UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Master's Thesis

ANALYSIS OF HYBRID RENEWABLE ENERGY SYSTEMS TO ENHANCE GRID USAGE

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Madrid, July 2019

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Abstract

Renewable Energy Source power plants are increasingly part of the energy mix in most of the countries. The main problem of these power plants is that they produce electricity when the resource is available, which limits the level of use these power plants are giving to the connection to grid infrastructure. Within this scenario, Hybrid Renewable Energy Systems could be a solution to enhance this low usage of the grid. Hybrid Renewable Energy Systems are the combination of two or more Renewable Energy Source power plants that produce electricity to inject it to the grid while sharing a connection to grid infrastructure. Hence, sharing the grid the usage of it increases. The main problem of sharing that infrastructure is that there would be hours where production of both power plants could exceed the grid connection capacity.

This Master's Thesis studies the profitability of developing certain of the aforementioned hybrid power plants. In order to assess the profitability of hybrid power plants, several key factors have been analysed, such as the complementarity of the production profiles of both technologies that comprise the hybrid power plant, the amount of energy that would be curtailed due to the capacity limit and the share on the increase in the grid usage. Besides, with the input of this analysis, an optimization problem has been built to compute the optimal capacity of the new production technology to be installed, in order to achieve the maximum net present value of the investment to be done.

This study allows to draw several conclusions. Hybridization allows to increase grid usage without having to curtail a high amount of energy. It is profitable to make hybridization in the power plants studied, but this profitability differs depending on each specific power plant. There are many factors that affect the profitability of hybrid power plants, such as the complementarity between the production profiles or the capacity factor of the technologies forming the hybrid power plant, so each hybrid power plant should be analysed individually.

Key words

Hybrid Renewable Energy Systems

Photovoltaic power plant

Wind power plant

Hydro power plant

Complementarity of production profiles

Energy curtailed

Grid usage

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Nomenclature

Abbreviations

$HRES$	—	Hybrid Renewable Energy Systems
PV	—	Photovoltaic
HY	—	Hydro

Indexes and sets

n	—	Set of the number of years,	$n = 1, .., 20$
t	—	Set of the hours of a year,	$n = 1, .., 8760$

Parameters

CF_n	—	Cash flow for the year n (€)
k	—	Interest rate of the investment (%)
I_0	—	PV power plant investment (€)
W_t	—	Hourly production of the wind power plant in the hour t (MW)
H_t	—	Hourly production of the hydro power plant in the hour t (MW)
$PV_{hib,t}$	—	Hourly production of the PV power plant installed in the hybrid power plant in the hour t (MW)
PV_t	—	Hourly production of the reference PV power plant in the hour t (MW)
$\overline{grid}$	—	Capacity of the grid connection infrastructure (MW)
$\overline{PV}$	—	Capacity of the reference PV power plant (MW)
GT	—	Generation tax (%)

$p_{n,t}$	—	Price of the market in each year n, and in each hour t (€/MWh)
$O\&M$	—	Operation and maintenance cost (€/MWh)
GAT	—	Grid access tariff (€/MWh)
C_{PV}	—	PV installation cost (€/MW)

Variables

$\overline{PV_{hib}}$	—	Optimal amount of PV capacity to be installed in the hybrid power plant (MW)

Chapter 1

Introduction

1.1 Introduction

Renewable energies are electricity generation technologies that are more and more present in countries' energy mix, and they will keep increasing in the future. This is mainly due to two factors. On the one hand, the preoccupation about climate change has led many countries to sign different environmental agreements. Electricity generation is one of the most polluting activity, so in order to reduce the emission of greenhouse gases (responsible of climate change) countries have agreed objectives to reduce CO2 emissions and to limit the increase of temperature in the Earth; and on the other hand, due to the reduction in costs both of the equipment and operation and maintenance that have made lvelized cost Of energy to decrease in a rapid way.

