Treball de Fi de Màster

Màster Universitari en Enginyeria Industrial (MUEI)

Design, Control and operation of a hybrid renewable power plant

MEMÒRIA

September 22, 2020

Autor: Pere Herraiz Pujol

Director: Eduardo Prieto Araujo

Convocatòria: Juny 2020

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

Abstract

One of the most important disadvantages of the renewable energy production in a grid scale is its dependence on the weather or local climate of the location. The weather conditions can be very changing and unpredictable in a world that depends on a constant connection to the grid. If the natural resources like sun and wind complement each other is a good opportunity to take into account the hybrid renewable power plants. In this work, centered in Spain, has been made a weather data research of 4 different locations. These locations have in common that there is already implanted a wind power plant.

This interaction between resorces, suggest that a good place to install a hybrid renewable power plant is in Sierra Costera, Aragón. A power plant that complement wind power with solar PV energy. But, even combining these two resources there is still a high dependence on the weather, because there are many time periods during a year with neither sun nor wind. That is the reason why in this project has been simulated and optimized the hybrid power plant with an extra element, electric energy storage system.

Once all meteorological data has been treated and interpreted, three different main parts of the project have been developed. Sizing and optimization to satisfy a constant load, development of a new power plant connected to the grid and development of a refurbishment of the wind power plant to hybridize it. In the three parts have been used Matlab to simulate the power plant behaviour with the meteorological data acquired.

To satisfy a constant load has been used a methodology called Deficiency of power supply probability (DPSP) programmed with Matlab. The results on this situation show that to satisfy a constant load with a high provability, over 95 % of the time, cause an oversizing of the power plant. A lot of power installed, for a very little load satisfied. Analyzing the second situation, development of a new power plant connected to the grid, has been made an study of interaction between the variables, solar PV power, wind power, power plant capacity power and storage system capacity. The results in these interactions are good, but too expensive considering there is already a wind power plant working in the area.

The third main part, development of a refurbishment of the wind power plant, has proved to be the best option. It has been simulated the profitability of this project for 15 years in 49 distinct combinations of battery systems and quantity of solar PV panels installed, helping to decide which one is the best combination. The energy shared to the grid has increased over 100 % and the battery system helps to decrease the energy wasted because of the power plant main transformer capacity.

Contents

List of Figures and Tables

List of Figures

List of Tables

Preface

In the last decades, in global terms, has been a clear fossil fuels energetic dependence. Bit by bit, for climate reasons and as these are not unlimited resources, it has been a certain migration to renewable energy production. This migration grows more every year. As all energy resources, renewable energies, have various disadvantages. One of them, for example in resources like solar photo-voltaic or wind energy, is that the produced energy has a very strong dependence on climate conditions of the region and the local weather. These climate and weather conditions can be very changing and unpredictable, which does not match with the kind of consumption of the modern society that tends to have consume with not dependence on the weather.

One of the solutions to avoid the disadvantage that presents the renewable energy is to hybridize the way we produce energy, this is the subject matter of this project.

Hybrid power plants consist in combine various energetic resources with two main objectives, to maximize the produced energy compared with the energy that resources offer, and minimize time slots that for weather conditions, are little or not productive.

The most common hybrid power plants are the ones that combine diesel with any other renewable resource like wind, solar thermal, solar photo-voltaic, hydro power among others. But lately, in order to avoid fossil fuels, new hybrid power plants have been designed only with renewable resources. We will name these new power plants, renewable hybrid power plants. The most common resources combined are photo-voltaic plus wind, photo-voltaic plus hydro power, hydro power plus wind and thermo-solar plus biomass. This resource combination help to fix a little the disadvantages exposed before, but in all combinations there is still a big dependence on the weather. That is the reason to think that may be an other new improvement in the hybrid power plant to avoid this weather dependence.

In recent years the use of energy storage systems like batteries has been extended in our society for many reasons, electric mobility, wireless machines and products, and the technology around these storage systems is enhancing every day. This new improvement will be discussed and developed in subject matter of this project. The combination of two different natural energy resources with a storage energy system is interesting for two reasons. Fist of all, to make use of the maximum amount of energy that natural resources offer in the minimum space with the minimum impact. On the other hand, the batteries system, will help to avoid these times of the day that the power production is to low or null. In the present project will be discussed and simulated the combination of the two renewable resources, wind and solar photo-voltaic, with a storage system.

Objectives and scope

The first objective of this work consist in acquire meteorological data of wind speed and sun irradiance of the studied locations. As more data get from these locations, more accurate will be the results. Is important to get hourly data in order to design a more versatile power plant. After the data acquisition it is wanted to evaluate how much energy are capable to produce the studied locations to visualize their potential of production. Compare statistically the data from the different studied locations, the best will be chosen in terms of best complementation of the resources.

Once the data is acquired and treated it is wanted to be used to make a design and operation process in different situations. This calculation of power production will be used in a power plant, consisting always of a wind, solar PV and storage system combination, that is designed to satisfy a known load or demand. After designing the optimal power plant it will be shown how this power plant operates.

It is also wanted to design a hybrid power plant which is intended to be connected to the grid. It will be designed by developing a program that simulates the behaviour of the power plant in many different combinations of, wind power, solar PV power, power plant capacity and storage system capacity. With this information it will be shown the operation of the optimal combination.

Finally, as the studied locations are places with wind farms already installed, it is wanted to study and design the possibility of refurbish the power plants. In other words, convert the wind farm in a renewable hybrid wind, solar PV and storage system power plant. In this case, the program will simulate the power plant behaviour in order to design it with the existing wind turbines and optimize the solar PV power installed and the storage system capacity in terms of economic benefits.

The scope of this project is to prove with results the synergy of the natural resources in different situations or objectives. See that the wind and the sun can be complementary resources, appropriate for the implementation of hybrid power plants. It will be also important to see how can enhance the clean energy production, reducing CO_2 emissions by designing a new hybrid power plant or refurbish an existing wind farm and reducing the environmental impact of the area.

1 Introduction

1.1 Hybrid renewable power plants

A hybrid renewable power plant is a power plant that combines various renewable resources with two main objectives. The first one is to produce the maximum amount of clean energy to reduce CO_2 emissions. The second main objective is to make the power plant less dependent on the weather conditions. Sometimes hybrid power pants are complemented with energy storage systems in order to satisfy the second main objective.

Fig. 1 show a basic diagram of a hybrid power plant. The wind and the solar PV (photo-voltaic) power, in parallel, are rectified and converted before being connected to the main power line. The storage system is also connected to the power line before the main transformer and is used depending on the renewable energy production or the design demand of the power plant.

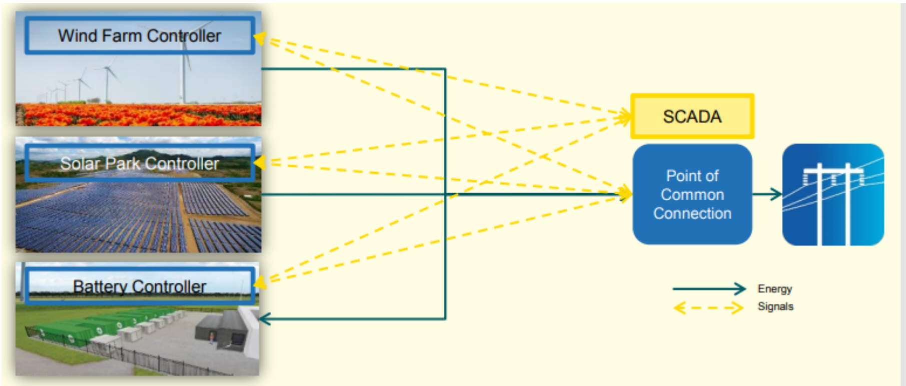


Figure 1: Scheme of a wind, sun, storage system hybrid power plant [14]

1.2 Existing hybrid renewable plants

At present there are some hybrid power plants with only renewable resources. Some of them are summarized in Table 1. The following examples of hybrid power plants have in common that they combine the same two natural resources, wind and solar PV energy. Only two of them have also started to combine these two resources with battery systems in order to enhance the power plant efficiency. In Table 1 are shown the name of the power plants, their location and the power capacity of each resource.

	Name	Country	Wind (MW)	PV (MW)	Storage (MW)	Storage (MWh)
1	Haringvliet	Netherlands	22	38	2	12
2	Parc Cynog	UK	8,4	5	0	0
3	kennedy Park	Australia	43,2	15	2	2,4
4	Louzes	Greece	24	1	0	0

Table 1: Existing hybrid plants

The Haringvliet power plant is still in development in the present by Vattenfall [8]. It is located in Netherlands in the region of South Netherlands.It consist of wind turbines, solar panels and storage system. The park will have 6 wind turbines, providing a power output of 22 MW. It will have also 124000 solar panels with a total capacity power of 38 MW. Finally the storage system will have an energy capacity of 12 MWh and a power output capacity of 2 MW that will be combined with the wind turbines and the solar PV panels. The storage system is based on BMW batteries. Haringvliet is one of the biggest hybrid power plants being developed in Europe.

Figure 2: Haringvliet hybrid power plant, Netherlands

Parc Cynog is a wind power plant located in The United Kingdom in the region of South Wales. It has been in operation for 14 years and last year Vattenfall has hybridized it with solar PV panels. It has a total wind power output of 8,4 MW and it has been complemented with 4,99 MW of solar panels array [5]. This power plant is not equipped with a storage system, but is located in a region where sun and wind resources complement each other very well.

Figure 3: Park Cynog hybrid power plant, UK

Kennedy Park will be one of the biggest hybrid renewable plant in the world as it is still in construction. It is located in Australia where also there are very good weather conditions to hybridize power plants. It combines 43,2 MW from Vestas 3,45 MW of power wind turbines and 15 MW of solar PV panels. These resources are also combined with 2 MW / 4 MWh of Li-on electical storage that gives flexibility to the power plant [13].

Figure 4: Kennedy Energy hybrid power plant, Australia

Louzes is a wind power plant in Greece. Is composed of 24 MW of wind turbines combined with 1 MW of solar PV panels. The wind power plant was established in 2008 and then Vestas integrated the photo-voltaic part in 2012. Thanks to the Vestas SCADA platform the two parts of the power plant can be controlled as a single one. In Louzes there is not a storage system that complements the rest of the power plant.

Figure 5: Louzes Energy Park, Greece

2 Data acquisition and data treatment

2.1 Meteorological data acquisition

The present chapter shows a summary of the meteorological data from 4 different locations on the Iberian Peninsula. In all these locations there are wind power production plants already installed. These plants have significant differences in terms of weather conditions. The variables under analysis are the velocity of the wind and the sun irradiance in the horizontal plane.

Figure 6: Wind power plants location

2.1.1 Sun irradiance data

The European Commission [10], shares information of solar irradiance all over the world from 2007 to 2016 in hourly time slots in its website as it is shown in Fig. 7. This information will help to predict the present and future irradiance values in the interest locations. This tool shows a lot of possibilities. It shares monthly, daily, and hourly data for very specific locations in all the continent. It can also calculate power production of solar PV panels depending on different variables like slope, azimuth, amount of power installed, panels technology and many more. For this section, have been collected data of irradiance in units of W/m^2, for the four different studied locations.

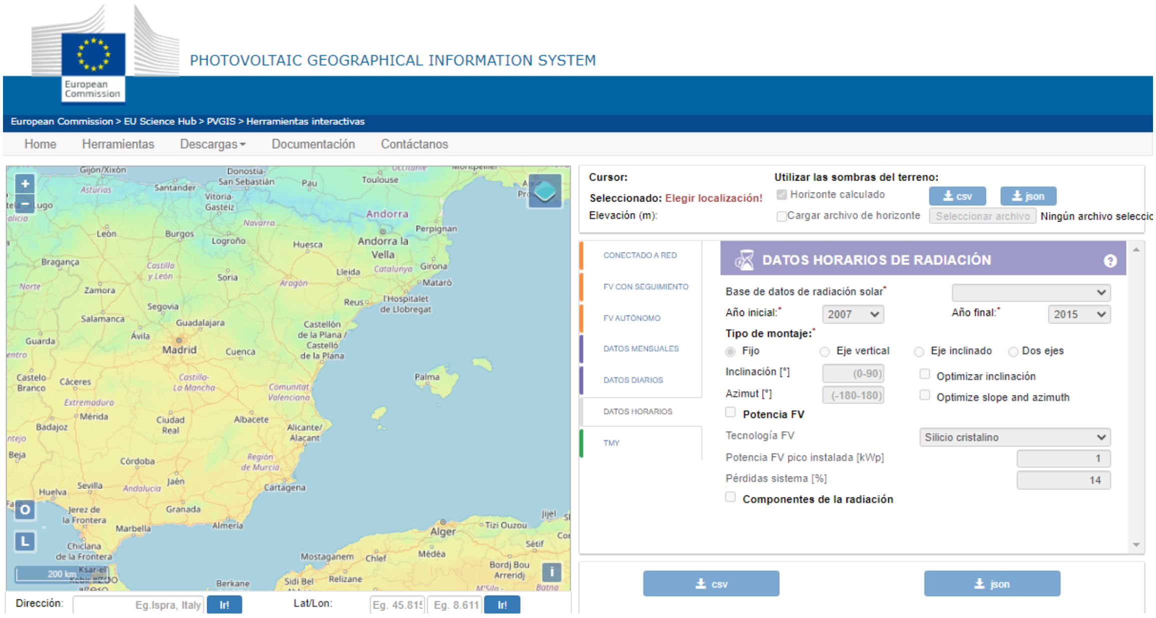


Figure 7: Solar data acquisition from European Commission website

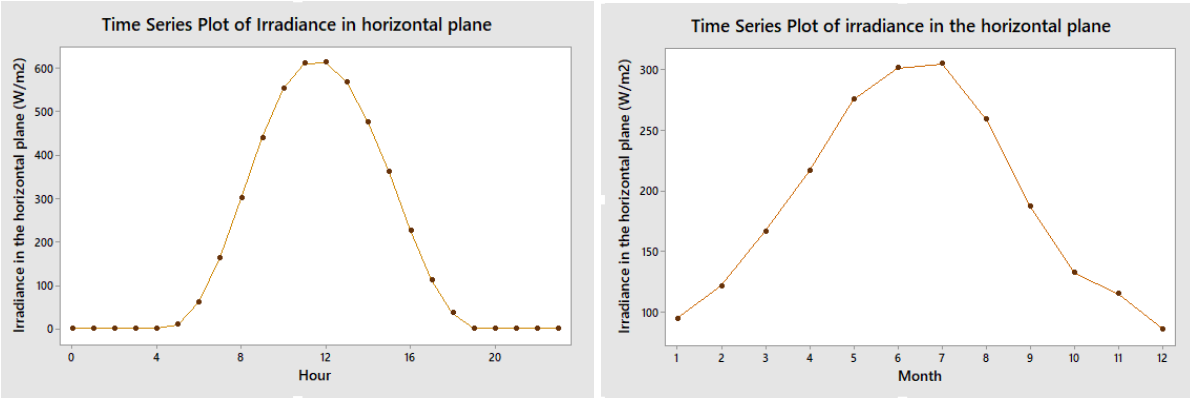
Serra de Rubió, Catalunya, Spain

Serra de Rubió is a wind power plant located in the mountain range that separates the region of Anoia and Bages in the center of Catalonia. This area has a good solar incidence, but no so good result in terms of wind power production.

The Table 2, Fig. 8a and Fig. 8b show the mean values obtained from more than 360 results for every hour and more than 700 values for every month taken for over 9 years.

Time	Mean irradiance (W/m^2)	Time	Mean irradiance	Month	Mean irradiance
0:00	0	12:00	612,83	1	94,22
1:00	0	13:00	566,80	2	121,06
2:00	0	14:00	474,71	3	166,33
3:00	0	15:00	359,79	4	216,12
4:00	0	16:00	225,50	5	275,24
5:00	8,16	17:00	112,24	6	301,09
6:00	60,73	18:00	35,07	7	304,73
7:00	163,04	19:00	0,78	8	258,64
8:00	300,12	20:00	0	9	186,62
9:00	439,21	21:00	0	10	132
10:00	551,68	22:00	0	11	114,51
11:00	610,16	23:00	0	12	85,38

Table 2: Irradiance data in Serra de Rubió



(a) Hourly mean irradiance (b) Monthly mean irraciance

Figure 8: Irradiance in Serra de Rubió

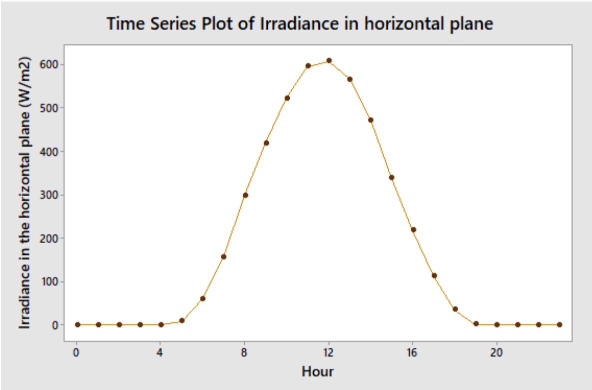
Ecovent, Tortosa, Catalunya

Ecovent, is a wind power plant located in Tortosa, a town in the south of Catalonia. This area is one of the windiest part in Catalonia and also has a very good solar incidence.

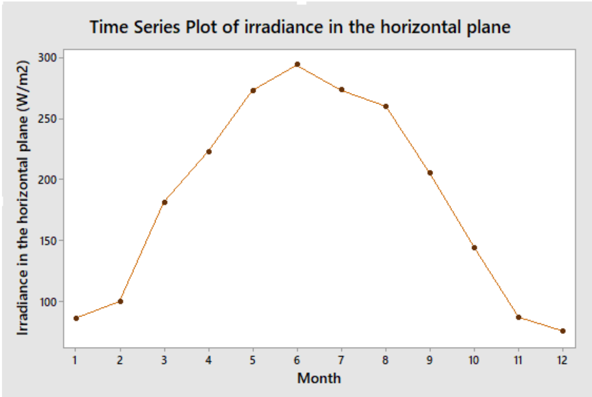
In Table 3 , Fig. 9b and Fig. 9a show the mean values obtained from more than 360 results for every hour and more than 700 values for every month taken for over 9 years.

Time	Mean irradiance (W/m^2)	Time	Mean irradiance	Month	Mean irradiance
0:00	0,00	12:00	607,93	1	85,82
1:00	0,00	13:00	565,98	2	99,55
2:00	0,00	14:00	471,86	3	180,75
3:00	0,00	15:00	338,52	4	222,50
4:00	0,00	16:00	217,81	5	272,45
5:00	8,25	17:00	113,85	6	293,77
6:00	60,44	18:00	34,52	7	272,90
7:00	157,04	19:00	0,91	8	259,38
8:00	299,03	20:00	0,00	9	204,77
9:00	419,08	21:00	0,00	10	143,72
10:00	522,20	22:00	0,00	11	86,69
11:00	595,53	23:00	0,00	12	75,44

Table 3: Irradiance data in Ecovent



(a) Hourly mean irradiance



(b) Monthly mean irraciance

Figure 9: Irradiance in Ecovent, Tortosa

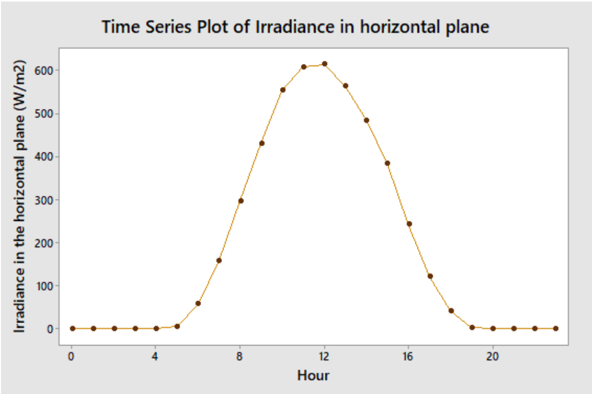
Sierra Costera, Teruel

The wind farm of Sierra Costera in Teruel, has excellent solar and wind resources. Is located in the south of Aragon, in the east of the Iberian Peninsula. As we will be able to observe is an arid climate with lot of sun and wind.

