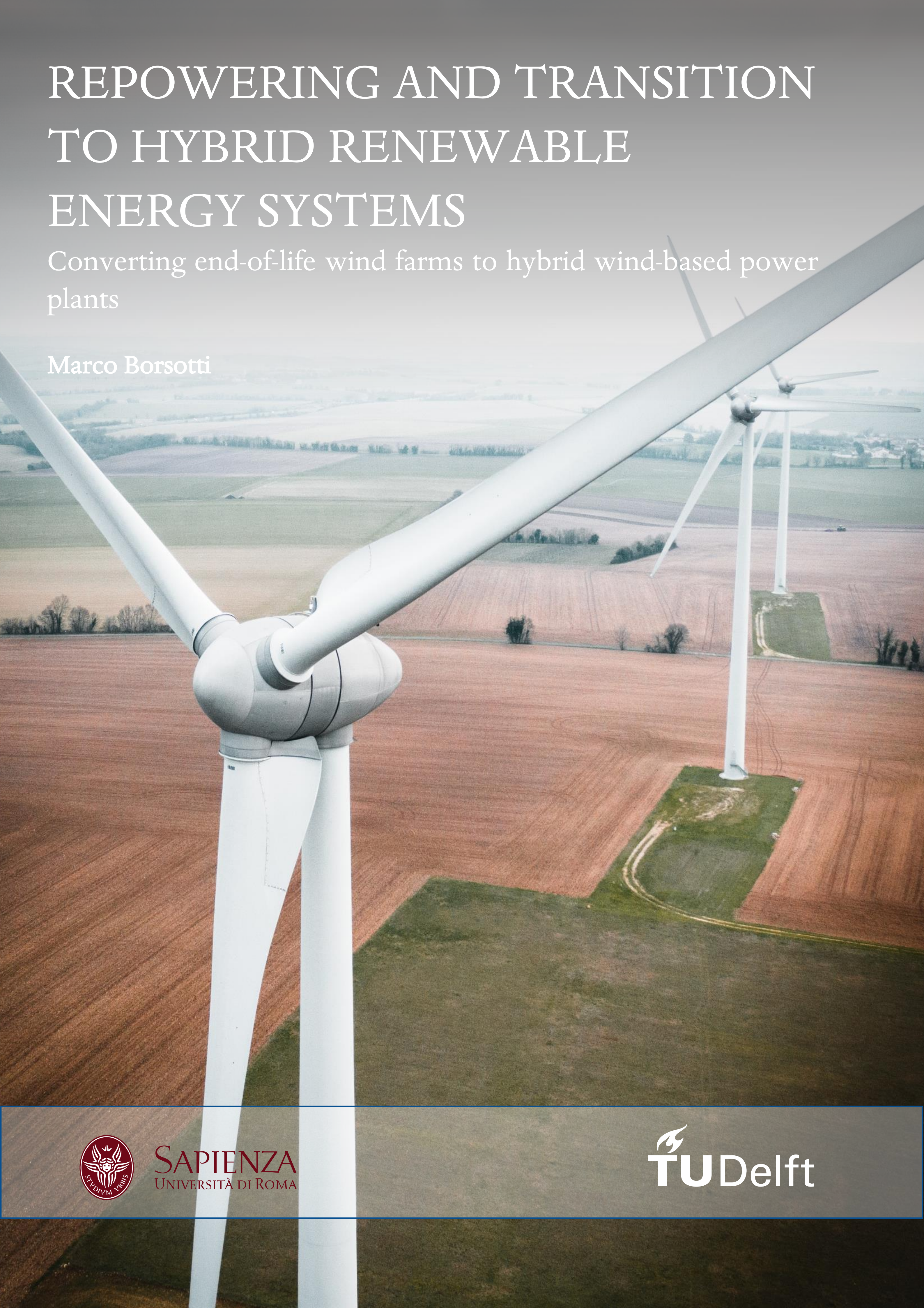
REPOWERING AND TRANSITION TO HYBRID RENEWABLE ENERGY SYSTEMS

Converting end-of-life wind farms to hybrid wind-based power plants

Marco Borsotti



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Facoltà di Ingegneria Civile e Industriale

Corso di laurea in Ingegneria Meccanica

Laureando:
Marco Borsotti

Relatore:
Prof. Alessandro Corsini

Relatore Esterno:
Prof. Dr. Dominic von Terzi
Dr. Ir. Michiel B. Zaayer
Ir. Mihir Mehta

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By

Marco Borsotti

Erasmus Exchange Program at TU Delft - Master of Science

in Mechanical Engineering

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Thesis Committee:	Prof. dr. D. von Terzi Dr. ir. M. B. Zaayer Ir. Mihir Mehta

Plus quam profligavimus restat, sed magna pars est profectus velle proficere.

- Lucius Anneus Seneca

There remains much more of the road than what we have put behind us, but the greater part of progress is the desire to progress.

Acknowledgements

I would like to thank…

… Prof. **Dominic von Terzi**, Prof. **Michiel Zaayer** and Ir. **Mihir Mehta,**
I am deeply grateful I had You mentoring me through this project, I have learnt so much from You.
No one in the same way, You all left me with something more than what I had started with.

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… My **Family**, **Mamma**, **Papà**, **Nonna** e **Luca,**
For the love and support You gave me, You made me curious and willing, You taught me kindness and resolution.
I know how many sacrifices You all made for me to be where I am now.
You rejoiced when I was happy and suffered with me the few times I was not; my successes will be Your successes.
I love You.

… My **Friends,**
To the people I said goodbye to when I left for the Netherlands, I missed You.
To the friends I found in Delft, we shared so much, I have been incredibly lucky to meet You all, I miss You now.

Preface

This work is the result of my five months exchange program at TU Delft.

Today's society finds itself on the verge of a radical and profound change in the way we manage the generation and distribution of energy; the traditional exploitation model of resources has helped us getting to the level of wealth and innovation that we enjoy today in ways we mostly give for granted but has also created a number of challenges that will seriously endanger our life on this planet and the environment we rely on to survive.
The technological progress must lead the way to cleaner, more efficient processes.
That does not only include energy generation but all the fields of production and consumption of goods and services.
Every effort to this mean leaves a footprint on the path.

Marco Borsotti
Delft, 2020

Abstract (English)

It is estimated that a significant portion of the EU wind fleet will reach the end of its lifetime between 2020 and 2030. A common response to this is Repowering, intended as the substitution of the old turbines with new ones. Adding storage and solar panels might provide benefits, but it is insufficiently known how much and under which circumstances. The goal of this study is to assess whether the complementarity of solar and wind resources, with the help of storage, could increase the profitability and the reliability of the system.

A case-study was carried out for the 21 MW wind power plant of Llanos de Juan Grande on Gran Canaria, a remote island on the Moroccan coast with strong interests in energetic independence, a stable political environment, and an accepting community with financial support for such projects. A program was written to determine the optimal wind turbine design and the best energy mix to be installed on the site, taking into account revenue and demand based objective functions. Similar results were obtained by repeating simulations with the commercial tool HOMER PRO.
Two scenarios were studied:
SCENARIO I: Maximizing the Internal Rate of Return (IRR) limiting the land use and the installed power based on the grid capacity.
SCENARIO II: Minimizing the Loss of Load Probability (LOLP) in order to produce a substantial part of the island energy demand, with a positive IRR being the only constraint.

The optimizations showed that the feasibility and potential of hybrid resources, for the site considered, vary according to the purpose of their installation. When the optimization was revenue driven, it became more profitable to only exploit the most economical resource (wind) rather than a combination. As the island applies a two-tariff system for electricity, the results contained also a small amount of storage capacity to increase income through arbitrage. When the final goal of the optimization was to better fit the demand curve, the use of a hybrid energy system showed the lowest LOLP with a positive IRR. In this case the small amount of storage played a different role, i.e. fulfilling the demand when neither wind nor solar were sufficiently available. To identify the drivers more clearly, an optimization was performed for scenario II minimizing the initial cost for various required levels of LOLP. Lower LOLP values called for a higher share of solar in the energy mix.

In conclusion, for a plant level revenue-driven optimization, considering only the energy market, there was only a marginal benefit for a hybrid plant. On the other hand, the complementarity of wind and solar was exploited when the optimization objective was the economical matching of the demand. In light of this difference in outcome, it is worthwhile to revisit the plant level revenue-driven optimization taking into account additional benefits of co-locating wind and solar, e.g. efficient land usage, shared infrastructure, additional revenue streams, etc.

Abstract (Italiano)

Si stima che una porzione significativa di parchi eolici dell'Unione Europea raggiungerà la fine del proprio ciclo-vita tra il 2020 e il 2030. In risposta a questo problema una possibilità consiste nell'effettuare azioni di Repowering, ovvero sostituire le vecchie turbine con nuove, generalmente più grandi ed efficienti. Esiste l'opportunità di ottenere ulteriori vantaggi con l'aggiunta contestuale di accumulatori energetici e pannelli solari ma non è ancora sufficientemente noto in che misura e in quali circostanze. L'obiettivo di questo studio è dunque di valutare se sia possibile aumentare la redditività e l'affidabilità del sistema ripotenziato sfruttando la complementarità delle risorse solare ed eolica, con l'ausilio di una certa capacità di stoccaggio.

È stato condotto un caso studio per l'impianto eolico da 21 MW di Llanos de Juan Grande a Gran Canaria, un'isola spagnola a circa 100 km dalla costa Ovest del Marocco caratterizzata da un profilo sociopolitico stabile e dalla presenza di finanziamenti significativi per progetti che promuovono l'indipendenza energetica dalla terraferma. È stato quindi elaborato un algoritmo di ottimizzazione per determinare il design dei nuovi aerogeneratori da collocare e il miglior mix energetico da installare sul sito, tenendo conto di funzioni oggetto basate su principi diversi, legati ai ricavi e/o alla richiesta energetica dell'isola.
Sono stati analizzati due scenari distinti con obiettivi diversi:
Nel primo caso si è cercato di massimizzare il tasso di rendimento interno (IRR) limitando l'occupazione del suolo e la potenza installata in base alla capacità della rete.
Nel secondo, l'obiettivo è stato di minimizzare la probabilità di perdite di carico (LOLP) al fine di produrre una parte sostanziale della domanda energetica dell'isola, come unico vincolo mantenendo un IRR positivo.

I risultati delle ottimizzazioni eseguite hanno evidenziato che la fattibilità e le potenzialità dell'utilizzo di risorse ibride, per il sito considerato, variano a seconda dello scopo della loro installazione. Quando l'ottimizzazione è stata effettuata nell'ottica di massimizzare i ricavi, è risultato più redditizio sfruttare solo la risorsa più economica (eolico) piuttosto che una combinazione di tecnologie diverse. Poiché l'isola applica un sistema a doppia tariffa per l'elettricità, viene mostrato anche che una certa capacità di stoccaggio permette di aumentare le entrate grazie all'arbitraggio. Quando l'obiettivo finale dell'ottimizzazione è stato invece quello di adattarsi meglio alla curva di domanda, il valore di LOLP più basso con un IRR positivo si è ottenuto con l'utilizzo di un sistema energetico ibrido. In questo caso la capacità di stoccaggio ha giocato un ruolo diverso, ovvero soddisfare la domanda quando né l'eolico né il solare erano disponibili a sufficienza. Per identificare i fattori in gioco più chiaramente, è stata eseguita un'ulteriore ottimizzazione per il secondo scenario cercando di minimizzare l'investimento iniziale per diversi valori massimi di LOLP imposti. Valori di LOLP inferiori richiedevano una quota maggiore di solare nel mix energetico. Risultati simili sono stati ottenuti ripetendo le simulazioni con il software commerciale HOMER PRO.

In conclusione, quando l'ottimizzazione è basata sui ricavi, per un impianto, i benefici potenziali di una soluzione ibrida sono risultati solo marginali. D'altro canto, la complementarità di eolico e solare viene sfruttata vantaggiosamente quando l'ottimizzazione è orientata all'adattamento alla domanda. Alla luce di questa differenza di risultati, vale la pena rivisitare l'ottimizzazione basata sui ricavi tenendo conto di vantaggi aggiuntivi legati alla collocazione contestuale di eolico e solare, ad es. uso efficiente del suolo, infrastrutture condivise, flussi aggiuntivi di entrate, ecc.

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Nomenclature

Definitions

C_n	Cash flow related to the year n
cp_{max}	Maximum power coefficient
$P_{installed}$	Total installed power [W]
P_{rated}	Rated power [W]
P_{spec}	Specific Power of the turbine [W/m^2]
R_n	Net cash inflow/outflow during a period n
Z_0	Roughness length, a corrective factor used to take into account the effect of the roughness of the surface on wind flow
#PV	Number of solar panels installed
#WT	Number of wind turbines installed
1h / 4h / 8h	Rate at which the battery can be completely charged/discharged
A	Available area
	Disequality matrix used for the optimizer's constraints
Aeq	Equality matrix used for the optimizer's constraints
Batt.Cap	Capacity of the battery [Wh]
Batt.in	Power input in the battery [W]
Batt.lim	Maximum amount of power that the battery can input or output in a hour [W]
Batt.low	Minimum state of charge that the battery can reach
Batt.out	Power output by the battery [W]
Batt.Ref	Reference capacity of the battery, used for its normalization [Wh]
beq	Vector used for the optimizer's constraints
c(x)	Nonlinear inequality constraint
ceq(x)	Nonlinear equality constraint
Charge Limit	Maximum amount of power that the battery can input in a hour [W]

Class I Sites	Location with an annual average wind speed of 10 m/s
Class II Sites	Location with an annual average wind speed of 8.5 m/s
d	Zero-plane displacement and can be approximated as $2/3$ to $3/4$ of the average height of the obstacles
D	Rotor diameter of the wind turbine [m]
D(i)	Energy demand during hour i [W]
Discharge Limit	Maximum amount of power that the battery can output in a hour
h	Height [m]
H(i)	Irradiation data during hour i [kW/m^2]
HH	Hub height [m]
i	Specific hour of the year
lb	Lower boundary, used for the optimizer's constraints
Len	Length [m]
N	Total number of periods in a year
n	Specific period of the year
O&M	Operation and maintainance costs
P(i)	Output power during hour i
PR	Performance ratio
price(i)	Cost of electricity during hour i (for the consumer)
R	Rotor radius
Sell(i)	Power sent to the grid during hour i [W]
SOC	State of charge
speed	Wind speed [m/s]
ub	Upper boundary, used for the optimizer's constraints
η	Efficiency
ν	Wind speed
ρ	Air density

Abbreviations

El	Electronics
ElWorks	Electrical works
HRES	Hybrid renewable energy systems
IRR	Internal rate of return
LCOE	Levelized cost of electricity
LOLP	Loss of load probability
MF	Mainframe
NPV	Net present value
OC	Other components
OECD	Organisation for Economic Co-operation and Development
RES	Renewable energy systems
XDSM	Extended Design System Matrix

Subscripts

NEW	Related to the new plant
OLD	Related to the old plant
PV	Related to solar panels
WT	Related to wind turbines

1 INTRODUCTION

The use of fossil fuels, since the second industrial revolution in the late XIX century, has paved the way for our society to the greatest achievements in the history of humankind. The way this technology has impacted our life is so deep it is virtually impossible to imagine anything we own and use without it. For nearly two hundred years we have harvested these million years old resources and used the energy released by their combustion, but the rate at which these natural compounds are depleted is much faster than the generation of new ones, which generally takes geological eras to form. It is necessary to underline the impact that the exploitation of these resources has had on the environment we live in. One of the main environmental concerns related to the use of fossil fuels is the emission of CO_2 in the atmosphere, their consumption is responsible for nearly 85% of the total CO_2 emissions from human sources, generated by coal (42%), oil (33%), gas (19%) and gas flaring (1%). Every year around 35 billion tonnes of CO_2 are released into the environment and this number is only increasing, as shown in Figure 1.1.

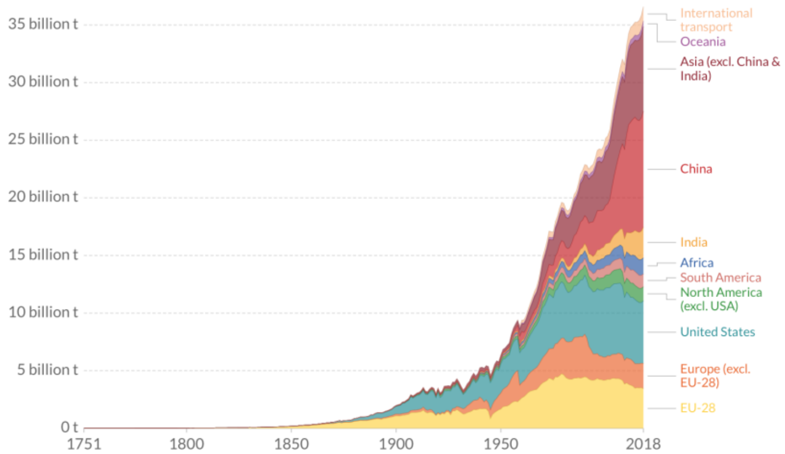


FIGURE 1.1 – CO_2 EMISSION THROUGH THE YEARS DIVIDED BY COUNTRY (1)

Being CO_2 a greenhouse gas, it has the property of absorbing infrared radiation from Earth's surface and reradiating it back, thus contributing to the greenhouse effect and the global increase in temperature (Figure 1.2).

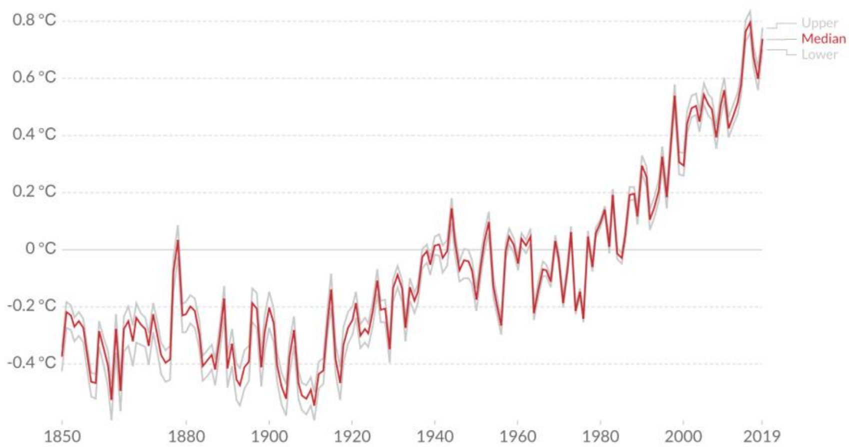


FIGURE 1.2 – GLOBAL INCREASE IN TEMPERATURE SINCE 1850

The Paris Agreement of 2015 (2) is the first-ever universal, legally binding global climate change agreement, it set the key elements to reach climate-neutrality before the end of the century.
The main resolutions are:

- A long-term goal of keeping the increase in global average temperature below 2°C above pre-industrial levels

- To limit the increase to 1.5°C, since this would significantly reduce risks and the impacts of climate change

- Need for global emissions to peak as soon as possible, recognizing that this will take longer for developing countries

- To undertake rapid reductions to achieve a balance between emissions and removals in the second half of the century.

To achieve these goals, we will have to increasingly rely on renewable energy sources that today only account for around 9% of the global energy balance. In Figure 1.3 it is possible to see the evolution of energy sources since 1990.

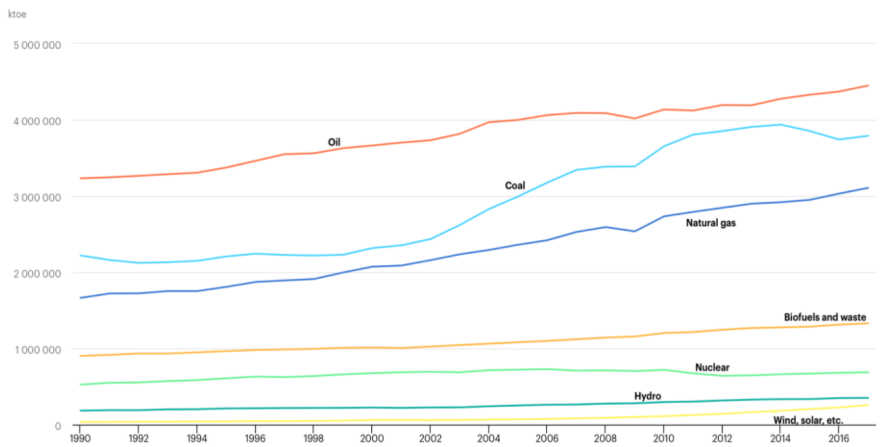


FIGURE 1.3 – EVOLUTION OF THE ENERGY SOURCES SINCE 1990 (3)

Fast deployment of renewables, combined with deep electrification and increased energy efficiency, could take over around 90% of the energy-related carbon dioxide emissions reductions needed by 2050 to meet the Paris climate targets. In this scenario, wind power, along with solar energy, could lead the way for the transformation of the energy sector. The evolution of these two technologies in the past 30 years is shown in Figure 1.4 and Figure 1.5.

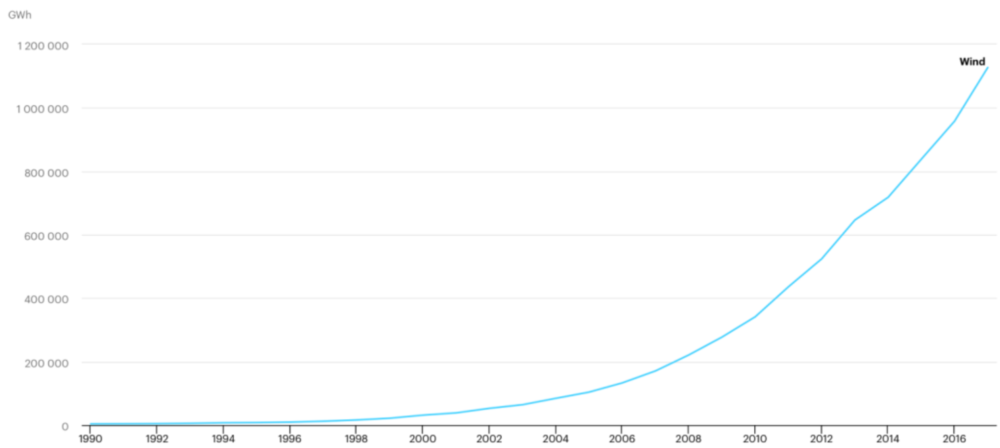


FIGURE 1.4 – EVOLUTION OF WIND POWER SINCE 1990

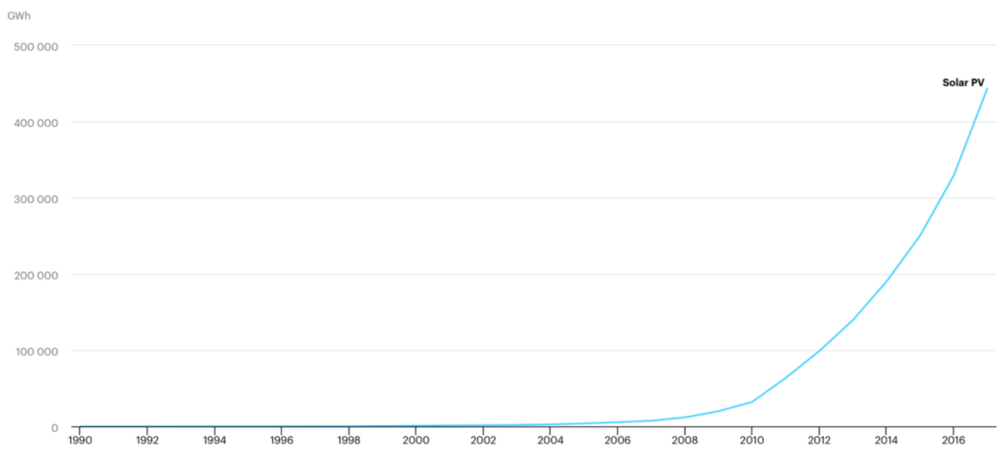


FIGURE 1.5 – EVOLUTION OF SOLAR POWER SINCE 1990

To accelerate this process, it is essential to increase the efficiency of the new technologies deployed. With this in mind, well-planned repowering actions and the use of hybrid resources can be of crucial importance, amongst many other factors and measures, for the scale-up of sustainable energy generation systems.