In 1997, after the publication of the second evolution report by the Intergovernmental Panel on Climate Change (IPCC), the governments participating in the United Nations Framework Convention on Climate Change (UNFCCC) agreed to sign the Kyoto Protocol [1]. The protocol, which came into force in February 2005, established objectives for the main developed countries and emerging economies in order to reduce net greenhouse gases emissions with a specific time frame. Industrialized countries committed to reduce greenhouse gases emissions a 5% below the levels of 1990, in the period 2008-2012, this period is know as the first Kyoto Protocol period. In 2006 the details for the extension of the Kyoto Protocol were started, the extension became official in the Doha Summit in 2012, were amendments to ensure the continuation of the Kyoto Protocol in the period 2013-2020. As the electricity sector is one of the most polluting activities, it was one of the main focus of action for the countries signing the protocol.

The European Union and its Member States assumed an 8% reduction during the first Kyoto Protocol period. This was a joint commitment between all the Member States, within which an internal distribution was made. In this way, the commitments assumed by each country depend on some reference parameters. In the case of Spain, the distribution obliged that the greenhouse gases average net emission could not be greater than the values of year 1990, during 2008-2012. To guarantee the accomplishment of the objective, the European Union released in 2007 a legislation package, the 2020 climate & energy package, known as the 2020 package, which had the objective of reducing a 20% the greenhouse gases emissions (with respect to the levels of 1990), increasing to a 20% the energy coming from renewable energy sources, and a 20% improvement in energy efficiency [2]; all this targets should be accomplished by 2020.

At the end of year 2015, it took place the Paris Climate Conference about climate change, from it a new global agreement arise, the Paris Agreement. With the sign of the Paris Agreement in 2015, the countries established objectives that are more ambitious than the ones from the Kyoto Protocol. In this agreement, governments agreed to keep the increase in the global average temperature way lower than 2C with respect to preindustrial levels and to double efforts to limit the increase to 1.5C [3]. The Paris Agreement covers the period beginning in 2020 after the Kyoto Protocol. Based on the Paris Agreement the European Commission presented the so called winter package, Clean energy for all Europeans [4]. This new energy policy framework sets binding objectives for the European Union for 2030, this objectives are:

- 40% Greenhouse gases decrease with respect to 1990 levels.
- 32% participation of renewable energy in the gross final energy consumption.
- 32.5% improve in energy efficiency.
- 15% interconnection between the member states.

The other factor that have made renewable energy to be more and more present in countries energy mix is the reduction in renewable energy costs. In the last years, renewable energies have undergone a progressively decrease in their cost, especially in wind energy and photovoltaic energy. These technologies have experienced a huge deployment that together with a high learning rate, have made prices to decrease in a rapid way, allowing renewable energies to compete with conventional power plants. The Renewable Power Generation Costs in 2018 report made by the International Renewable Energy Agency (IRENA) [5], shows this decrease in costs over the last years by comparing the LCOE of different renewable technologies, figure 1.1.