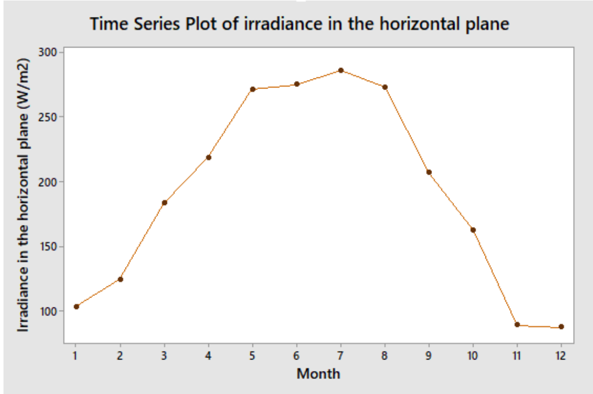
The following Table 4, Fig. 10a and Fig. 10b show the mean values obtained from more than 360 results for every hour and more than 700 values for every month taken for over 9 years.

Time	Mean irradiance (W/m^2)	Time	Mean irradiance	Month	Mean irradiance
0:00	0	12:00	614,08	1	102,87
1:00	0	13:00	562,41	2	123,83
2:00	0	14:00	483,52	3	182,79
3:00	0	15:00	383,37	4	218,30
4:00	0	16:00	242,30	5	270,69
5:00	4,59	17:00	121,79	6	274,58
6:00	57,01	18:00	41,93	7	285,30
7:00	158,55	19:00	2,62	8	272,63
8:00	297,25	20:00	0	9	206,47
9:00	430,73	21:00	0	10	162,05
10:00	553,22	22:00	0	11	88,62
11:00	608,05	23:00	0	12	86,99

Table 4: Irradiance data in Sierra Costera



(a) Hourly mean irradiance



(b) Monthly mean irraciance

Figure 10: Irradiance in Sierra Costera, Teruel

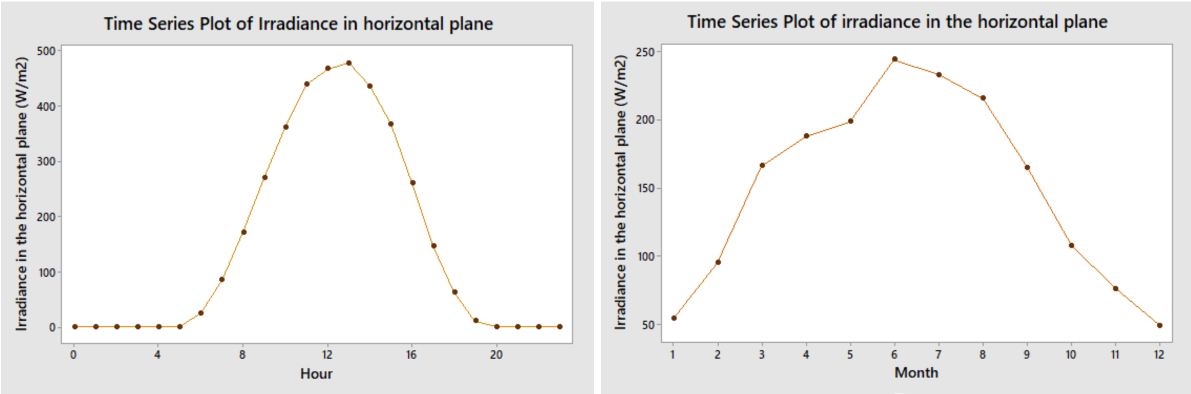
A Capelada 1, A Coruña

A Capelada 1 is a wind farm located in the north of the region of A Coruña, Galicia. Is one of the windiest areas in the Iberian Peninsula since is in the Atlantic Ocean Coast, exposed to large amounts of westerns winds. On the other hand, Galicia is one of the rainiest areas with few sunny days, however, more than many European countries.

The following Table 5 , Fig. 11a and Fig. 11b show the mean values obtained from more than 360 results for every hour and more than 700 values for every month taken for over 9 years.

Time	Mean irradiance (W/m^2)	Time	Mean irradiance	Month	Mean irradiance
0:00	0	12:00	467,35	1	53,60
1:00	0	13:00	477,43	2	94,57
2:00	0	14:00	435,85	3	165,61
3:00	0	15:00	367,65	4	187,51
4:00	0	16:00	261,23	5	198,25
5:00	0,31	17:00	146,45	6	243,90
6:00	25,18	18:00	63,25	7	232,46
7:00	84,56	19:00	10,55	8	215,29
8:00	171,72	20:00	0	9	164,46
9:00	269,36	21:00	0	10	107,56
10:00	360,85	22:00	0	11	75,62
11:00	439,18	23:00	0	12	48,69

Table 5: Irradiance data in A Capelada 1



(a) Hourly mean irradiance (b) Monthly mean irraciance

Figure 11: Irradiance in A Capelada 1, A Coruña

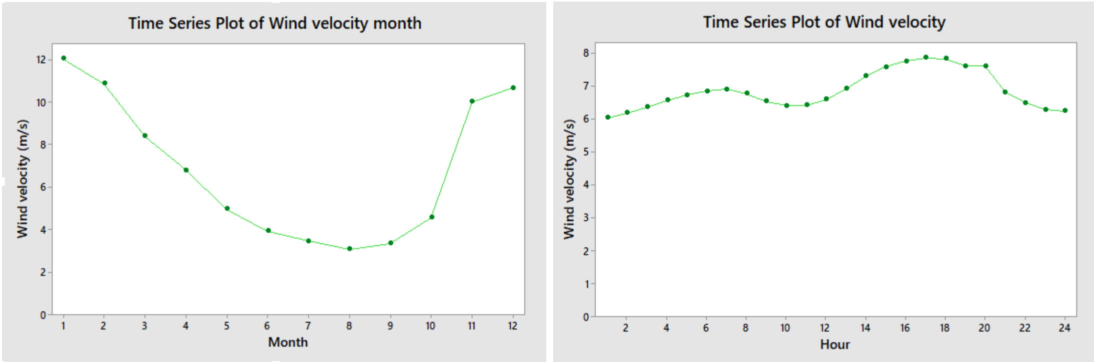
2.1.2 Wind velocity data

Serra de Rubió, Catalunya

In the following Table 6 and Fig. 12a and Fig. 12b is shown the mean wind velocity data for every month and every hour. 120 samples have been obtained for each hour time slot and 240 per each monthly time slot in Serra de Rubió.

Hour	Mean wind Velocity (m/s)	Hour	Mean Velocity	Month	Mean velocity
0:00	6,03	12:00	6,91	1	12,04
1:00	6,16	13:00	7,29	2	10,86
2:00	6,34	14:00	7,57	3	8,38
3:00	6,55	15:00	7,74	4	6,78
4:00	6,71	16:00	7,85	5	4,96
5:00	6,83	17:00	7,81	6	3,91
6:00	6,89	18:00	7,59	7	3,44
7:00	6,75	19:00	7,59	8	3,04
8:00	6,53	20:00	6,80	9	3,33
9:00	6,38	21:00	6,48	10	4,55
10:00	6,41	22:00	6,26	11	10,01
11:00	6,58	23:00	6,22	12	10,66

Table 6: Wind velocity data



(a) Monthly mean wind velocity (b) Hourly mean wind velocity

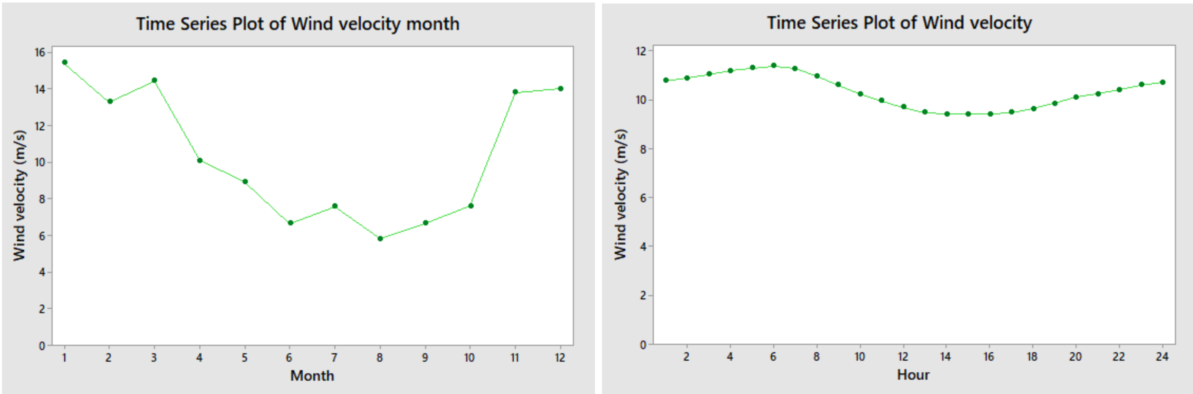
Figure 12: Wind velocity in Serra de Rubió

Ecovent, Tortosa, Catalunya

In the following Table 7 and Fig. 13a and Fig. 13b is shown the mean wind velocity data for every month and every hour. 120 samples have been obtained for each hour time slot and 240 per each monthly time slot in Ecovent.

Hour	Mean wind velocity (m/s)	Hour	Mean velocity	Month	Mean velocity
0:00	10,78	12:00	9,49	1	15,42
1:00	10,88	13:00	9,42	2	13,28
2:00	11,04	14:00	9,42	3	14,43
3:00	11,18	15:00	9,41	4	10,06
4:00	11,31	16:00	9,48	5	8,91
5:00	11,38	17:00	9,63	6	6,62
6:00	11,28	18:00	9,85	7	7,56
7:00	10,97	19:00	10,11	8	5,78
8:00	10,61	20:00	10,25	9	6,62
9:00	10,24	21:00	10,41	10	7,59
10:00	9,95	22:00	10,60	11	13,79
11:00	9,70	23:00	10,72	12	14,01

Table 7: Wind velocity data



(a) Monthly mean wind velocity (b) Hourly mean wind velocity

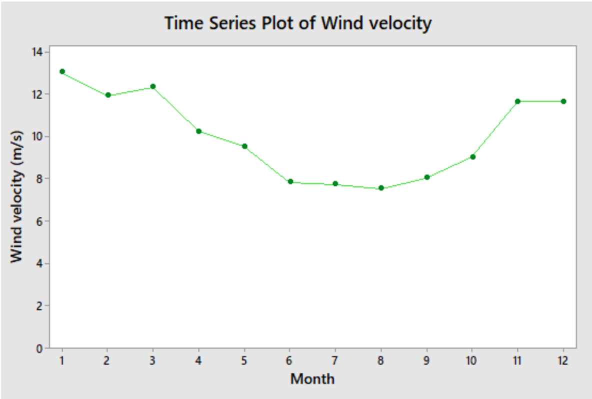
Figure 13: Wing velocity in Ecovent, Tortosa

Sierra Costera, Teruel

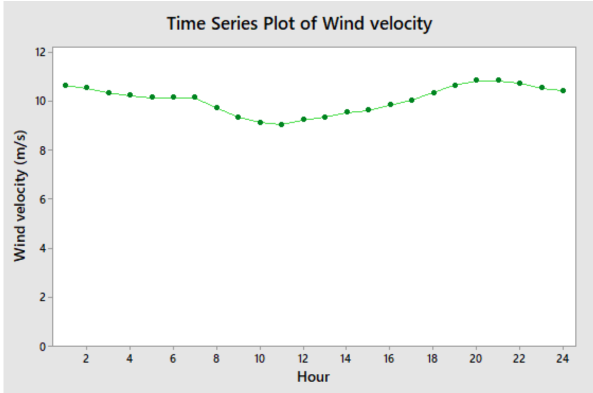
In Table 8 and Fig. 14a and Fig. 14b is shown the mean wind velocity data for every month and every hour. 120 samples have been obtained for each hour time slot and 240 per each monthly time slot in the wind farm of Sierra Costera, Teruel.

Hour	Mean wind velocity (m/s)	Hour	Mean velocity	Month	Mean velocity
0:00	10,61	12:00	9,31	1	13,03
1:00	10,51	13:00	9,51	2	11,93
2:00	10,31	14:00	9,61	3	12,33
3:00	10,21	15:00	9,81	4	10,23
4:00	10,11	16:00	10,01	5	9,52
5:00	10,11	17:00	10,31	6	7,82
6:00	10,11	18:00	10,61	7	7,72
7:00	9,71	19:00	10,81	8	7,52
8:00	9,31	20:00	10,81	9	8,02
9:00	9,15	21:00	10,71	10	9,02
10:00	9,01	22:00	10,51	11	11,63
11:00	9,21	23:00	10,41	12	11,63

Table 8: Wind velocity data in Sierra costera



(a) Monthly mean wind velocity



(b) Hourly mean wind velocity

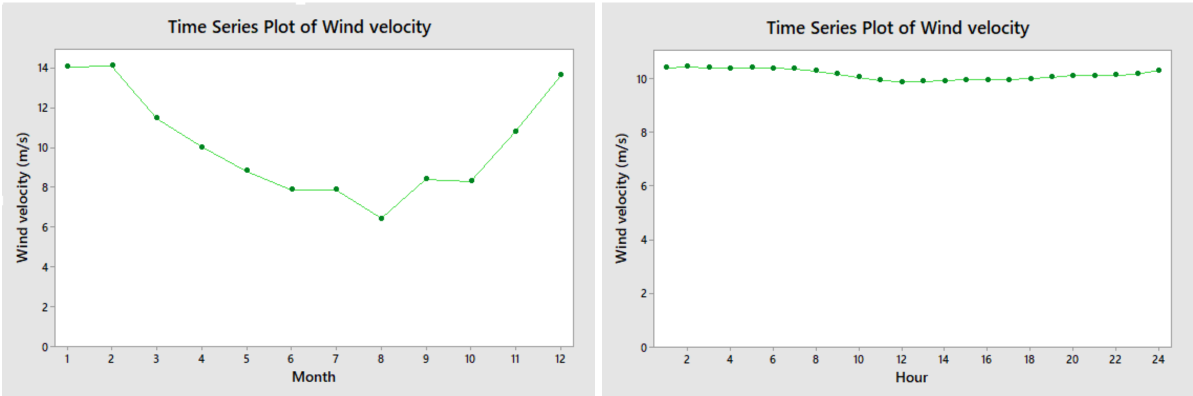
Figure 14: Wind velocity in Sierra Costera, Teruel

A Capelada 1, A Corunya

In the following Table 9 and Fig. 15a and Fig. 15b is shown the mean wind velocity data for every month and every hour. 120 samples have been obtained for each hour time slot and 240 per each monthly time slot in the wind farm of A Capelada 1, Galicia.

Hour	Mean wind velocity (m/s)	Hour	Mean velocity	Month	Mean velocity
0:00	10,39	12:00	9,88	1	14,05
1:00	10,43	13:00	9,90	2	14,11
2:00	10,38	14:00	9,93	3	11,45
3:00	10,36	15:00	9,93	4	10,01
4:00	10,39	16:00	9,94	5	8,80
5:00	10,37	17:00	9,98	6	7,85
6:00	10,34	18:00	10,04	7	7,87
7:00	10,27	19:00	10,10	8	6,40
8:00	10,15	20:00	10,09	9	8,39
9:00	10,03	21:00	10,12	10	8,28
10:00	9,92	22:00	10,16	11	10,80
11:00	9,85	23:00	10,29	12	13,62

Table 9: Wind velocity data in Sierra Costera



(a) Monthly mean wind velocity (b) Hourly mean wind velocity

Figure 15: Wind velocity in A Capelada 1, A Coruña

2.2 Comparing the wind and the sun resources

In this section the sun and the wind resource will be compared in each area of study. With this information, we will be able to see if is interesting to invest in a hybrid power plant in any of the shown zones.