1.1 Repowering

It is estimated that a significant portion of the EU wind fleet will reach the end of its lifetime between 2020 and 2030, this could hinder the achievement of the EU's objective of 50% share of electricity generated by renewables by 2030.
The re-utilization of already used sites brings with it some potential benefits, from the decrease in installation costs due to the use of existing infrastructures to the convenient presence of data and statistics regarding wind speed and direction. Repowering might be considered crucial to the scale-up of wind power capacity, increasing the efficiency of already existing plants and minimizing at the same time the investment capital needed. Wind farms currently have an estimated lifetime of around 20 to 25 years, the older the turbines get, the higher the maintenance costs are.
Dealing with end-of-life wind plants' assets it is essential to ensure their efficiency, this typically implies either a full repowering, that is the dismantling of a number of wind turbines and the subsequent installation of new ones, generally bigger and with higher capacity; or a revamping i.e. an extension of the plant's lifetime through the upgrading of some of the components of an existing wind turbine.

The benefits of repowering include:

- Cost reduction of wind energy: new technologies and modernization of the turbines, together with stable regulatory frameworks and appropriate market arrangements can drive down the price of O&M wind energy generation and finally contribute to the EU decarbonization objectives with a lower price to society.
- New units, able to provide grid support services can better integrate the variable wind resource into electricity grids contributing to systems' stability and reliability, adding better control possibilities.
- Better utilization of class I and class II sites, this feature is particularly important for small islands where the available space for new plants is limited.
- Use of existing infrastructures (e.g. roads and substations), resulting in lower installation costs.

It is estimated that, by 2027, the yearly repowering volume will grow from 2-3 GW to 5.5-8.5 GW as shown in Figure 1.6.

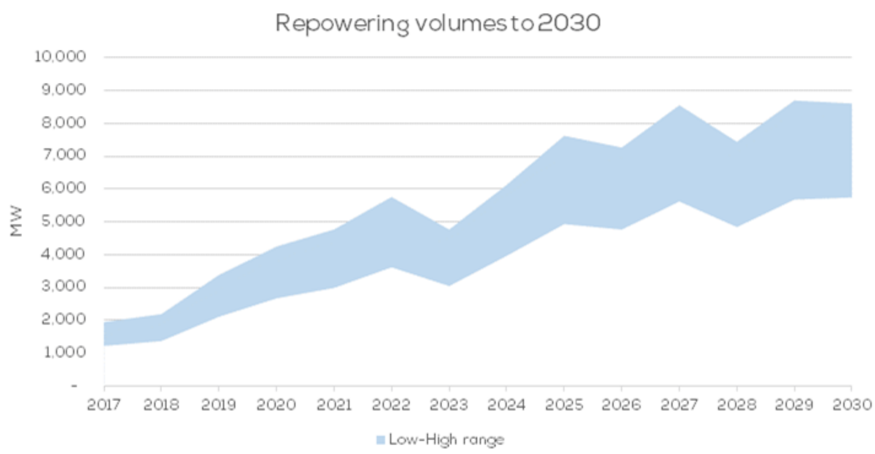


FIGURE 1.6 – REPOWERING VOLUMES 2017-2030 (4)

1.2 Hybrid Renewable Energy Systems

When one considers remote or isolated locations, for which the extension of the continental grid is impossible or economically disadvantageous, particular attention has to be reserved for hybrid systems. The particular circumstances in which small islands find themselves have favored the development of specific action plans which concentrate on Renewable Energy Sources.
Hybrid Renewable Energy Systems consist of two or more renewable energy technologies combined to provide a more efficient and balanced energy supply; where a single renewable resource can be discontinuous and not always reliable, a combination of different ones can guarantee stand-alone generation the ability to meet the energy demand with more precision. In a few words, where the cost of energy becomes prohibitive due to the remoteness of the location, HRES can address emissions, reliability, efficiency and economic limitations of single renewable energy sources (5).
The most common solutions for Hybrid Systems consist of the combination of solar and wind energy, wind and hydro, wind and hydrogen, or even a mix of different kinds of aerogenerators.

1.2.1 Wind and Solar

The natural intermittence of these two resources makes their combination the most popular for Hybrid Systems, where wind appears to be stronger during winter night-time, sun is obviously more consistent during summer days. This intermittence is highlighted in Figure 1.7 where the lines indicate the intensity of these two sources, such intensities are normalized with their maximum value of the year to show and compare wind speed $[m/s]$ and solar irradiance $[kW/m^2]$. It is easy to appreciate that the peaks of the wind speed usually fall around the hours of no solar irradiance (night).

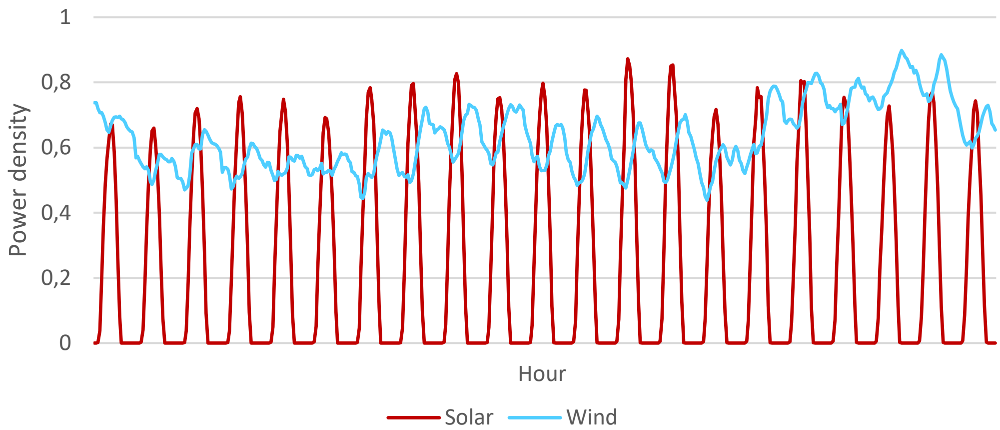


FIGURE 1.7 – SOLAR AND WIND NATURAL INTERMITTENCE

Moreover, both resources' outcomes are easily predictable and follow recognizable patterns, making it easy to plan for times of scarcity. A simplified scheme of the combination of these two technologies is shown in Figure 1.8.

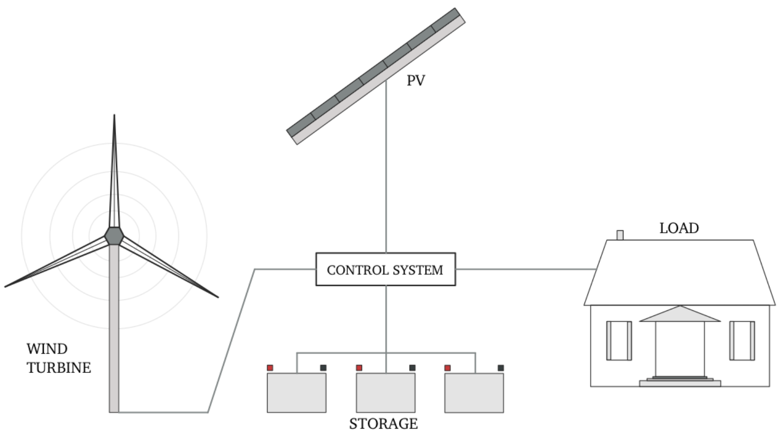


FIGURE 1.8 – WIND AND SOLAR HYBRID SYSTEM

1.2.2 Wind and Hydro

A common solution when the power density of wind has a strong seasonal variability is the utilization of wind turbines and hydroelectric storage systems. A significant example of this combination (Figure 1.9) can be found in

El Hierro Island in the Canaries, this island is said to be the first 100% renewable self-sustainable location in the world (6). Part of the generated power, when the demand is lower than the generation, can be stored into pumped storage water reservoirs at a certain elevation, its potential energy can be used releasing it in a hydropower plant if and when needed.

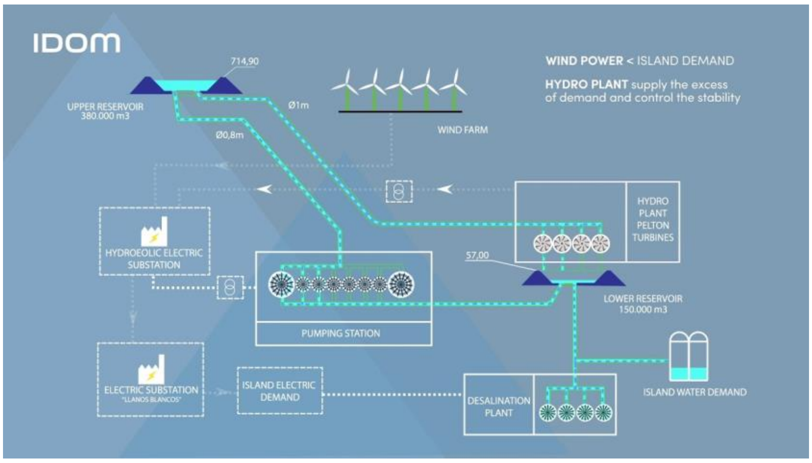


FIGURE 1.9 – EL HIERRO HYBRID WIND-PUMPED HYDRO STORAGE SYSTEM

1.3 Research Questions

The previous paragraphs highlighted the importance of scaling up the renewable quote of energy generation and hinted at the advantages of repowering end-of-life wind power plants and using hybrid systems, especially in the case of remote places or islands.

This study investigates the potential benefits of repowering, not in a conventional way, but by integrating a hybrid system. The idea is to exploit the complementarity of wind and sun to increase the profitability and reliability of the system while taking advantage of the reduced cost for repowered plants. Various factors will be taken into account in this analysis: economical, technical and social drivers will be evaluated and a conclusion will be drawn on its feasibility.

The research will ultimately try to answer the following questions:

- What is the most profitable way to repower a wind farm?
- What are the potential benefits of converting a wind farm into a hybrid wind-based power plant?
- What scenarios are favorable for the installation of hybrid wind/solar systems?

The following chapters will describe how it is intended to answer these questions.

The *methodology* is the backbone of the program written on Matlab for this purpose, is thoroughly explained in the next chapter. The program is later applied to a *case study* carefully chosen to fit the profile needed for this study. The *results* of the different optimizations are finally shown in the last chapter

2 METHODOLOGY

2.1 Optimization Algorithm

Fmincon is a gradient-based non-linear programming solver that allows finding the minimum of a problem, such a problem is specified as follows:

$$\min_{x} f(x) \; such \; that \begin{cases} c(x) \leq \; 0 \\ ceq(x) = 0 \\ A \cdot x < b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

Where b and beq are vectors, A and Aeq are matrices, $c(x)$ and $ceq(x)$ are functions that return vectors, and $f(x)$ is a function that returns a scalar, $f(x)$, $c(x)$, and $ceq(x)$ can be nonlinear functions. All the parameters, as well as the variable x, are normalized with respect to nominal values in order for the optimizer to be more precise. The first cycle starts with the iteration number $k = 0$ and a starting point x_k. Its functioning can be summarized in four steps:

1. **Test for convergence**
   If the conditions for convergence are satisfied, then the optimizer can stop and x_k is the solution

2. **Compute a search direction**
   It computes the vector p_k that defines the direction in n-space along which the optimizer will search

3. **Compute the step length**
   Finds a positive scalar, a_k such that $f(x_k + a_k p_k) < f(x_k)$

4. **Update the design variables**
   The optimizer sets $x_{k+1} = x_k + a_k p_k$, $k = k + 1$ and tries again with $x_{k+1} = x_k + \underbrace{a_k p_k}_{\Delta x_k}$

There are two subproblems in this type of algorithm for each major iteration: computing the search direction p_k and finding the step size (controlled by α_k). The definition of the problem will depend on the final aim of the particular optimization of interest but the principle of operation remains the same (7).

2.2 Problem Formulation

The optimizations aim to find the best energy mix to replace the old turbines, maximizing the benefits, having chosen a specific goal. For the realization of the program, it is necessary to specify the design variables, the constraints and a number of functions and models to be applied.

2.2.1 Design Variables

The variables used are:

x_1	Number of Wind Turbines
x_2	Number of Solar Panels
x_3	Storage Capacity
x_4	Rotor Diameter
x_5	Rated Power
x_6	Hub Height

The first two variables are normalized with respect to the maximum installed power permitted by law in order to increase the optimizer's precision, which means that they in fact represent the percentage of the total installed power given by the specific source. The third one is normalized with a high reference value for the storage capacity chosen arbitrarily. Those values will influence the power output of the two sources and define the optimal mix to be used.

$$x_1 = \frac{\#WT \cdot Prated(WT)}{TOT\ Installed\ Power}$$

$$x_2 = \frac{\#PV \cdot Prated(PV)}{TOT\ Installed\ Power}$$

$$x_3 = \frac{Batt.Cap}{Batt.Ref}$$

Because of how these variables are defined, when the grid constraint has to be respected those are by nature bounded to be between 0 and 1 and their sum cannot exceed 1.

2.2.2 Non-Linear Constraints

Normally there is a number of constraints that limit the freedom of choice while repowering an old wind farm, these constraints vary depending on the current legislation, technical restrictions and the specifics of the existing plant. The non-linear constraints applied depend on what case we are considering, the main ones are related to the land availability or the grid capacity and are implemented as follows:

- Length Constraint

Generally speaking, a certain distance between two turbines must be respected, normally given as a function of the rotor diameter ($f(D) = a \cdot D$ with $a = const$). The following relation must be implemented:

$$f(D) \cdot (\#WT - 2) \leq Len_{MAX}$$

Where Len_{MAX} is the total length available for the rows of turbines, D is the rotor diameter of the aerogenerator chosen and #WT is the number of wind turbines installed without taking into account the four outermost turbines for which it will not be considered the length of influence that technically falls out of the plant's property. In terms of c(x), in order for it to be used for the optimization, it will be written:

$$cLen = -1 + \frac{f(D) \cdot (x(1) - 2)}{Len_{MAX}} \tag{10}$$

- Area Constraint

The land available can be taken into consideration implementing the following relation which, with respect to the length constraint, also uses the area and number of the solar panels (respectively A and $\#PV$):

$$\#WT \cdot D^2 + \#PV \cdot A \leq A_{MAX}$$

Or again, in terms of c(x):

$$cArea = -1 + \frac{\frac{D^2}{2} \cdot (x(1) + 2) + A \cdot x(2)}{A_{MAX}} \tag{11}$$

Area and length constraints are considered *land* constraints and are normalized respectively with the maximum area and length of the plant in order to increase the precision of the optimizer. These relations can be simply varied by multiplying for a constant number on the right-hand side of the equations.

- Grid Constraint

The installed power for a repowered plant is normally limited by law to be equal or lower than a certain function of the existing plant's one, this can be expressed as a percentage of the old plant's installed power (P_{OLD}) and implemented as follows:

$$P_{installed} = \#WT \cdot Prated_{WT} + \#PV \cdot Prated_{PV} \leq f(P_{OLD})$$

In terms of c(x):

$$cPower = -1 + \frac{x(1) \cdot Prated_{WT} + x(2) \cdot Prated_{PV}}{f(P_{OLD})} \tag{12}$$

Where $Prated_{WT}$ and $Prated_{PV}$ are the rated powers respectively of the wind turbines chosen and the solar panels.

2.2.3 NPV – Net Present Value

The NPV is defined as the difference between the present value of cash inflows and the present value of cash outflows over a period of time and can be used to analyze the profitability of a project. The formula to calculate its value is the following:

$$NPV = \sum_{n=1}^{N} \frac{R_n}{(1+i)^n} \tag{13}$$

Where:

R_n	Net cash inflow-outflow during a single period n
I	Discount rate of return that could be earned in alternative investments, set to be 6 %
n	Period taken into consideration
N	Number of periods

This value will be computed through the pvvar function from the Matlab library *Financial Toolbox*, using as inputs the Cash Flow and the rate of return *i*. To have the Cash Flow of the investment it is necessary to compute the yearly revenues, in order to do that the hourly price of energy is multiplied for the output power (sum of the solar panels, wind turbines and eventually the battery discharge):

$$Revenues = \sum_{i=1}^{8760} price(i) \cdot P(i) \tag{14}$$

Being:

$$P(i) = P_{WT}(i) + P_{PV}(i) - Batt.in(i) + Batt.out(i) \tag{15}$$

Operation and maintenance costs are taken into account as a function of the yearly energy yield of the turbines and the solar panels:

$$O\&M_{WT} = -0.005 \left[\frac{€}{kWh}\right] \cdot E\ [kWh] \tag{16}$$

$$O\&M_{PV} = -0.015 \left[\frac{€}{kWh}\right] \cdot E\ [kWh] \tag{17}$$

$$O\&M = O\&M_{WT} + O\&M_{PV} \tag{18}$$

Considering 25 years of life for both the new turbines and the solar panels, the cash flow consists of an initial investment to be computed through the cost models previously described and 25 elements equal to the difference of the revenues and the O&M costs.

2.2.4 IRR – Internal Rate of Return

In order to compute the economic benefits of the eventual repowering, the IRR has been chosen to measure the investment's expected future rate of return. This value is computed as the rate of return that makes the net present value equal to zero (8):

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} = 0 \tag{19}$$

Where:

N	Total number of periods
C_n	Cash flow related to the year n

It is often impossible to find the solution to this equation analytically, for this reason, the *irr* function from the Matlab library *Financial Toolbox* has been used. This function takes as input only the cashflow and it can be used as the objective function for the revenue-based optimizations as well as a constraint for the demand-driven ones. The process is described in Figure 2.1:

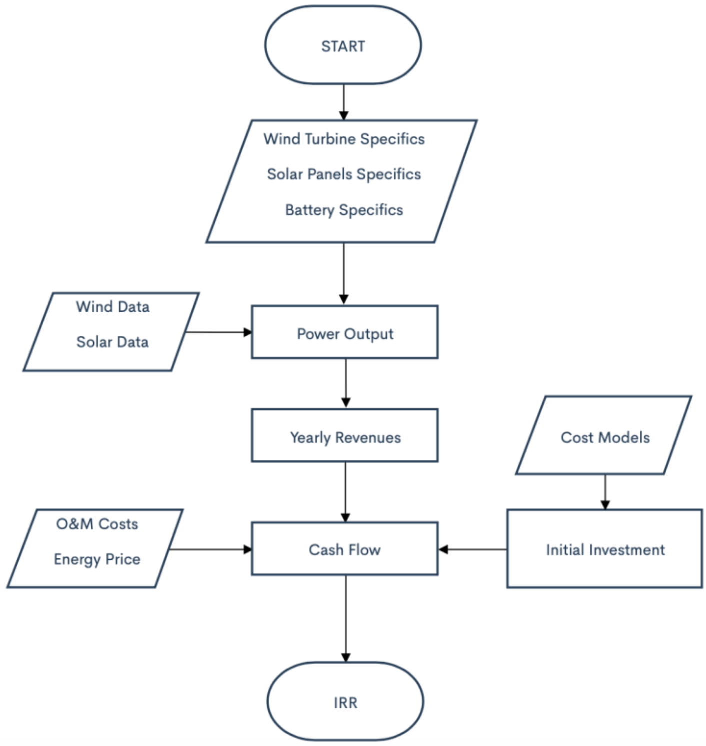


FIGURE 2.1 – FLOWCHART FOR IRR COMPUTATION

2.2.5 LOLP – Loss of Load Probability

The objective function to be implemented in the optimizer depends on the case studied. The function to be maximized/minimized will be either the IRR or the LOLP (*loss of load probability*), the former has already been explained in chapter 2.3.4, the latter is defined as the ratio between the estimated energy deficit and the energy demand over one year and technically quantifies the reliability of the supply (9). The LOLP can be expressed as follows:

$$LOLP = 1 - \frac{Energy\ Produced}{Energy\ Demand} \tag{20}$$

Where:

$$Energy\ Produced = \sum_{i=1}^{8760} P(i) \tag{21}$$

$$Energy\ Demand = \sum_{i=1}^{8760} D(i) \tag{22}$$

Also, this function can be set arbitrarily as the objective function or as a constraint. The flowchart in Figure 2.2 explains the procedure in a schematic way.

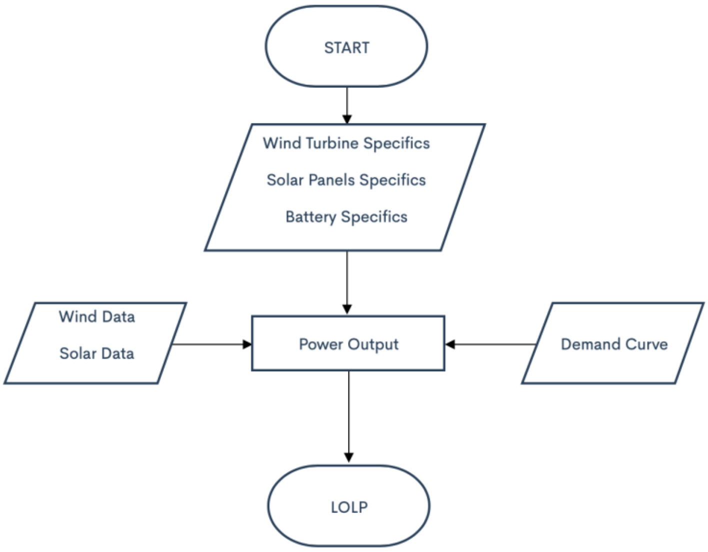


FIGURE 2.2 – FLOWCHART FOR LOLP COMPUTATION

In order to compute the values just described (NPV, IRR and LOLP) it is necessary to define the models used for wind, solar and battery-related computations. These models will have their own set of equations and constraints that maintain their validity in the main optimization.

2.3 Wind Turbine

It will often be necessary to specifically design the wind turbine depending on the objective function and the constraints of the case. The model implemented is described in the following paragraphs.

2.3.1 Design Variables

The design variables used to define the optimal wind turbine are:

$$x_4 = \frac{D_{NEW}}{D_{OLD}} \qquad \text{Diameter}$$

$$x_5 = \frac{Prated_{NEW}}{Prated_{OLD}} \qquad \text{Rated Power}$$

$$x_6 = \frac{HH_{NEW}}{HH_{OLD}} \qquad \text{Hub Height}$$

Every variable is normalized with respect to the correspondent value of the old wind turbines originally used in the plant.