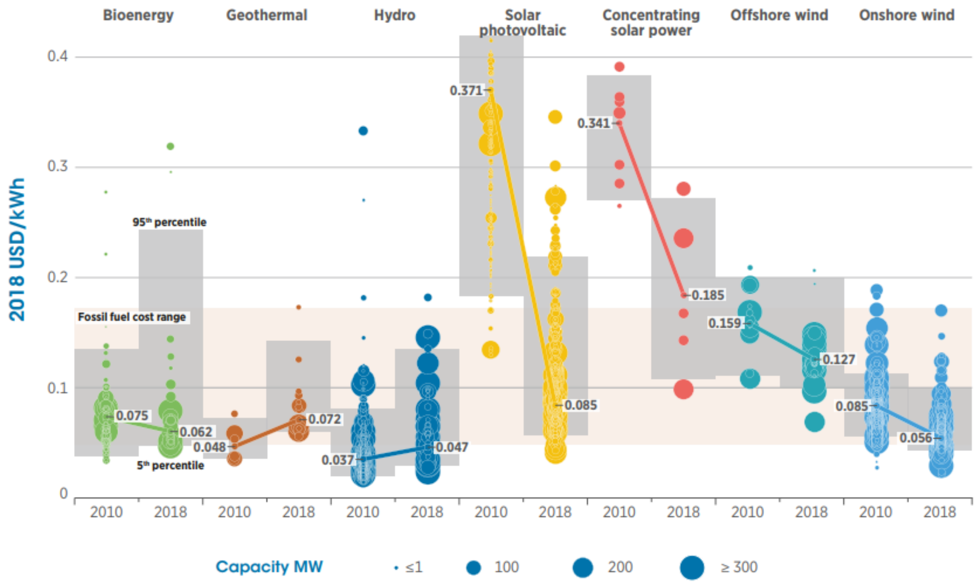

Figure 1.1: Global LCOE of utility-scale renewable power generation technologies, 2010−2018. Source [5].

In figure 1.1 it can be observed how most of the renewable technologies depicted are right now in the fossil fuels cost range, meaning that they are mature enough to compete in energy prices with the conventional power plants.

With further expected reduction of costs and, especially with the stable regulatory framework set by the international agreements, it is likely to expect a huge increase in the penetration of renewable energies in the countries power systems. This higher share of renewable energies will increase the amount of grid to be developed in order to allocate all this new renewable energy in the electric systems. The main problem of this renewable energies when compared with conventional power plants is their intermitence, the production cannot be scheduled, they produce when the resource is available; this makes that the renewable energies power plants usually have low capacity factors, as shown in figure 1.2 and in figure 1.3, meaning that also the grid they are connected to is going to work low portion of the time. If the generation profile of two or more different renewable energy technologies have some complementarity in the time, different renewable energy technologies could be installed in the same connection point, this is what is called Hybrid Renewable Energy Systems (HRES). This HRES could allow to make more use of the already existing grid while avoiding the deployment of more new grid infrastructures. Another advantage of HRES could be the reduction in the total costs of the new renewable projects, leading to a reduction also in the LCOE.

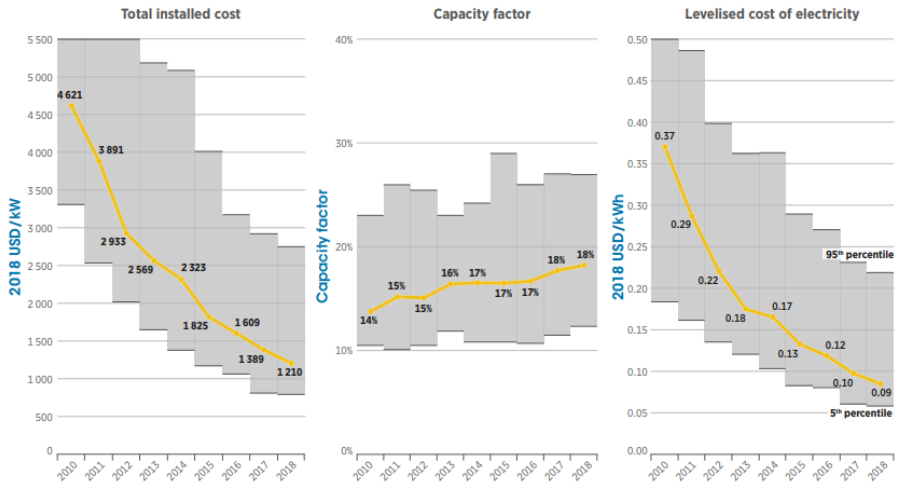

Figure 1.2: PV global weighted average total installed costs, capacity factors and LCOE, 2010−2018. Source [5].