Serra de Rubió, Catalunya

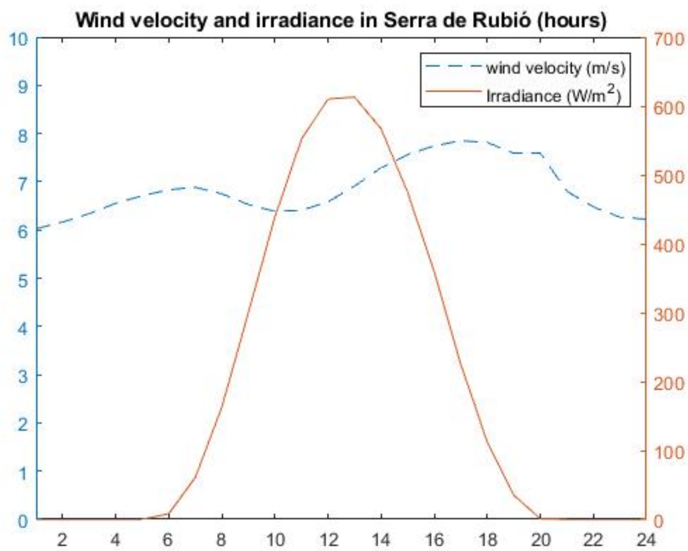


Figure 16: Sources comparison in periods of one hour in Serra de Rubió

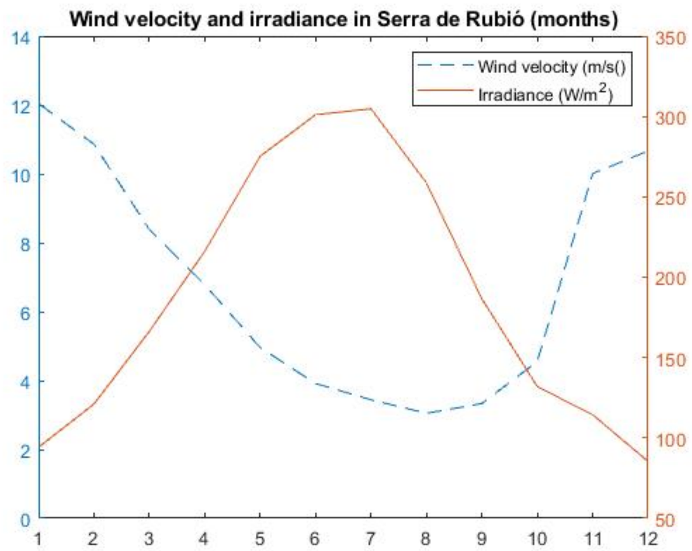


Figure 17: Sources comparison in periods of one month in Serra de Rubió

Ecovent, Tortosa

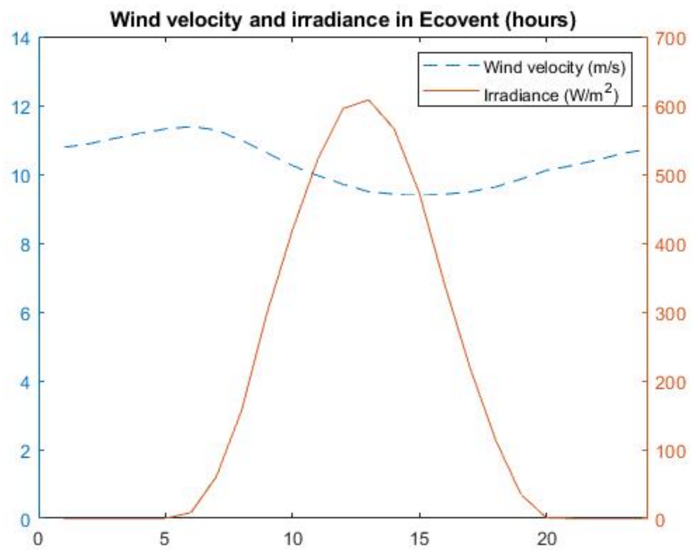


Figure 18: Sources comparison in periods of one hour in Ecovent

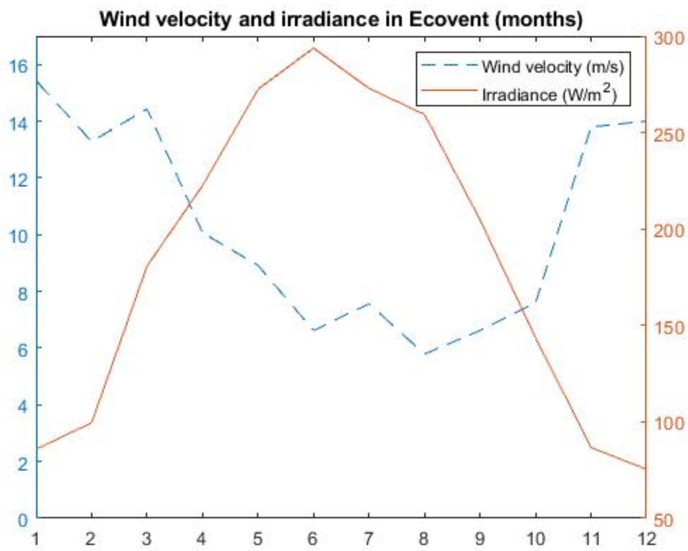


Figure 19: Sources comparison in periods of one month in Ecovent

Sierra Costera, Teruel

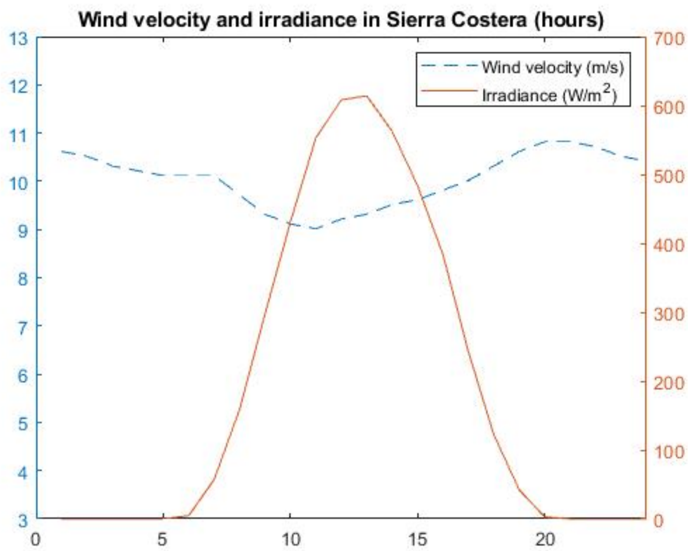


Figure 20: Sources comparison in periods of one hour in Sierra Costera

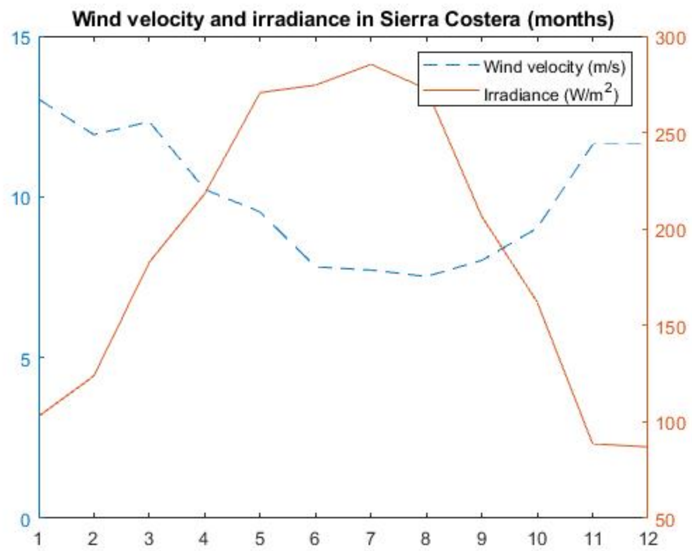


Figure 21: Sources comparison in periods of one month in Sierra Costera

A Capelada 1, A Coruña

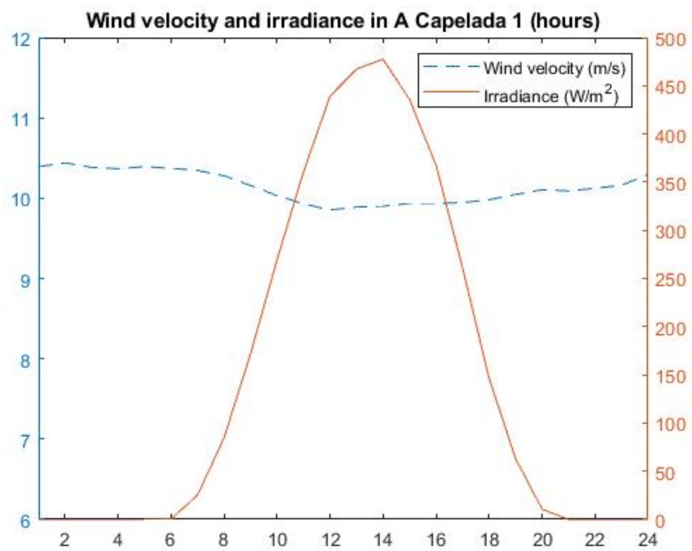


Figure 22: Sources comparison in periods of one hour in A Capelada 1

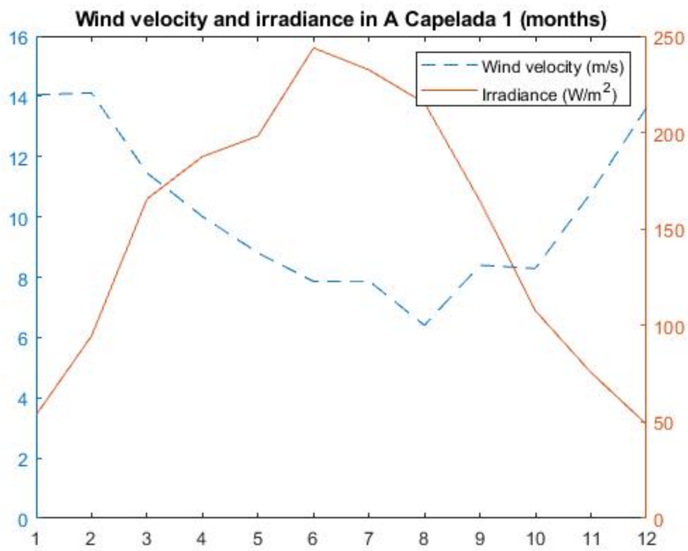
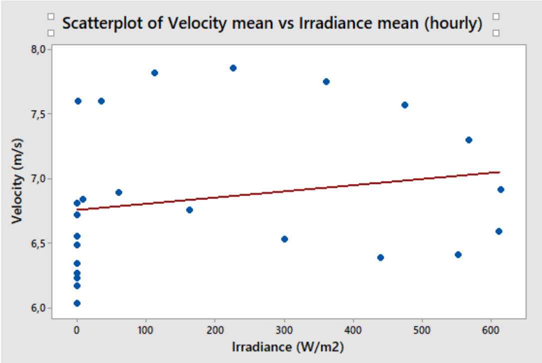


Figure 23: Sources comparison in periods of one month in A Capelada 1

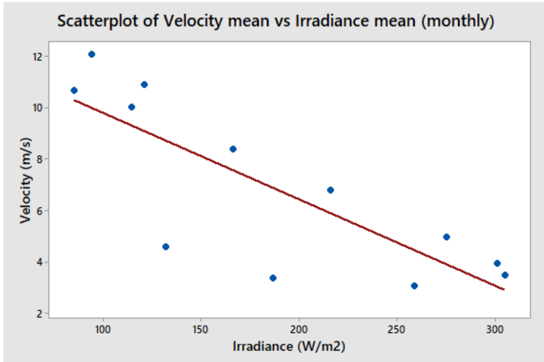
As we can see in all the studied areas, the wind is higher in the coldest seasons, autumn and winter. Logically these seasons the irradiance of the sun is lower, fact which proves that these areas are compatible with the installation of hybrid power plants. The same happens the other way around on the warmest seasons.

Also, if we observe the variation of the values in the different hourly segments are also interesting for hybrid plants. In all the studied cases there is some relation with hours of more sun and hours of less wind and vice versa. But in periods of one hour, results are less clear than in months values. In conclusion, all the analyzed areas show a good rapport between wind and solar PV power production.

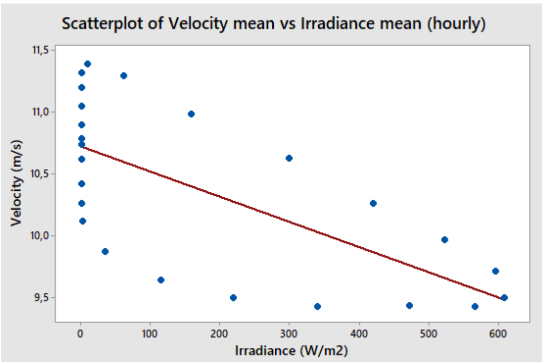
Now, we will see in a more specific point of view, if these locations are suitable for hybrid power plants and which is the best one. To be able to observe this, we will distribute each value for solar irradiance compared with the wind speed value of the same period of time in the same chard. In the next figures, is shown the correlation and the regression line for each studied area. As can be noted, the regression line has normally a negative slope, which indicates that exist a negative correlation between the variables. This means that when a variable is low, the other one is high, and vice-versa.



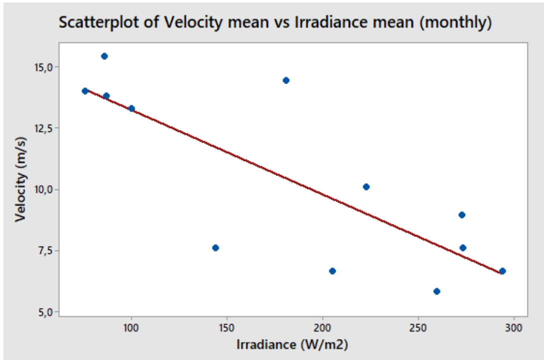
(a) Correlation of hourly values in Serra de Rubió



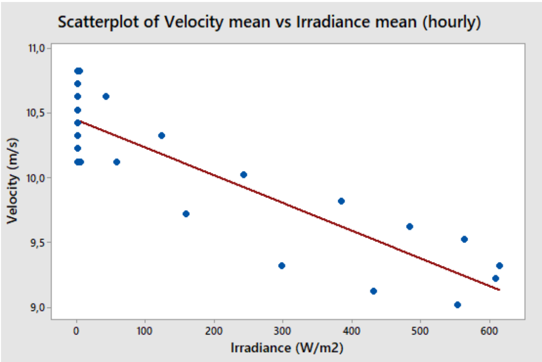
(b) Correlation of monthly values in Serra de Rubió



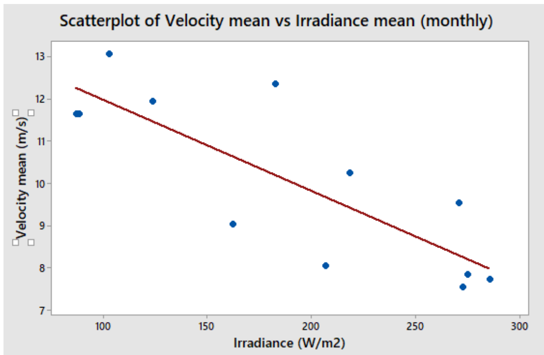
(c) Correlation of hourly values in Ecovent



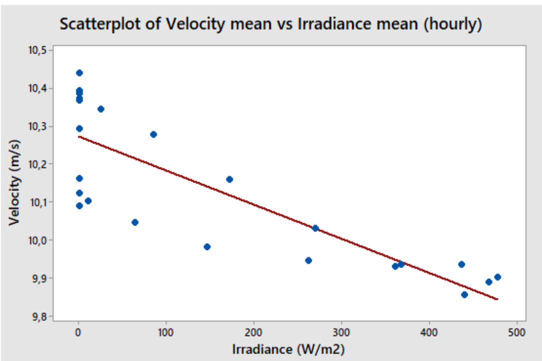
(d) Correlation of monthly values in Ecovent



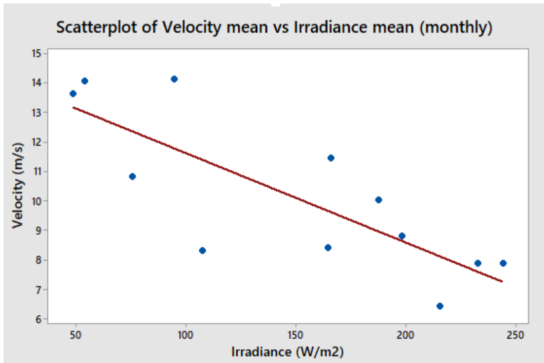
(e) Correlation of hourly values in Sierra Costera



(f) Correlation of monthly values in Sierra Costera



(g) Correlation of hourly values in A Capelada 1



(h) Correlation of monthly values in A Capelada 1

Figure 24: Scatterplots and regression lines of wind speed and sun irradiance in the studied locations.

The Table 10 shows the values of correlation and the p value between wind speed and sun irradiance.

	Hourly correlation	P_value	Monthly correlation	P_value
Serra de Rubió	0,19	0,36	-0,81	0,001
Ecovent	-0,68	0	-0,79	0,002
Sierra Costera	-0,88	0	-0,81	0,001
A Capelada	-0,83	0	-0,79	0,002

Table 10: Correlation and p_value between variables

2.3 Power generation in the case-study areas

2.3.1 Wind power generation

In this section has been calculated the amount of power and energy available in the studied areas, by comparing them with the power and energy produced depending on the number of the working or installed wind turbines.

The Weibull distribution is a continuous probabilistic distribution. It was applied originally to describe the distribution of the size of some particles. In the field of meteorology is commonly used to describe wind speed distributions. In (1) and in Fig. 25 is shown the distribution of Weibull depending on the 2 constants, λ and k.

$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{(k-1)} \cdot e^{-\left(\frac{x}{\lambda}\right)^k} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{1}$$

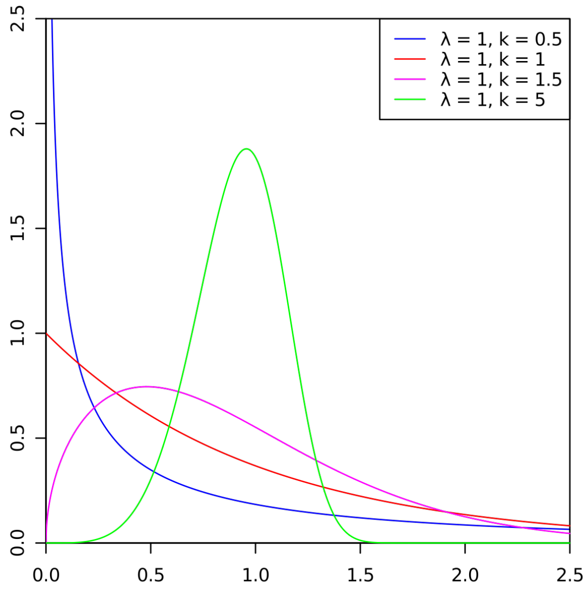


Figure 25: Weibull distribution depending on the constants λ and k

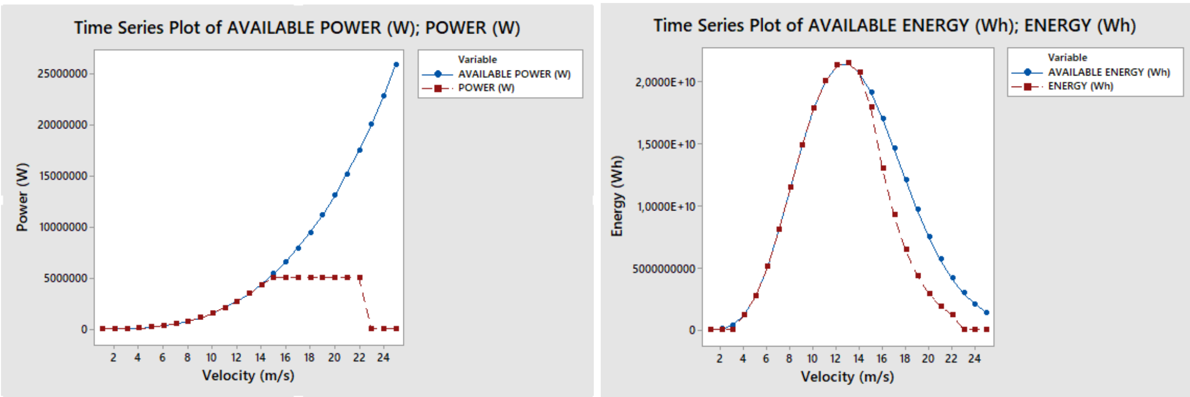
With the provided data form the Global Wind Atlas, we are able to calculate the constants λ and k for every area of study. With this values we can calculate the possibility of every wind speed in each hour of the day. The results are shown in the Fig. 11 below. In this case, all the results obtained are for one wind turbine.

	Serra de Rubió	Ecovent	Sierra Costera	A Capelada 1
Weighted c (m/s)	8,13	11,78	10,32	12,99
Weighted k	1,83	2,31	1,91	2,43

Table 11: Weibull values for every case-study area

In the different tables below we see the energy and power available in each location and also the energy and power produced in each location. It has been calculated for one turbine.

Serra de Rubió, Catalunya

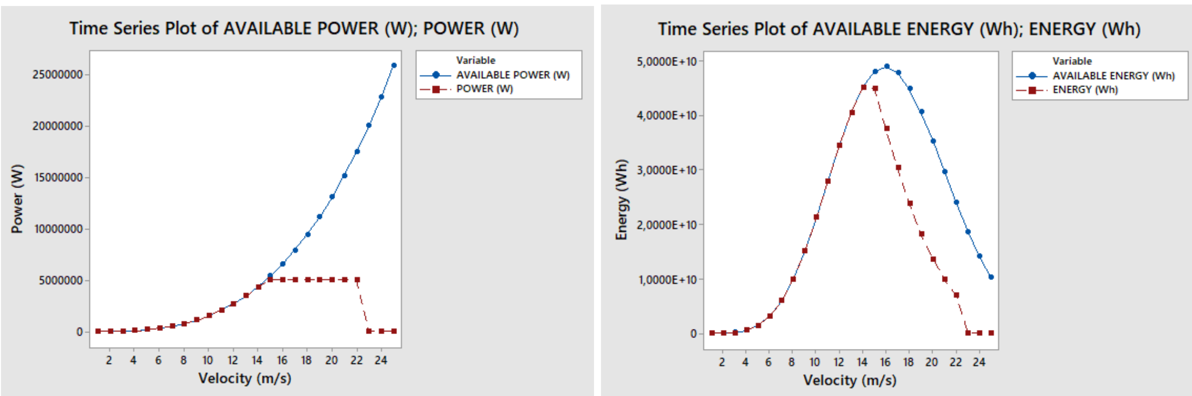


(a) Available and produced power

(b) Available and energy produced

Figure 26: Capacity of wind power generation in Serra de Rubió

Ecovent, Tortosa

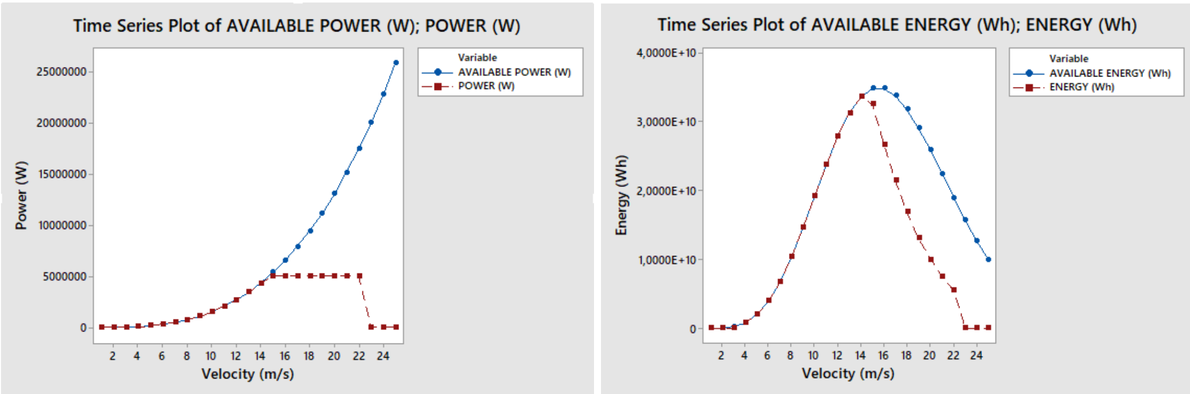


(a) Available and produced power

(b) Available and energy produced

Figure 27: Capacity of wind power generation in Ecovent

Sierra Costera, Teruel

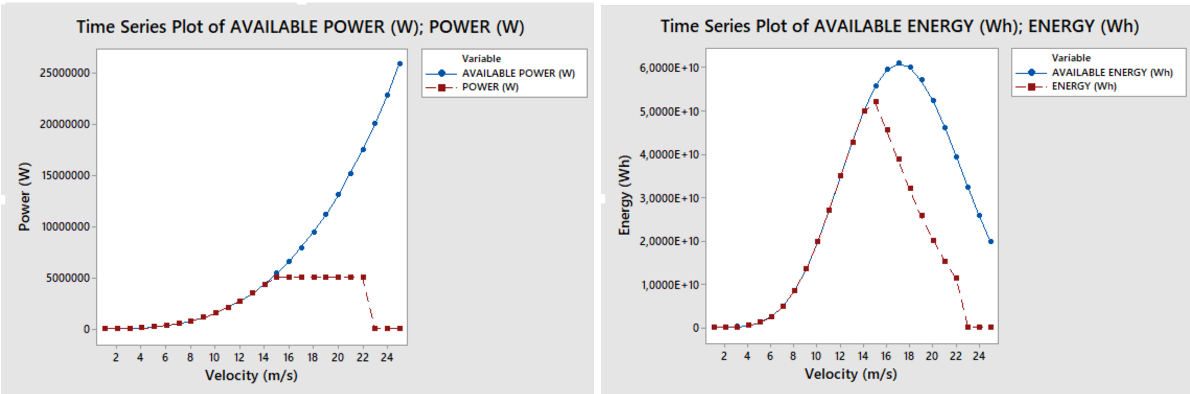


(a) Available and produced power

(b) Available and energy produced

Figure 28: Capacity of wind power generation in Sierra Costera

A Capelada 1, A Coruña



(a) Available and produced power

(b) Available and energy produced

Figure 29: Capacity of wind power generation in A Capelada 1

In brief, in the following Table 12, are shown the mean values of wind energy production by one turbine every hour.