2.3.2 Non-Linear Constraints

The technical constraints implemented regard the dependence between the hub height, radius of the rotor and rated power of the turbine. The relations between these values are empirical and can be expressed as follows:

- Hub Height – Radius

$$R < HH - 30m \tag{2}$$

Or in terms of c(x), in order for it to be used as a parameter for Fmincon:

$$cHR = \frac{{}^{D}/_{2} - HH}{30} + 1 \tag{3}$$

It is obvious that the radius of the rotor cannot be longer than the tower height and generally speaking, is also desirable for the hub to be high enough for the rotor to reach the fully developed wind profile, out of the influence of the obstacles on the ground. For this reason, it was set that the minimum distance between the ground and the tip of the rotor must be higher than 30 m.

- Rated Power – Radius

$$P_{spec} > 190\frac{W}{m^2}$$

$$P_{spec} > 500\frac{W}{m^2}$$

Being:

$$P_{spec} = \frac{Prated}{\pi \cdot R^2} \tag{4}$$

A wind turbine's specific power is the ratio between its rated power and the area swept by its rotor, a lower specific power allows a larger rotor, able to intercept a wider area, therefore a larger portion of the incoming wind. The relations can be expressed in terms of c(x) as:

$$cPS1 = 1 - Prated\left(190 \cdot \left(\pi \cdot \left(\frac{D}{2}\right)^2\right)\right) \tag{5}$$

$$cPS2 = Prated\left(500 \cdot \left(\pi \cdot \left(\frac{D}{2}\right)^2\right)\right) - 1 \tag{6}$$

2.3.3 Upper and Lower Bounds

Upper and lower boundaries have been implemented in the model to limit the values of the variables used by the optimizer. Hub height of the turbine has been bound to be:

$$30\,m \leq D \leq 150\,m$$
$$30\,m \leq HH \leq 120\,m$$

These limitations have been used considering that longer blades may not be allowed to be transported on certain roads and could, anyway, exponentially increase transportation costs.
Looking for an ideally bigger turbine, the rated power can be set to be:

$$Prated_{OLD} \leq Prated_{NEW} \leq 7.500\,kW$$

Where $Prated_{OLD}$ is the rated power of the old wind turbines present on the original plant.

2.3.4 Power Output

The power output of the turbine is computed hour by hour using the wind data imported, cut-in and cut-out wind speeds are set to be respectively 3 m/s and 25 m/s, below the former and above the latter, the power output is zero. The equation used is the following:

$$P_{WT}(i) = 0.5 \cdot \rho \cdot cp_{max} \cdot \eta \cdot v(i)^3 \cdot \pi R^2 \tag{7}$$

Where:

$\rho = 1.225\ [kg/m^3]$	Air density at sea level
$\eta = 0.969$	Efficiency of the drive train
R	Radius of the rotor, it depends on the Diameter which is set as a variable to use for the optimizer
$v(i)$	Wind speed at the corresponding hour
$cp_{max} = 0.48$	Power coefficient and is considered to be fixed in order to compute the nominal wind speed for the turbine unless v_{Rated} is listed in the literature

A power curve for the wind turbines considered can be drawn with the following cycle (Figure 2.3).

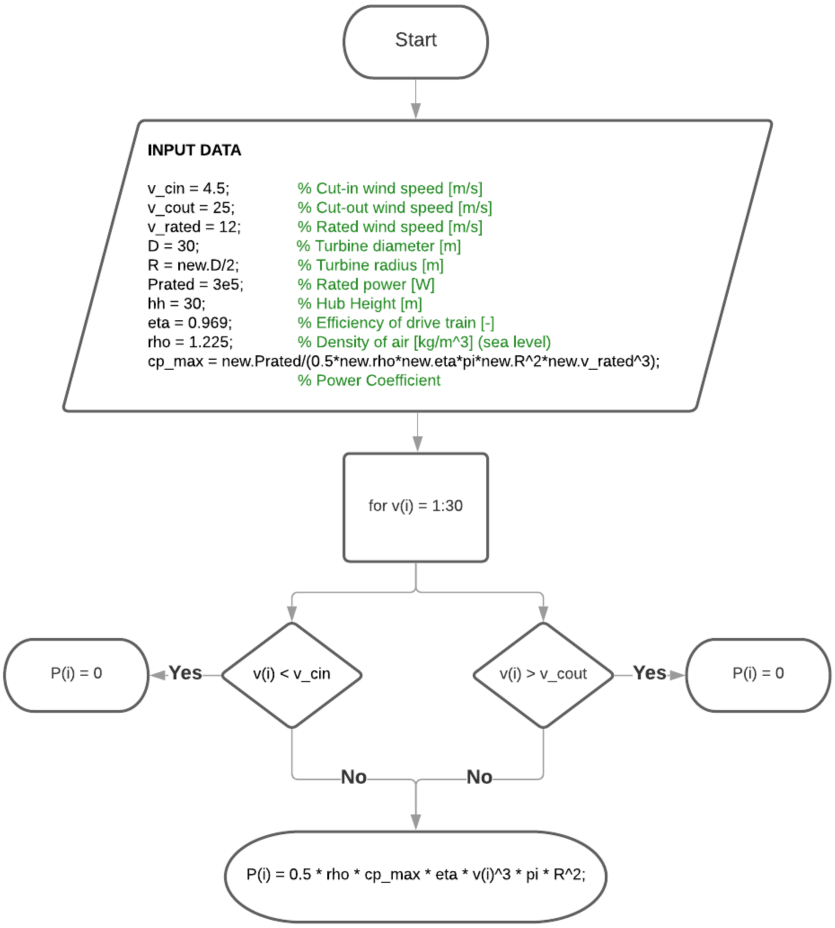


FIGURE 2.3 – FLOWCHART FOR POWER CURVE

2.3.5 Cost Model

The design of wind turbines deeply influences their cost and can be customized to increase productivity and profitability for a specific site. For this reason, it is firs necessary to have a cost model that depends on the design variables used for the optimization, specifically rotor diameter, rated power and hub height. The cost per kW of wind turbines has dramatically decreased over the last decades. The prices have in fact fallen by between 44% and 64% since their peak in 2007–2010, depending on the market considered as shown in Figure 2.4.

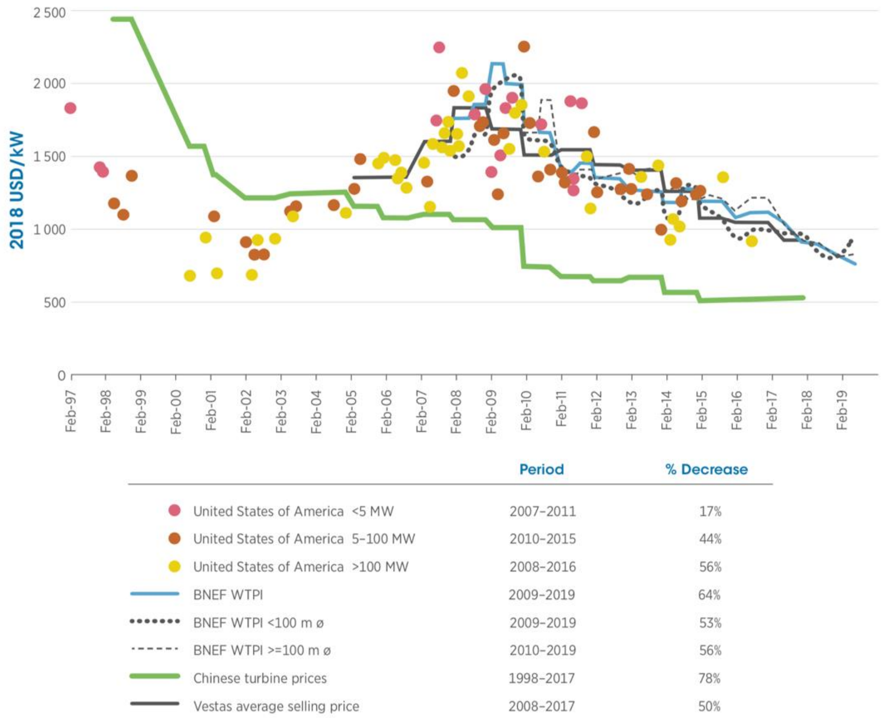


FIGURE 2.4 – INSTALLATION COST OF WIND TURBINES SINCE 1997

The cost model used for this study is based on the empirical analysis from the National Renewable Energy Laboratory (NREL) [Figure 2.5].

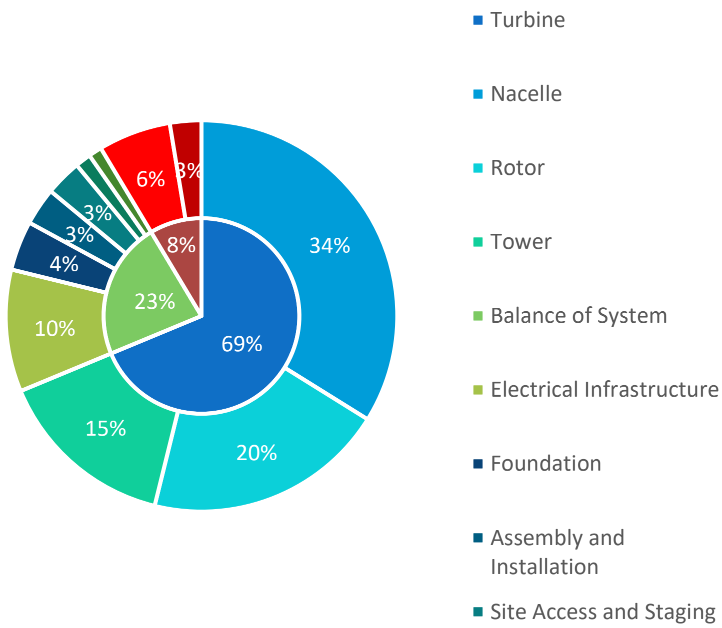


FIGURE 2.5 – CAPEX FOR THE LAND-BASED REFERENCE WIND POWER PLANT PROJECT

These costs can be furtherly divided into Financial costs (8%, in brown), costs directly linked to the turbine (69%, in blue) and costs for the balance of the system (23% in green). The actual cost model has been implemented with the following equations:

- **Tower**

Considering a steel cylindrical hollow structure, its cost can be computed simply by multiplying its weight with the price $\left[\frac{€}{kg}\right]$ of the steel used:

$$Cost_{Tower}(1) = Tower_{Mass} \cdot Cost_{Steel}$$

$$Tower_{Mass} = 0.3907 \cdot A_{rotor} \cdot HH$$

Considering the cost of steel being:

$$Cost_{Steel} = 1{,}26 \frac{€}{kg}$$

- **Rotor**

For a three-blade rotor in plastic material, reinforced with fiberglass, the cost of the blades can be considered 72% of the whole rotor cost.

$$Cost_{Rotor}(2) = \frac{3 \cdot 0.9 \cdot R^{2.85}}{0.72}$$

Where the multiplier 3 stands for the number of blades.

- **Nacelle**

The nacelle is composed of different parts, all with their related cost.

GearBox	$Cost_{Gearbox} = 17 \cdot Prated^{1.17}$
Generator	$Cost_{Generator} = (-4 \cdot 10^{-3} \cdot Prated + 57) \cdot Prated$
Electronic used for speed control	$Cost_{VariableSpeedElectronic} = (-4 \cdot 10^{-3} \cdot Prated + 82) \cdot Prated$
YAW control system	$Cost_{YAW} = (-2 \cdot 10^{-8.5} \cdot (2R)^{2.964} + 0.0678) \cdot (2R)^{2.864}$
Mainframe	$Cost_{MF} = (-4 \cdot 10^{-4} \cdot (2R)^{1.75} + 9.5) \cdot (2R)^{1.853}$
Electronics	$Cost_{El} = (-3.3 \cdot 10^{-3} \cdot Prated + 43) \cdot Prated$
Other Components	$Cost_{OC} = (-3.3 \cdot 10^{-3} \cdot Prated + 48) \cdot Prated$

The total cost of the nacelle is computed as the sum of these components:

$$Cost_{Nacelle}(3) = \sum Cost_{NacelleComponents_i}$$

- **Foundations**

Foundations are needed to sustain the weight of the turbine, its cost is expressed as a function of the mass of the turbine, therefore of its height and rotor radius:

$$Cost_{Foundations}(4) = (-(5 \cdot 10^{-2} \cdot H \cdot A)^{0.4037} + 342.24) \cdot (H \cdot A)^{0.4037}$$

- **Transport**

The cost model for the transportation of the turbine is a non-linear function of its size:

$$Cost_{Trasport}(5) = (1.58 \cdot 10^{-5} \cdot Prated^2 - 0.0375 \cdot Prated + 54.7) \cdot Prated$$

- **Civil Works**

All those works that allow access to the site and prepare it for the installation such as the external access road and the roads internal to the park make up the total cost for civil works. Such cost is again a function of the size of the turbine:

$$Cost_{CivilWork}(6) = (1.09 \cdot 10^{-6} \cdot Prated^2 - 0.0145 \cdot Prated + 71.5) \cdot Prated$$

- **Installation**

This cost takes into account the assembly and installation of the turbine.

$$Cost_{Installation}(7) = 1.965 \cdot (2H \cdot R)^{-1.1586}$$

- **Electrical Works**

The main costs related to electrical works are due to the construction of one or more MV power lines inside the park and one outside the park, a sorting booth, and a connection point to the national electricity grid.

$$Cost_{ElWorks}(8) = (1.09 \cdot 10^{-6} \cdot Prated^2 - 0.0145 \cdot Prated + 71.5) \cdot Prated$$

- **Accidental Damage**

An average of 6% of the total cost is taken into account to consider eventual accidental damage during the installation of the turbine.

$$Cost_{Damage}(9) = 0.065 \sum_i Cost_i$$

The total cost for one turbine is computed as the sum of all the previously described components:

$$Cost = \frac{1.5}{ED}\sum_{i=1}^{9} Cost_i \qquad (8)$$

Where 1.5 is a corrective factor suggested by NREL to have a better approximation of a real repowering of a wind power plant and ED is the Euro-USD conversion, currently equal to 1.13.
Operation and Maintenance costs can account for between 11% and 30% of onshore wind projects levelised cost of electricity (LCOE), in major wind markets it averages between USD 0.01/kWh and USD 0.025/kWh and will later be taken into account for the computation of the IRR (10).

2.4 Solar Panels

To compute the power output and evaluate the overall performance of the solar panels, the following specifics have been used.

Efficiency	0.25
Performance Ratio	0.85
Rated Power	350 W
Length	1.956 m
Width	0.992 m
Area	1,94 m^2

The performance ratio has been considered as a mean, taking into account the average weather conditions of the island.

2.4.1 Power Output

Having as input the irradiation data hour by hour as an array of 8760 cells (i.e. hours in a year), the power output of a single panel is computed as follows:

$$P_{PV}(i) = H(i) \cdot \eta \cdot PR \cdot A \qquad (9)$$

Being:

H(i)	irradiation data at time I in $[kW/m^2]$
η	efficiency
PR	performance ratio
A	Area of the solar panel $[m^2]$

2.4.2 Cost Model

Solar PV module prices have fallen by around 90% since the end of 2009 [Figure 2.6], the actual cost has been set to be 0.995 €/W.

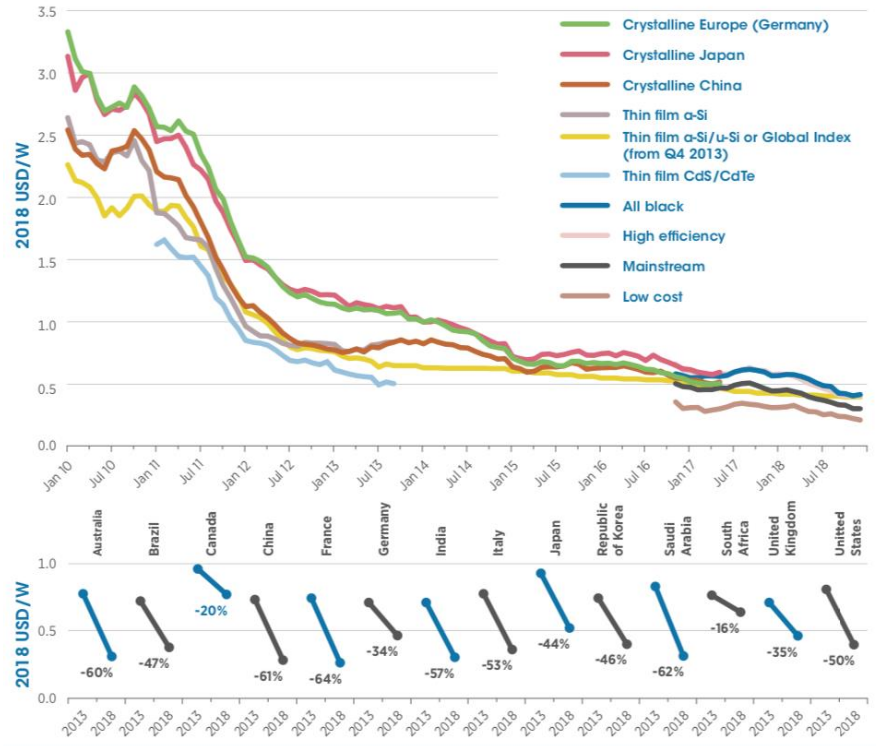


FIGURE 2.6 – COST OF SOLAR PANELS SINCE 2013

O&M costs for utility-scale plants in the United States have been reported to be between 0.25 USD/W (0.21 €/W) per year to 0.5 USD/W (i.e. 0.43 €/W) per year. O&M costs in OECD markets account for 20–25% of the LCOE (11).

2.5 Battery Storage

Interest in the implementation of energy storage might be driven by the discontinuity of renewable sources. A battery can in fact be used to better fit the demand curve, shaving off the production peaks and adding to the power curve when needed. It can also be used to increment profits through arbitrage.

2.5.1 State of Charge Model

The model for the state of charge of the battery for demand fitting purposes follows the flowchart in Figure 2.7.

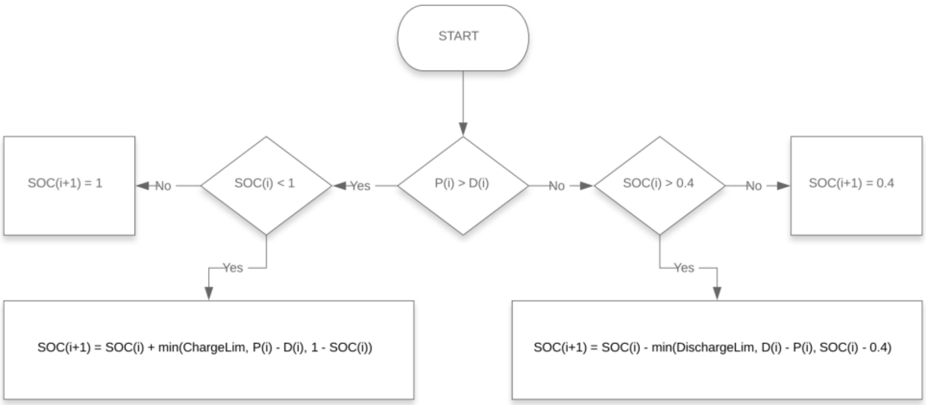


FIGURE 2.7 – FLOWCHART FOR BATTERY STATE OF CHARGE

Having defined:

$0.4 < SOC < 1$	state of charge
P(i)	power production at time i
D(i)	demand
Charge and Discharge limits	maximum amount of power that the battery can intake or discharge

Assuming a two-tariff pricing for energy, arbitrage can be modeled as follows [Figure 2.8]:

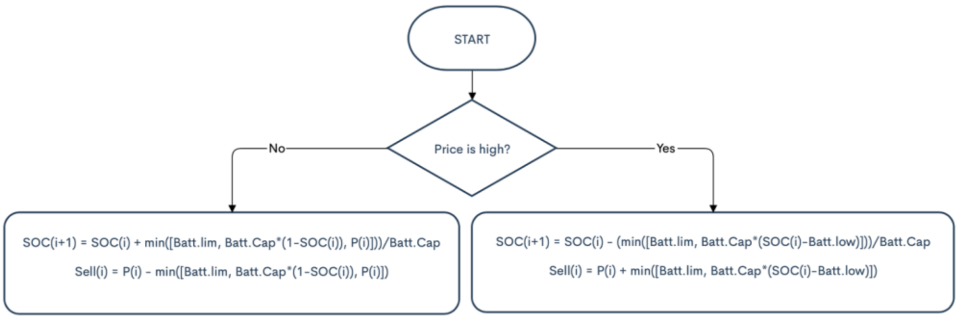


FIGURE 2.8 – FLOWCHART FOR BATTERY STATE OF CHARGE (ARBITRAGE)

Where:

Sell(i)	power sent to the grid at time i
Batt.Cap	capacity of the battery

In this case, energy is stored when the price is low in order for it to be sold when the price is high, a mixed version of these two approaches is modeled as shown in Figure 2.9:

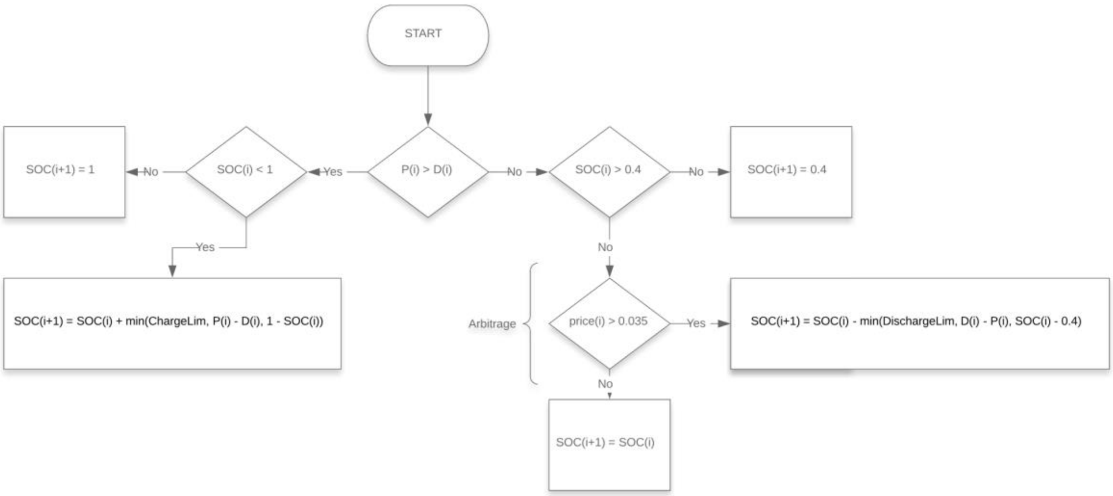


FIGURE 2.9 – FLOWCHART FOR BATTERY STATE OF CHARGE WITH ARBITRAGE

Where the low price is set at 0.035 €/W as an example and can be changed arbitrarily.