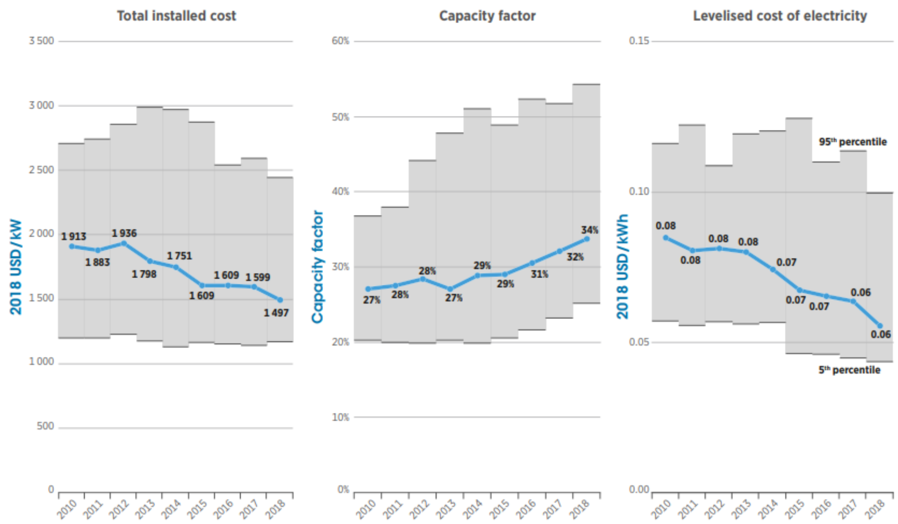

Figure 1.3: Onshore wind global weighted average total installed costs, capacity factors and LCOE, 2010−2018. Source [5].

1.2 What are Hybrid Renewable Energy Systems?

The meaning of Hybrid is basically something that is a mixture of two or more different things. Hybrid Energy Systems have been used for many years, mainly to provide electricity to remote areas or to microgrids. This kind of systems consist in the use of some renewable systems, as photovolaic systems or wind turbines, in combination with back-up generators as it could be a diesel generator, or storage system as Lithium-ion batteries, all this technologies combine to provide reliable energy.

When is Hybrid Renewable Energy Systems what we are referring to, the definition would be the combination of two or more Renewable Energy Source power plants that produce electricity to inject it to the grid while sharing a connection to grid infrastructure. The main problem of sharing that infrastructure is that there would be hours where production of both power plants could exceed the grid connection capacity. This HRES could also have some kind of storage system, but it is not a condition. In particular in this Master's Thesis, the application that is going to be considered for HRES is grid scale electricity production. There are mainly to types of HRES that it could be considered.

On the one hand, there exists the possibility of hybridize an already existing renewable energy power plant, for example a wind power plant, with a new renewable energy power plant, for example a photovoltaic power plant. In this case, the main limitation that the hybrid plant would face is the limitation of the grid interconnection capacity. As this interconnection to the grid was already built together with the power plant, its capacity is thought to cover the necessities of the "old" power plant, these necessities may not match with the necessities of the hybrid plant. A crucial point in this kind of hybridization is how the production profiles of both power plants complement each other in order to have few overlaps, so that there are not a huge amount of energy that exceeds the interconnection capacity; in order to analyse the production profile's complementarity is important to study not only the intraday complementarity, but also the seasonal complementarity.

On the other hand, the hybridization could be done as whole new project. In this case, all the technologies being part of the project, as well as the connection infrastructure, would be design from scratch. In this case the grid interconnection capacity would not be a limitation, as it could be designed to allocate the majority of the energy production, provided that it is profitable. The complementarity between production profiles keeps on being a crucial point, as the lower the overlaps the lower the capacity of grid interconnection that should be constructed.

Apart from the types of hybridization mentioned before, there is another way of making more use of grid connection capacity called overpowerment. This consists in installing more electricity production capacity than the nominal capacity of the connection grid. This is commonly done in PV power plants. In PV power plants, the solar field usually has a peak power grater than the capacity of the connection line, and it is the inverter of the plant the one that usually has the same power than the connection line. In the case of wind power plants, overpowerment could be done, for example, in the process of repowerment of the wind power plant. The repowerment process consists in removing the old wind turbines by new ones that have higher capacity factor, this process allows the owner to have a "new" wind power plant and reuse the already constructed grid connection. The main problem faced by overpowerment is that all the capacity installed is going to produce at the same time , contrary to the case of hybridization. In overpowerment there is not possibility of complementarity between two different production profiles, so it could be expected that more energy is going to exceed the interconnection limit than in the case of the hybridization.