	Wind energy produced by turbine, per hour (MWh)
Serra de Rubió	1,15
Ecovent	2,22
Sierra Costera	1,76
A Capelada 1	2,54

Table 12: Wind energy production by one turbine

2.3.2 Solar photovoltaic power generating

In this section, we will calculate the solar PV available power and the hypothetical produced power in the four studied areas.

With the average irradiance of every time slot, we are able to calculate the energy produced using the characteristics of a standard solar PV panel commonly used in this kind of infrastructures.

The solar PV panel characteristics bellow are the ones used to calculate the energy produced in the following Tables 13, 14, 15, 16 for each location.

- Number of panels: 1
- Power of peak: 400 W
- Efficiency: 0,21
- Panel length: 2000 mm
- Panel width: 1000 mm

Serra de Rubió, Catalunya

Hour	Mean Available Power (W/m^2)	Produced Power (W)	Available Energy (Wh/m^2)	Energy produced (Wh)
0:00	0	0	0	0
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	8,16	3,42	8,16	3,43
6:00	60,73	25,50	60,73	25,50
7:00	163,04	68,47	163,04	68,47
8:00	300,12	126,05	300,12	126,05
9:00	439,21	184,47	439,21	184,47
10:00	551,67	231,70	551,67	231,70
11:00	610,16	256,27	610,16	256,27
12:00	612,83	257,39	612,83	257,39
13:00	566,79	238,05	566,79	238,05
14:00	474,71	199,38	474,71	199,38
15:00	359,78	151,11	359,79	151,11
16:00	225,50	94,71	225,50	94,71
17:00	112,24	47,14	112,24	47,14
18:00	35,07	14,73	35,07	14,73
19:00	0,78	0,33	0,78	0,33
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0

Table 13: Solar PV power and energy production in Serra de Rubió

Ecovent, Tortosa

Hour	Mean Available Power (W/m^2)	Produced Power (W)	Available Energy (Wh/m^2)	Energy produced (Wh)
0:00	0	0	0	0
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	8,25	3,46	8,25	3,46
6:00	60,44	25,38	60,44	25,38
7:00	157,04	65,96	157,04	65,96
8:00	299,03	125,59	299,03	125,59
9:00	419,08	176,01	419,08	176,01
10:00	522,20	219,33	522,20	219,33
11:00	595,53	250,12	595,53	250,12
12:00	607,92	255,33	607,92	255,33
13:00	565,98	237,71	565,98	237,71
14:00	471,86	198,18	471,86	198,18
15:00	338,52	142,18	338,52	142,16
16:00	217,81	91,48	217,81	91,48
17:00	113,85	47,82	113,85	47,82
18:00	34,52	14,50	34,52	14,50
19:00	0,91	0,38	0,91	0,38
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0

Table 14: Solar PV power and energy production in Ecovent

Sierra Costera, Teruel

Hour	Mean Available Power (W/m^2)	Produced Power (W)	Available Energy (Wh/m^2)	Energy produced (Wh)
0:00	0	0	0	0
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	4,59	1,93	4,59	1,928
6:00	57,01	23,94	57,01	23,94
7:00	158,55	66,59	158,55	66,59
8:00	297,24	124,84	297,24	124,84
9:00	430,72	180,90	430,72	180,90
10:00	553,21	232,35	553,21	232,35
11:00	608,05	255,38	608,05	255,38
12:00	614,08	257,91	614,08	257,91
13:00	562,40	236,21	562,40	236,21
14:00	483,51	203,07	483,51	203,07
15:00	383,37	161,01	383,37	161,01
16:00	242,30	101,76	242,30	101,76
17:00	121,79	51,15	121,79	51,15
18:00	41,93	17,61	41,93	17,61
19:00	2,62	1,10	2,62	1,10
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0

Table 15: Solar PV power and energy production in Sierra Costera

A Capelada 1, A Coruña

Hour	Mean Available Power (W/m^2)	Produced Power (W)	Available Energy (Wh/m^2)	Energy produced (Wh)
0:00	0	0	0	0
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	0,31	0,13	0,31	0,13
6:00	25,17	10,57	25,17	10,57
7:00	84,56	35,51	84,56	35,51
8:00	171,71	72,12	171,71	72,12
9:00	269,36	113,13	269,36	113,13
10:00	360,85	151,55	360,85	151,55
11:00	439,17	184,45	439,17	184,45
12:00	467,34	196,28	467,34	196,28
13:00	477,43	200,52	477,43	200,52
14:00	435,84	183,05	435,84	183,05
15:00	367,64	154,41	367,64	154,41
16:00	261,23	109,71	261,23	109,71
17:00	146,45	61,51	146,45	61,51
18:00	63,24	26,56	63,24	26,56
19:00	10,55	4,43	10,55	4,43
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0

Table 16: Solar PV power and energy production in A Capelada 1

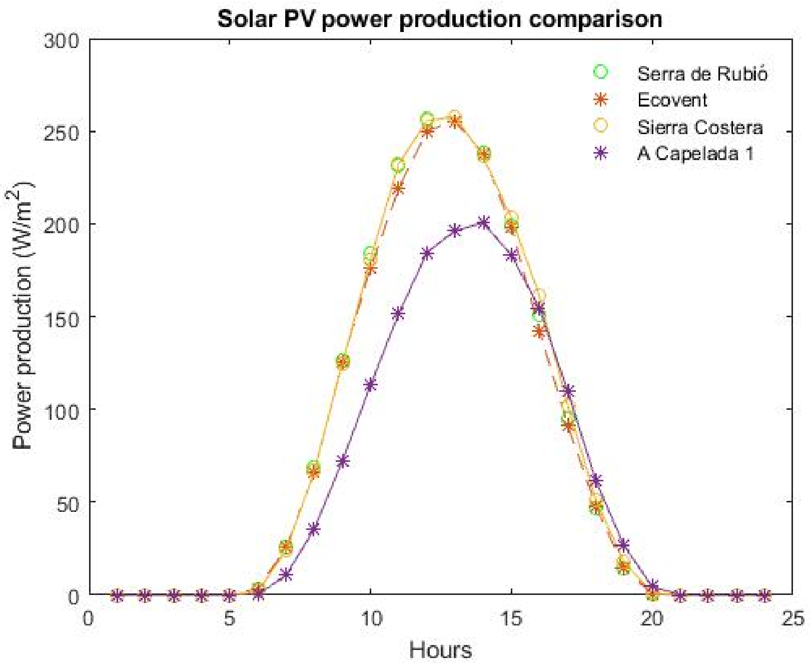


Figure 30: Solar PV power production comparison between locations

To sum up, in the following Table 17, are shown the mean values of solar PV energy produced by one panel every hour.

	Solar PV energy produced by panel per hour (Wh)
Serra de Rubió	79,11
Ecovent	77,23
Sierra Costera	79,82
A Capelada 1	62,67

Table 17: Solar PV energy production by one panel

2.3.3 Comparison of wind and solar PV power generation in the studied areas

Once all the data, seen in the previous sections, has been collected, the best location must be selected from the hybrid plant perspective.

A methodology called the weighted factor is used to reach a decision[9]. This methodology helps to decide which alternative is the best in a project or a purpose. In our case, we must decide which of the locations previously shown is the best one in order to install a hybrid power plant. The alternatives are:

- A: Serra de Rubió, Anoia
- B: Ecovent, Tortosa
- C: Sierra Costera, Teruel

- D: A Capelada 1, A Coruña

After this, we must decide which are the factors that will influence directly in our decision.

- Solar PV production (the hourly mean value)
- Wind production (the hourly mean value)
- Hour correlation between wind and sun irradiance
- Month correlation between wind and sun irradiance

Finally, we weight these factors from 0 to 1 according to the relevance of each one. In this case, we have distributed 0,25 for each factor except for the wind and solar PV production, that are weighted depending on the different price of the plant installation. As wind power production is lightly cheaper than solar PV production, the weighted factor is a little bit higher.

Solar PV power production	→	0,26
Wind power production	→	0,24
Hourly correlation	→	0,25
Monthly correlation	→	0,25

In the next summary Table 18, it is shown the energy production per hour of each energy kind. The darker is the cell, the higher is the production.

	Solar PV energy produced by panel per hour (Wh)	Wind energy produced by turbine per hour (MWh)
Serra de Rubió	79,11	1,15
Ecovent	77,22	2,22
Sierra Costera	79,82	1,75
A Capelada 1	62,66	2,54

Table 18: Energy produced by resource

The highest results have been rated with a 10, and the other ones have been rated proportionally to the higher one. In this Table 19, are shown the results of this metodology.

		Rating alternatives			
Factors	Relative weight	A	B	C	D
Solar PV production	0,26	9,9	9,67	10	7,85
Wind production	0,24	4,54	8,75	6,92	10
Hour correlation	0,25	0	7,73	10	9,43
Month correlation	0,25	9,91	9,74	10	9,80
Result		6,14	8,99	9,26	9,25

Table 19: Weight factor methodology to decide the best location

In conclusion, the different alternatives, sorted with the best on top, are:

1. Sierra Costera (C)
2. A Capelada 1 (D)
3. Ecovent (B)
4. Serra de Rubió (A)

The greatest difference is in between A and B, but we can see that the alternatives B, C and D have very similar results.

3 Design and operation of a hybrid renewable power plant

3.1 Sizing design to satisfy a constant load

Once compared the different studied areas, and decided that Sierra Costera is the best in matter of hybrid power plants, a simulation has been made. It is a sizing simulation in order to be able to predict the characteristics of the hybrid power plant.

As the plant shown here is located in an already existing wind power plant, the variable of the numbers of wind turbines and its features are fixed. Knowing this information the sizing simulation will help to decide: number of active solar PV panels, size of the energy storage with the aim of ensure the power requirement, usage of the storage system, capacity to reach the requirements and more information.

Wind power production

In this simulation is used a vector of 8760 numbers ($P_{w,gen}$) corresponding to the wind power production in Sierra Costera in 2016. In Section 2.3.1 is shown how is obtained this data, depending on the wind velocity and other characteristics of the wind turbine. The vector dimension correspond to the number of hours in a whole year.

The variables used in the simulation related to the wind power system are: P_w. And the constant values are: $P_{w,min}$, $P_{w,max}$, ΔP_w.

P_w is the wind power operating in each iteration. $P_{w,min}$ is the minimum value operating in the plant and $P_{w,max}$ is the maximum possible value operating in the plant. ΔP_w is the wind power added in each iteration with the aim of reaching the optimal configuration. This value is the same as the power of a single wind turbine due to the power of the plant increases as a new turbine stars operating.

Solar PV power production

As is detailed in Section 2.3.2 a vector of 8760 values ($P_{pv,gen}$) is obtained corresponding to the solar PV power production in the studied area, using meteorological data.

The variables used in the simulation related to the solar PV power system are: P_{pv}, $P_{pv,min}$, $P_{pv,max}$, ΔP_{pv}.

P_{pv} is the solar PV power operating in each iteration. $P_{pv,min}$ is the minimum value operating in the plant and $P_{pv,max}$ is the maximum possible value operating in the plant. ΔP_pv is the solar PV power added in each iteration with the aim of reach the optimal configuration. This value matches the power of a single PV panel due to the power of the solar PV system increases as a new panel starts operating.

Energy generated in time t

To calculate the energy generated in one time slot is as simple as adding the wind and solar PV energy generated in time t. Then, in every iteration is created a 8760 length vector: $E_{gen}(t)$, which can be used, or not, depending on the obtained results.

Storage system

In every different iteration a 8760 length vector is created. This vector is $SOC(t)$. Every single position of the vector shows the battery state of charge in time t.

SOC_{max} is the maximum storage system state of charge and SOC_{min} is the minimum. This two constant values are related to DOD (depth of discharge). Manufacturers advise not to reach the DOD of 0,5 in order to increase to the maximum the battery life time. In the present study is used a $DOD = 0,5$.

$$SOC_{min} = DOC \cdot SOC_{max} \tag{2}$$

If the state of charge of the storage system is neither the maximum nor the minimum the state of charge has to be calculated. The storage system could be charging if the energy generated is grater than the energy that the load requires, or discharging in the opposite case. If it is charging, (3) shows how to obtain the $SOC(t)$.

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) + \left(E_{gen}(t) - \frac{E_L(t)}{\eta_{inv}}\right) \cdot \eta_B \tag{3}$$

If it is discharging (4) shows how to obtain the $SOC(t)$.

$$SOC(t) = SOC(t-1) \cdot (1-\sigma) - \left(\frac{E_L(t)}{\eta_{inv}} - E_{gen}(t)\right) \tag{4}$$

The σ refers to the hourly self-discharge rate. η_{inv} is the inverter efficiency and η_B is the storage system efficiency. A $SOC_{max} = 10$ MWh has been used in the simulations.

Load

The load of the system is the demand required to the power plant. It has been created a 8760 length vector ($E_L(t)$) which shows a variable hourly demand but also it keeps constant every day to simplify the calculations.

The mean of this load profile is 172917 kW and a standard deviation of 87823 kW. This type of distribution is commonly found in cities around this area.

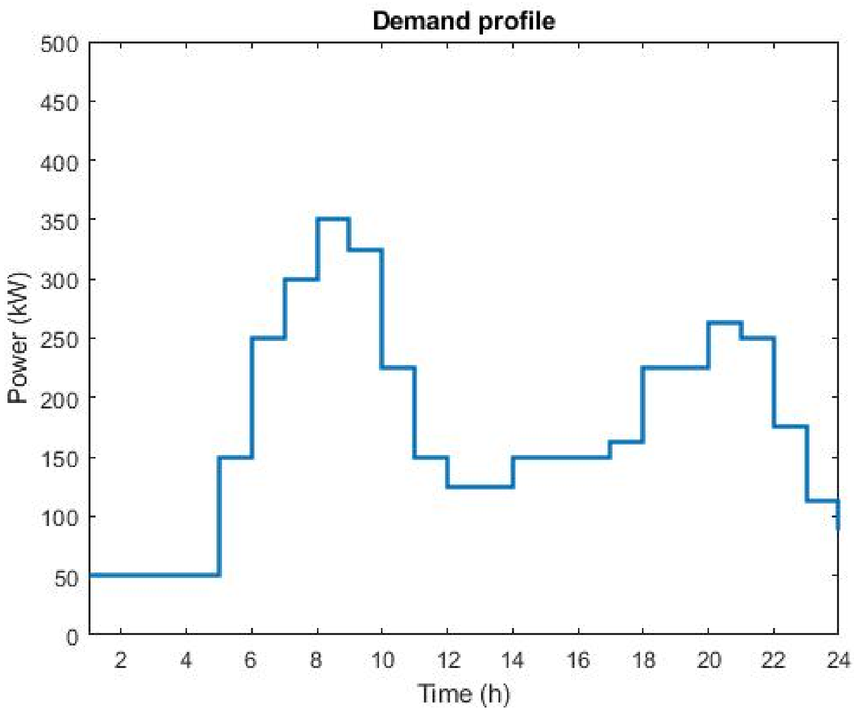


Figure 31: Power requirement profile

Simulation operation

A Matlab program has been made to iterate different configurations and observe which ones are good or not. The criteria to decide if a configuration is correct is the analysis of *Deficiency of power supply probability* ($DPSP$) which is described below in Fig. 32 [7]. If the $DPSP_y$ obtained is 0 means that the load is always satisfied and if the $DPSP_y$ obtained is 1 means that the load is never satisfied.

Even the number of wind turbines is fixed in the power plant, various iterations with different numbers of operating turbines have been made to predict a situation where not all wind turbines works.

The input data of this simulation is: wind power generation, solar PV power generation and connected load in the studied area.