2.5.2 Cost Model

The cost model for the battery depends on the hour capacity chosen (the rate at which the battery can get fully charged or discharged) and on its total capacity. For the time being, the following prices will be used:

1h	545 [€/kWh]
4h	350 [€/kWh]
8h	295 [€/kWh]

It has to be taken into account that battery storage is a cutting-edge technology for which incredible research effort is being financed and carried on, so these prices are quickly decreasing and are expected to drop by 25% in the next ten to twenty years [Figure 2.10]. (12)

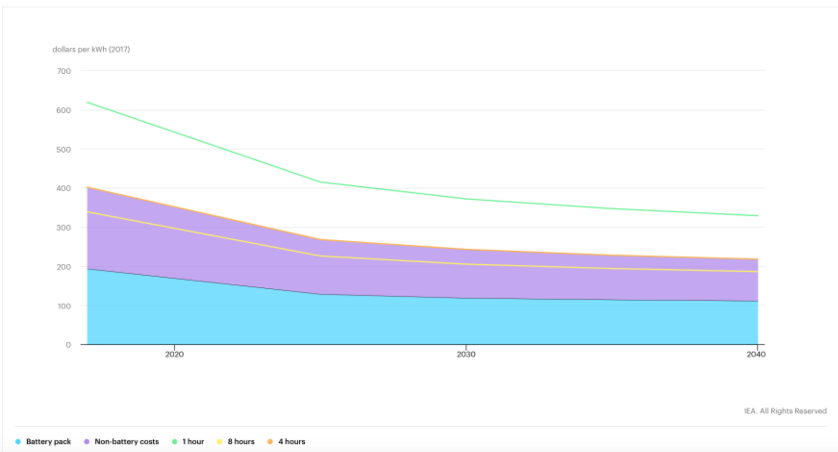


FIGURE 2.10 – COST OF BATTERY STORAGE FORECAST 2015-2040

For the optimization cycles it will be necessary to run the optimization separately for the 1h, 4h and 8h battery and compare the results.

2.6 Input Data

Weather and demand data hour by hour need to be inputted as excel files, there is thus a total of 8760 cells for every one of the following measures:

Wind Speed	$[m/s]$
Solar Irradiation	$[kWh/m^2]$
Demand	$[\mathrm{k}W]$

Hourly wind data of a number of years, at 10m and 80m of altitude, are necessary. For all the intermediate altitudes a logarithmic wind profile has been implemented through the following function:

$$speed(h) = speed(10\,m) \cdot \frac{\log\left(\frac{(h - d)}{Z_0}\right)}{\log\left(\frac{(10 - d)}{Z_0}\right)} \tag{1}$$

Being:

h	Altitude at which the wind speed is being computed in meters,
d	zero-plane displacement and can be approximated as $\frac{2}{3}$ to $\frac{3}{4}$ of the average height of the obstacles
Z_0	Roughness length, a corrective factor used to take into account the effect of the roughness of the surface on wind flow

The Weibull distribution can be later computed through the Matlab function *wblfit*.
For the solar data, a CSV file must contain the in-plane irradiation measure, hour by hour, for the last 10 to 15 years. The demand data, hour by hour for a number of years, are saved as a CSV file and must be imported on Matlab before starting the simulations. For these values, a mean over the available years will be computed in order to guarantee the reliability of the results.

2.7 Cases Definition

To analyze the drivers that could influence the results of the study, a reference case and three other scenarios are defined, characterized by different constraints and objective functions:

- **Reference Case**

The first optimization only takes into account the substitution of the old wind turbines with new ones, limitations on the grid capacity and land use are implemented.
It can be considered as a conventional revenue-driven repowering sizing.

- **Grid Constraint Case**

In this case, the objective function is the IRR and the only constraint is the power installed, this is a plant-level optimization.

- **Land Constraint Case**

Here the optimizer is forced to fill all the available land with wind turbines and solar panels to show the total generation potential of the plant and the influence of their combination on the performances.

- **Demand Fitting Case**

In this last case, no constraints on the land use or the installed power are implemented, the goal is to minimize the Loss of Load Probability (LOLP) in order to produce a substantial part of the island energy demand, with a positive IRR being the only limitation.
To identify the drivers more clearly, an optimization is performed for this scenario minimizing the initial cost for various required levels of LOLP.

2.8 Extended Design Structure Matrix (XDSM)

It is possible to visualize the process just described with the help of an XDSM.
The first modules evaluate wind and solar performances, knowing hourly irradiance and wind speed, while the optimizer tries different combinations of turbine design and wind/solar mixes.
Constraints such as the land use and the limitation on the installed power are computed and the Battery Operations module assesses the generation characteristics, the battery cycles, compute the LOLP and estimate the revenues. The IRR is finally computed knowing the initial investment (through the Cost block) and the Cash Flow as the difference between the revenues and the O&M costs.
Figure 2.11 shows the case where IRR is the objective function with land and grid constraints while Figure 2.12 shows the optimization for the LOLP using the IRR as a constraint.

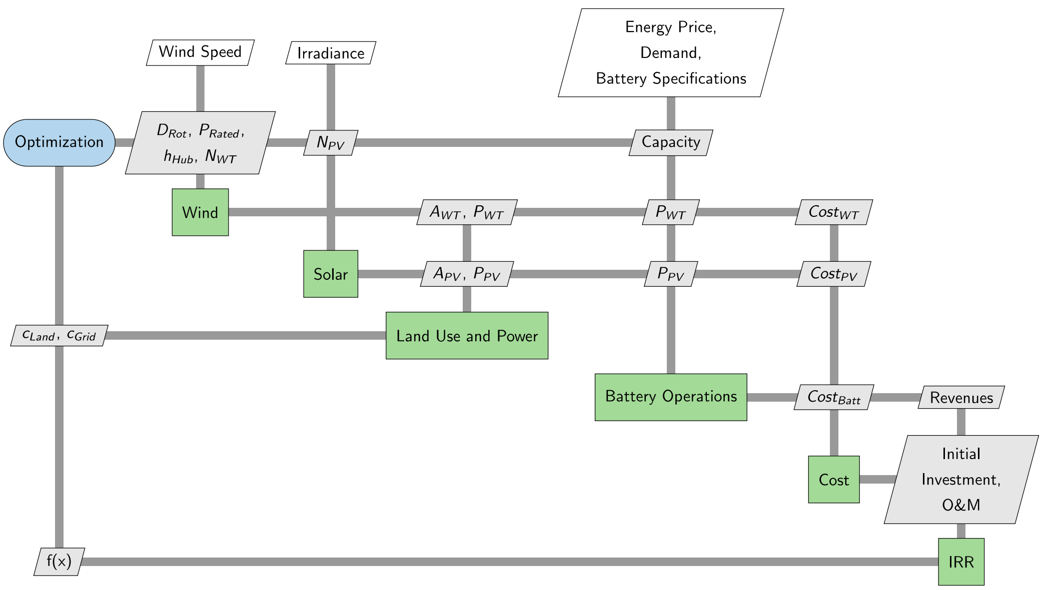


FIGURE 2.11 – EXTENDED DESIGN STRUCTURE MATRIX (XDSM) OPTIMIZING IRR

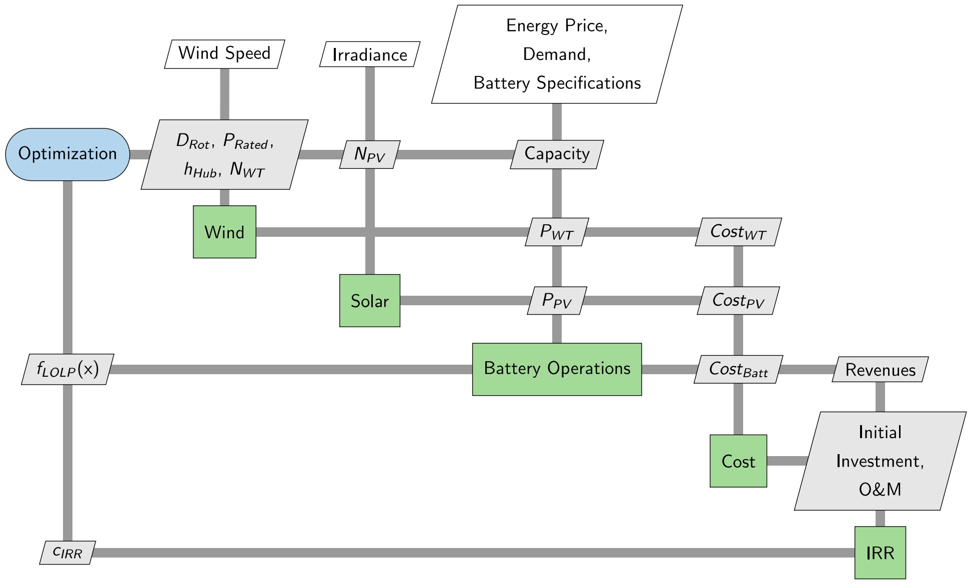


FIGURE 2.12 – EXTENDED DESIGN STRUCTURE MATRIX (XDSM) OPTIMIZING LOLP

2.9 Sensitivity Analysis and Benchmarking

Validating models have been implemented to test the reliability of the optimization's results. While these do not constitute irrefutable proof of the validity of the results obtained, these tests have been run for every optimization and have helped through the building of the program to discard certain solutions and modify the code accordingly. The guidelines followed are here listed:

i. **Changing Wind/Solar Cost Model**

Setting the cost models to favor one of the two technologies is expected to shift the result toward that technology. Ideally setting the price of Wind (Solar) to be equal to zero leads to an all Wind (all Solar) optimal power plant.

ii. **Changing Battery Cost Model**

Increasing and decreasing the cost per kWh of the battery must influence the outcome of the optimization, increasing its price obviously drives the final result to its absence while lowering it makes its capacity grow.

iii. **Changing Cost of Electricity**

A higher cost of electricity means higher profit thus higher IRR, and vice versa.

These tests have been applied to every optimization and it has been directly verified that the results were consistent with the expected ones. The results of part of the simulations have also been benchmarked using the commercial software HOMER PRO taking into consideration the same approximations and simplifying assumptions of this study.

3 CASE STUDY

The choice of the case study depended on several factors that will be thoroughly explained in this chapter. Ideally, it had to be a place where HRES benefits would have been more evident: a remote island with strong interests in energetic independence, a stable political environment and an accepting community with financial support for such projects and already existing wind farms, old enough to make repowering economically feasible.

3.1 Canary Islands and the Need for Repowering

The Canary Islands (Figure 3.1) are a Spanish archipelago and the southernmost autonomous community of Spain, located in the Atlantic Ocean approximately 1000 Km from the Spanish mainland coast, the closest land is situated at 100 Km from the Moroccan West coast. The total surface area of the archipelago is 7446,62 Km^2 and the population density is about 200 inhabitants per Km^2. Climate is tropical and desertic, moderated by the presence of the sea and by the trade winds, but a high number of microclimates dependent on orographical features and height above sea level exists.

FIGURE 3.1 – SATELLITE IMAGE OF THE CANARY ISLANDS

Energy supply is strongly dependent on imported oil burnt in the nine existing large thermal plants.
Scarcity of rainwater is met by the pumping of fossil water with extraction methods that require increasingly greater depths, thus leading to gradually more severe desertification and salinization of soil. Treatment plants for potable water, characterized by high energy consumption (30% of all electrical consumption in the islands), are necessary and make the island highly vulnerable to any sort of energy crisis.
To face these dangers and to exploit the strengths of these islands, rich in renewable sources as sun and wind, an Action Plan (CE2000) was instituted to guarantee a safe and stable energy supply by diversified energy technologies to promote energy independence, minimize energy cost and to contribute to the protection of the environment (13). Thanks to this Action Plan, the Canary Islands saw the mobilization of more than 10M € and an increasing economic interest in the field of renewable energy technologies.
While continental power stations benefit from higher economies of scale, these islands' energy profile is characterized by small-sized power plants and an excessive cost of imported fuel.
For this reason, increasing autonomous RES generation would have a positive impact, reducing the *excess-cost* of the Canary Islands electric system and its contribution to the National *tariff-deficit*.

Maximizing the penetration of renewable energy sources, although highly desirable, is however hindered by a number of limitations mainly regarding spatial constraints as territorial protection and air-safety restrictions. Nearly 70% of the territory is currently heavily protected as shown in Figure 3.2 where the most significant habitats and the main centers of biodiversity of the archipelago are represented.

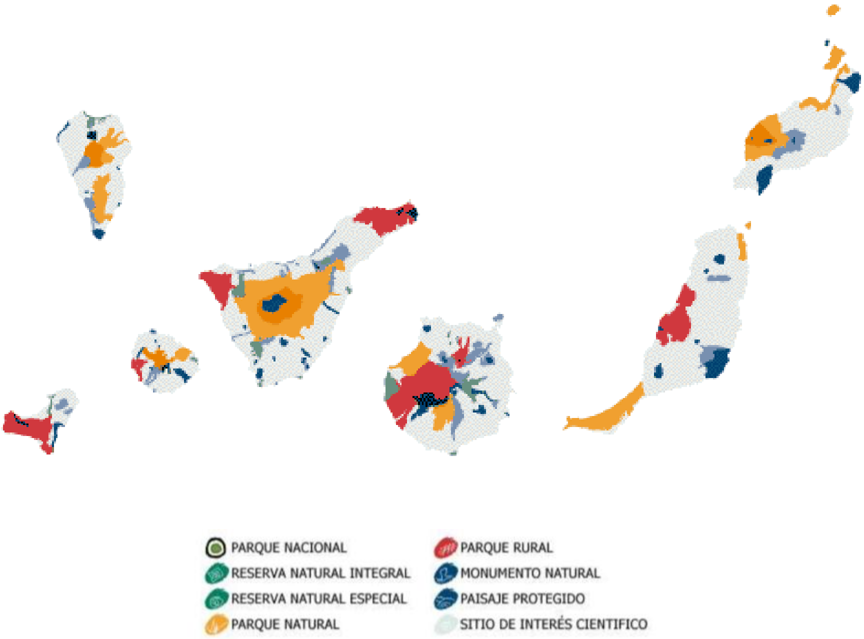
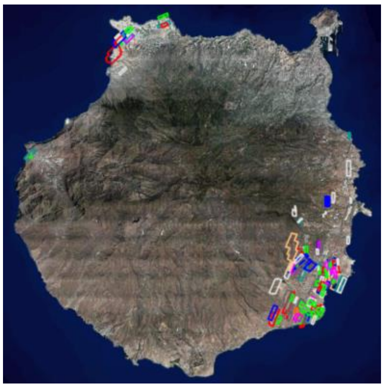
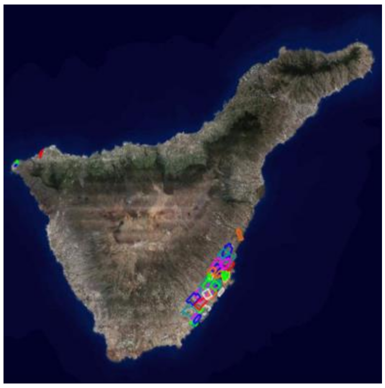


FIGURE 3.2 – PROTECTED AREAS IN THE CANARY ISLANDS (14)

Another factor to be taken into consideration is that the most suitable areas, where the best wind resource is present, are already affected by existing wind farms (Figure 3.3) or in proximity to populated areas and airports where technical and legal restrictions do not allow the creation of new wind farms.



GRAN CANARIA



TENERIFE

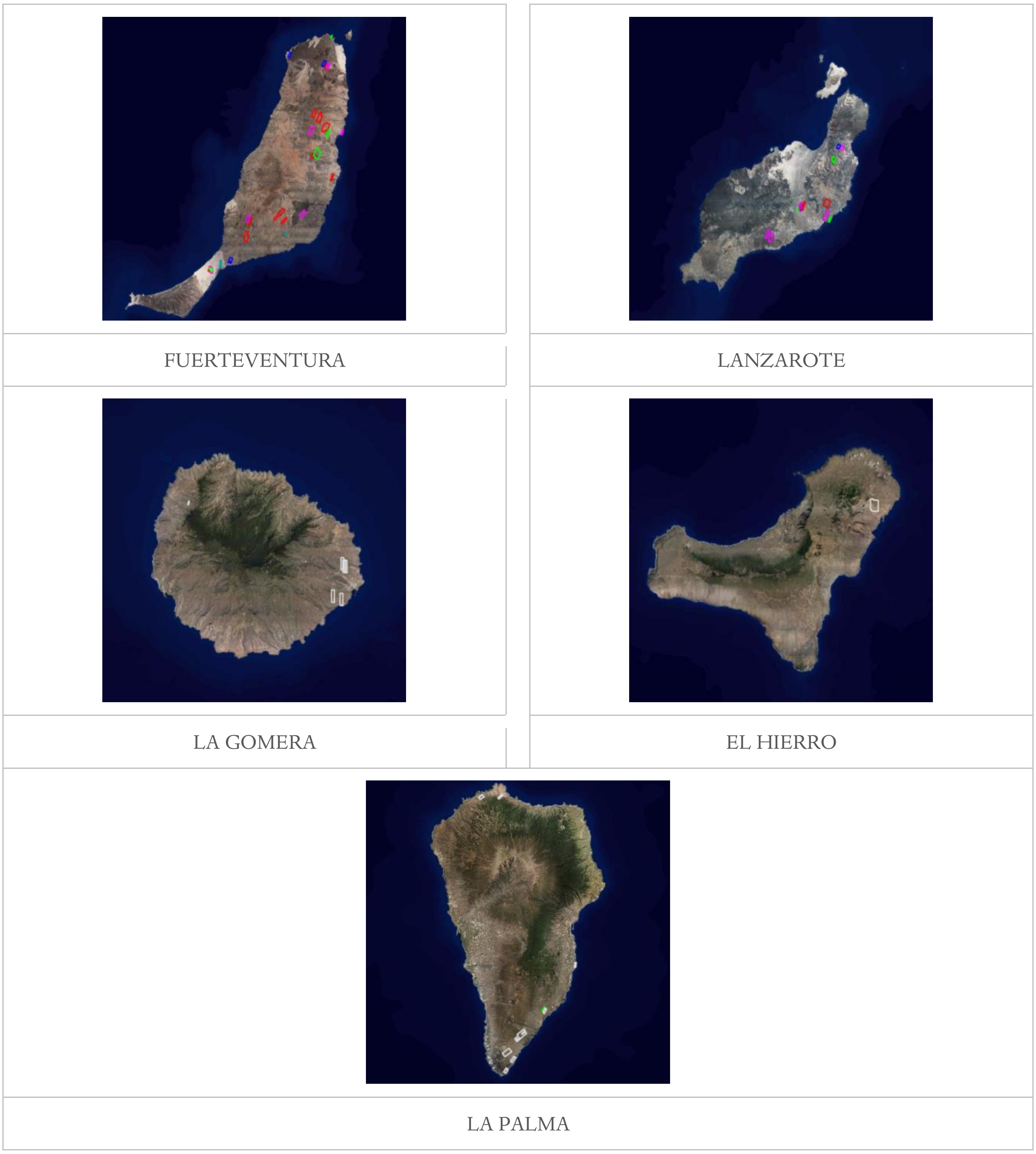


FIGURE 3.3 – INFLUENCE AREA OF EXISTING WIND FARMS ON THE ISLANDS (15)

Having already talked about the advantages of repowering, mainly because of the limited land availability for new farms, the particular circumstances in which these islands find themselves make them a perfect candidate for this study.

3.2 Energy Balance

The Canary electric system has six electrically isolated systems, small in size and weakly meshed. These conditions make these systems less stable and secure than large interconnected systems in which it is possible to guarantee

supply during peaks in demand or in certain situations of lack of generation, such as shortages of wind or due to failures and unavailability of network elements.
The evolution of the Canary Islands energy balance since 2011 is shown in Table 3.1.
Primary energy has been calculated as the sum of net imports of primary energy resources and domestic energy production, deducting the exports produced from these products, supplies to international shipping and changes in inventories.

Year	Domestic Production [Tep]	Import-Export [Tep]	Primary Energy [Tep]	Final Energy [Tep]
2011	57.914	7.235.924	4.873.515	**3.410.486**
2012	60.785	6.982.391	4.831.116	**3.349.622**
2013	63.959	7.070.635	4.831.059	**3.341.420**
2014	66.397	6.395.707	4.562.073	**3.366.465**
2015	67.372	7.080.974	4.509.232	**3.303.792**
2016	68.189	7.015.082	4.728.936	**3.504.302**
2017	70.491	7.321.567	4.900.683	**3.634.526**
2018	100.563	7.291.769	4.893.022	**3.697.980**
Final Energy Cumulative Growth (%)				
2018/2017	42.66%	-1.39%	-0.16%	**1.75%**

TABLE 3.1 – EVOLUTION OF THE CANARY ISLANDS ENERGY BALANCE 2011-2018

It is clear that, although the domestic production shows an upward trend, it still represents a relatively small fraction of the primary energy, amounting to a total of roughly 2.1% of the primary energy in 2018. The following pie chart (Figure 3.4) shows the distribution of final demand in 2018, distinguishing mainly between the demand for petroleum products and the electricity demand.
It is easy to notice the great preponderance of the supply of petroleum products within the Canarian energy system, reaching 80.23% of the total final energy demand. The rest is divided between electricity 19.31% and solar thermal 0.47%.

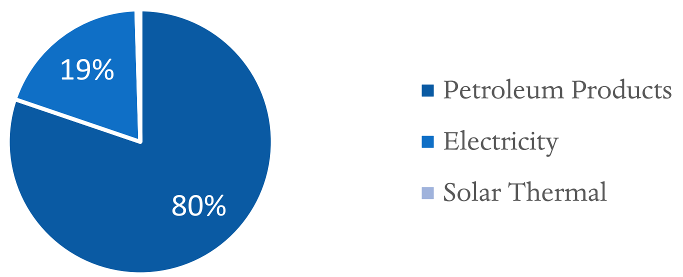


FIGURE 3.4 – FINAL ENERGY DEMAND IN THE CANARY ISLANDS BY TYPE OF ENERGY, 2018

Regarding final energy consumption by sector, the following graph (Figure 3.5) shows a predominant influence of the transportation and service industry, while the low specific weight of the industries justifies the absence of constant energy demands.

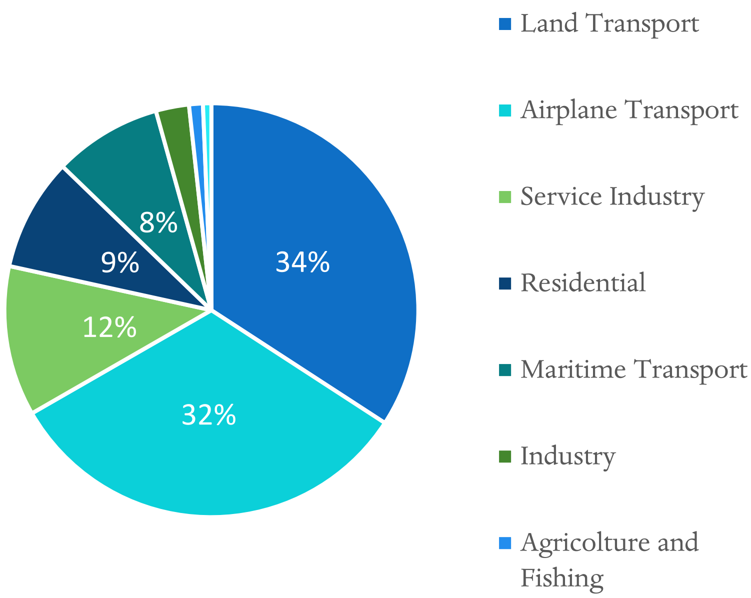


FIGURE 3.5 – ENERGY CONSUMPTION IN THE CANARY ISLANDS BY SECTOR

The historical evolution of the Canarian energy system has been based, since it was introduced in the Archipelago at the beginning of the twentieth century, on oil, constituting until today the main and almost only source of energy. Thus, although the Islands great potential, the evolution of renewable energies has not been as fast as expected. In the second half of the 1980s, a wind farm was installed in Tenerife, constituted as an experimental park to test the behavior of different models of wind turbines (including one with a vertical axis). At that time, in Gran Canaria, several machines were also installed. From the '90s on, the first wind farms for the production of electrical energy in Tenerife and Gran Canaria came into operation. The evolution of installed power from renewable energy sources in the last 15 years (up to 2018) is shown in Figure 3.6 for the different islands of the archipelago, expressed in [KW].