The main point of hybridization of renewable energies is to share part of the grid connection infrastructure between two or more different power plants. By sharing the grid connection infrastructure new projects could reduce the rated costs of the projects, and also to be more efficient increasing the usage of the grid infrastructure.

1.3 Evolution of renewable energy in Spain

This Master's Thesis is going to focus on the possibility to make HRES in Spain, so it could be good to know which is the point of deployment of these technologies right now.

The Spanish electricity mix is composed by the technologies shown in figure 1.4, where also it is shown the evolution in the last years.

As it has been shown in figure 1.4, the wind technology is the second biggest technology in the mix and the first of the renewable technologies. As it is observed in the figure, the wind installed capacity has remained constant for the last six years, this can be observed much better in figure 1.5.

As it has been mentioned, the figure 1.5 shows that the accumulated wind capacity in Spain has remained more or less constant for the last seven years. This means that the wind power plants in Spain are old, having more than 10 or even 15 years in average, this old wind turbines have also an old technology with low capacity factors compared with which could be achieved with newer

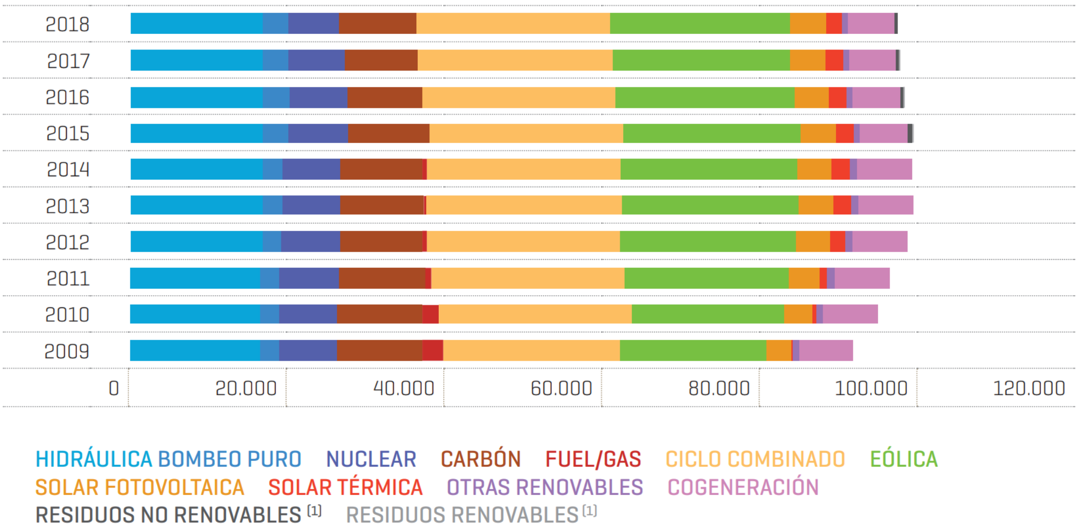

Figure 1.4: Evolution of the Spanish electricity mix. Source [7].