The first iteration starts with the simple configuration of one wind turbine and one solar PV panel. A sub-iteration, starts. All the time dependent vectors start growing until the time reach 8760. In every time slot the generated energy and the load energy are compared. If the first is grater than the second one, the battery start charging and the position t of the vector $SOC(t)$ is filled with a value. The position t of deficiency supply power vector ($DPSP(t)$) will be filled with a 0 (As the energy generation covers the needs). If the load energy is grater than the generated energy, then the battery starts discharging and the position t of the vector $SOC(t)$ is filled with a value depending on the minimum state of charge of the storage system. If the state of charge is under the minimum the position t of $DPS(t)$ is calculated with (5) bellow . If it is not, then the $DPS(t)$ is 0.

$$DPS(t) = E_L(t) - [E_{gen}(t) + SOC(t-1) - SOCmin] \cdot \eta_{inv} \tag{5}$$

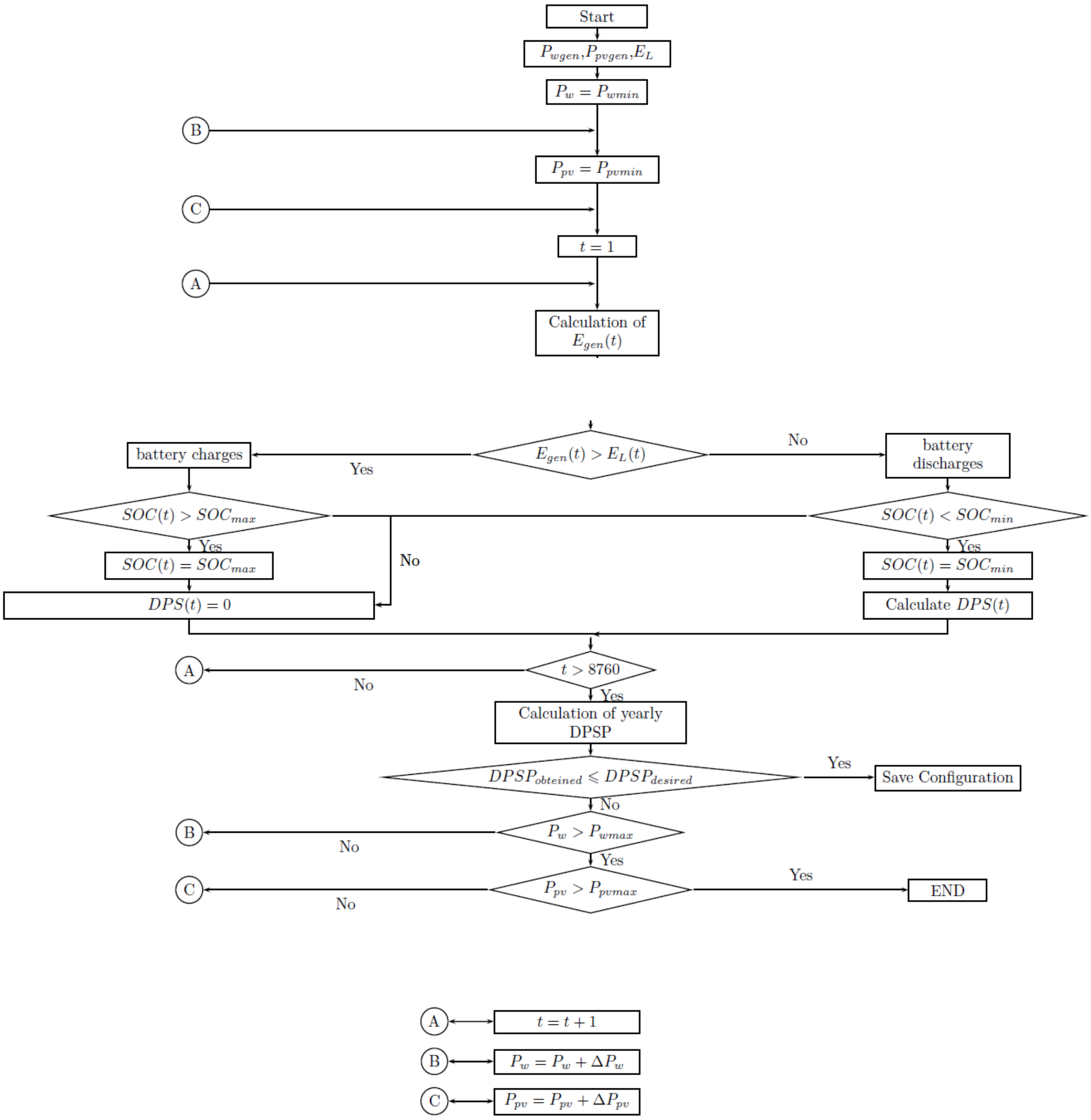


Figure 32: Flowchart of the DPSP program operation

Once the time 8760 is reached, with (6) the yearly DPSP is calculated.

$$DPSP_y = \sum_{t=1}^{T} DPS(t) / \sum_{t=1}^{T} E_L(t) \tag{6}$$

If $DPSP_y$ is lower than $DPSP_{desired}$ the program stops and the current configuration is saved. The results will be the current $DPSP_y$, number of wind turbines used, number of solar PV panels used and any other created vector in the program. If the $DPSP_y$ is grater than the desired the configuration is changed, adding one wind turbine in the configuration until the maximum is reached. When all the wind turbines are installed, the program starts adding solar PV panels and iterates from time 0 to time 8760 for each configuration. If the $DPSP_{desired}$ is never fulfilled the program stops and returns the last $DPSP_y$ which would be grated than the desired one.

Results

Various tests have been made with different situations, changing the $DPSP_{desired}$ taking these values: 0,1 0,2 0,3 0,4 and 0,5. Also, changing the operating wind turbines taking these values: 8 16 24 32 40 and 48. Fig. 33 shows how many solar PV panels are needed for each configuration.

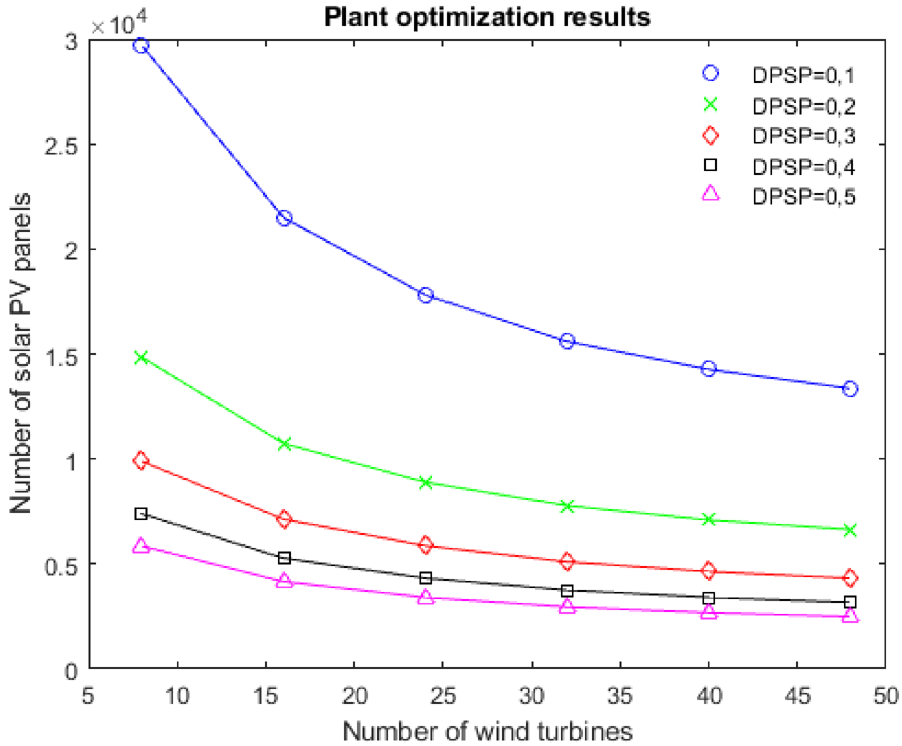


Figure 33: DPSP optimization results

With the goal of analyze other variables of the system the configuration chosen is a $DPSP_{desired} = 0,3$ (the 97% of time the demand is fulfilled), and the number of operating wind turbines is 48 (all the installed turbines in the plant are working). Then, 4322 solar PV panels are needed to be installed in order to meet the specifications.

3.2 Operation to satisfy a constant load

In the following plotted results is shown how the power plant responds to satisfy the constant load.

Reaching the $DPSP_{desired}$ is partly thanks to the storage system. In Fig. 34 is shown how the storage system responds when it is needed.

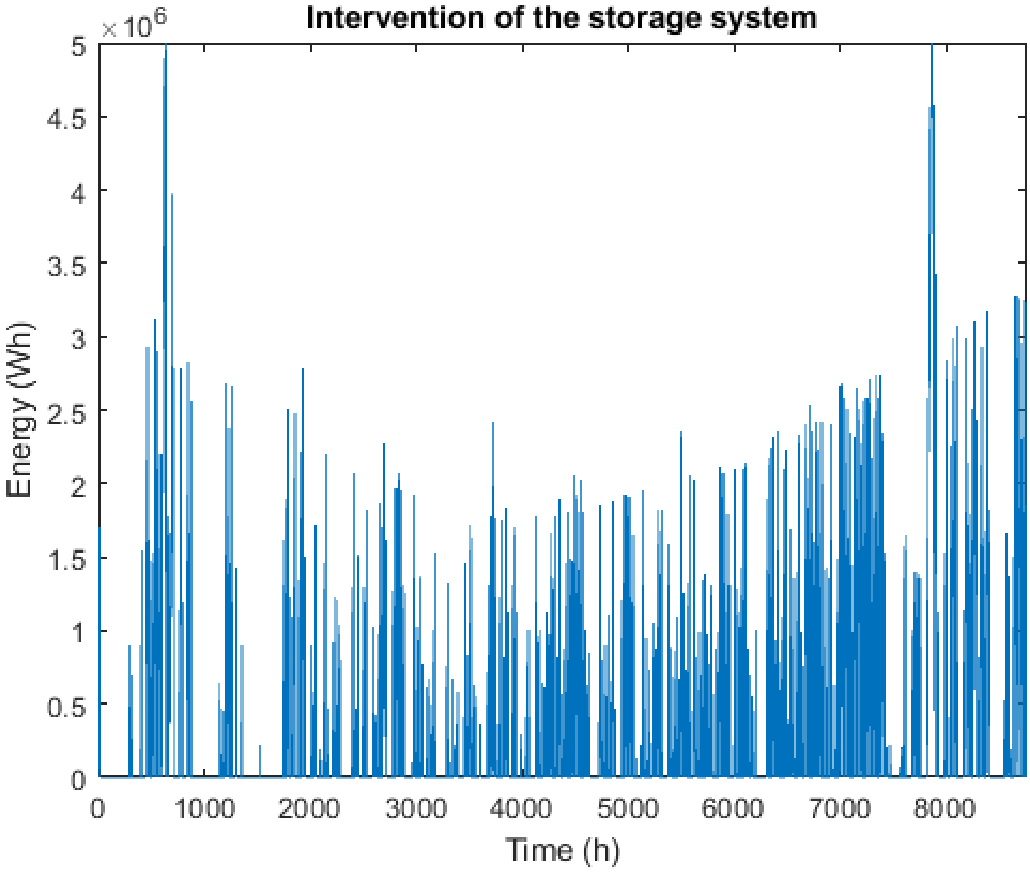


Figure 34: Storage system intervention

In order to see how behave the variables in the simulation, in the following figures, Fig. 35 and Fig. 36 are plotted the variables, E_{gen}, $SOC(t)$ and E_L in different time slots examples.

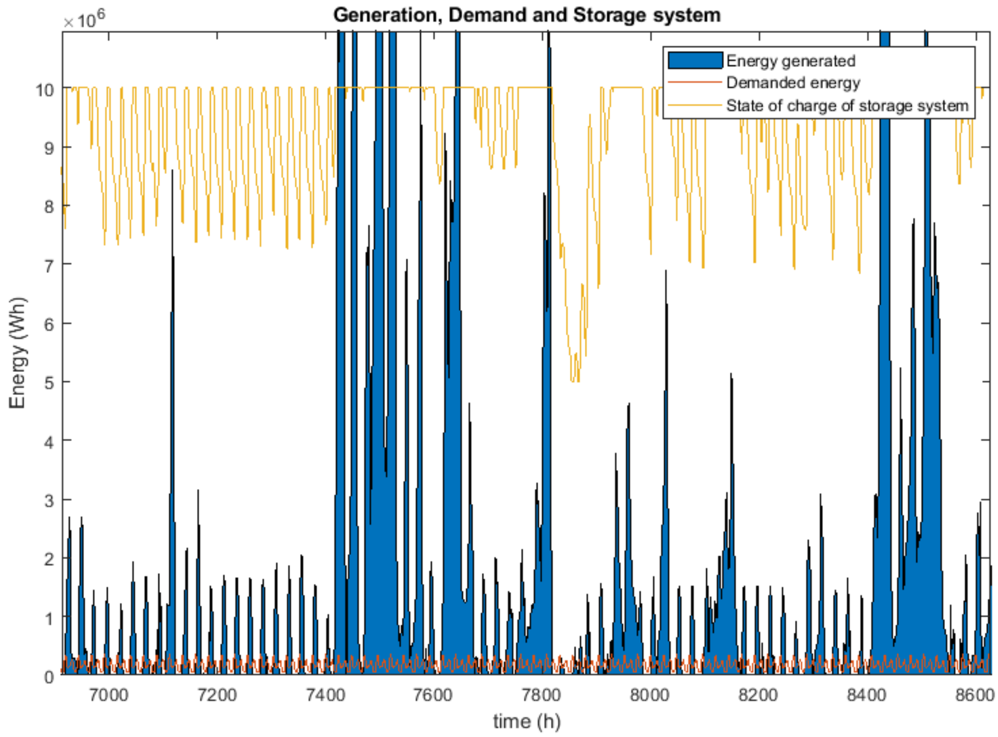


Figure 35: Energy generated, Load and State of charge

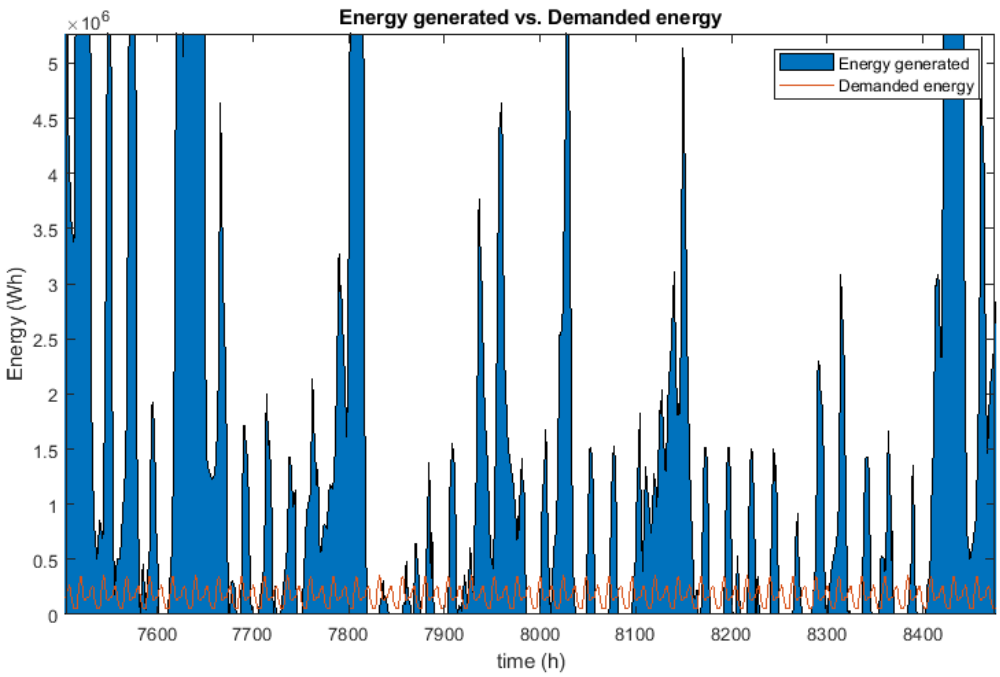


Figure 36: Energy generated and Load

Although this configuration shown above is able to meet the demand the 97 % of time, there is a huge amount of energy which is not exploited and it is useless. In other words, the system needs to be really oversized to fulfill a really low constant load during a whole year. This way of sizing the hybrid power plant would be more appropriate to design a micro grid for a more isolated areas with electricity access difficulties.

4 Design and operation of a grid connected hybrid power plant

4.1 Design of the hybrid power plant

In this section is shown a new simulation that helps to size the new elements installed in the wind power plant to make it a hybrid one. The main difference with the previous section is that the demand is not the main concern, as this plant is not connected to a micro-grid, but rather to the national network. Probably, depending on the energy produced by the turbines and the solar PV panels, may be time periods that the energy produced is 0. But this is only because in this section the main concern is to compensate the investment made.

In this simulation are used also all the data obtained in Section 2.3.1 and Section 2.3.2, used as vectors of 8760 positions, as hours in a year. The following Fig. 37 illustrates a program loop for a single time period. Every time the program reach an end node, repeats from the beginning with a new time $t = t + 1$. After 8760 iterations the program shows 5 vectors of 8760 numbers length: Energy generated by the renewable resources (E_{gen}); Energy used and transferred to the grid (E_{used}); Energy wasted and not used because of the transformer limitations (E_{wasted}); Batteries state of charge during the simulation (SOC).

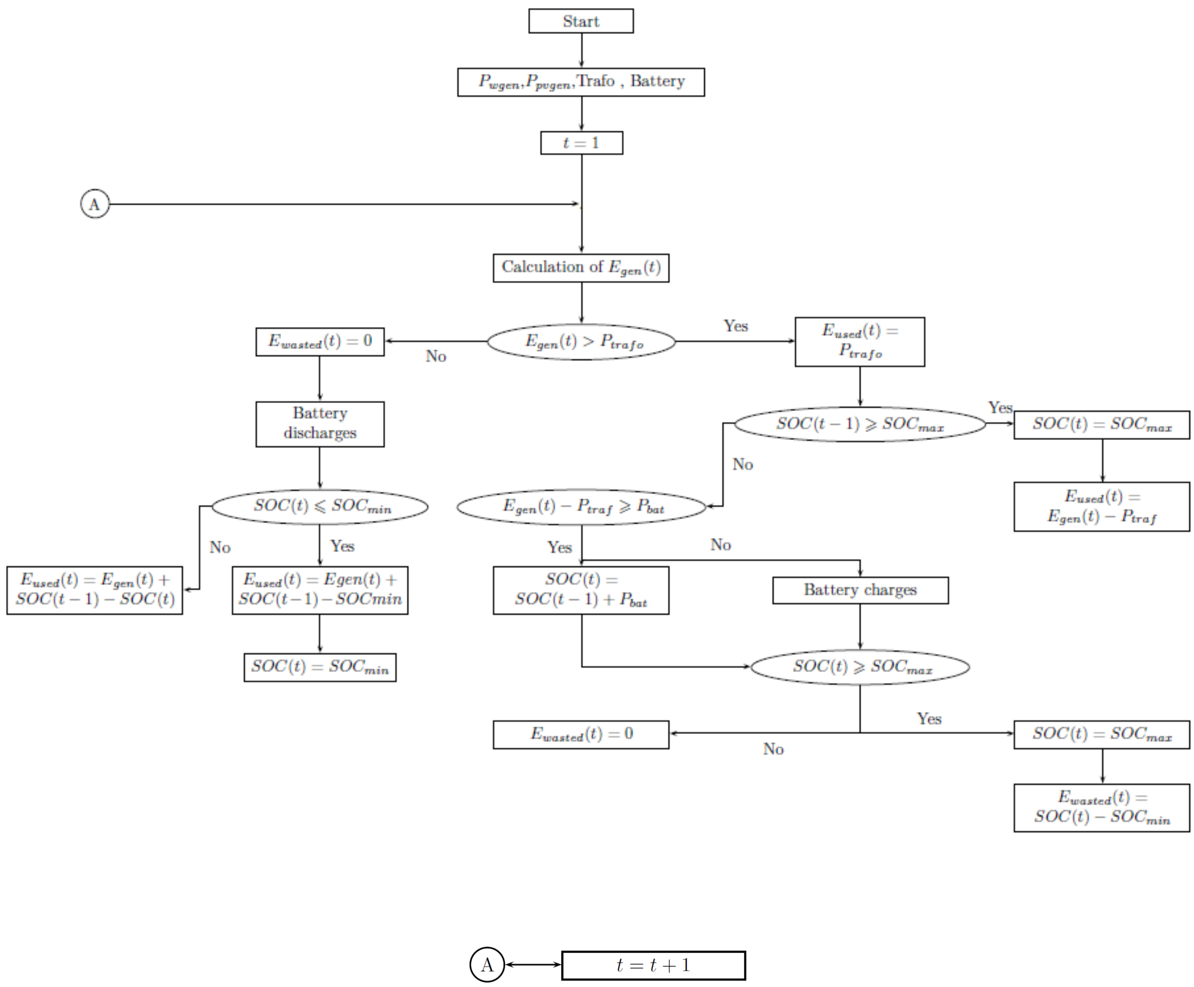


Figure 37: Flowchart of the maximizing benefits program

4.1.1 Interaction between storage systems and plant power transformer capacity

Furthermore, are used vectors that store the power capacity of the main transformer of several models with different characteristics (P_{traf}) and a same length vector that store the investment of each one ($Price_{traf}$). Also to evaluate which kind of battery install, there are vectors that store the nominal power of the battery, the energy storage capacity and the investment of each different battery model.

In a higher level of the program designed, are created loops that simulate the situation described in Fig. 37 for each combination of transformer and battery system. This way, are obtained the following values for every different combination: total energy used from the battery system, all energy used and transferred to the grid, all energy wasted, total gains from the electricity used, the total investment of the battery systems and transformer and finally, the benefits of the combination. It is important to say that it is not supposed to be an economic study of the viability of the project, these calculations are only used to decide which is the best combination of variables.

As the benefits of each combination are calculated, some costs must be known. These costs are an approximate number that helps to predict the value of each element simulated in Matlab.They are expressed in USD \$. In the case of wind turbines, if is needed in the simulation to include new ones, the cost assigned to each wind turbine [2] is 900000 \$. For each new solar PV panel installed the associated cost is 297 \$ [3].

In this simulation is also important to know how the costs increases as the storage system grows. The cost of the storage system[4] is 209 \$ for each KWh of storage. In spite it is a very general number and many factors affect to the cost of an storage system, this is a good approximation that take account many elements.