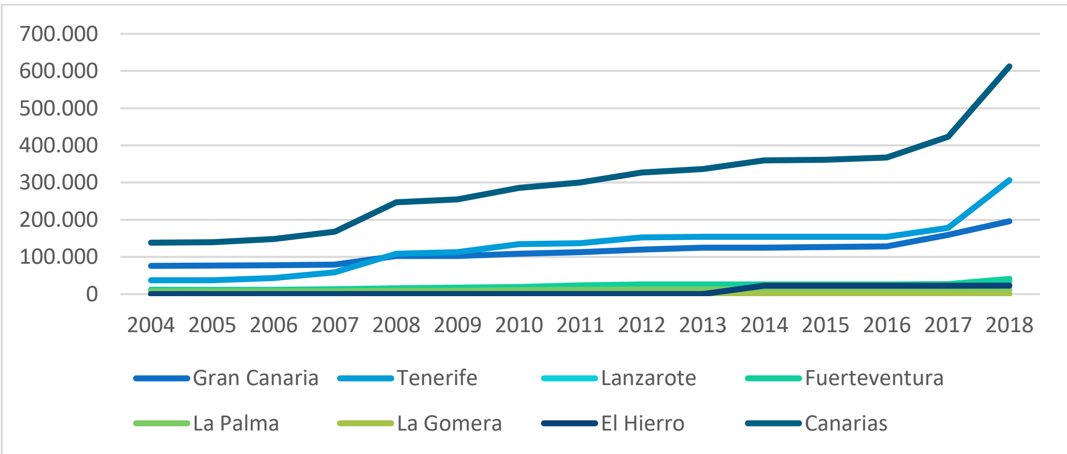


FIGURE 3.6 – EVOLUTION OF THE RES INSTALLED POWER IN THE CANARY ISLANDS (16)

The participation of different renewable energies in the energy generation of each island is shown in Figure 3.7.

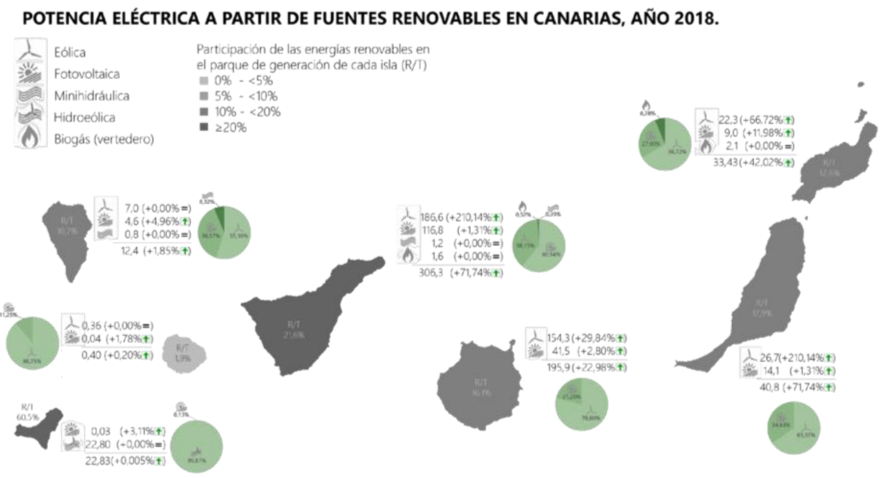


FIGURE 3.7 – DISTRIBUTION OF RES INSTALLED POWER IN THE CANARY ISLANDS

3.3 Price of Energy

The price of energy in the Canary Islands (Figure 3.8) is the same as in mainland Spain through a tariff-cross subsidy. The model used for the program is based on the customer price multiplied for a factor of 0.5 that takes into account the plant's profit over the selling and is divided into two tariffs, $0.035\frac{€}{kW}$ from midnight to 13 pm, $0.0713\frac{€}{kW}$ from 13 pm to midnight (17).

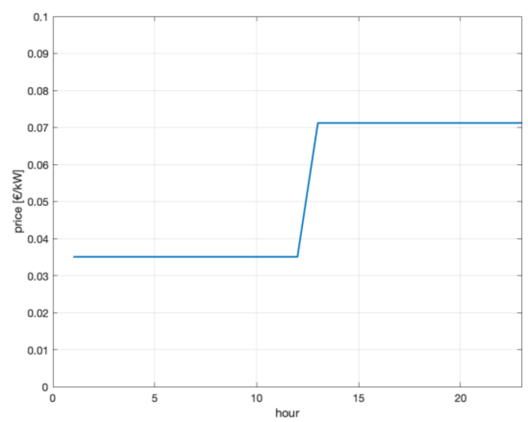


FIGURE 3.8 – PRICE OF ENERGY

3.4 Gran Canaria

Due to its size, greater penetration of RES into its electrical system and the presence of farms that look suitable for repowering actions, the island of Gran Canaria (Figure 3.9) has been chosen. As of 2019 Renewable Energy in Gran Canaria only accounts for 17% of the total energy production. The highest peak of renewable energy production (47,7%) on the island has been registered at 3.30 am (11 November 2019). The energy mix of the island can be seen in Figure 3.10.

FIGURE 3.9 – SATELLITE IMAGE OF GRAN CANARIA

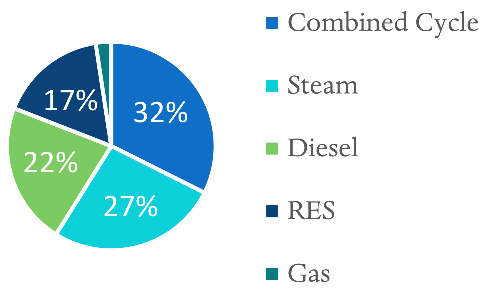


FIGURE 3.10 – ENERGY MIX OF GRAN CANARIA

The choice of the plant to be repowered depended on different factors such as power installed and age of the turbines, in Table 5.7 (Appendix C) a list of all the wind farms on the island is shown (18).
Below (Figure 3.11) it is presented the distribution of the different wind farms installed on the Island.

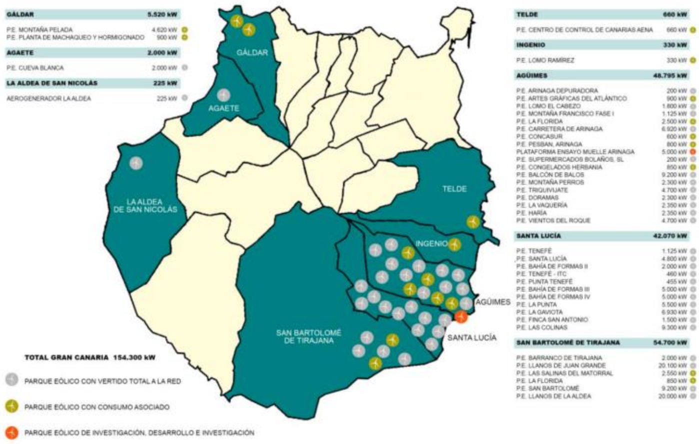


FIGURE 3.11 – DISTRIBUTION OF WIND FARMS ON THE ISLAND OF GRAN CANARIA

The plant chosen for this study is Llanos de Juan Grande.

3.5 Llanos de Juan Grande

This plant has the highest installed power on the island and its aerogenerators are amongst the oldest, situated in the south-eastern region of Barranco de Tirajana it consists of 67 wind turbines DESA A300 and amounts to a total installed power of 20.100KW. An aerial view of the plant is shown in Figure 3.12.

FIGURE 3.12 – DISTRIBUTION OF WIND TURBINES IN THE PLANT OF LLANOS DE JUAN GRANDE

The turbines already present on the site are highlighted by the blue place-cards and it is noticeable how, given the predominant direction of the wind from North/North-East, they are placed along two main lines that face that direction in order to avoid wake effects and maximize the energy production [Figure 3.13].

FIGURE 3.13 – VIEW OF THE PLANT OF LLANOS DE JUAN GRANDE

The turbines that are currently being used are DESA A300 and have the specifics shown in Table 5.1 in the appendix. The power curve for this turbine is here presented (Figure 3.14).

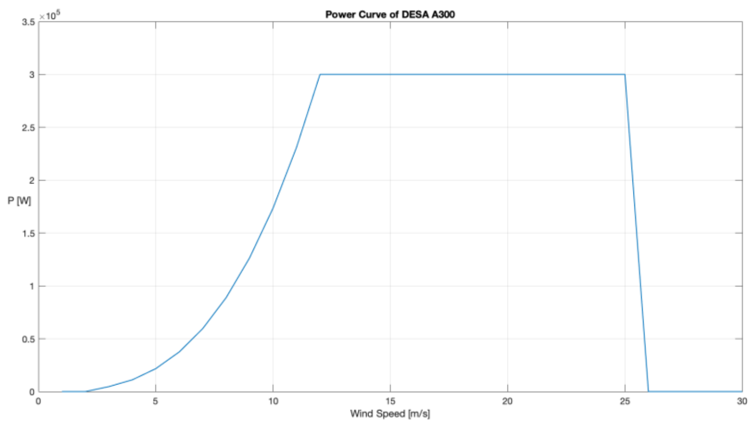


FIGURE 3.14 – POWER CURVE OF DESA A300

The variables that will be used for the design optimization of the new wind turbine (diameter, rated power and hub height) will then be normalized with respect to these values:

D_N	30 m
$Prated_N$	300 kW
HH_N	30 m

3.6 Weather and Demand Data

3.6.1 Wind

Wind data have been kindly provided by meteoblue and show a mean wind speed at 10 m of 4,7 m/s (7,5 m/s at 80 m) (19). The following images show an overview of those data (Figure 3.15, Figure 3.16 and Figure 3.17).

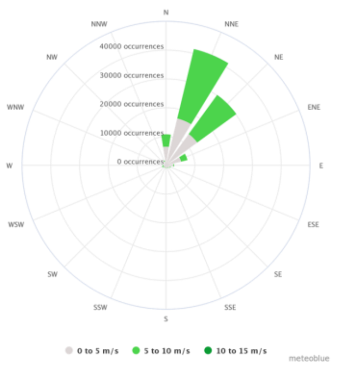


FIGURE 3.15 – WIND ROSE AT 10 M

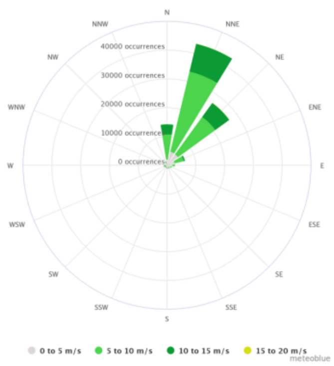


FIGURE 3.16 – WIND ROSE AT 80M

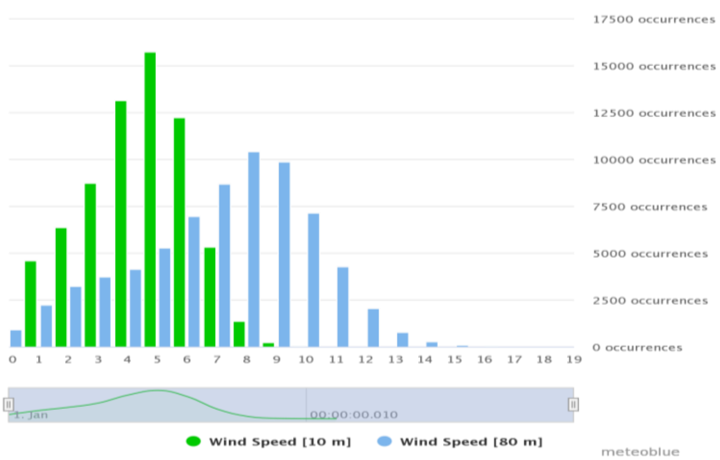


FIGURE 3.17 – WIND HISTOGRAM

From the wind rose it is clear to deduce that there is a predominant direction for the wind, this justifies the disposition of the turbines along a line that faces North-East. The wind profile appears as in Figure 3.18.

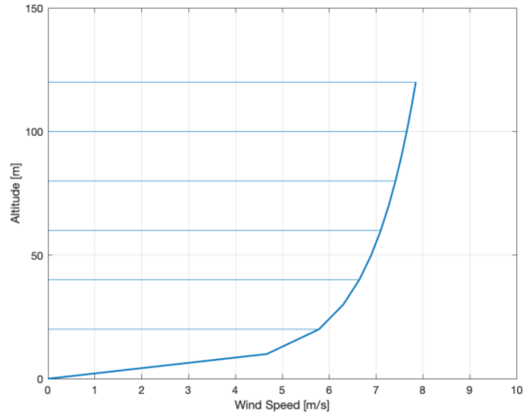


FIGURE 3.18 – WIND PROFILE

The wind Weibull distribution is the following (Figure 3.19):

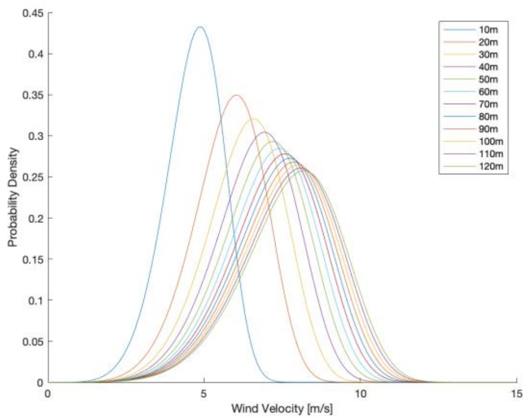


FIGURE 3.19 – WIND WEIBULL DISTRIBUTION

3.6.2 Solar

Irradiation data for the selected location show a yearly in-plane irradiation of 2310.54 $\frac{kWh}{m^2}$ (20). The monthly irradiation values are shown in Figure 3.20. Such data have been gathered from the photovoltaic geographical information system of the European Commission.

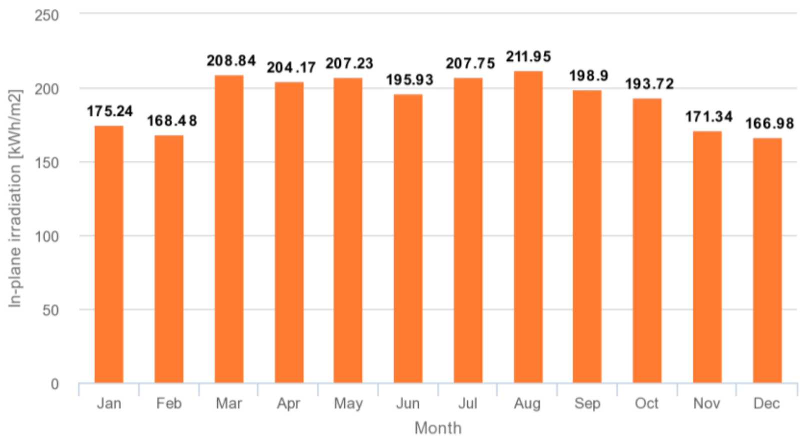


FIGURE 3.20 – MONTHLY IN-PLANE IRRADIATION

3.6.3 Demand

Demand data for the island have been taken on the official website of REE (Red Eléctrica de España), a Spanish company involved in electricity systems and transport. It shows an average hourly demand of 380 MW (21), an overview of the demand curve is shown in Figure 3.21.

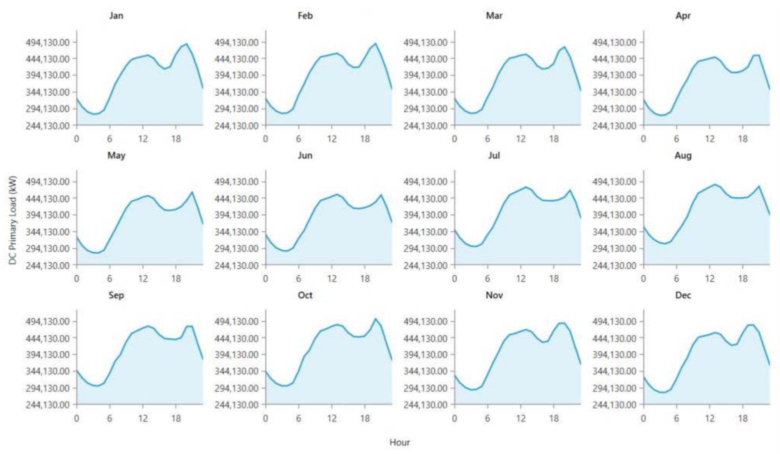


FIGURE 3.21 – DEMAND CURVE FOR THE FIRST 40 DAYS OF THE YEAR

3.7 Impact on Tourism

The island receives the second most visitors in the archipelago with approximately 4.3 million holidaymakers in 2019. Its attractiveness relies primarily on its microclimates and the untamed natural landscapes. Most of the service industry on the island is related to tourism, it represents in fact around 75% of its Gross Domestic Product (Figure 3.22).

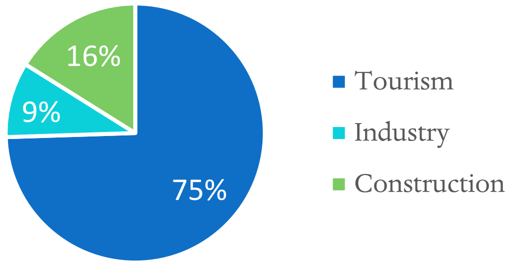


FIGURE 3.22 – GDP OF GRAN CANARIA

Although wind power plants have relatively little impact on the environment compared to conventional power plants, these are the main concerns:

Noise Pollution:	Mainly due to the rotor, gearbox and electric generator
Visual Impact:	Changes in the landscapes linked to the turbines' layout
Impact on Wildlife:	Birds have been killed by flying into spinning turbine blades

When it comes to the people's perspective on wind farms there are two main points of view:

The "*Not In My Backyard*" point of view (NIMB) can be considered the resident perspective on the installation of wind farms close to where he lives and its characterized by these features:

- Wind turbines seem to be less plagued by the NIMB behaviour
- Large parks may induce stronger negative effects on the landscape
- Anachronism when in proximity to old villages is generally badly perceived

The visitor's perspective instead can be defined as "*Not In My Hiking Trail*" (NIMHT) and consists of the following features:

- Visual dimension is among the most important predictors of a tourist destination
- Technical design and non-natural materials might attract negative attention
- Empirical negative relation between wind turbines and tourism demand (22)

Given the importance of tourism and its impact on the island's economy, it is important to take that into account when planning the installation of new wind turbines.

3.8 Constraints

Once the site is chosen there is a certain number of constraints that are defined by technical and legal limitations. The main constraints are related to land use and grid capacity which limit the number of solar panels and wind turbines that can be installed.

3.8.1 Grid Constraint

As stated in the *Boletín Oficial de Canarias núm. 61, martes 28 de marzo de 2006, Articulo 7*:
Holders of wind farms connected to the grid currently in operation, who intend to introduce improvements to their wind facilities, may increase their power:

a) Increasing the unit power of the wind turbines by replacing them with new ones that have not been put into production previously.

b) Increasing the unit power of the wind turbines through the introduction of technical changes, which without affecting their basic structure, improve their energy efficiency.

In case *a*, the power may be increased up to a limit of 50% of the total power of the replaced wind turbines.

In case *b*, the power may be increased up to a limit of 50% of the total power of the modified wind turbines.

The resulting installed power may be adjusted based on the standardized power stage on the market, closest to the chosen wind turbine, with a tolerance of 15% with respect to the limit previously established and as long as other wind turbines, of lower nominal power, that are better adjusted to the 50% limit established previously exist on the market.
In any case and during the exploitation of the park, the simultaneous power may not exceed the authorized power, therefore, if necessary, an individual power regulation system of the mentioned machines will be adopted, guaranteed by the manufacturer, as well as the power limitation devices that the competent energy management center deems necessary (23).

Being the actual installed power 20.1 MW, the following relation must be included in the constraints:

$$P_{installed} = \#WT \cdot Rated_{WT} + \#PV \cdot Rated_{PV} \leq 20.1 \cdot 1.5 = 30.15\ MW$$

Or again, in terms of c(x):

$$cPower = -1 + \frac{x(1) \cdot Prated_{WT} + x(2) \cdot Prated_{PV}}{30.15 \cdot 10^6}$$

3.8.2 Land Constraint

Given the predominant direction of the wind from North-East, the turbines will still be facing the same direction, all aligned along the two original lines for a total length of 3550 m.
By law two turbines must have at least two diameters between each other, and there must be at least five diameters between different lines of turbines (Figure 3.23), the second constraint is considered when the total available length is computed, being the two rows at a 500 m distance.

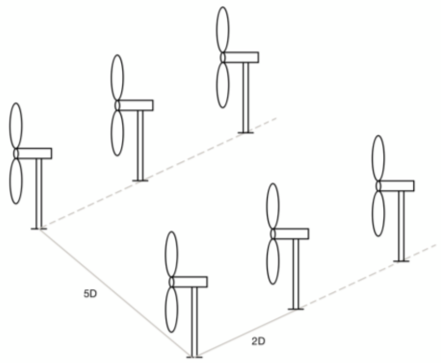


FIGURE 3.23 – DISTANCE BETWEEN TURBINES

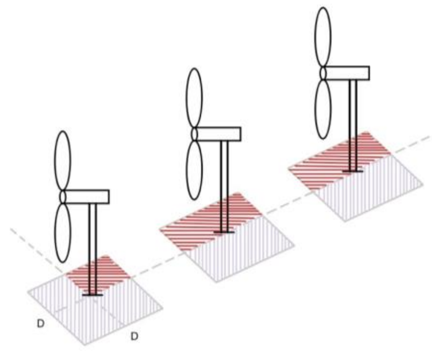


FIGURE 3.24 – TURBINE'S AREA OF INFLUENCE

From Figure 3.24 it is easy to appreciate the fact that only part of the turbine's area of influence falls into the plant's property, this will be taken into consideration for the definition of the area constraint.
Considering the current availability of land, a second constraint will be used to limit the space for solar panels which will depend also on the number of aerogenerators installed and on their rotor diameter. The available land is equal to $1.3\ km^2$ (Figure 3.25).

FIGURE 3.25 – LENGHT AND AREA AVAILABLE

The following relations must be respected for the optimizer iterations:

Length Constraint	$2D \cdot (\#WT - 2) \leq 3550\ m$
Area Constraint	$\#WT \cdot D^2 + \#PV \cdot A \leq 1.32\ km^2$

Or in terms of c(x), in order for it to be used for the optimization:

$$cLen = -1 + \frac{2D \cdot (x(1) - 2)}{3550}$$

$$cArea = -1 + \frac{\frac{D^2}{2} \cdot (x(1) + 2) + A \cdot x(2)}{1.32 \cdot 10^6}$$

Where D is the rotor diameter of the aerogenerator chosen, #WT is the number of wind turbines installed without taking into account the four outermost turbines for which it will not be considered the final spacing, #PV is the number of solar panels and A is their area. The constraints are normalized respectively with the length and area of the plant in order to increase the precision of the optimizer.

4 RESULTS

4.1 Reference Case

A first optimization cycle has been run to find the most profitable wind turbine to be used on the site, without considering any other technology (no battery or solar panels). This could be considered as a first step for a conventional repowering.