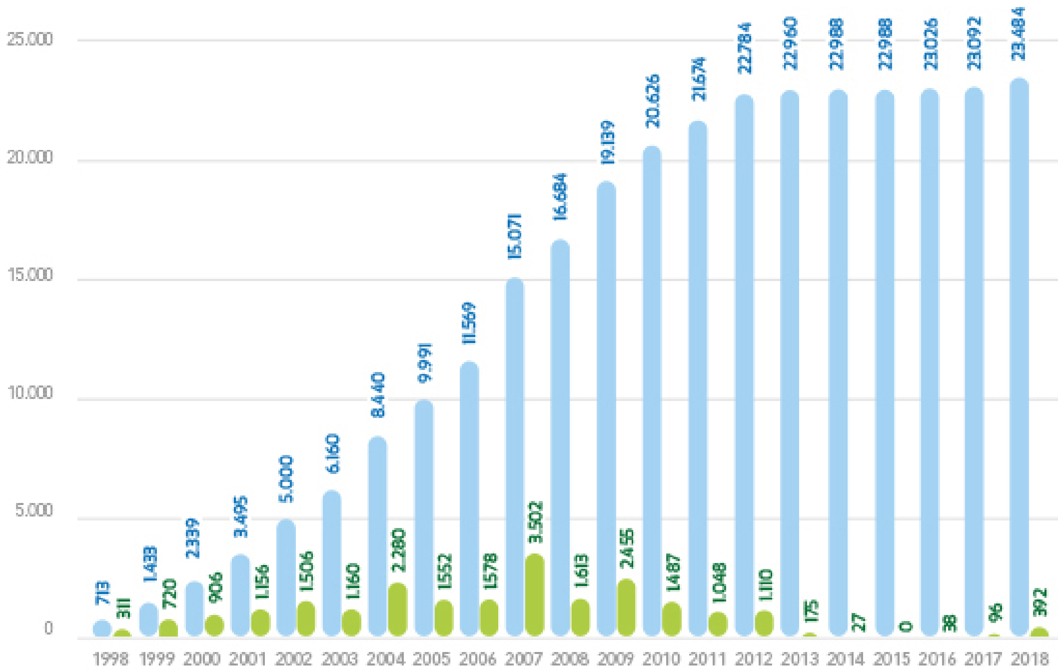

Figure 1.5: Installed (green) and accumulated (blue) wind capacity installed in Spain. Source [8].

technology, this low capacity factors also mean that this wind power plants are not making a high use of their grid connection infrastructure, so it could be a good option to hybridize them with new PV power plants.

Recently it was published the draft of the Plan Nacional Integrado de Energía y Clima, in this plan the Spanish government established the roadmap in energy and climate matters for the period 2021-2030. One of the main point is the expected evolution of the Spanish electricity mix until 2030, figure 1.6.

Parque de generación del Escenario Objetivo (MW)				
Año	**2015**	**2020**	**2025**	**2030**
Eólica	22.925	27.968	40.258	50.258
Solar fotovoltaica	4.854	8.409	23.404	36.882
Solar termoeléctrica	2.300	2.303	4.803	7.303
Hidráulica	14.104	14.109	14.359	14.609
Bombeo Mixto	2.687	2.687	2.687	2.687
Bombeo Puro	3.337	3.337	4.212	6.837
Biogás	223	235	235	235
Geotérmica	0	0	15	30
Energías del mar	0	0	25	50
Biomasa	677	877	1.077	1.677
Carbón	11.311	10.524	4.532	0-1.300
Ciclo combinado	27.531	27.146	27.146	27.146
Cogeneración carbón	44	44	0	0
Cogeneración gas	4.055	4.001	3.373	3.000
Cogeneración productos petrolíferos	585	570	400	230
Fuel/Gas	2.790	2.790	2.441	2.093
Cogeneración renovable	535	491	491	491
Cogeneración con residuos	30	28	28	24
Residuos sólidos urbanos	234	234	234	234
Nuclear	7.399	7.399	7.399	3.181
Total	105.621	113.151	137.117	156.965

Figure 1.6: Expected evolution of the Spanish electricity mix until 2030. Source [9].

In figure 1.6 the most important points, apart from the closure of the vast majority of the coal power plants, are the installation of almost 23 GW of wind and 28 GW of PV. In order to make more profitable the installation of this capacities, it could be studied the possibility of hybridizing part of this capacity with already existing wind or PV power plants, or even constructing new hybrid wind and PV power plants.

1.4 Grid which usage could be enhanced

When speaking about grid it is usually thought about huge transmission lines or distribution lines, but when constructing a new renewable power plant, there is a lot of connection to the grid infrastructure to be constructed by the promoter of the installation in order to connect to the transmission or distribution evacuation node the power plant. This nodes are usually located some kilometres away from power plants. An example scheme of a real node of the Spanish power system is depicted in figure 1.7.