Finally, the plant power capacity (the maximum power that the transformer is able to send to the grid) is a variable that has been studied in the simulation. The associated cost to each KW of power [15] is 97,8 \$.

The following Table 20 and 21, show the 5 different situations that have been studied for the plant power capacity and 5 more different situations that have been studied for the storage system capacity.

Plant power capacity	1	2	3	4	5
Maximum Power	1 MW	4 MW	6 MW	10 MW	20 MW
Price [\$]	97800	319200	586800	978000	1956000

Table 20: Models of Transformers

Storage system model	1	2	3	4	5
Storage capacity	1 MWh	2 MWh	5 MWh	12 MWh	20 MWh
Price [\$]	209000	418000	1045000	2508000	4180000

Table 21: Models of Battery systems

The exact value of the benefits is not important because, as it is said above, this is a single year simulation and it is not supposed to be an economic study of the viability of the project. This way, in this section and the following ones is better to get relative benefits results, with a single value that is the origin of the comparison for the rest. Fig. 38 is a Matlab surface plot in 3D that show how these different models of storage systems and plant power capacities interact with each other, and react to the simulation explained above. The combination that show the best behaviour of the power plant for this interaction is number 4 (10 MW) for the plant power capacity and number 1 (1 MWh) for the storage system. The main idea is to see that the benefits obtained with this combination are grater than with any other combination. As the figure shows, many results are grater than 1, that is because the origin number chosen to be compared with the rest, is the best combination obtained in Section 4.1.2.

In this section, the interaction between plant power capacity number 4 and storage system number 1 has a relative benefit of 3,18.

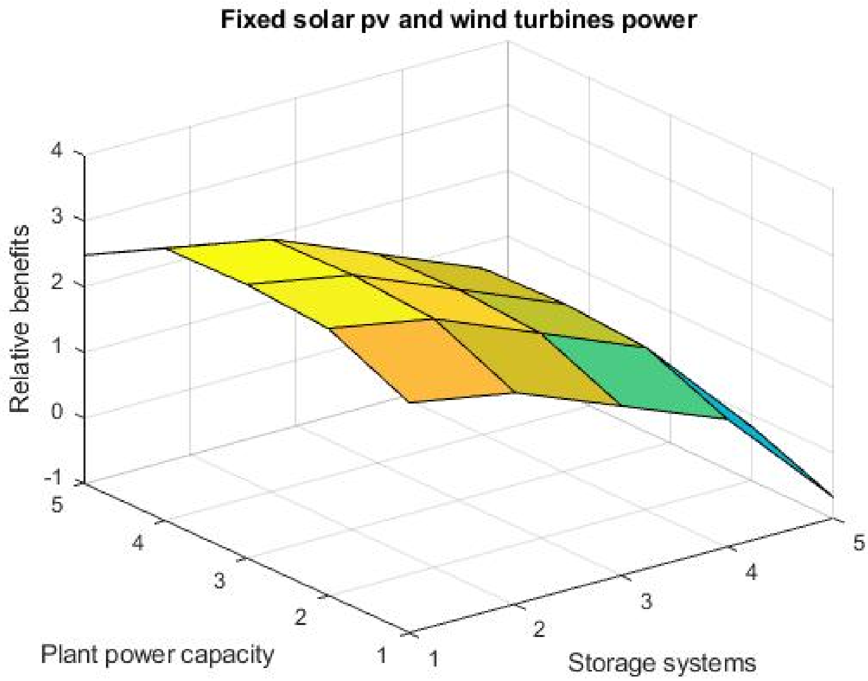


Figure 38: Economic benefits for each combination

4.1.2 Interaction between wind turbine power and plant power capacity

As there are 4 different variables that affect the possible benefits obtained from the power plant, and to be able to plot the results, these variables are compared in pairs, fixating the other two. In the previous Section 4.1.2, the two variables compared were the plant power capacity and the different storage systems. This way, the number of wind turbines and solar PV panels were fixed.

In this section, the variables compared are the number of active wind turbines and the plant power capacity. The different plant power capacities are the same shown in Table 21. The different active wind turbines configurations are shown in Table 22. The fixed variables are the storage system (6 MWh) and the number of solar pv panels (4322).

Wind turbine configurations	1	2	3	4	5
Number of wind turbines	5	10	20	30	40

Table 22: Wind turbine configurations for the simulation

In this iteration the best configuration is the combination of the plant power capacity, number 3 (6 MW), with the wind turbine configuration number 5, the highest one (40). The value obtained is 1 as it is the value used to be compared with the other studied cases. In spite this result, in relative terms is worse than the ones obtained in the previous section.

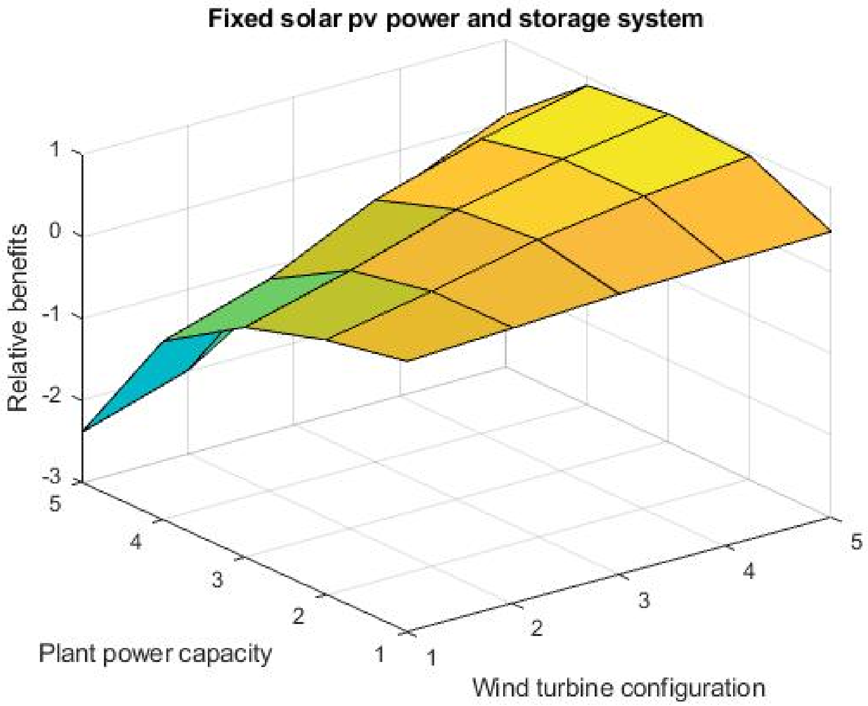


Figure 39: Economic benefits for each combination

4.1.3 Interaction between wind turbine power and storage systems

In this other simulation, the variables compared are the number of solar PV panels and the plant power capacity. The fixed ones are the storage system installed (6 MW) and the number of active wind turbines (48). It has been used five different configurations for the number of installed solar PV panels as shown in Table 23.

Solar PV configurations	1	2	3	4	5
Number of solar PV panels	1000	2000	3000	3700	4322

Table 23: Solar PV panels configurations for the simulation

The results obtained are plotted in Fig. 40. The configuration number 3 for the plant power capacity (6 MW), and the configuration number 1 for the solar PV panels (1000) show the best relative benefits in this iteration. Even though this is a good result, is not as good as in other simulation.

In this section, the interaction between the plant power capacity number 3 and the solar pv configuration number 1 has a relative benefit of 2,48.

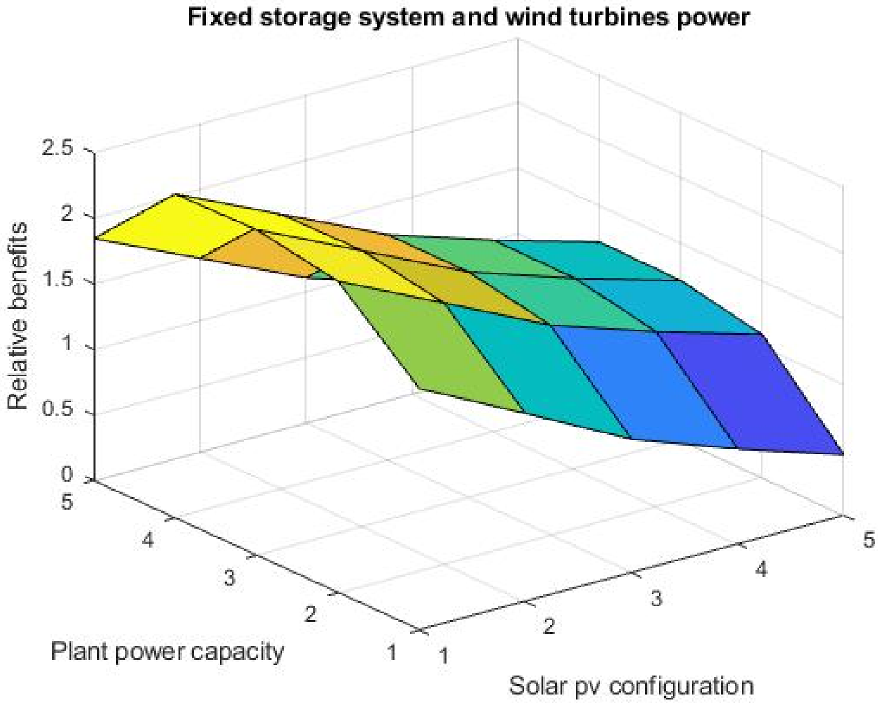


Figure 40: Economic benefits for each combination

4.1.4 Interaction between solar PV power and storage systems

This section is the last one to show the interaction of the different variables of the hybrid power plant. In this case the compared variables are the storage system and the solar PV panels configuration. This variables have been already used, this way, the different configurations for each variable are the same as in section 4.1.1 (for storage systems) and section 4.1.3 (for solar PV panels). The fixed variables are: active wind turbines (48) and plant power capacity (5 MW).

The results plotted in Fig. 41 show a very poor information for this interaction. As can be noted the relative benefits vary very little as the storage systems change. This response is probably because the main energy stored in this power plant may have a wind origin. On the other hand, most of the solar PV energy produced is sent to the grid.

Despite some combinations of this interaction are good, they are not as good as in other interactions shown in previous sections. The best relative benefits obtained with solar PV configuration number 1 are around 2,4.

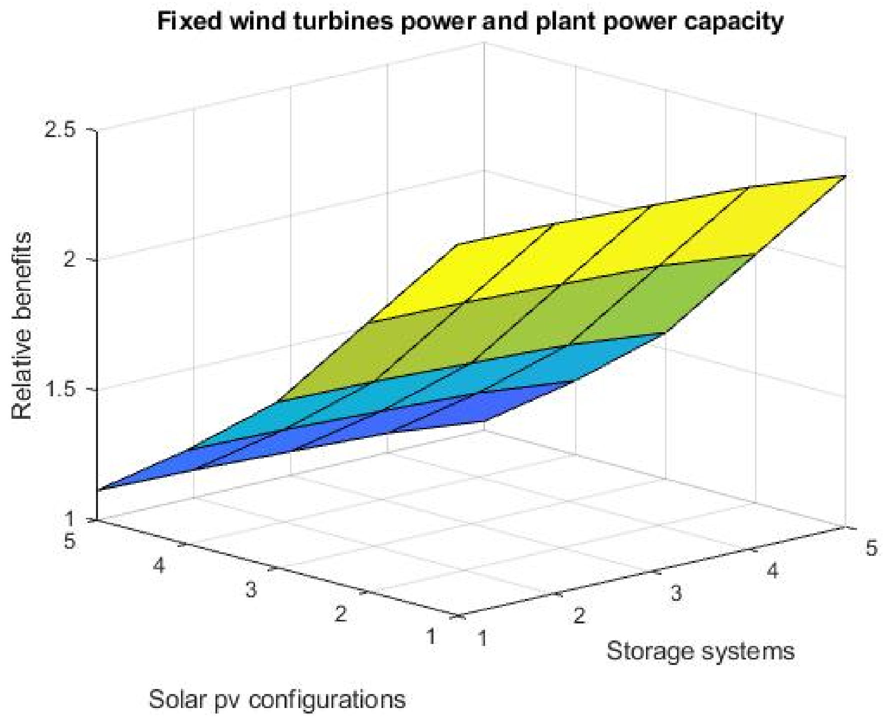


Figure 41: Economic benefits for each combination

4.2 Operation of the hybrid power plant

In the previous sections the interactions studied were only related with the possible benefits of the different configurations. Now that the best configuration has been decided, a more specific study will be made in order to get better view of how this hybrid power plant works. In Fig. 37, in Section 4.1.1, there is an schematic flow chart that shows how the hybrid power plant is supposed to work. Now, an other iteration will be made with the same flow chart but only for the best combination found in the same section. The following plots show different types of the hybrid power plant behaviour considering the best combination found in the previous sections. This power plant is composed of 4322 solar PV panels and 48 wind turbines (all of the already installed turbines are working).

The Matlab program simulates an entire year with real weather conditions and show how the plant behaves. In Fig. 42 are plotted for an entire year the energy produced, energy used and the state of charge of the storage system.

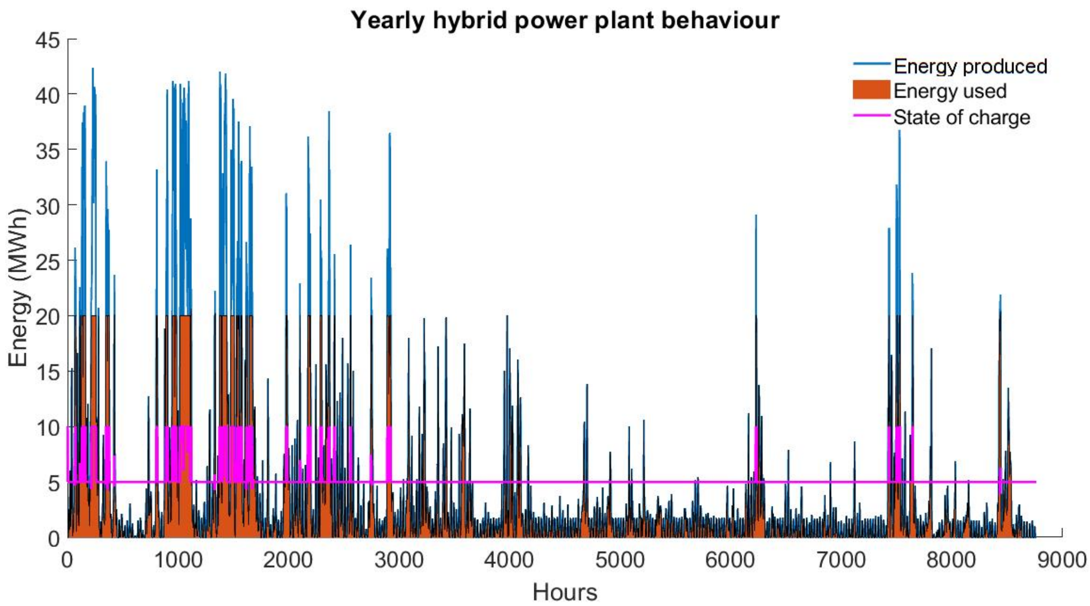


Figure 42: Hybrid power plant behaviour

In the following plots is shown how the is used in many possible situations affected by different weather conditions in magnified images of Fig. 42. In Fig. 43 is shown a time slot of approximately 100 hours. In this period of time the energy produced is always under the plant power capacity. For this reason the energy used is always equal as the energy produced. In other words, all the energy produced, solar and wind, is transferred to the grid as there is no excess to charge the storage system. In this case, the battery systems will remain in the lowest state of charge which is the same as the 50 % of the maximum storage system capacity. In this case, the hybrid power plant does not show any difference between having or not the storage system. It could happen in shorts time slots due to poor weather condition, which does not mean that is like this the whole year.

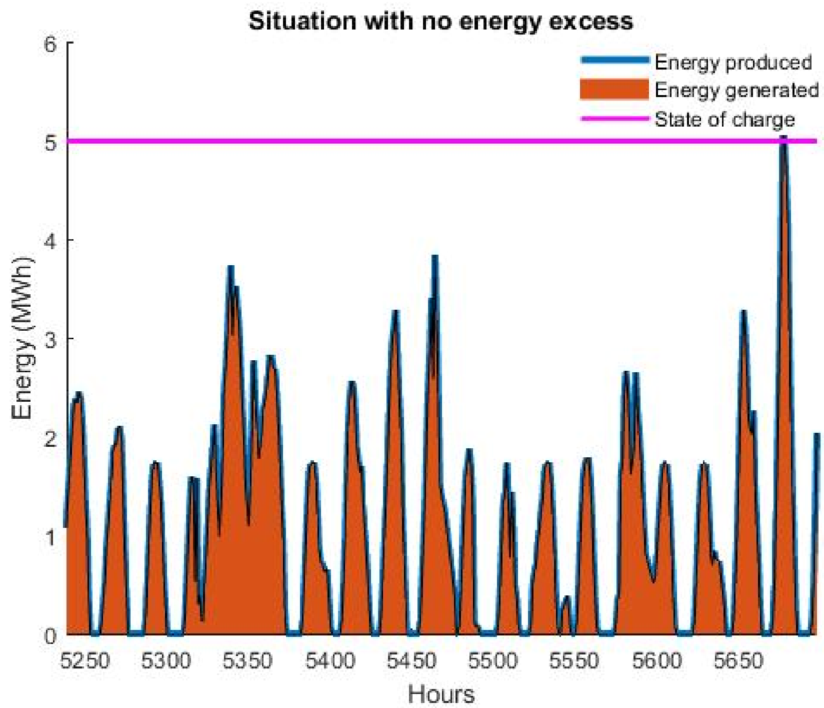


Figure 43: Example of time slot with no energy exces

Now, in Fig. 44 the hybrid power plant does not works properly earthier. In this case is shown an approximately 50 hours time slot where the storage system is in its maximum state of charge. In the other hand, the energy produced, is grater than the plant power capacity, so the difference between the energy produced and the maximum power of the main transformer is wasted energy. This amount of wasted energy is the one that is supposed to be minimized thanks to the hybrid system. The state of charge, show that the storage system remains in its maximum state, prepared to be used if the energy produced decreases. As is happening in Fig. 43 the weather conditions are not optimal in this time slots, which does not mean that will happen in the rest of the year, as we will see in the next plots.

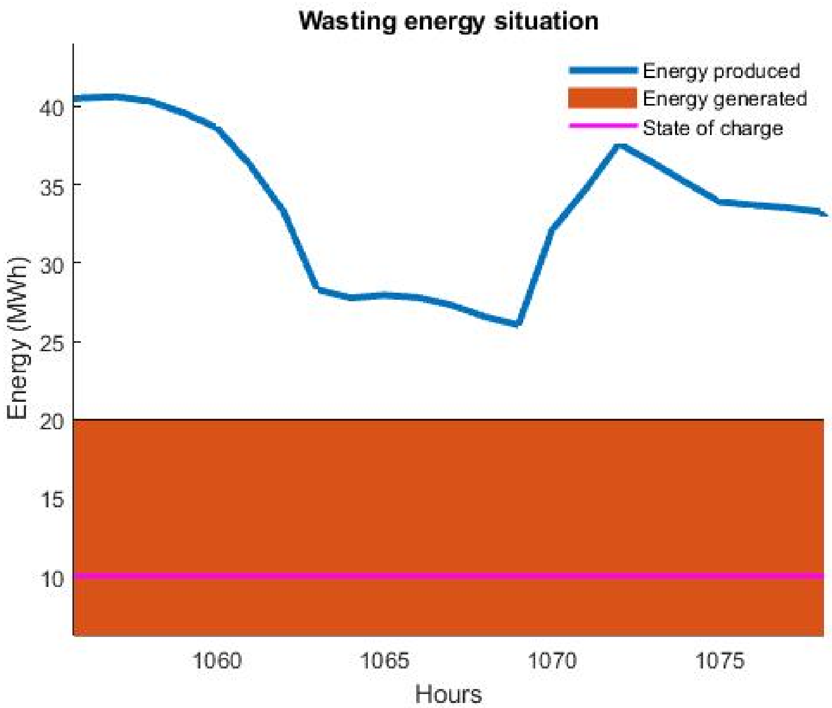


Figure 44: Example of time slot with big amount of wasted energy

If the energy produced is grater than the plant power capacity, there is an excess of energy. This hybrid power plant tries to store this energy to reduce the total amount of non energy used. The Fig. 45 show how this happens. In the hour 2241 the wind, the sun irradiance or both, start to be sufficiently good to produce energy, and the storage system remain in its lower state of charge. This amount of energy produced start to grow until in hour 2245, exceeds the plant power capacity. At that moment the storage system start to store energy, until it reaches its maximum state of charge in hour 2247. From then on, the difference between the energy produced and the plant power capacity is energy not used.