The optimization shows the following results:

Optimal Diameter	$87\ m$
Optimal Hub Height	$90\ m$
Optimal Rated Power	$1.14\ MW$
IRR	15,91 %
Capacity Factor	64 %

There are at least 70 turbines with rated power between 950 kW and 1200 kW available on the market, out of these, different solutions from various manufacturers have been tested with the following results (Table 4.1):

Turbine	Rated Power	Rotor Diameter	Capacity Factor	IRR
Leitwind LTW90 950	950 kW	90,3 m	66,3 %	13,85 %
Leitwind LTW90 1000	1 MW	90,3 m	66,3 %	14,37 %
Mitsubishi MWT-62/1.0	1 MW	61,4 m	35,6 %	11,05 %
BWU 57-1000	1.05 MW	57 m	32,1 %	10,68 %
Made-Endesa AE-61/1.100	1,1 MW	61 m	21,5 %	5,6 %
AutoFlug A1200	1.2 MW	61 m	32,1 %	10,74 %
Goldwind GW 62/1200	1.2 MW	62 m	35,6 %	12,04 %

TABLE 4.1 – HIGHEST IRR WIND TURBINES FOR CONVENTIONAL REPOWERING

Their performances, compared, is shown in Figure 4.1

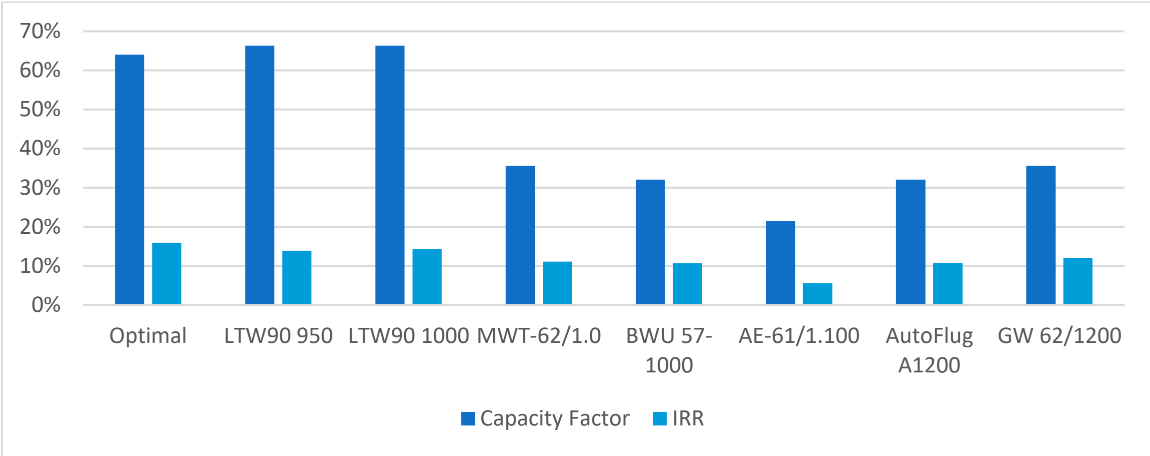


FIGURE 4.1 – IRR AND CF FOR DIFFERENT COMMERCIAL WIND TURBINES

The option that seems to result in the highest IRR (as well as the highest capacity factor) is the Leitwind LTW90 1000, its specifics are listed in Table 5.2.

The turbine follows the power curve in Figure 4.2.

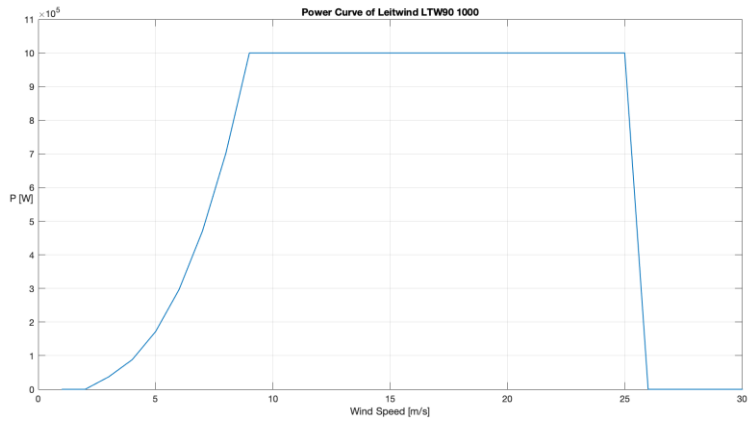


FIGURE 4.2 – LEITWIND LTW90 1000 POWER CURVE

4.2 Grid Constraint Case

Initially, all the constraints are respected. A first try has been done only implementing wind turbines and solar panels (no battery), the objective function of the optimization is the internal rate of return (IRR). Given the higher profitability of the wind turbines chosen through the previous optimization (Leitwind LTW90 1000, IRR = 14,37%), compared to solar panels (IRR = 9,96%), the optimal mix of these technologies results to be a 100% of wind turbines. The IRR as a function of the number of WT and PV is shown in Figure 4.3, considering only the x, y solutions that respect the constraints. It is easy to appreciate that no solution where $x1 + x2 > 1$ (Grid constraint) or $x1 > 0.72$ (Length Constraint) can be considered while the Area constraint is never met.

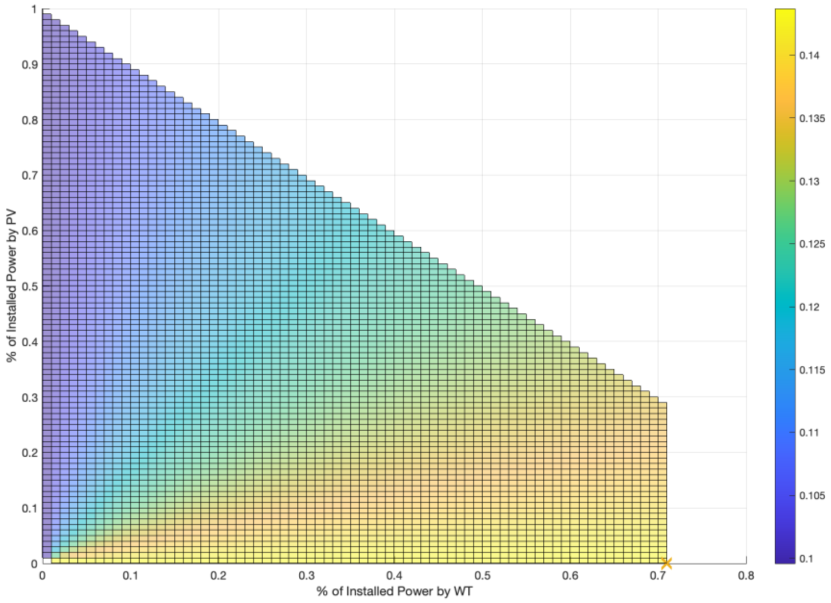


FIGURE 4.3 – HEATMAP OF IRR AS A FUNCTION OF #WT AND #PV

Once the number of solar panels is set to be zero, the IRR of the plant is 14,37 % independently on the number of aerogenerators installed, the solution that gives the highest net present value (NPV) is then to be chosen. It is possible to show how the net present value linearly increases as the number of wind turbines installed grows (Figure 4.4).

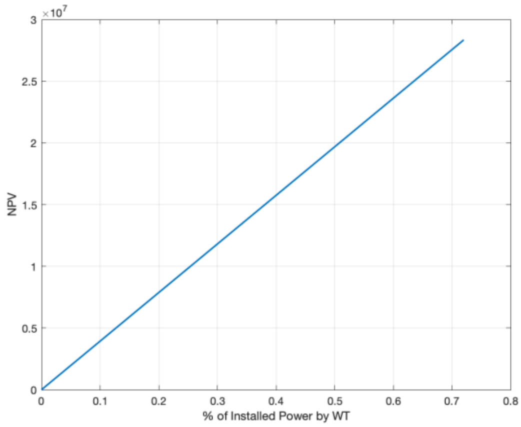


FIGURE 4.4 – EVOLUTION OF NPV WITH THE NUMBER OF WIND TURBINES INSTALLED

The optimal solution is given by the maximum number of turbines installable, given the constraints.
That would mean a total of 22 turbines, arranged on two rows facing North/North-East as shown in Figure 4.5. The distance between each turbine is 180 m and the two rows are 450 m apart.

FIGURE 4.5 – POSSIBLE DISTRIBUTION OF NEW WIND TURBINES IN THE REPOWERED PLANT

Total installed power is 22 MW, with an increase with respect to the original plant's capacity of 9%, the grid constraint is not met because the land available is already filled. The initial investment is 31,8 M€ which, considering yearly revenues of 4,73 M€ and O&M costs of 1,9 M€, results in an IRR = 14,37 % and an NPV = 28,7 M€. Annual energy yield would be around 130,000 MWh.

A second optimization was run to study the benefits of adding storage to the same case.
Adding storage to use arbitrage gives out different results, still setting the IRR as the objective function:

Rotor Diameter	$90\ m$	
Rated Power	$1.57\ MW$	
Hub Height	$80\ m$	
Number of Wind Turbines	19	
Number of Solar Panels	80	
Battery Capacity	$7\ MW$h	(8h battery)

The 8h battery has been chosen comparing the performances of 1h, 4h and 8h, shown in Figure 4.6.

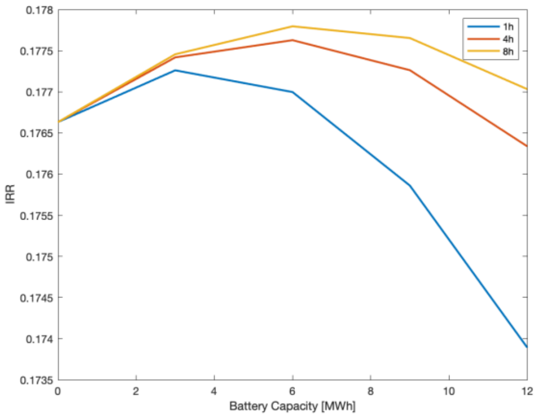


FIGURE 4.6 – EVOLUTION OF IRR WITH THE STORAGE CAPACITY INSTALLED

Such a plant would result in an $IRR = 17.93\%$, with a two percentage points increase with respect to the ideal case of the previous optimization. The small number of solar panels can be explained by a small number of hours where their presence could be highly profitable but, being an insignificant percentage of the energy mix of the plant and not having considered several implications of installing different technologies (e.g. blade shadows), their use would probably be unfavourable so they will not be considered. The most similar turbines (considering also similar power densities) found available on the market are the following (Table 4.2):

Turbine	Rated Power	Rotor Diameter	IRR
Leitwind LTW101 2000	2 MW	101 m	13,5 %
Vestas V100-1.8	1.8 MW	100 m	12,9 %
Goldwind GW 93/1500	1.5 MW	93 m	17,78 %

TABLE 4.2 – HIGHEST IRR WIND TURBINES FOR GRID CONSTRAINT OPTIMIZATION WITH BATTERY STORAGE

Their IRR is compared in the graph below (Figure 4.7).

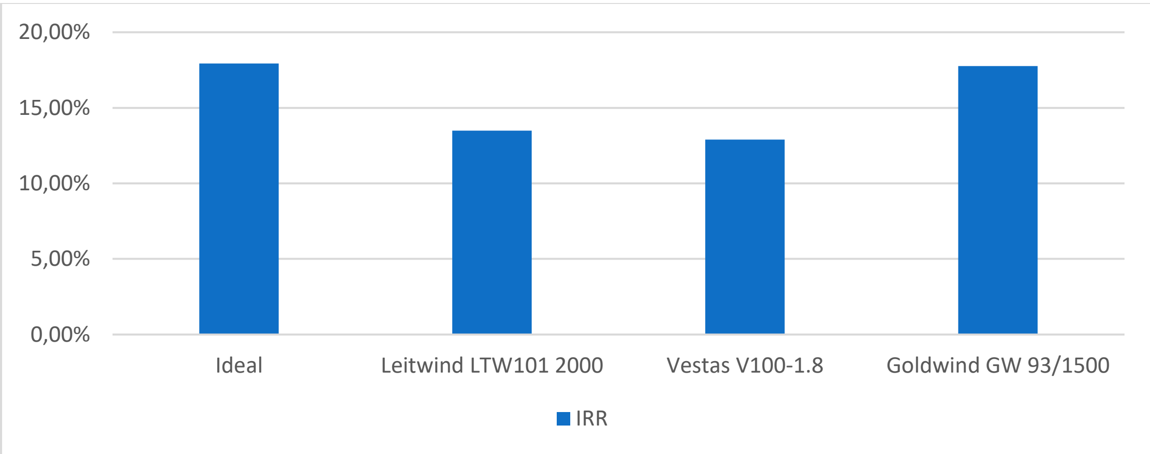


FIGURE 4.7 – IRR OF DIFFERENT WIND TURBINES

The Goldwind GW 93/1500 appears to be the best solution for this case with an $IRR = 17{,}78\%$.
The specifics of this turbine are in Table 5.3 while its power curve is shown in Figure 4.8:

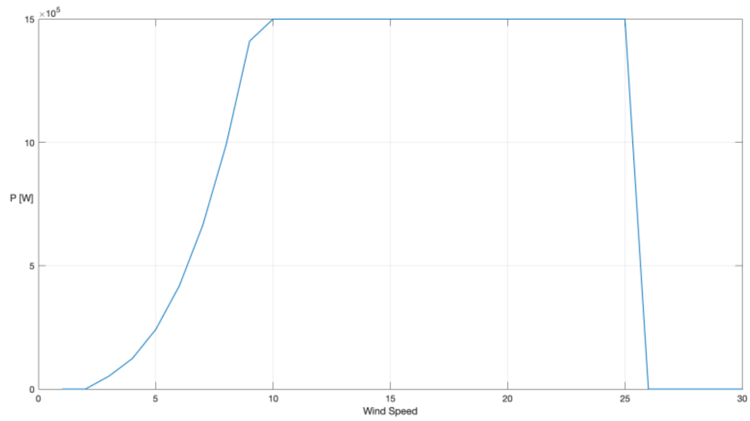


FIGURE 4.8 – GOLDWIND GW 93/1500 POWER CURVE

A possible arrangement of the turbines, similar to the one previously shown, is in Figure 4.9.

FIGURE 4.9 – POSSIBLE ARRANGEMENT OF THE REPOWERED PLANT WITH STORAGE

It is possible to show the cycles of charge and discharge of the battery as well as the sold energy with respect to the generated power (Figure 4.10).

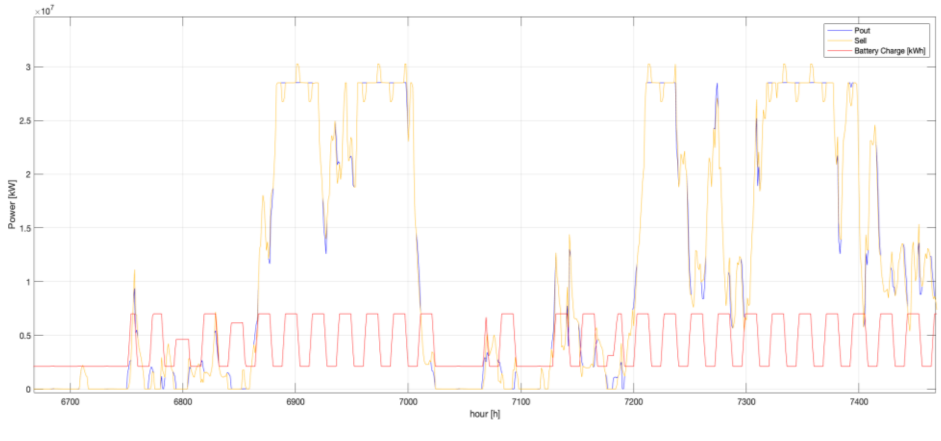


FIGURE 4.10 – OUTPUT POWER [KW], SOLD ENERGY [KW] AND BATTERY CHARGE [KWH]

It has been chosen a period of the year with a particularly low power production to show both when the battery is used at its maximum and when it is not. It is to be noted that the battery charge is indicated in kWh.

4.3 Land Constraint Case

This chapter will investigate the potential of the plant if only the land constraints were to be respected, not considering the limit on the total installed power. cLen and cArea, which used to be non-linear constraints for the optimization, are now set to be equality constraints, the relations are the following:

$$cLen = -1 + \frac{2D \cdot (x(1) - 2)}{3550} = 0$$

$$cArea = -1 + \frac{D^2 \cdot x(1) + A \cdot x(2)}{1.32 \cdot 10^6} = 0$$

This will force the program to completely fill the available land, practically imposing the mix between wind turbines and solar panels, to verify whether there may be benefits in that. As of the last optimization the full length of the plant was already filled with wind turbines, since it has already been shown that wind turbines appear to be more profitable than solar panels, those turbines are left in place while the remaining area is later filled with PVs. The results are:

Number of Wind Turbines	22
Number of Solar Panels	638986
IRR	10,5 %
NPV	118 M€
Initial Cost	257 M€
Installed Power	245 MW
LOLP	81 %

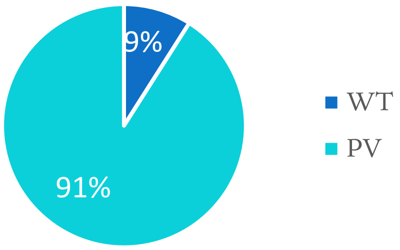


FIGURE 4.11 – WIND AND SOLAR MIX FOR THE LAND CONSTRAINT OPTIMIZATION

Such a farm would produce an average of 7% of the yearly demand of Gran Canaria, exploiting the full potential of the plant would bring that to around 20%.
A second optimization cycle has been run to exploit arbitrage through a battery storage system, implementing once again the turbine design to leave more freedom to the program.
The results in this case are the following:

Optimal Diameter	118 m
Optimal Hub Height	140 m
Optimal Rated Power	3.45 MW
Number of Wind Turbines	16
Number of Solar Panels	1017400
Battery Capacity	11 MWh
IRR	11,1 %
NPV	217 M€
Initial Cost	420 M€
Installed Power	411 MW

LOLP 68 %

The most similar turbines found on the market are shown in Table 4.3:

Turbine	Rated Power	Rotor Diameter	IRR
Vestas V117-3.45	3.45 MW	117 m	10,1 %
Siemens SWT-3.6-120	3.6 MW	120 m	10,9 %
Enercon E-126 EP3 4.0	4 MW	126 m	11 %

TABLE 4.3 – HIGHEST IRR WIND TURBINES AVAILABLE FOR LAND CONSTRAINT OPTIMIZATION

Their IRR is graphically compared in Figure 4.12.

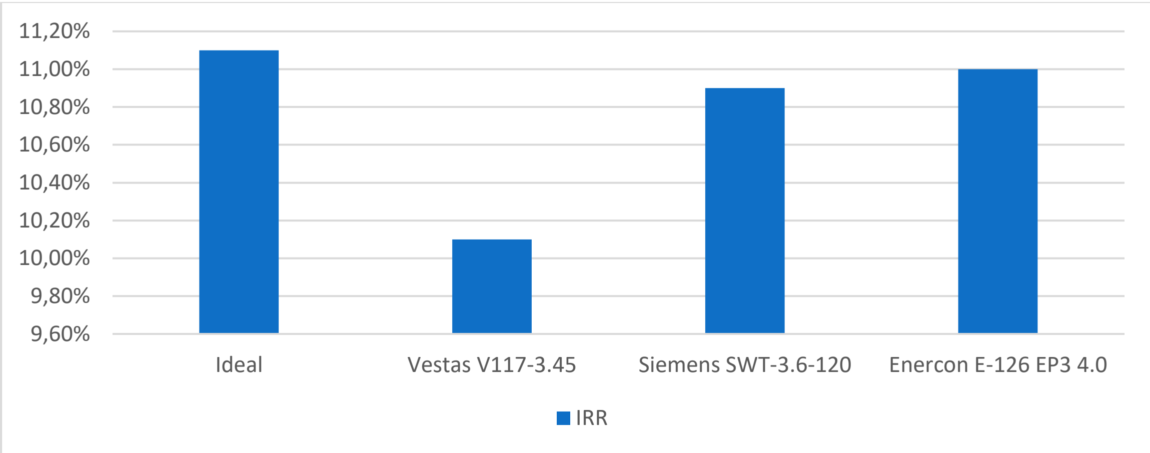


FIGURE 4.12 – IRR OF DIFFERENT WIND TURBINES

The Enercon E-126 EP3 4.0 shows the highest IRR and its use results in a system with the following specifics:

Number of Wind Turbines 16

Number of Solar Panels 1017400

Battery Capacity $11\ MW$ (8h Battery)

IRR $11\ \%$

NPV 225 M€

Initial Cost 427 M€

Installed Power $420\ MW$

LOLP 68 %

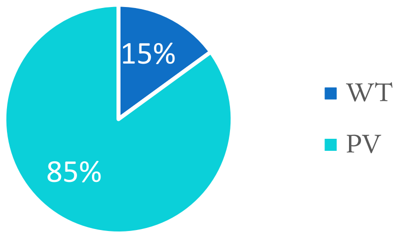


FIGURE 4.13 – WIND AND SOLAR MIX FOR LAND CONSTRAINT OPTIMIZATION WITH STORAGE

The specifics of this turbine are shown in Table 5.4 and the power curve is the following Figure 4.14:

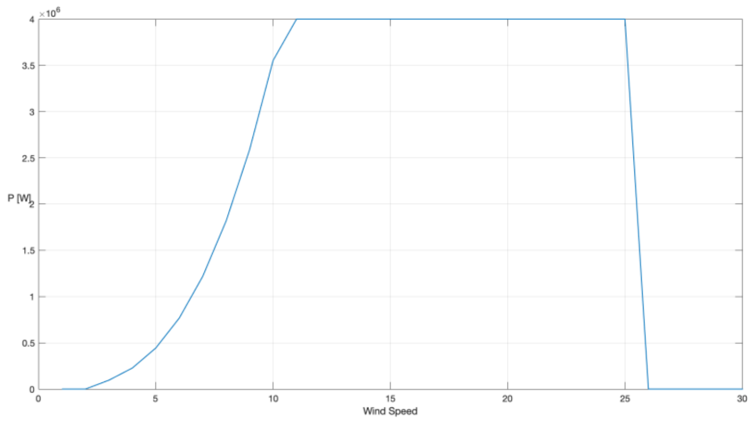


FIGURE 4.14 – ENERCON E-126 EP3 4.0 POWER CURVE

The 8h battery has been chosen, being the one that showed the highest IRR, even if by a small amount with respect to the 4h and the 1h batteries (Figure 4.15).

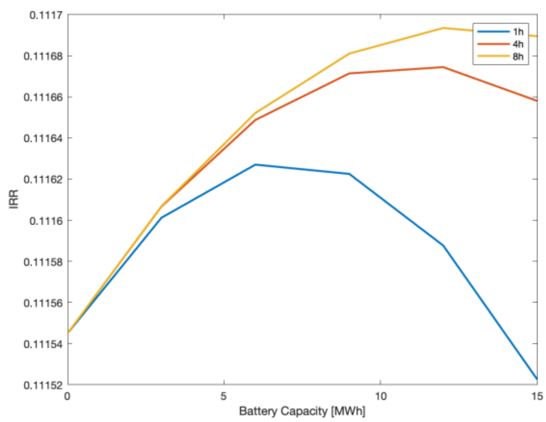


FIGURE 4.15 – IRR EVOLUTION WITH STORAGE INSTALLED CAPACITY

Installing this turbine results in a system that could guarantee an average of 33% (with peaks up to 80%) of the total energy demand of the island, this leads directly to the question of weather is possible, freeing the optimization also from the land constraints, to power the whole island of Gran Canaria with a single plant and weather increasing the percentage of solar in the plant's energy mix could bring some advantages. The percentage of the demand met for the first 3000 hours of the year is shown in Figure 4.16.