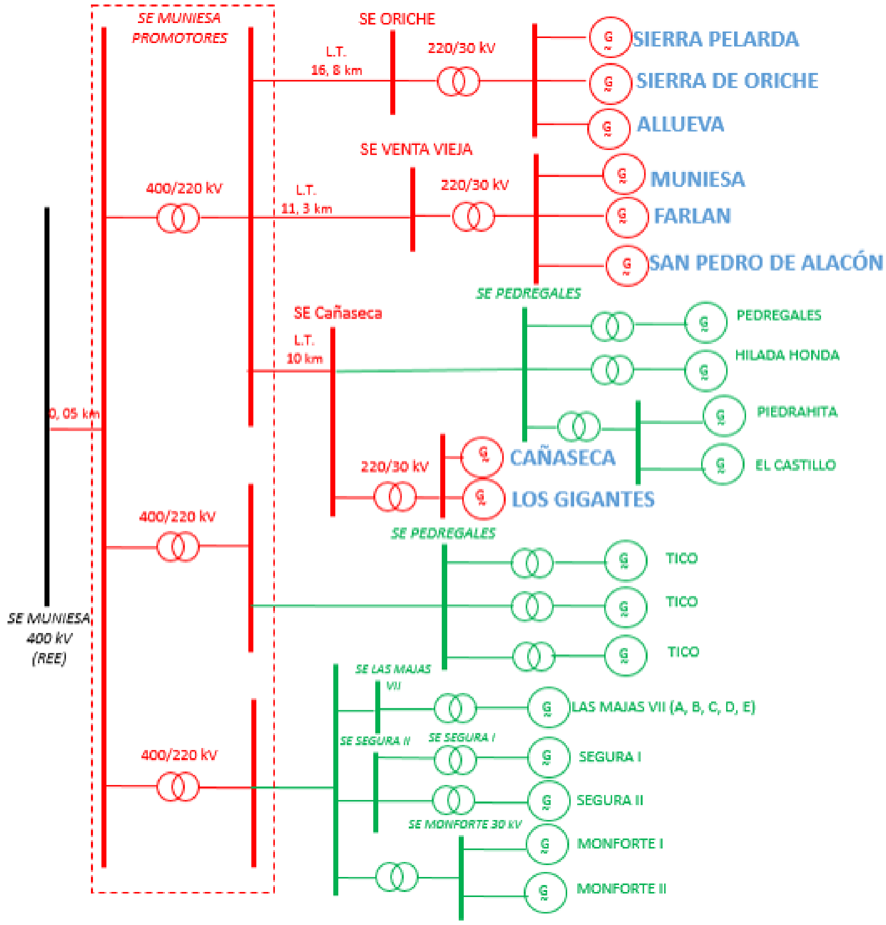

Figure 1.7: Single-line diagram of Muniesa's 400 kV substation. Source Enel Green Power (EGP) internal data.

In figure 1.7 it is depicted a single-line diagram of Muniesa's transport grid node, located in Teruel (Aragón), its a 400 kV node and belongs to the Fuendetodos-Mezquita 400 kV line. As it can be observed there are a 20 different power plants connected to the node, the ones in blue are the power plant belonging to Enel Green Power (EGP) and the ones in green are the ones belonging to other promoters. Also, in black is represented the grid infrastructure already existing, and in red the grid infrastructure that had to be deployed. The Muniesa' substation node was recently updated to allocate 1090 megawatts coming from renewable energy sources, 940 megawatts coming from wind energy and 150 megawatts coming from photovoltaic energy.

As it can be observed in figure 1.7, a lot of kilometers of lines and substations have to be deployed in order to connect a power plant to the grid. This process has to be done each time that a power plant is constructed, so a solution to the deployment of all this connection infrastructure could be to hybridize renewable technologies, as some of this power plants have low capacity factors and are using the grid a reduce number of hours of the year.