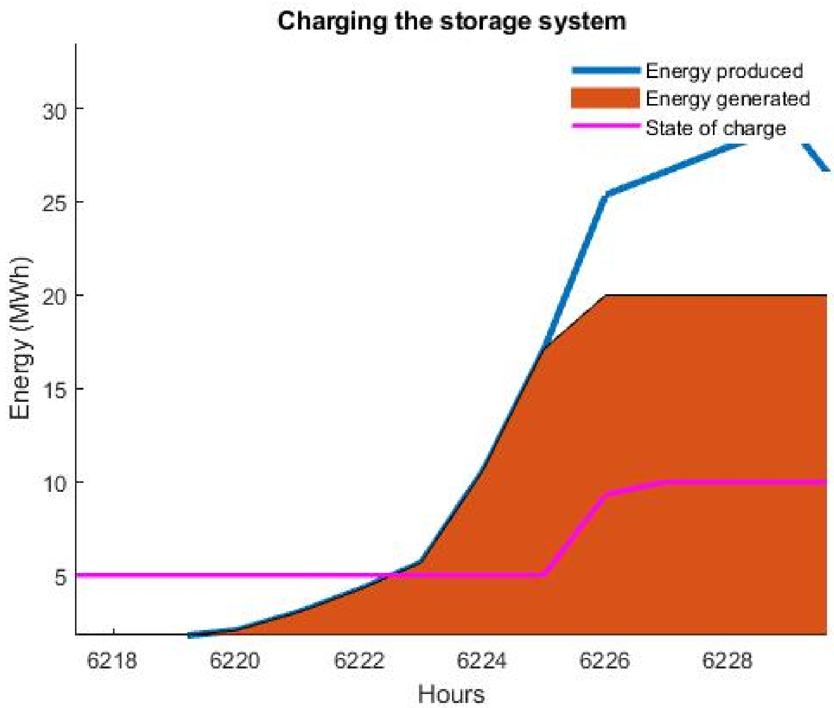


Figure 45: Example of storage system charging

Finally, the last possible working situation of the hybrid power plant is when the energy produced is lower than the used. This is only possible if the power plant is equipped with a storage system. As it is shown in Fig. 46, before hour 1555, the energy produced is grater than the plant power capacity, and the storage system is in its maximum state of charge. From hour 1556, the energy produced decreases until it gets under the plant power capacity. As can be noted, the state of charge of the storage system starts to decrease making possible to keep the used energy at the maximum some time slots more. Finally, as might be expected, when the state of charge reaches its minimum, the amount of energy produced and the amount of energy used will be the same.

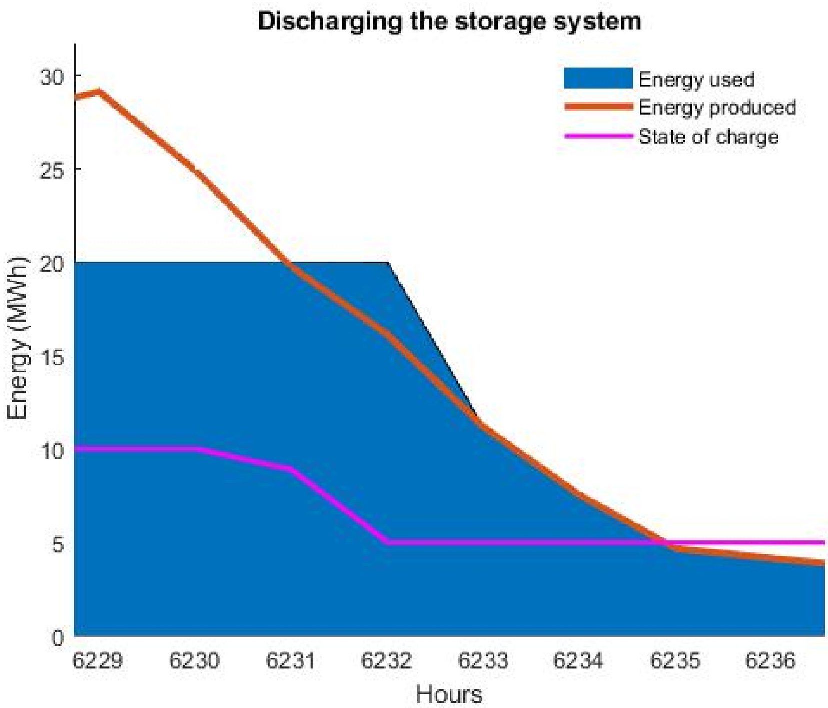


Figure 46: Example of storage system discharging

5 Refurbishment of the wind power plant of Sierra Costera

So far, it has been discussed and studied meteorological data, power production and interaction between various energy resources in certain locations, where there is already installed a wind power plant. Is interesting to take benefit of this situation and reduce the possible investment by convert the wind power plant to a hybrid renewable power plant.

5.1 Design of the refurbished power plant

This refurbishment of the power plant will entail the introduction of two new elements, the solar PV panels and the electrical energy storage system. To avoid bigger investments, the maximum output power of the main transformer of the wind farm will remain the same, and the new elements introduced in the refurbishment will be connected before this main transformer that is connected to the grid. The wind power plant of Sierra Costera has a power capacity of 40,8 MW generated by 48 turbines of 850 KW of nominal power. There is no information about the total output power capacity of the main transformer, we will assume that is around 50 and 75 % of the total wind turbines power.

In order to know the viability of the refurbishment is needed to know the different costs of the new elements installed, from the photo-voltaic part and from the storage system. The following exposed prices in this section will be in units of $ USD as most of the information in the referenced papers and articles is in $ USD. Also, is important to know that all the costs exposed below are approximate figures as price in this sector are considerably changing .

5.1.1 Solar PV investment, maintenance and operation cost

In the last years costs around installing solar PV panels has decreased significantly. These prices reductions have occurred by decreasing the solar PV panels production costs, by increasing the amount of production and by increasing the efficiency of the panels [11]. This costs decrease is around 50 % only in the last decade [12].

Investment of the energy solar PV system entail, modules, mounting system, electrical system, inverters, substation infrastructure, construction, engineering and the rest of factors in total investment costs. Modules and mounting system are the most important part of the investments amounting to more than 50 % of the total costs. To sum up, the total installed capital cost is, in approximately terms, 1,20 $ USD/W [12]. In Section 5.1.3 a Net Value Added will be made to analyze the viability of the project in the next years. For this reason, is important also to know the operating and maintenance costs of the installation. In this simulation will be considered a total estimated cost of 0,04 $USD/W·year that is arround 2,5 % of the annual capital [12].

5.1.2 Energy storage system investment, maintenance and operation cost

There are a lot of different battery technologies that already exist. For requirements like the ones exposed in this project (large installations connected to the grid), Li-on batteries are suitable [1]. Like in solar PV technologies, in lithium-ion batteries, costs have decreased significantly in recent years because of the rise of electric vehicles and also their application in energy storage systems. Tesla large scale Li-on batteries will be used in this simulation, as they are one of the most economic alternatives. We will assume that the total installation cost of the batteries is 562 $USD/kWh [12]. The associated cost to the operating and maintenance is assumed to be 5,62 $USD/kWh·year which correspond to the 1% of the total investment cost.

5.1.3 Refurbishment project viability

Is noticeable that the electricity price is not a constant value during the year, not even during the day, but is a very unpredictable value to calculate for every time slot. For this reason, for the next simulation, a constant price that correspond to the predicted mean value for the year will be assumed [6]. The price for the output electricity shared to the grid is assumed to be 62 €/MWh. As all the investment costs from the solar PV system and the energy storage system are in units of $ USD, the electricity price will be calculated also in $ USD. This correspond to a electricity price of 73,57 $ USD/MWh.

Now, considering the investment costs and the operating and maintenance costs that appear every year, a simulation of the hybrid power plant will be made. The operation of the simulation is the same as in previous sections, but now this simulation will be 10 year long to have big enough amount of information to evaluate the viability of the refurbishment.

This simulation is repeated 49 times for 49 different circumstances or combinations with 7 numbers of installed solar PV panels and 7 different power energy capacity storage systems shown in Table 24 and in Table 25.

PV configuration	1	2	3	4	5	6	7
Number of panels	2000	4000	8000	15000	20000	30000	35000

Table 24: Number of panels by configuration

Battery configuration	1	2	3	4	5	6	7
Storage capacity	0,1 MWh	0,5 MWh	1 MWh	3 MWh	4 MWh	5 MWh	10 MWh

Table 25: Storage system capacity by configuration

To establish which combination is the most profitable the Net Present Value (NPV) for the next 15 years will be calculated for every single combination. The NPV is used in investment planning to examine the profitability of a project. In (7) is shown the formula to calculate it.

$$NPV = I_0 + \sum_{n}^{t=1} \frac{F_t}{(1+k)^t} = I_0 + \frac{F_1}{(1+k)^1} + \frac{F_2}{(1+k)^2} + ... + \frac{F_n}{(1+k)^n} \tag{7}$$

where:

I_0 is the investment done in period $t = 0$.

F_t is the Net cash inflow-outflows in a period t.

k is the discount rate.

t time periods (years).

		Battery system configuration						
		1	2	3	4	5	6	7
PV configuration	1	28,06	28,05	28,05	28,01	27,98	27,96	27,84
	2	28,49	28,49	28,48	28,44	28,42	28,39	28,28
	3	29,35	29,34	29,34	29,31	29,28	29,26	29,14
	4	30,82	30,81	30,81	30,78	30,76	30,73	30,62
	5	31,83	31,83	31,83	31,80	31,78	31,76	31,65
	6	33,73	33,73	33,73	33,72	33,71	33,69	33,62
	7	34,59	34,59	34,60	34,60	34,59	34,58	34,53

Table 26: NPV matrix results for the 49 iterations. Units in Million $ USD

Table 7 show the NPV results matrix obtained after executing the simulation for 15 years for every combination. The rows are the solar PV different number of panels shown in Table 24 and the columns are the battery system configuration exposed in Table 25. The results are in units of millon $ USD. After obtaining these results is noticeable that the best combination, the one that is more profitable in terms of investment planing, is the one in the green cell. The combination that entails configuration number 7 (35000) of number of solar panels and configuration number 4 (3 MWh) of storage system.

5.2 Operation of the refurbished power plant

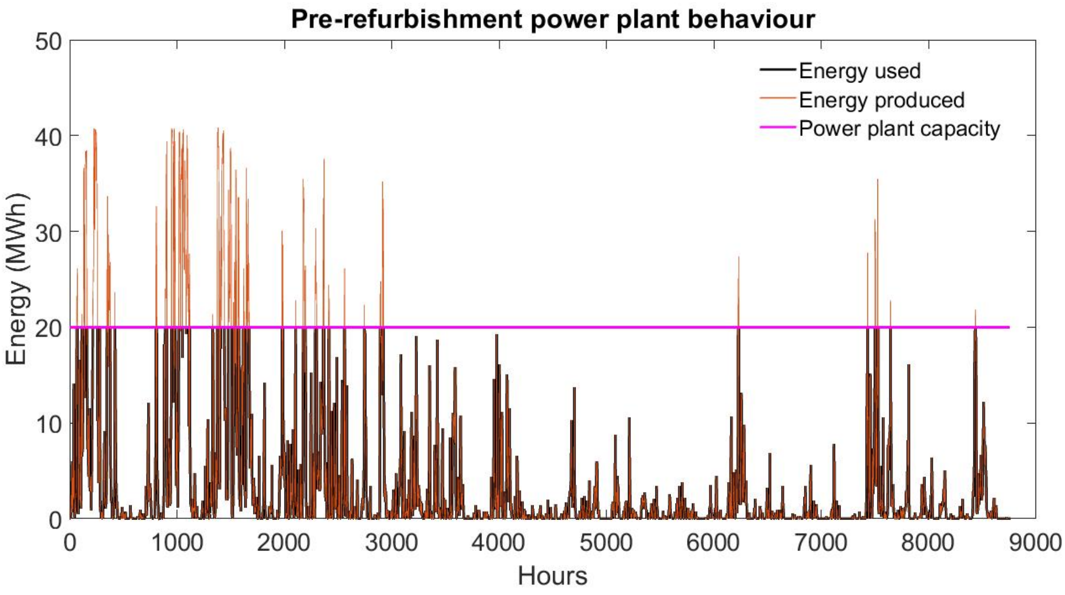


Figure 47: Power plant behaviour with out hybridization

In Fig. 47 is shown how the wind power plant of Sierra Costera works now a days. It is assumed that the maximum output power of the main transformer is 20 MW, as mentioned before, there is no information about this output power. This plot show only the energy obtained by the wind turbines for one year (8760 time periods). The energy produced by the wind turbines is the most of the time under the power plant capacity, and only the firsts months of the year and in some time periods at the end of the year the energy produced exceeds the power plant capacity, which means that this energy will be non profitable. When this happens, the energy used, or transferred to the grid, is different to the energy produced. The aim of the refurbishment is to minimize the wasted energy, but also to reduce the difference between the power plant capacity and the energy used.

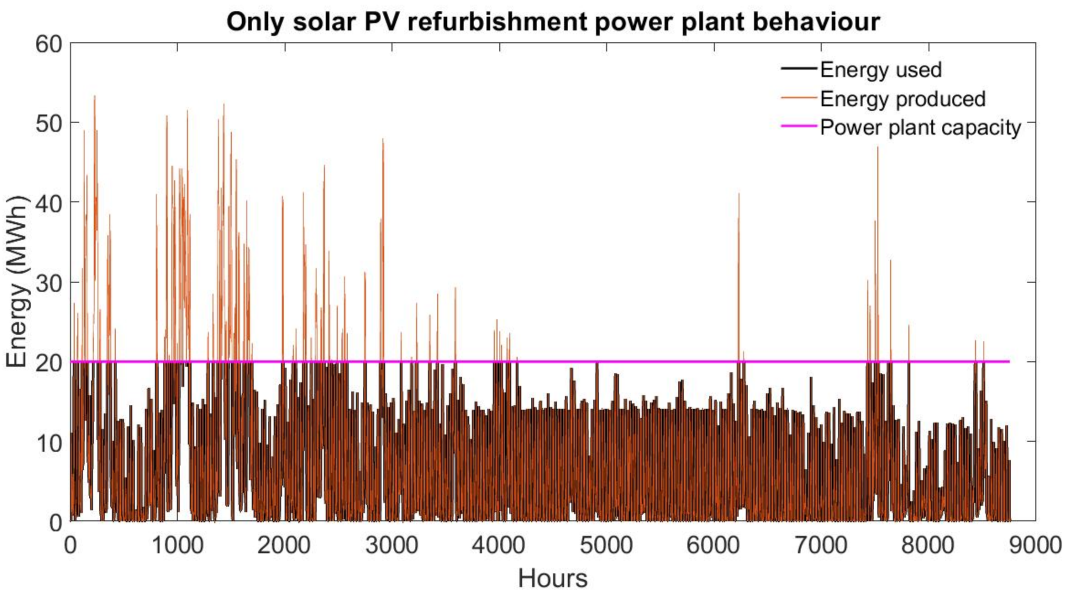


Figure 48: Power plant behaviour with only solar PV hybridization

The refurbishment of the wind power plant has been made in two steps, to see how affect to the results every change performed in the power plant. Fig 48 show also energy produced, energy used and the main transformer capacity, but now, with all the solar panels installed. The number of solar PV panels installed is 35000 because is the one that match with the best result obtained in the NPV calculations. It is noticeable that the difference between the output power plant capacity and the energy used has decreased considerably (there is less empty space above the power plant capacity line). In is also important to say, as will be shown above in the summarize chart that the fact of installing the solar PV panels does not produce a big growth in the energy wasted.

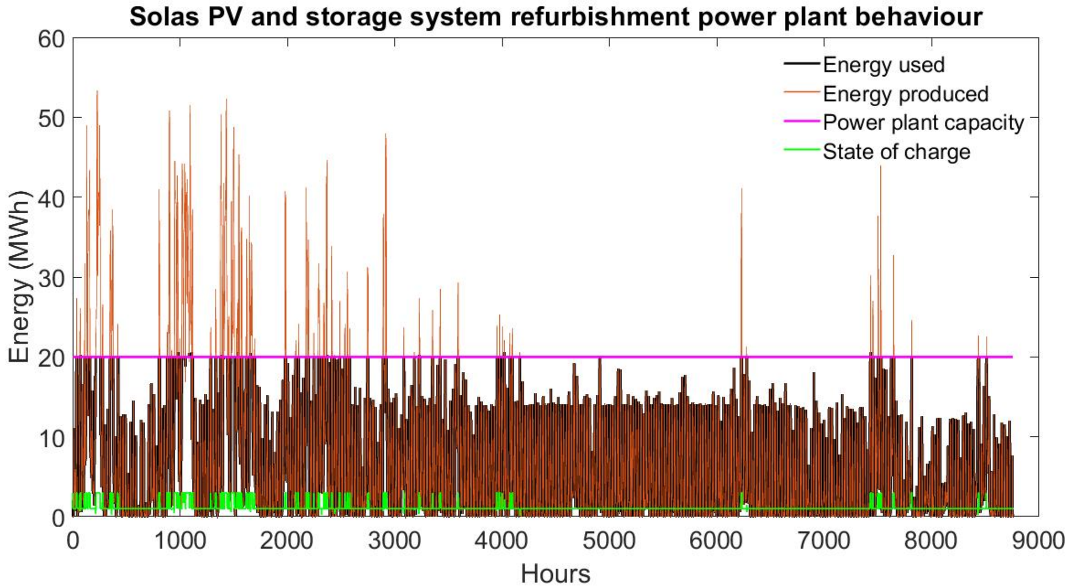


Figure 49: Power plant behaviour with solar PV and storage system hybridization

Finally, the same plot has been made for the full refurbishment situation. The whole year has been simulated with 35000 solar PV panels and with a storage system of 3 MWh of capacity. The results are plotted in Fig. 49. The variables are the same as in the previous plots, energy used, energy produced an power plant capacity, but now with the state of charge of the battery system. As can be noted, the state of charge is always between two values, the maximum state of charge and the minimum state of charge, that i never fully empty because that would affect seriously the the life time battery.

In Table 27 and Table 28 are summarized the results shown in the different steps of the refurbishment shown in the plots above. It is given the energy produced, energy used and energy wasted for the three situations. The refurbishment steps are organized in three columns. Column 0 refers to the wind power plant without any change. Column 1 refers to the wind power plant hybridized with solar PV panels. Column 2 refers to the wind power plant hybridized with solar PV panels and the electrical energy sotrage system. As the rows show the total energy in a entire year, the units are in GWh.

	Refurbishment steps		
	0	1	2
Energy produced (GWh)	30,21	58,03	58,03
Energy used (GWh)	25,20	50,65	52,61
Energy wasted (GWh)	5,01	7,37	7,10

Table 27: Refurbishment results

	Refurbishment steps	
	0 to 1	1 to 2
Energy produced	+ 92.06 %	+ 0,00 %
Energy used	+ 100,98 %	+ 3,86 %
Energy wasted	+ 47,17 %	- 3,71 %

Table 28: Refurbishment results in percentage

The installation of the solar PV park produce a clear rise in the energy produced, used and wasted. The rise in energy produced and energy used is around 100 % which means that the solar panels fill the gap between the energy produced and the power plant capacity. The energy wasted, predictably, also increases, but around 50 % which is good because it grows in a lower rate that the energy used.

