy Rev* 2018; 81: 2088–2103.

[51] Schallenberg-Rodríguez J. Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal. *Renew Sustain Energy Rev* 2013; 20: 219–239.

[52] Sharp. Sharp 250 Watt Solar Panel, https://www.solarelectricsupply.com/sharp-nd-250qcs-solar-panels (accessed 23 August 2018).

[53] Spanish Wind Energy Association. Ceuta Isolation creates barries for renewables integration (Spanish), https://www.aeeolica.org/es/new/ceuta-el-aislamiento-energtico-traba-la-incorporacin-de-las-renovables/ (2010, accessed 7 June 2018).

[54] Labussière O, Nadaï A. *Renewable Energies and European Landscapes*. Epub ahead of print 2015. DOI: 10.1007/978-94-017-9843-3.

[55] Gong C. *IEC International Standard 61400-1*. 2008.

[56] Zhang MH. *IEC Classification of Wind Turbines*. 2015.

[57] Siemens-Gamesa. Onshore SG Windturbine 2.1-122 de Siemens Gamesa, https://www.siemensgamesa.com/es-es/products-and-services/onshore/aerogenerador-sg-2-1-122 (accessed 23 August 2018).

[58] IRENA. *Renewable Power Generation Costs in 2017*. Epub ahead of print 2018. DOI: 10.1007/SpringerReference_7300.

[59] MarineTraffic. Marine Traffic, https://www.marinetraffic.com/ (accessed 20 August 2018).

[60] Connolly D, Lund H, Mathiesen B V., et al. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl Energy* 2010; 87: 1059–1082.

[61] Lyden A, Pepper R, Tuohy PG. A modelling tool selection process for planning of community scale energy systems including storage and demand side management. *Sustain Cities Soc* 2018; 39: 674–688.

[62] HOMERENERGY. Total Net Present Cost, https://www.homerenergy.com/products/pro/docs/3.11/total_net_present_cost.html (accessed 18 August 2018).

[63] Freyman T, Tran T. *Renewable energy discount rate survey results*, http://www.cleanenergypipeline.com/Resources/CE/ResearchReports/renewable-energy-discount-rate-survey-2017.pdf (2018).

[64] TradingEconomics. Spain Inflation Rate. 1955-2018, https://tradingeconomics.com/spain/inflation-cpi (accessed 18 August 2018).

[65] HOMERENERGY. Salvage Value, https://www.homerenergy.com/products/pro/docs/3.11/salvage_value.html (accessed 18 August 2018).

[66] Sanidad MDE, Social T. Boletín oficial del estado. 2009.

[67] Red Eléctrica. *Interconexión Eléctrica Submarina Península Ceuta. Documento Inicial*. 2016.

[68] Renewable I, Agency E. *IRENA Cost and Competitive Indicators: Rooftop solar PV*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Dec/IRENA_Cost_Indicators_PV_2017.pdf (2017).

[69] IRENA. *Solar PV in Africa: Costs and Markets*, https://www.irena.org/DocumentDownloads/Publications/IRENA_Solar_PV_Costs_Africa_2016.pdf (2016).

[70] Peake S. *Renewable Energy: Power for a Sustainable Future*. 2018.

[71] Canales FA, Beluco A. Modeling pumped hydro storage with the micropower optimization model (HOMER). *J Renew Sustain Energy* 2014; 6: 043131.

[72] OMIE. Daily market average price of electricity,

http://www.omie.es/reports/index.php?report_id=411 (accessed 16 August 2018).

[73] Blazquez J, Martin-Moreno JM, Perez R, et al. Fossil Fuel Price Shocks and CO2 Emissions: The Case of Spain. *Energy J* 2017; 38: 161–177.

APPENDIX

- Solar rooftop photovoltaic chosen

250 WATT

ND-250QCS

Module output cables: 12 AWG PV Wire (per UL Subject 4703)

ELECTRICAL CHARACTERISTICS	
Maximum Power (Pmax)*	250 W
Tolerance of Pmax	+5%/-0%
PTC Rating	223.6 W
Type of Cell	Polycrystalline silicon
Cell Configuration	60 in series
Open Circuit Voltage (Voc)	38.3 V
Maximum Power Voltage (Vpm)	29.8 V
Short Circuit Current (Isc)	8.90 A
Maximum Power Current (Ipm)	8.40 A
Module Efficiency (%)	15.3%
Maximum System (DC) Voltage	600 V (UL)/1000V (IEC)
Series Fuse Rating	15 A
NOCT	47.5°C
Temperature Coefficient (Pmax)	-0.485%/°C
Temperature Coefficient (Voc)	-0.36%/°C
Temperature Coefficient (Isc)	0.053%/°C

*Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (ASTM E892 global spectral irradiance) at a cell temperature of 25°C.