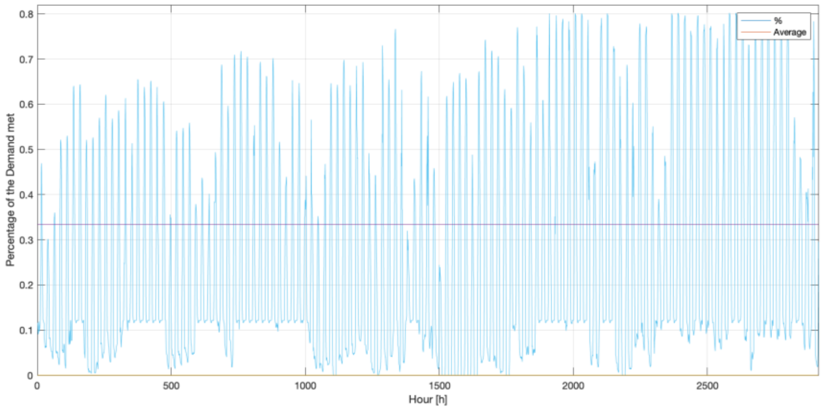


FIGURE 4.16 – PERCENTAGE OF DEMAND MET IN CASE OF OPTIMIZATION FOR LAND CONSTRAINT WITH STORAGE

4.4 Demand Fitting Case

Relaxing also the last constraints (length and area) the point of view changes considerably, we now have the potential to power the entire island and it is in a nation's interest to find the least costly way to do that. The optimization can be run either trying to minimize the initial cost while imposing a maximum LOLP or setting the IRR to be at least higher than zero while minimizing the LOLP.

4.4.1 Minimizing the Initial Cost

From a national point of view, the main goal is not increasing the profitability of the plant anymore but meeting the demand of the island with the lowest possible initial investment. A first optimization has been run considering the initial cost as the function to be minimized and the LOLP as a constraint, this allows to identify more clearly the drivers that push the results to higher or lower percentages of solar power in the energy mix.
Setting the LOLP to be:

$$LOLP \leq 10\%$$

The result is the following:

Number of Wind Turbines	230
Number of Solar Panels	1890000
Battery Capacity	$90\ MW$
Rotor Diameter	$150\ m$
Rated Power	$4.7\ MW$
Hub Height	$105\ m$

This mix would result in an initial investment of 2.075 M€. Seven different turbines, with specifics similar to the ideal one, are shown in Table 4.4:

TURBINE	RATED POWER	DIAMETER
Eno energy eno 114 4.8	4.8 MW	114 m
eno energy eno 126 4.8	4.8 MW	126 m
GE 4.8-158	4.8 MW	158 m
Nordex N133/4800 Delta	4.8 MW	133 m
Goldwind GW 136/4800	4.8 MW	136 m
Enercon E-136 EP5	4.65 MW	136 m
Enercon E-160 EP5	4.6 MW	160 m

TABLE 4.4 – BEST WIND TURBINES TO MINIMIZE COST

The LOLP and initial costs (normalized with respect to the ideal initial cost) of these turbines are compared in Figure 4.17, testing their expected performance with the same number of turbines, solar panels and battery capacity.

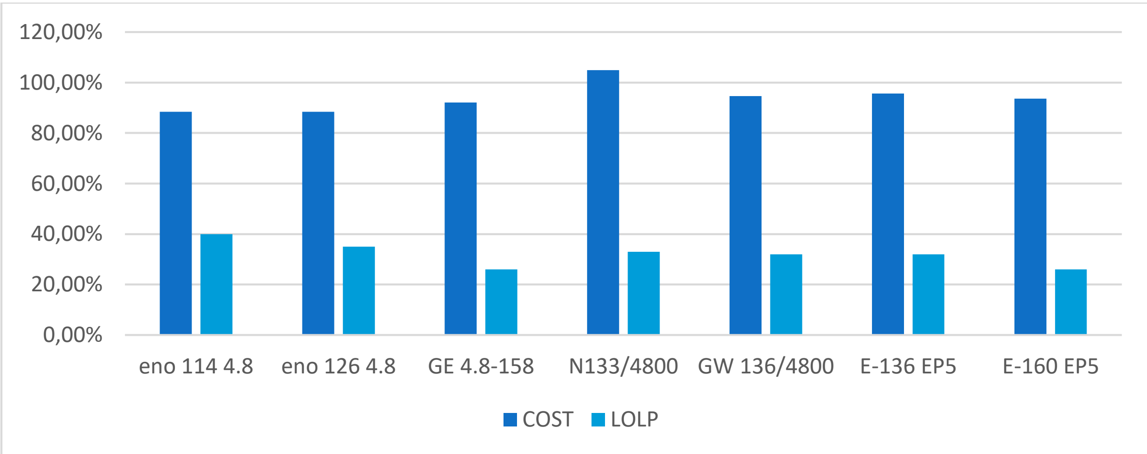


FIGURE 4.17 – COST AND LOLP OF DIFFERENT WIND TURBINES

For completeness, also five wind turbines with similar power densities have been tested (Table 4.5), being the ideal turbine power density $265\ W/m^2$:

TURBINE	RATED POWER	DIAMETER
Vestas V162-5.6 EnVentus	5.6 MW	162 m
Vestas V126-3.3	3.3 MW	126 m
Vestas V136-4.0	4.0 MW	136 m
SWT-DD-142	4.1 MW	142 m
SG 4.5-145	4.5 MW	145 m

TABLE 4.5 – SIMILAR POWER DENSITY WIND TURBINES

These turbines' LOLP and initial cost can again be compared to the ideal ones (Figure 4.18) and show a lower LOLP with respect to the previous ones studied:

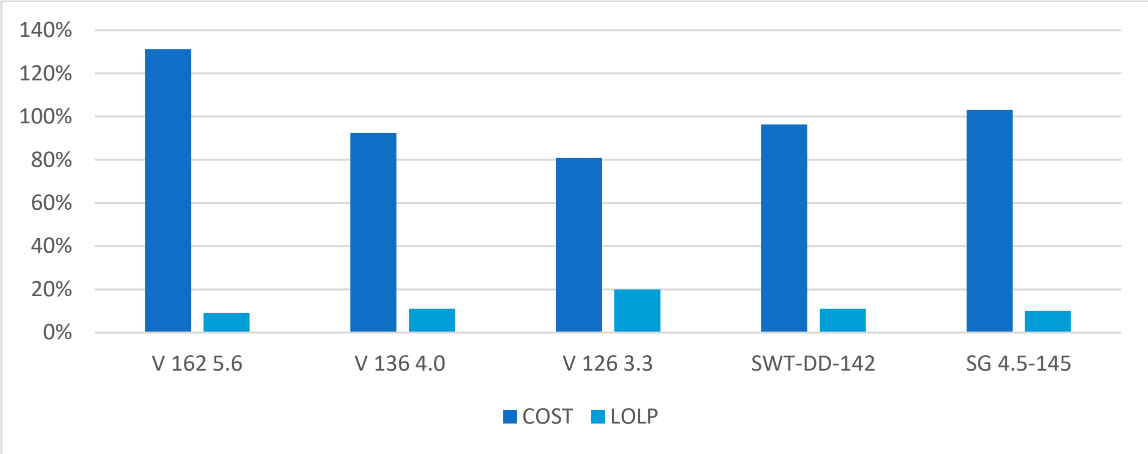


FIGURE 4.18 – COST AND LOLP OF DIFFERENT WIND TURBINES WITH SIMILAR POWER DENSITIES

Out of all the turbine tested the Vestas V136-4.0 shows the best combination of Initial cost and LOLP, its specifics are described in Table 5.5 and the power curve is the following (Figure 4.19):

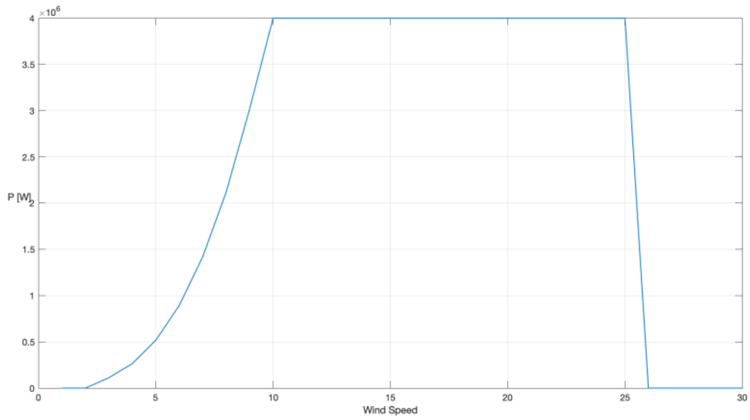


FIGURE 4.19 – VESTAS V136-4.0 POWER CURVE

A second optimization has been run using the new wind turbine specifics, once again setting $LOLP \leq 10\%$, this time using as variables just the number of WT, PV and the Battery's capacity.
The results are the following:

Number of WT	356
Number of Solar Panels	2370900
Battery Capacity	$107\ MW$

The Initial cost, in this case, is 2.500 M€ while the LOLP is of course been driven to be the maximum possible (10%).
Setting $LOLP \leq 20\%$ drives down the price to almost 50% of the previous optimization.

Number of WT	184
Number of Solar Panels	1004000

Battery Capacity	28 MWh

With an initial cost of 1.225 M€.
If the optimization is run with $LOLP \leq 30\%$ as a constraint we obtain the following result:

Number of Wind Turbines	138
Number of Solar Panels	599100
Battery Capacity	15 MWh

And the initial cost decreases to 885 M€.

Figure 4.20 shows how the energy mix varies changing the constraint on the LOLP.

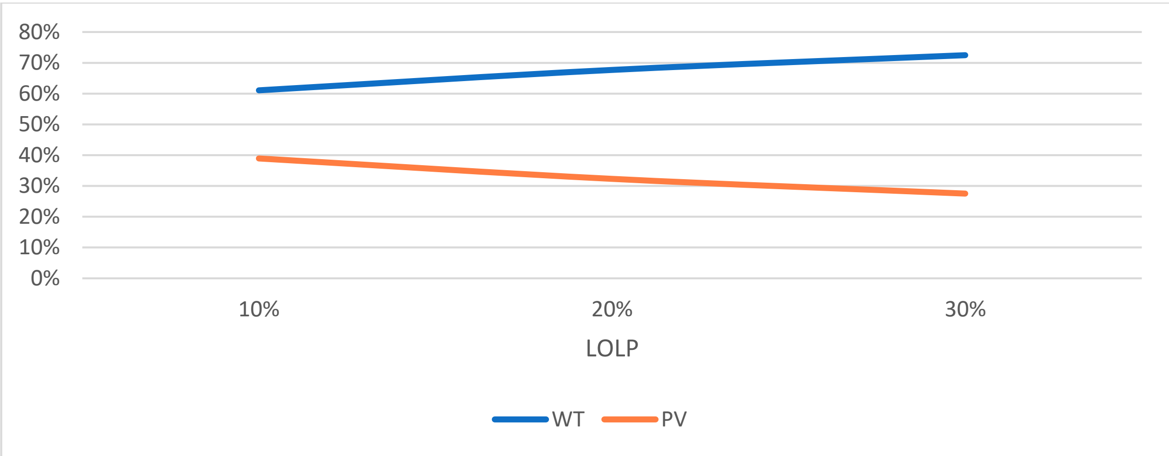


FIGURE 4.20 – VARIATION OF THE ENERGY MIX WITH HIGHER LOLP IMPOSED

These solutions all have a negative IRR and might then result in a loss of capital for the investor, but they clearly show how lower values of LOLP call for a higher percentage of solar panels and storage in the energy mix. However insightful this observation can be, a different approach has been used to find a feasible solution, minimizing the LOLP.

4.4.2 Minimizing the LOLP

This optimization has been run setting the LOLP as the objective function while using as a constraint the IRR, set to be equal or higher than zero. This results in a minimum possible LOLP around 8% (where IRR=0), which is achieved with a plant with the following properties:

Number of Wind Turbines	140
Number of Solar Panels	1906000
Battery Capacity	$171\ MWh$
Rotor Diameter	$210\ m$
Rated Power	$6.6\ MW$
Hub Height	$142\ m$

The resulting power density for this ideal turbine is $190\ W/m^2$, this was the minimum value set as a constraint. It is interesting to understand why the optimizer met this limit to minimize the objective function. A low power density is the result of a low ratio between the rated power and the swept area (which depends on the rotor diameter). A possible explanation is that the diameter dimension is pushed towards the limit in order to have a lower rated wind speed.
For the ideal turbine found, setting $cp_{\max} = 0.48$:

$$v_{rated} = 9.8\ m/s$$

A lower-rated wind speed might be a crucial factor in increasing the capacity factor of the farm in a site that is considered III class. Large turbines similar to the ideal one found are too big to be built onshore, for this reason, smaller turbines with analogous power densities have been tested and confronted (Table 4.6 and Figure 4.21):

TURBINE	RATED POWER	DIAMETER
GW 184/6450	6.45 MW	184 m
GW 155/4500	4.5 MW	155 m
E-160 EP5	5.0 MW	160 m

TABLE 4.6 – BEST WIND TURBINES TO MINIMIZE THE LOLP

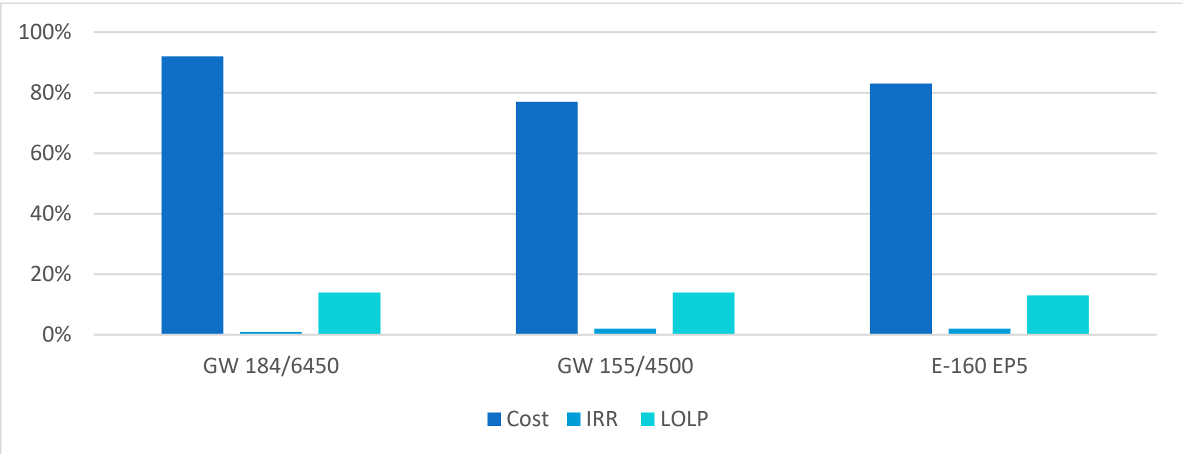


FIGURE 4.21 – COST, IRR AND LOLP OF DIFFERENT WIND TURBINES

Out of these turbines only the GW 155/4500 has a dimension that respects the maximum rotor diameter set as a constraint for the ideal turbine, conveniently enough is also the one that shows the best Cost-IRR-LOLP mix. Running the optimization using this specific turbine gives the following result:

Number of Wind Turbines	185	
Number of Solar Panels	1685000	
Battery Capacity	$171\ MWh$	(4h Battery)
IRR	0%	
LOLP	11%	
Initial Investment	$1880\ M€$	

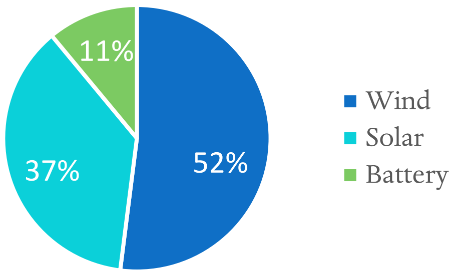


FIGURE 4.22 – ENERGY MIX IN OPTIMIZATION FOR MINIMIZING LOLP

To give an idea of the power production of such a plant with respect to the demand, a plot of these two values for the first 300 hours of a year is shown in Figure 4.23:

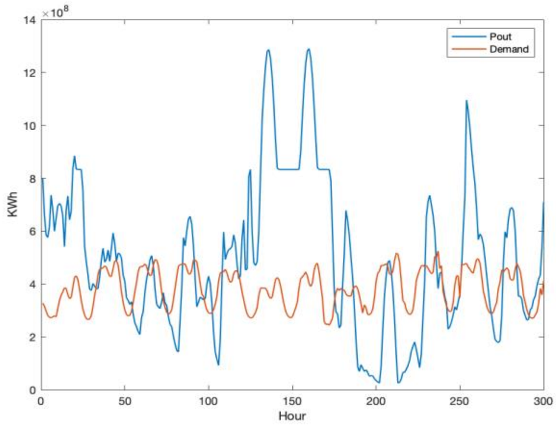


FIGURE 4.23 – POWER OUTPUT AND DEMAND CURVE

The turbine's specifics are in Table 5.6 and the power curve is the following (Figure 4.24).

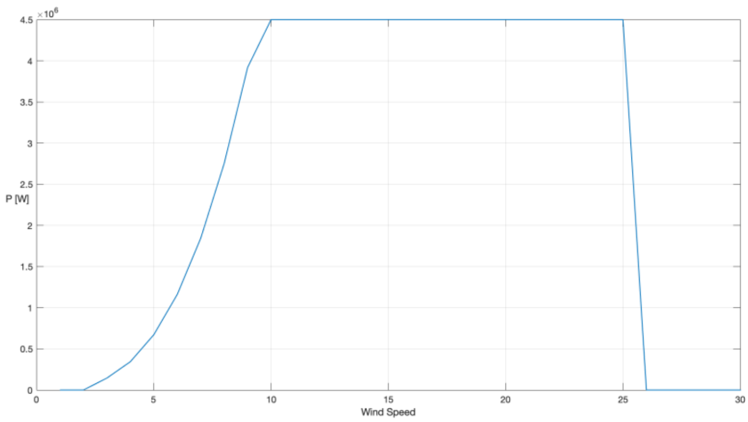


FIGURE 4.24 – GW155-4.5 POWER CURVE

4.5 Benchmarking

This last optimization has been compared with a simulation run on HOMER PRO. The optimal energy mix appears to be similar to the one found with this study, as it can be seen in Figure 4.25:

Architecture						Cost	
			WT	PV	Batt	NPC (€)	Initial capital (€)
			182	1,617,183	170	€4.30B	€1.84B
			182	1,617,183	170	€4.30B	€1.84B

FIGURE 4.25 – ENERGY MIX USING HOMER PRO

Evaluating the differences in the results as a percentage makes it easier to appreciate the comparison [Figure 4.26], such differences vary from 1% to 4%, more information on the results obtained can be found in Appendix B.

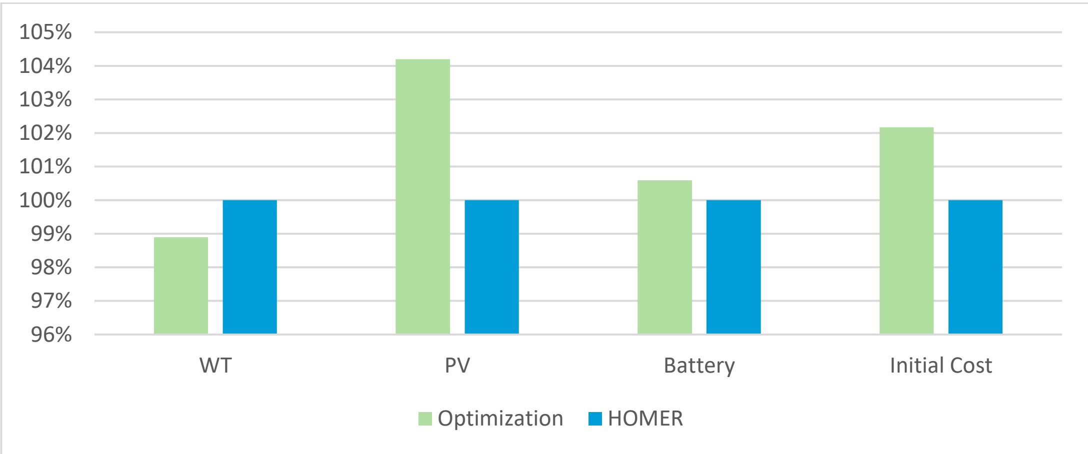


FIGURE 4.26 – BENCHMARKING

5 CONCLUSIONS

5.1 Key Findings

The benefits of repowering have been explained in the first chapter and are shown already in the methodology with a reduced cost model for repowered plants. Its importance is even greater for the case study chosen because of the scarcity of new land in the Canary Islands (and many other remote islands in the world) thus the interest in keeping end-of-life plants working.

The feasibility and potential of hybrid resources vary according to the purpose of their installation.
The optimizations ran showed that, where one resource's presence is stronger than the other, it appears more profitable to use the former and discard the latter. Given the particular site considered and the still cheaper technology of wind turbines with respect to solar panels, a conventional repowering (with the addition of a battery to take advantage of arbitrage) seemed to be the most favorable option.

It is when the sizing is demand-driven, rather than revenue-driven, that HRES attract real interest. The complementarity of solar and wind resources with the help of storage helps to better fit the demand curve while minimizing the initial cost. The choice of a remote island was punctual because of the importance of energy independence from the mainland and the high cost of conventional resources.

Energy is a world-wide essential need and the quality of its generation is crucial to the well-being of humanity for the next generations. Higher reliability of renewable energy sources, with an expected decrease in installation, maintenance and storage costs might make the difference for a cleaner future.

5.2 Recommendations

In conclusion, for a plant level revenue-driven optimization, considering only the energy market, there appears to be only a marginal benefit for a hybrid plant. On the other hand, the complementarity of wind and solar can be exploited when the optimization objective is the economical matching of the demand. In light of this difference in outcomes, it is worthwhile to revisit the plant level revenue-driven optimization taking into account some additional benefits of co-locating wind and solar, e.g. efficient land usage, shared infrastructure, additional revenue streams, etc.

It is possible to apply the program written to a vast number of different plants, it is important however to vary the constraints depending on the legislation of the country chosen. The only other input values are the weather conditions and demand data hour by hour that have to be given properly. I hope that this work will be of help to whoever will approach this field of research, possibly going deeper into the details that were discarded and avoiding some of the approximations and simplifications made here.