When the storage system take action, the energy produced remains the same, because batteries does not produce new energy, but stores the extra energy. In the step 2 the energy used grows to nearly a 4 %. The energy wasted decreases also nearly a 4 %. This results is under expectations, but the storage system capacity is highly affected by the expensive investment of the system. However this rise on the energy shared to the grid is big enough to affect positively to the economic profitability of the project. Analyzing these results it can be said that this configuration of refurbishment in the wind power plant of Sierra Costera is profitable from the economic point of view, but also is very interesting from an environmental point of view, as it is doubling the clean energy produced.

6 Conclusions

The results of the meteorological data analysis show a very good correlation between the wind and solar source in all of the studied locations, they show that most of the time the wind velocity is low, the sun irradiance is high. This prove that the four studied areas are suitable for hybridisation of power plants. Comparing these correlations allows to decide that the best studied location is Sierra Costera, in the region of Aragon, Spain.

The analysis of Deficiency of power supply probability (DPSP) that tries to design a power plant with the objective of guarantee a determined load, has not produced the results that were hoped. The simulation show that is needed an oversized infrastructure of power generation to ensure a very weak demand. This cause a non economically profitable project. It would be provably suitable for different demand profiles or off-grid infrastructures. In spite these results, the operation obtained results of the power plant show that the Matlab program designed works as it was expected.

In the design of the new hybrid power plant the designed program has simulated the interactions between variables, and has shown a study that would help to design and size a new project. However, the predicted costs and the obtained results has guided the project to a refurbishment of the wind farm, exploiting the fact that there are already wind farms working in the studied locations.

Finally, very good results have been obtained in the wind farm refurbishment. The study made by comparing the NPV of the different configurations of the hybrid power plant, in the design part, has helped to decide which is the best solar PV and storage system configuration, for the refurbishment of the Sierra Costera wind farm. The NPV obtained for the best configuration prove the viability of the project. The operation of the refurbished plant show a good behaviour and compatibility of the three resources. The used energy of the power plant is doubled with the refurbishment, and the storage system helps to reduce the non profitable energy considerably. The impact of the battery system is lower than expected but it is because the present costs of storage systems are still high.

7 Enviromental impact

CO_2 emissions

This project has a very important objective, increase the clean energy production by renewable resources and reduce the CO_2 emissions.

The energy used in the refurbished wind farm has increased from 25,2 GWh to 52,61 GWh in a year. This is approximately the 110 %. The increase of clean energy is of 27,41 GWh a year.

The emissions of CO_2 in Spain from non renewable energy are around 0,252 Kg CO_2/kWh. If the difference that cause the refurbishment was not produced by renewable energies, it would produce 6907,32 tons of CO_2 every year.

Solar PV panels

The energy produced by PV panels does not produce CO_2 emissions as it is not required a combustion. PV panels are mainly produced of silicon, a mineral that is present massively in nature and its extraction does not affect the terrain structure. In spite this, manufacturing solar PV panels cause CO_2 emissions. It depends on the way they are produced and installed and it normally depends on the installer company.

The installation of massive solar PV power plants can affect negatively to the flora and fauna that was already living in the location.

Li-on batteries

As far as environment concerns, using Li-on batteries in order to store clean energy has potential benefits. It avoids using fossil fuels and thus the CO_2 emissions. It is also interesting because they can store energy for many cycles with a minimum loss of capacity with a life time of around 10 years. The storage system also uses energy that has already been generated, energy that in other conditions would have been wasted.

On the other hand, Li-on batteries present some negative characteristics, like the use of flammable substances that increase the security and environmental risks. The bio degradation time that requires a Li-on battery is more than a thousand years. Is important to send them to a specialized plant to be dismantled. These kind of batteries are produced with some toxic materials like mercury, zinc, chromium, arsenic, lead and cadmium.

8 Budget

An engineer has draft this project who has performed all the tasks. In Table 29 it is shown inverted hours and their costs by tasks. The total amount of hours invested in the project are 325 h.

	Unit cost	Number of hours	Total
State of art	40 €/h	20 h	800 €
Data acquisition	40 €/h	40 h	1600 €
Data treatment	75 €/h	90 h	6750 €
Programs design	75 €/h	60 h	4500 €
Simulations	75 €/h	55 h	4125 €
Thesis draft	30 €/h	60 h	1800 €
Matlab licence	2000 €	1	2000 €
Total	-	-	**21575 €**

Table 29: Summary budget

Agraïments

First of all, I would like to thank to my thesis director, Eduardo Prieto Aruajo, that has guided and helped me during all the project. He has always been available, and has shown great interest in my project.

I would like to thank also to my family that has been always next to me and supporting my work not only in this Master Final Thesis, but in all the years in this university.

ETSEIB

Annex

Wind speed low (m/s)	Wind speed high (m/s)	Avarage Wind Speed (m/s)	Acum. Prob. Low	Acum. Prob. High	Interval Prob.	Hours	Available Power (MW)	Available Energy (MWh)	Range OK	Power (MW)	Energy (MWh)
0	1	0,5	0	0,0213	0,0213	3739,4	0,0002	0,8196	0	0	0
1	2	1,5	0,0213	0,0739	0,0525	9199,9	0,0059	54,444	0	0	0
2	3	2,5	0,0739	0,1488	0,075	13137	0,0274	359,92	0	0	0
3	4	3,5	0,1488	0,2388	0,09	15759	0,0752	1184,8	1	0,0752	1184,8
4	5	4,5	0,2388	0,3367	0,0979	17148	0,1598	2740	1	0,1598	2740
5	6	5,5	0,3367	0,4362	0,0995	17441	0,2917	5088	1	0,2917	5088
6	7	6,5	0,4362	0,5323	0,0961	16831	0,4815	8104,8	1	0,4815	8104,8
7	8	7,5	0,5323	0,621	0,0887	15547	0,7397	11501	1	0,7397	11501
8	9	8,5	0,621	0,6999	0,0789	13823	1,0768	14885	1	1,0768	14885
9	10	9,5	0,6999	0,7677	0,0678	11875	1,5034	17853	1	1,5034	17853
10	11	10,5	0,7677	0,8241	0,0564	9884,2	2,0298	20063	1	2,0298	20063
11	12	11,5	0,8241	0,8697	0,0456	7987,6	2,6668	21301	1	2,6668	21301
12	13	12,5	0,8697	0,9055	0,0358	6277	3,4247	21497	1	3,4247	21497
13	14	13,5	0,9055	0,9329	0,0274	4802,9	4,3141	20720	1	4,3141	20720
14	15	14,5	0,9329	0,9534	0,0204	3582	5,3456	19148	1	5	17910
15	16	15,5	0,9534	0,9683	0,0149	2606,1	6,5296	17017	1	5	13031
16	17	16,5	0,9683	0,9788	0,0106	1851,1	7,8767	14581	1	5	9255,5
17	18	17,5	0,9788	0,9862	0,0073	1284,4	9,3974	12070	1	5	6422
18	19	18,5	0,9862	0,9911	0,005	871,03	11,102	9670,3	1	5	4355,1
19	20	19,5	0,9911	0,9944	0,0033	577,62	13,002	7510	1	5	2888,1
20	21	20,5	0,9944	0,9966	0,0021	374,72	15,106	5660,7	1	5	1873,6
21	22	21,5	0,9966	0,9979	0,0014	237,9	17,426	4145,8	1	5	1189,5
22	23	22,5	0,9979	0,9988	0,0008	147,86	19,973	2953,3	0	0	0
23	24	23,5	0,9988	0,9993	0,0005	89,995	22,756	2047,9	0	0	0
24	25	24,5	0,9993	0,9996	0,0003	53,654	25,786	1383,5	0	0	0

Table 30: Calculations of power and energy production in Serra de Rubió

Wind speed low (m/s)	Wind speed high (m/s)	Avarage Wind Speed (m/s)	Acum. Prob. Low	Acum. Prob. High	Interval Prob.	Hours	Available Power (MW)	Available Energy (MWh)	Range OK	Power (MW)	Energy (MWh)
0	1	0,5	0	0,003	0,003	582,89	0,000	0,128	0	0	0
1	2	1,5	0,003	0,016	0,013	2293,33	0,006	13,572	0	0	0
2	3	2,5	0,016	0,041	0,025	4375,77	0,027	119,886	0	0	0
3	4	3,5	0,041	0,079	0,038	6576,70	0,075	494,431	1	0,075	494,431
4	5	4,5	0,079	0,129	0,050	8715,76	0,160	1392,632	1	0,160	1392,632
5	6	5,5	0,129	0,189	0,061	10637,91	0,292	3103,402	1	0,292	3103,402
6	7	6,5	0,189	0,259	0,070	12213,55	0,482	5881,330	1	0,482	5881,330
7	8	7,5	0,259	0,335	0,076	13345,72	0,740	9872,321	1	0,740	9872,321
8	9	8,5	0,335	0,415	0,080	13976,96	1,077	15050,923	1	1,077	15050,923
9	10	9,5	0,415	0,495	0,080	14092,89	1,503	21186,757	1	1,503	21186,757
10	11	10,5	0,495	0,574	0,078	13721,17	2,030	27851,763	1	2,030	27851,763
11	12	11,5	0,574	0,648	0,074	12925,89	2,667	34470,485	1	2,667	34470,485
12	13	12,5	0,648	0,715	0,067	11798,05	3,425	40404,868	1	3,425	40404,868
13	14	13,5	0,715	0,775	0,060	10443,80	4,314	45056,085	1	4,314	45056,085
14	15	14,5	0,775	0,826	0,051	8972,10	5,346	47961,397	1	5,000	44860,521
15	16	15,5	0,826	0,868	0,043	7483,64	6,530	48865,379	1	5,000	37418,182
16	17	16,5	0,868	0,903	0,035	6062,35	7,877	47751,435	1	5,000	30311,755
17	18	17,5	0,903	0,930	0,027	4770,42	9,397	44829,492	1	5,000	23852,075
18	19	18,5	0,930	0,951	0,021	3646,67	11,102	40486,003	1	5,000	18233,339
19	20	19,5	0,951	0,967	0,015	2708,13	13,002	35210,124	1	5,000	13540,672
20	21	20,5	0,967	0,978	0,011	1953,73	15,106	29513,430	1	5,000	9768,651
21	22	21,5	0,978	0,986	0,008	1369,14	17,426	23859,265	1	5,000	6845,705
22	23	22,5	0,986	0,991	0,005	931,91	19,973	18613,031	0	0	0
23	24	23,5	0,991	0,994	0,004	616,02	22,756	14018,115	0	0	0
24	25	24,5	0,994	0,997	0,002	395,40	25,786	10195,890	0	0	0

Table 31: Calculations of power and energy production in Ecovent

Wind speed low (m/s)	Wind speed high (m/s)	Avarage Wind Speed (m/s)	Acum. Prob. Low	Acum. Prob. High	Interval Prob.	Hours	Available Power (MW)	Available Energy (MWh)	Range OK	Power (MW)	Energy (MWh)
0	1	0,5	0	0,0115	0,0115	2010,38	0,0002	0,4406	0	0	0
1	2	1,5	0,0115	0,0425	0,0310	5433,51	0,0059	32,1549	0	0	0
2	3	2,5	0,0425	0,0899	0,0475	8313,49	0,0274	227,7703	0	0	0
3	4	3,5	0,0899	0,1507	0,0608	10643,68	0,0752	800,1830	1	0,0752	800,1830
4	5	4,5	0,1507	0,2214	0,0707	12382,36	0,1598	1978,4923	1	0,1598	1978,4923
5	6	5,5	0,2214	0,2985	0,0771	13514,58	0,2917	3942,6130	1	0,2917	3942,6130
6	7	6,5	0,2985	0,3788	0,0803	14059,82	0,4815	6770,3850	1	0,4815	6770,3850
7	8	7,5	0,3788	0,4591	0,0803	14069,44	0,7397	10407,6813	1	0,7397	10407,6813
8	9	8,5	0,4591	0,5368	0,0777	13619,80	1,0768	14666,3116	1	1,0768	14666,3116
9	10	9,5	0,5368	0,6099	0,0731	12803,45	1,5034	19248,2578	1	1,5034	19248,2578
10	11	10,5	0,6099	0,6768	0,0669	11719,91	2,0298	23789,5227	1	2,0298	23789,5227
11	12	11,5	0,6768	0,7365	0,0597	10467,18	2,6668	27913,6548	1	2,6668	27913,6548
12	13	12,5	0,7365	0,7887	0,0521	9134,88	3,4247	31284,2809	1	3,4247	31284,2809
13	14	13,5	0,7887	0,8332	0,0445	7799,34	4,3141	33647,5087	1	4,3141	33647,5087
14	15	14,5	0,8332	0,8704	0,0372	6520,89	5,3456	34858,1801	1	5,0000	32604,4742
15	16	15,5	0,8704	0,9009	0,0305	5342,99	6,5296	34887,7581	1	5,0000	26714,9561
16	17	16,5	0,9009	0,9254	0,0245	4293,06	7,8767	33815,2022	1	5,0000	21465,2847
17	18	17,5	0,9254	0,9447	0,0193	3384,43	9,3974	31804,8730	1	5,0000	16922,1686
18	19	18,5	0,9447	0,9597	0,0149	2619,03	11,1022	29076,9347	1	5,0000	13095,1336
19	20	19,5	0,9597	0,9710	0,0114	1990,21	13,0016	25875,8944	1	5,0000	9951,0299
20	21	20,5	0,9710	0,9795	0,0085	1485,62	15,1062	22442,0562	1	5,0000	7428,0969
21	22	21,5	0,9795	0,9857	0,0062	1089,68	17,4264	18989,1865	1	5,0000	5448,3811
22	23	22,5	0,9857	0,9902	0,0045	785,56	19,9729	15689,9916	0	0	0
23	24	23,5	0,9902	0,9934	0,0032	556,75	22,7561	12669,4706	0	0	0
24	25	24,5	0,9934	0,9956	0,0022	388,00	25,7865	10005,0459	0	0	0

Table 32: Calculations of power and energy production in Sierra Costera

Wind speed low (m/s)	Wind speed high (m/s)	Avarage Wind Speed (m/s)	Acum. Prob. Low	Acum. Prob. High	Interval Prob.	Hours	Available Power (MW)	Available Energy (MWh)	Range OK	Power (MW)	Energy (MWh)
0	1	0,5	0	0,002	0,002	342,29	0,0002	0,0750	0	0	0
1	2	1,5	0,002	0,010	0,009	1496,89	0,0059	8,8584	0	0	0
2	3	2,5	0,010	0,028	0,017	3047,71	0,0274	83,5002	0	0	0
3	4	3,5	0,028	0,055	0,027	4811,52	0,0752	361,7261	1	0,0752	361,7261
4	5	4,5	0,055	0,093	0,038	6654,17	0,1598	1063,2244	1	0,1598	1063,2244
5	6	5,5	0,093	0,142	0,048	8451,76	0,2917	2465,6355	1	0,2917	2465,6355
6	7	6,5	0,142	0,199	0,058	10088,24	0,4815	4857,9060	1	0,4815	4857,9060
7	8	7,5	0,199	0,265	0,065	11460,58	0,7397	8477,8130	1	0,7397	8477,8130
8	9	8,5	0,265	0,336	0,071	12485,92	1,0768	13445,3102	1	1,0768	13445,3102
9	10	9,5	0,336	0,411	0,075	13108,24	1,5034	19706,4672	1	1,5034	19706,4672
10	11	10,5	0,411	0,487	0,076	13302,88	2,0298	27002,6842	1	2,0298	27002,6842
11	12	11,5	0,487	0,561	0,075	13077,93	2,6668	34875,9414	1	2,6668	34875,9414
12	13	12,5	0,561	0,632	0,071	12472,19	3,4247	42713,5968	1	3,4247	42713,5968
13	14	13,5	0,632	0,698	0,066	11549,74	4,3141	49827,2671	1	4,3141	49827,2671
14	15	14,5	0,698	0,758	0,059	10392,06	5,3456	55551,9339	1	5,0000	51960,3028
15	16	15,5	0,758	0,810	0,052	9088,72	6,5296	59345,9851	1	5,0000	45443,6018
16	17	16,5	0,810	0,854	0,044	7728,10	7,8767	60872,0748	1	5,0000	38640,5028
17	18	17,5	0,854	0,890	0,036	6389,30	9,3974	60042,8270	1	5,0000	31946,5146
18	19	18,5	0,890	0,919	0,029	5136,23	11,1022	57023,4372	1	5,0000	25681,1640
19	20	19,5	0,919	0,942	0,023	4014,34	13,0016	52192,9191	1	5,0000	20071,7043
20	21	20,5	0,942	0,960	0,017	3050,04	15,1062	46074,4741	1	5,0000	15250,1916
21	22	21,5	0,960	0,973	0,013	2252,38	17,4264	39251,0067	1	5,0000	11261,9065
22	23	22,5	0,973	0,982	0,009	1616,34	19,9729	32283,0317	0	0	0
23	24	23,5	0,982	0,988	0,006	1126,88	22,7561	25643,2992	0	0	0
24	25	24,5	0,988	0,993	0,004	763,06	25,7865	19676,7190	0	0	0

Table 33: Calculations of power and energy production in A Capelada 1

Bibliografia

[1] Andreas Abdon, Xiaojin Zhang, David Parra, Martin K Patel, Christian Bauer, and Jörg Worlitschek. Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales. *Energy*, 139:1173–1187, 2017.

[2] Mark Bolinger and Ryan Wiser. Understanding wind turbine price trends in the us over the past decade. *Energy Policy*, 42:628–641, 2012.

[3] Mehmet Sait Cengiz and Mehmet Salih Mamiş. Price-efficiency relationship for photovoltaic systems on a global basis. *International Journal of Photoenergy*, 2015, 2015.

[4] Ran Fu, Timothy W Remo, and Robert M Margolis. 2018 us utility-scale photovoltaics-plus-energy storage system costs benchmark. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018.

[5] Anca D Hansen, Panagiota Adamou, Xenofon Giagkou, Filippos Rigas, Jayachandra Sakamuri, Müfit Altin, Edgar Nuno, and Poul Sørensen. Dynamic modelling of wind-solar-storage based hybrid power plant. 2019.

[6] Jesús Hernández Blanco. Análisis de inversión en una planta fotovoltaica mediante opciones reales y computación acelerada por gpu. 2018.

[7] A Kaabeche, M Belhamel, and R Ibtiouen. Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system. *Energy*, 36(2):1214–1222, 2011.

[8] Vasiliki Klonari, Daniel Fraile, Raffaele Rossi, and Michael Schmela. Exploring the viability of hybrid wind-solar power plants. In *Proceedings of the 4th International Hybrid Power Systems Workshop, Crete, Greece*, pages 22–23, 2019.

[9] R Timothy Marler and Jasbir S Arora. The weighted sum method for multi-objective optimization: new insights. *Structural and multidisciplinary optimization*, 41(6):853–862, 2010.

[10] John K Page, Michel Albuisson, and Lucien Wald. The european solar radiation atlas: a valuable digital tool. 2001.

[11] Steven D Percy, Mohammad Aldeen, Christopher N Rowe, and Adam Berry. A comparison between capacity, cost and degradation in australian residential battery systems. In *2016 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*, pages 202–207. IEEE, 2016.

[12] Greg Perkins. Techno-economic comparison of the levelised cost of electricity generation from solar pv and battery storage with solar pv and combustion of bio-crude using fast pyrolysis of biomass. *Energy Conversion and Management*, 171:1573–1588, 2018.

[13] Lennart Petersen, Bo Hesselbæk, Antonio Martinez, Roberto M Borsotti-Andruszkiewicz, German C Tarnowski, Nathan Steggel, and Dave Osmond. Vestas power plant solutions integrating wind, solar pv and energy storage. In *Proceedings of the 3rd International Hybrid Power Systems Workshop, Tenerife, Spain*, pages 8–9, 2018.

[14] Alin George Raducu, Nikolaos Styliaras, Jonas Funkquist, Claudiu Ionita, and Vattenfall Ab. Design and implementation of a hybrid power plant controller. In *Proceedings of the*

3rd International Hybrid Power Systems Workshop, Tenerife, Spain, pages 8–9, 2018.

[15] Sergio Shimura, Rafael Herrero, Marcelo Knorich Zuffo, and Jose Aquiles Baesso Grimoni. Production costs estimation in photovoltaic power plants using reliability. *Solar Energy*, 133:294–304, 2016.