MECHANICAL CHARACTERISTICS	
Dimensions (A x B x C to the right)	39.1" x 64.6" x 1.8"/994 x 1640 x 46 mm
Cable Length (G)	43.3"/1100 mm
Output Interconnect Cable	12 AWG with *SMK Locking Connector
Hail Impact Resistance	1" (25 mm) at 52 mph (23 m/s)
Weight	41.9 lbs / 19.0 kg
Max Load	50 psf (2400 Pascals)
Operating Temperature (cell)	-40 to 194°F / -40 to 90°C

*Intertek recognized for mating with MC-4 connectors (part numbers PV-KST4; PV-KBT4)

CERTIFICATIONS

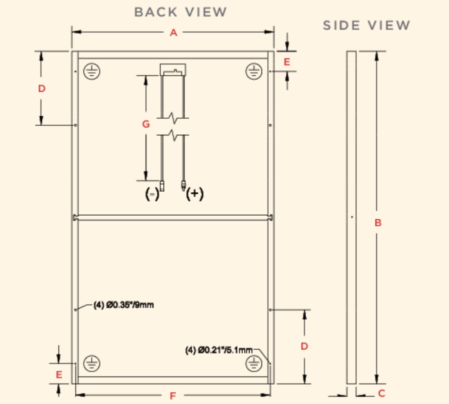
UL 1703, ULC/ORD-C1703, IEC 61215, IEC 61730, CEC, FSEC

WARRANTY

25-year limited warranty on power output
Contact Sharp for complete warranty information

Design and specifications are subject to change without notice.
Sharp is a registered trademark of Sharp Corporation. All other trademarks are property of their respective owners. Cover photo: Solar installation by Pacific Power Management, Auburn CA.

DIMENSIONS



A	B	C	D	E
39.1"/994 mm	64.6"/1640 mm	1.8"/46 mm	14.4"/365 mm	3.9"/100 mm

F	G
37.7"/958 mm	43.3"/1100 mm

Contact Sharp for tolerance specifications

ISO QUALITY & ENVIRONMENTAL MANAGEMENT

Sharp solar modules are manufactured in ISO 9001:2000 AND ISO 14001:2004 certified facilities.

"BUY AMERICAN"

Sharp solar modules are manufactured in the United States and Japan, and qualify as "American" goods under the "Buy American" clause of the American Recovery and Reinvestment Act (ARRA).

SHARP

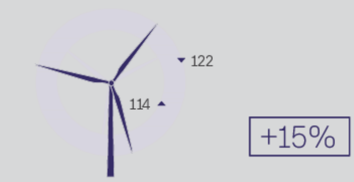
SHARP ELECTRONICS CORPORATION
5700 NW Pacific Rim Boulevard, Camas, WA 98607
1-800-SOLAR-06 • Email: sharpsolar@sharpusa.com
www.sharpusa.com/solar

© 2012 Sharp Electronics Corporation. All rights reserved. Printed in U.S.A. on recycled paper. 12F-111*PC 08-12

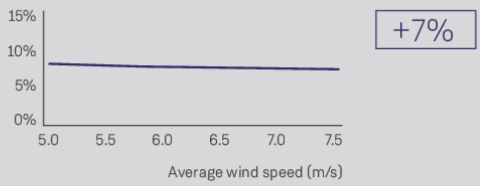
Figure 40. Solar rooftop photovoltaic panel selected for the project

- Onshore wind turbine selected

Swept area increase



AEP increase SG 2.1-122 vs. SG 2.1-114



One of the greatest capacity factors in low-wind sites

The SG 2.1-122 wind turbine is one of the latest additions to the Siemens Gamesa 2.X product platform, a benchmark in the wind power sector thanks to its excellent capacity factor and high profitability. Specifically optimized for low-wind low-turbulence conditions, this model seeks competitive positioning in markets with locations of this type, such as China and India.

Boasting a 122-meter rotor combined with a 2.1 MW generator, this new turbine will address our customers' needs at Class S sites thanks to its extremely low power density and reduced Levelized Cost of Energy.

Proven Siemens Gamesa technology

The knowledge acquired through our latest products, specifically in the optimization of design, prototyping, validation and industrialization processes, has been a key factor in the development of the SG 2.1-122 wind turbine.

SG 2.1-122 has a 60-meter blade. This is a new development from the 56-meter variant extensively validated in Siemens Gamesa projects involving wind turbines with a 114-meter rotor, through which we have achieved maximum production combined with reduced noise emission levels. In addition, the electrical system that it incorporates is also common to all other solutions with 2.1 MW of nominal power.

Versatility and extensive experience

With a 7% increase in energy production compared to the SG 2.1-114 model, the SG 2.1-122 turbine completes the Siemens Gamesa range in the 2 to 3 MW segment for low-wind sites.

Endorsed by its reliability, with an average fleet availability greater than 98%, and by its extensive experience, Siemens Gamesa 2.X stands out for its versatility and maximum performance at all locations and in all wind conditions. Its range of rotors and tower heights (63-153 meters) combined with different environmental options creates an excellent proposal for harvesting maximum energy from the wind with the greatest efficiency.

Technical specifications

General details	
Rated power	2.1 MW
Wind class	IEC III/S
Control	Pitch and variable speed
Standard operating temperature	Range from -20ºC to 40ºC (1)
Rotor	
Diameter	122 m
Swept area	11,690 m^2
Rotational speed	13.07 rpm
Power density	179.64 W/m^2
Blades	
Length	60 m
Airfoils	Siemens Gamesa
Material	Fiberglass reinforced with epoxy or polyester resin
Tower	
Type	Multiple technologies available
Height	108, 127 m and site-specific
Gearbox	
Type	3 stages
Ratio	1:128.5 (50 Hz)
Generator	
Type	Doubly-fed induction machine
Voltage	690 V AC
Frequency	50 Hz/60 Hz
Protection class	IP 54
Power factor	0.95 CAP-0.95 IND throughout the power range (2)

(1) Different versions and optional kits are available to adapt machinery to high or low temperatures and saline or dusty environments.
(2) Power factor at generator output terminals, on low voltage side before transformer input terminals.

Figure 41. Onshore wind turbine selected for the project