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Appendix A – Wind Turbines

5.3 Desa A300

DESA A300	
Power	
Rated Power	$300\ kW$
Cut-in wind speed	$5.0\frac{m}{s}$
Rated wind speed	$12.0\frac{m}{s}$
Cut-out wind speed	$25.0\frac{m}{s}$
Survival wind speed	$56.0\frac{m}{s}$
Rotor	
Diameter	$30\ m$
Swept area	$755.0\ m^2$
Number of blades	3
Rotor speed (max)	$43.2\frac{U}{min}$
Tip speed	$68\frac{m}{s}$
Type	14.99
Material	$GFRP$
Power density 1	$397.4\frac{W}{m^2}$
Power density 2	$2.5\frac{m^2}{kW}$
Gear Box	
Type	$Spur$
Stages	2.0
Ratio	$1:35$
Manufacturer	$Flender$
Generator	
Type	$Asynchronous$
Number	1
Speed (max)	$1{,}500.0\frac{U}{min}$
Voltage	$660\ V$
Grid Connection	$IGBT$
Grid Frequency	$50\ Hz$
Tower	
Hub height	$30\ m$
Type	$Steel\ Tube$
Shape	$Conical$

Corrosion protection	*Painted*

TABLE 5.1 – DESA A300 SPECIFICS

5.4 Leitwind LTW90 1000

Leitwind LTW90 1000	
Power	
Rated Power	$1\ MW$
Cut-in wind speed	$3.0 \frac{m}{s}$
Rated wind speed	$9.0 \frac{m}{s}$
Cut-out wind speed	$25.0 \frac{m}{s}$
Rotor	
Diameter	$90.3\ m$
Swept area	$6{,}404.0\ m^2$
Number of blades	3
Rotor speed (max)	$15.0\ \frac{U}{min}$
Tip speed	$71\ \frac{m}{s}$
Type	$LS44.0$
Material	$GFRP - EP$
Manufacturer	*Schütz*
Power density 1	$156.2\ \frac{W}{m^2}$
Power density 2	$6.4\ \frac{m^2}{kW}$
Gear Box	
Type	*Direct Drive*
Generator	
Type	*Synchronous Permanent*
Number	1
Speed (max)	$15.0 \frac{U}{min}$
Voltage	$690\ V$
Grid Connection	$IGBT$
Grid Frequency	$50/60\ Hz$
Manufacturer	*Leitner*
Tower	
Hub height	$90\ m$
Type	*Steel Tube*
Shape	*Conical*
Corrosion protection	*Painted*

TABLE 5.2 – LEITWIND LTW90 1000 SPECIFICS

5.5 Goldwind GW 93/1500

Goldwind GW 93/1500	
Power	
Rated Power	$1.5\ MW$
Cut-in wind speed	$3.0\frac{m}{s}$
Rated wind speed	$10.0\frac{m}{s}$
Cut-out wind speed	$25.0\frac{m}{s}$
Rotor	
Diameter	$93\ m$
Swept area	$6{,}793.0\ m^2$
Number of blades	3
Gear Box	
Type	$Direct\ Drive$
Generator	
Type	$Synchronous\ Permanent$
Number	1
Voltage	$690\ V$
Grid Connection	$Inverters$
Grid Frequency	$50/60\ Hz$
Manufacturer	$GoldWind$
Tower	
Hub height	$80\ m$
Type	$Steel\ Tube$
Shape	$Conical$
Corrosion protection	$Painted$

TABLE 5.3 – GOLDWIND GW 93/1500 SPECIFICS

5.6 Enercon E-126 EP3 4.0

Enercon E-126 EP3 4.0	
Power	
Rated Power	$4\ MW$
Cut-in wind speed	$3.0\frac{m}{s}$
Rated wind speed	$10.0\frac{m}{s}$
Cut-out wind speed	$25.0\frac{m}{s}$
Rotor	
Diameter	$126\ m$
Swept area	$12{,}667.0\ m^2$
Number of blades	3
Gear Box	
Type	$Direct\ Drive$
Generator	
Type	$Synchronous$

Number	1
Voltage	$690\ V$
Grid Connection	*Inverters*
Grid Frequency	$50/60\ Hz$
Manufacturer	*Enercon*
Tower	
Hub height	$140\ m$
Type	*Steel Tube*
Shape	*Conical*
Corrosion protection	*Painted*

TABLE 5.4 – ENERCON E-126 EP3 4.0 SPECIFICS

5.7 Vestas V136-4.0

Vestas V136-4.0	
Power	
Rated Power	$4\ MW$
Cut-in wind speed	$3.0\frac{m}{s}$
Rated wind speed	$10.0\frac{m}{s}$
Cut-out wind speed	$25.0\frac{m}{s}$
Rotor	
Diameter	$136\ m$
Swept area	$14{,}527.0\ m^2$
Number of blades	3
Power Density	$275{,}3\ W/m^2$
Gear Box	
Type	*Direct Drive*
Generator	
Type	*two planetary stages and one helical stage*
Stages	2
Tower	
Hub height	$105\ m$
Type	*Steel Tube*
Shape	*Conical*
Corrosion protection	*Painted*

TABLE 5.5 – VESTAS V136-4.0 SPECIFICS

5.8 GoldWind GW 155/4500

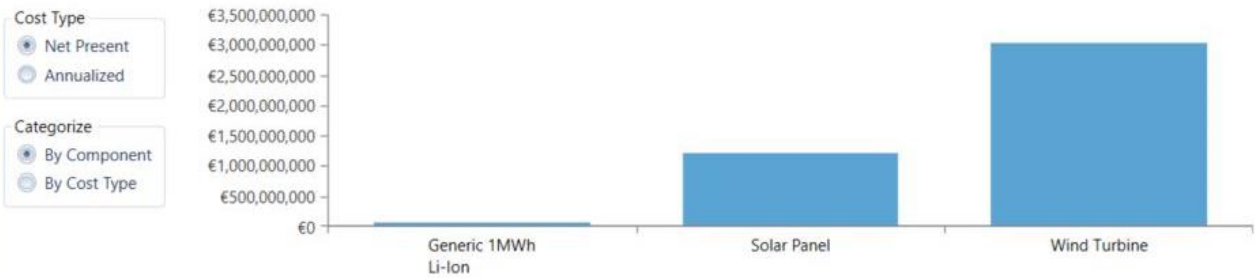
GW 155/4500	
Power	
Rated Power	$4.5\ MW$
Cut-in wind speed	$3.0\frac{m}{s}$

Rated wind speed	$10.5 \frac{m}{s}$
Cut-out wind speed	$25.0 \frac{m}{s}$
Rotor	
Diameter	$155\ m$
Swept area	$18{,}869.0\ m^2$
Number of blades	3
Gear Box	
Type	$Direct\ Drive$
Generator	
Type	$Permanent\ Magnet\ Synchronous$
Number	1
Voltage	$690\ V$
Grid Connection	$IGBT\ Full\ Power\ Converter$
Grid Frequency	$50/60\ Hz$
Manufacturer	$GoldWind$
Tower	
Hub height	$140\ m$
Type	$Steel\ Tube$
Shape	$Conical$
Corrosion protection	$Painted$

TABLE 5.6 – GW 155-4.5 SPECIFICS

Appendix B – HOMER PRO Results

5.9 Cost Summary



Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic 1MWh Li-Ion	€59,500,000.00	€0.00	€0.00	€0.00	€0.00	€59,500,000.00
Solar Panel	€562,779,555.24	€0.00	€646,873,052.00	€0.00	€0.00	€1,209,652,607.24
Wind Turbine	€1,217,685,755.52	€0.00	€1,811,057,289.60	€0.00	€0.00	€3,028,743,045.12
System	€1,839,965,310.76	€0.00	€2,457,930,341.60	€0.00	€0.00	€4,297,895,652.36

FIGURE 5.1 – COST SUMMARY

5.10 Electrical

Production	kWh/yr	%
Wind Turbine	4,835,616,515	78.7
Solar Panel	1,309,098,215	21.3
Total	6,144,714,731	100

Consumption	kWh/yr	%
AC Primary Load	0	0
DC Primary Load	3,087,321,800	100
Deferrable Load	0	0
Total	3,087,321,800	100

Quantity	kWh/yr	%
Excess Electricity	3,055,556,342	49.7
Unmet Electric Load	379,601,500	10.9
Capacity Shortage	453,721,975	13.1

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	409	%

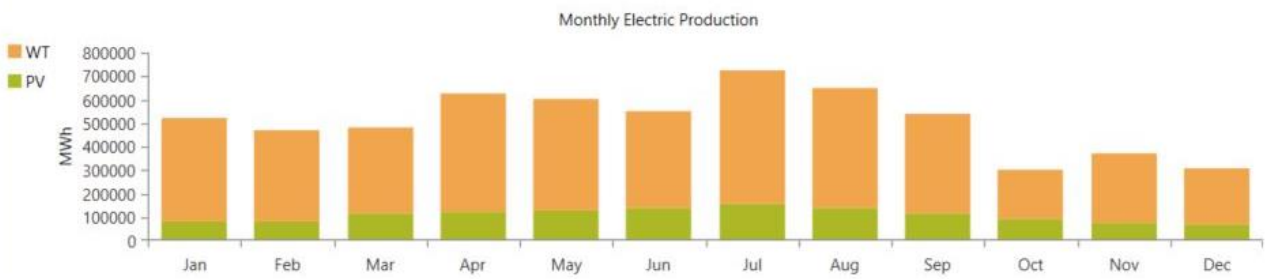


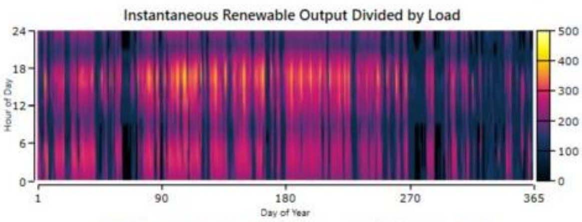
FIGURE 5.2 – ELECTRIC PRODUCTION

5.11 Renewable Penetration

Capacity-based metrics	Value	Units
Nominal renewable capacity divided by total nominal capacity	100	%
Usable renewable capacity divided by total capacity	100	%

Energy-based metrics	Value	Units
Total renewable production divided by load	199	%
Total renewable production divided by generation	100	%
One minus total nonrenewable production divided by load	100	%

Peak values	Value	Units
Renewable output divided by load (HOMER standard)	409	%
Renewable output divided by total generation	100	%
One minus nonrenewable output divided by total load	100	%



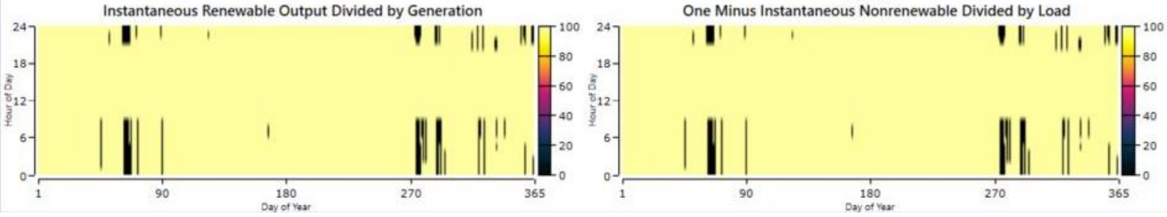


FIGURE 5.3 – RENEWABLE PENETRATION

5.12 Wind Turbine

Quantity	Value	Units
Rated Capacity	182	
Mean Output	552,011	kW
Mean Output	13,248,264	kWh/d
Capacity Factor	67.4	%
Total Production	4,835,616,515	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	819,071	kW
Hours of Operation	8,184	hrs/yr
Levelized Cost	0.0251	€/kWh

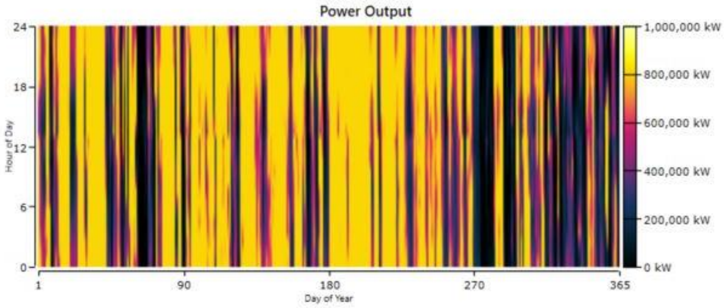


FIGURE 5.4 – WIND TURBINE'S PERFORMANCE

5.13 Solar Panel

Quantity	Value	Units
Rated Capacity	1,617,183	
Mean Output	149,440	kW
Mean Output	3,586,570	kWh/d
Capacity Factor	26.4	%
Total Production	1,309,098,215	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	566,014	kW
Hours of Operation	4,651	hrs/yr
Levelized Cost	0.0370	€/kWh

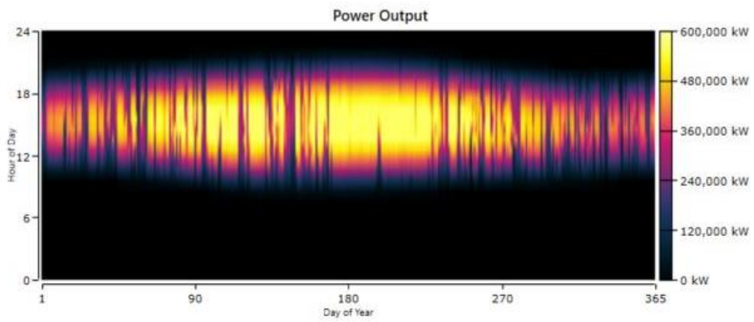


FIGURE 5.5 – SOLAR PANEL'S PERFORMANCE

5.14 Load and Generation

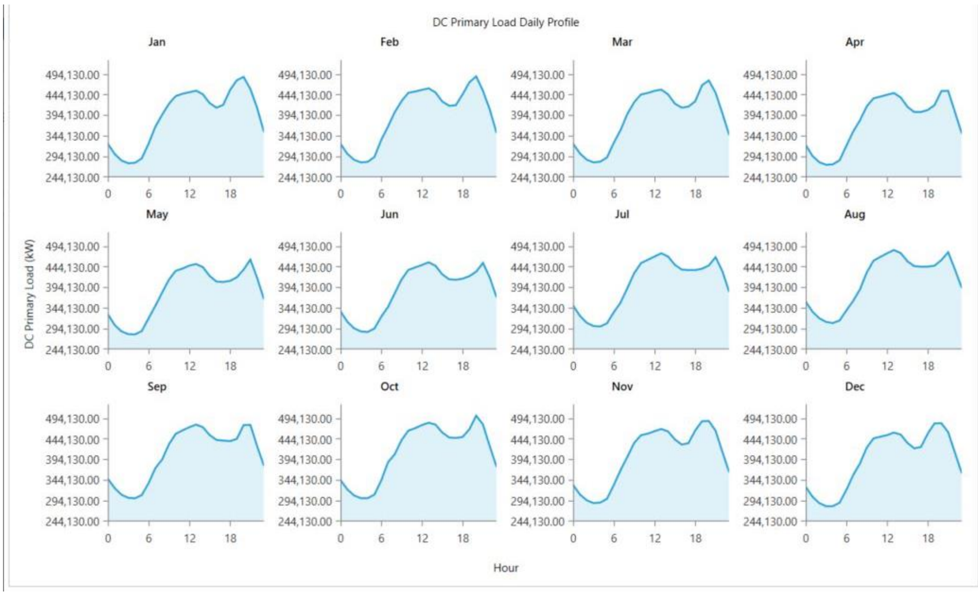


FIGURE 5.6 – PRIMARY LOAD DAILY PROFILE

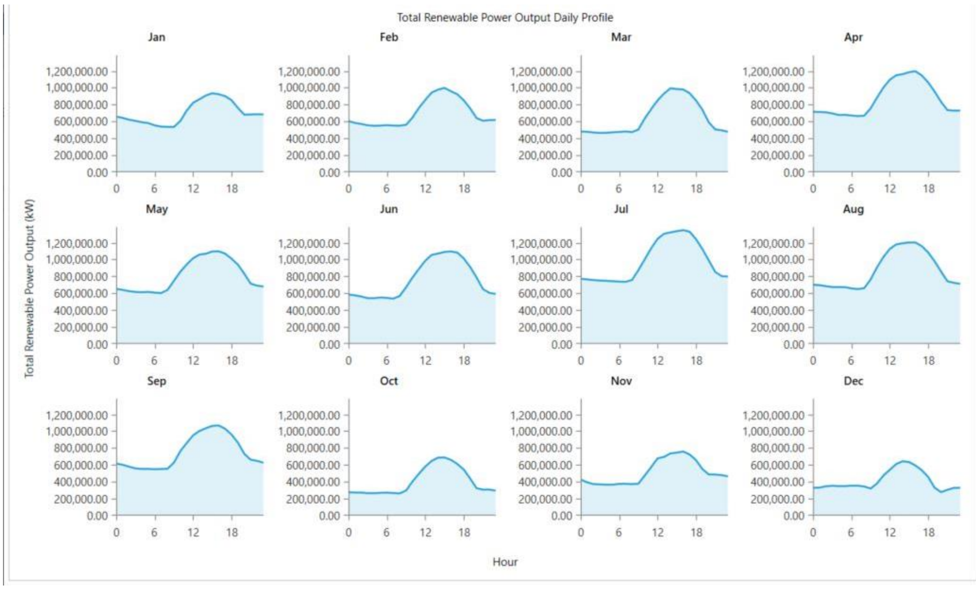


FIGURE 5.7 – POWER OUTPUT DAILY PROFILE

FIGURE 5.8 – PRIMARY LOAD SERVED DAILY PROFILE

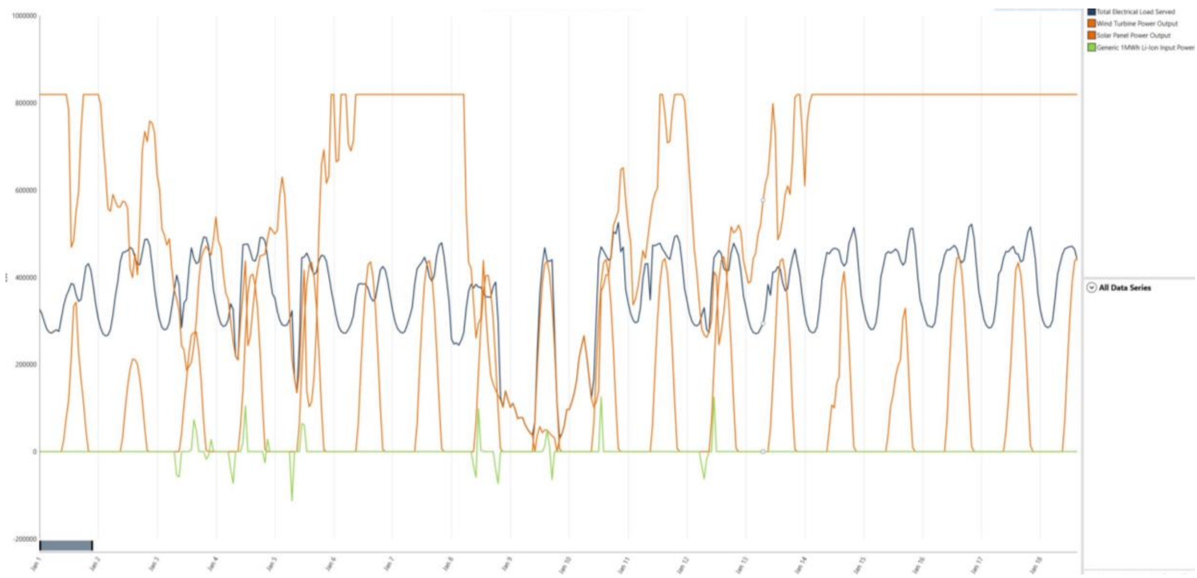


FIGURE 5.9 – POWER OUTPUT AND DEMAND CURVE

Appendix C – Wind Farms on Gran Canaria

Name	Turbine	N°	Rated Power of the Turbines [KW]	Installed Power [KW]	Specific Power [KW/m^2]	Municipality	Year
P.E. Arinaga Depuradora	Vestas	1	200	200	0,407	Agüimes	1991
P.E. A. G. del Atlantico	Vestas	4	225	900	0,393	Agüimes	98/02
P.E. Lomo el Cabezo	Enercon	3	600	1.800	0,470	Agüimes	1999
P.E. Montana Francisco	Vestas	5	225	1.125	0,393	Agüimes	2001
P.E. La Florida	Gamesa	4	660	2.500	0,380	Agüimes	2002
P.E. Carretera de Arinaga	Enercon	1	2.000	6.920	0,429	Agüimes	02/12
	Made	7/1	660/300				
P.E. Concasur	Izar Bonus	1	600	600	0,395	Agüimes	2004
P.E. Pesbar, Arinaga	Gamesa	1	850	850	0,377	Agüimes	2005
Plataf Ensayo M. Arinaga	Gamesa	1	5.000	5.000	0,389	Agüimes	2013
P.E. S. Bolanos	Electria Wind	1	200	200	0,325	Agüimes	2015
P.E. C. Herbania	Enercon	1	850	850	0,559	Agüimes	2017
P.E. Tenefé	Vestas	5	225	1.125	0,393	Santa Lucìa	1992
P.E. Santa Lucìa	Made	16	300	4.800	0,467	Santa Lucìa	1998
P.E. B. de Formas II	Enercon	4	600	2.000	0,392	Santa Lucìa	1998
P.E. ITC Tenefé (CIEA)	Enercon	2	230	460	0,356	Santa Lucìa	1998
P.E. P. Tenefé Ampliaciòn	Vestas	1/1	230/225	455	0,397	Santa Lucìa	1999
P.E. B. de Formas III	Enercon	10	600	5.000	0,392	Santa Lucìa	2000
P.E. B. de Formas IV	Enercon	10	600	5.000	0,392	Santa Lucìa	2000
P.E. La Punta	Enercon	11	500	5.500	0,392	Santa Lucìa	2000
P.E. La Gaviota	Ecotenia	11	630	6.930	0,414	Santa Lucìa	2001
P.E. Finca S. Antonio	Made	5	300	1.500	0,467	Santa Lucìa	1999
P.E. Barranco de Tirajana	Enercon	1	2.000	2.000	0,520	S. B. Tirajana	94/16
P.E. Llanos de Juan Grande	Desa	67	300	20.100	0,424	S. B. Tirajana	1996
P.E. Las Salinas del M.	Gamesa	3	850	2.550	0,400	S. B. Tirajana	08/12/15
P.E. La Florida – J. Bonny	Gamesa	1	850	850	0,400	S. B. Tirajana	2011
P.E. S. Bartolomé (Mocàn)	Enercon	4	2.300	9.200	0,581	S. B. Tirajana	2017
P.E. Llanos de la Aldea	Enercon	25	800	20.000	0,442	S. B. Tirajana	2017
P.E. Lomo R.- Muescanarias	Enercon	1	330	330	0,397	Ingenio	2008
P.E. C. C. Canarias AENA	Made	1	660	660	0,397	Telde	2003
P.E. Montana Pelada	Made	7	660	4.620	0,397	Gàldar	2001

P.E. P. de m. hormigonado	Enercon	1	900	900	0,592	Gàldar	2017
P.E. Cueva Blanca	Enercon	1	2.000	2.000	0,520	Agaete	97/16
Aerogenerador La Aldea	Vestas	1	225	225	0,393	La Aldea De SN	1996
P.E. Balcòn De Balos	Enercon	4	2.300	9.200	0,436	Agüimes	2018
P.E. Montana Perros	Enercon	1	2.300	2.300	0,346	Agüimes	2018
P.E. Triquivijate	Enercon	2	2.350	4.700	0,354	Agüimes	2018
P.E. Doramas	Enercon	1	2.300	2.300	0,581	Agüimes	2018
P.E. La Vaquerìa	Enercon	1	2.350	2.350	0,354	Agüimes	2018
P.E. Harìa	Enercon	1	2.350	2.350	0,354	Agüimes	2018
P.E. Vientos del Roque	Enercon	2	2.350	4.700	0,354	Agüimes	2018
P.E. Las Colinas	Enercon	2/2	2.350/2.300	9.300	0,438	Santa Lucìa	2018

TABLE 5.7 – WIND FARMS ON GRAN CANARIA