As hybridization, and in particular making more use of the grid, is a topic under regulatory discussion right now, there are different points of view about how it should be implemented, mainly the one coming from regulator and from the promoters. In the perspective of the Regulator there are mainly two schemes for making more use of the grid. The first of them is to allow new power plants to be installed in nodes which are already saturated, this new power plants would only be allowed to produce when there is remaining space in the grid, this means that they would inject electricity to the grid when other power plants are not saturating the grid. Other scheme proposed by the Regulator is to permit to all the power plants connected to a node to install a "complementary power" within its power plants, this complementary power, as in the previous scheme, would only be allowed to inject electricity if the grid is not saturated by the no complementary power of the other power plants.

Contrary to this point of view, the scheme proposed by the promoters aims to be able to install the amount of capacity that they consider, taking into account that they have a limitation that is the interconnection capacity, so, provided that they do not exceed this connection capacity they should be allowed to install the capacity that they consider.

As it has been explained before, the renewable energy sources costs are decreasing, nonetheless, the cost of grid infrastructure is not decreasing, this means that grid infrastructure is acquiring a more significant percentage of the cost of a renewable power plant. Hybridize renewable technologies could allow to reduce this cost, increasing the net present value of renewable investments, while making the most of grid infrastructure.

1.5 Objectives of the work

The objectives of this Master's Thesis are mainly three. The first of them is to model mathematically HRES, focusing on hybridization of already existing wind power plants with a new PV power plant and hybridization of already existing hydro power plants with a new PV power plant. Once that they are modelled the optimal amount of PV to be installed is going to be calculated for maximizing the net present value of the investment.

The second objective is to analyse the capability of overpowerment of wind power plants to increase grid usage, and compare its performance with the hybrid PV wind power plant.

The last objective of this Master's Thesis is to study some regulatory aspects that have to do with the deployment of HRES, as it could be the market participation, or the grid access and connection.

1.6 Structure of the document

- **Chapter 1**: Introduction. It is explained why Renewable Energy Source power plants make a low use of the grid. Also, the concept of Hybrid Renewable Energy Systems is defined. Moreover, a brief description of the evolution of renewable energy in Spain is provided. Then, the type of grid which usage could be enhanced is described. Finally, the objectives of this Master's Thesis are set.
- **Chapter 2**: Wind PV hybridization. It is studied the profitability of installing a new PV power plant together with an already existing wind power plant, for this it is analysed the complementarity between production profiles, the curtailed energy and the increase in the grid usage, then, an optimization problem is built to calculated the optimal amount of PV to be installed. Also, the increase of grid usage that an overpowered wind power plant could have is studied.
- **Chapter 3**: Hydro PV hybridization. It is studied the profitability of installing a new PV power plant together with an already existing hydro power plant, for this it is analysed the complementarity between production profiles, the curtailed energy and the increase in the grid usage, then, an optimization problem is built to calculated the optimal amount of PV to be installed.
- **Chapter 4**: Regulatory aspects. It is analysed how current regulation may affect the deployment of Hybrid Renewable Energy Systems.

- **Chapter 5**: Conclusions and future working lines. The final conclusions of the study are presented. Furthermore, some improvements of the models elaborated and future working lines are provided.

- **Annexes**: Here it is shown all the additional information that, because of its level of detail, is not included in the body of this document.

Chapter 2

Hybridization of wind and photovoltaic

2.1 Introduction

Wind power plants are the main renewable technology in the Spanish power system, as it has been said in section 1.3. Firstly in this chapter it is going to be explained which could be the synergies between hybridizing wind and PV power plants that could make wind PV hybrid power plants profitable.

Furthermore, it is going to be analysed which is the profitability that wind-PV hybrid power plant could have. For doing so the complementarity of both production profiles is going to be studied. Other study that is going to be carried out is the possible performance of the PV power plant that is going to be installed, for doing so the expected curtailments of energy and the increase of grid usage are going to be analysed. Once that all this studies are done the next step is to build an optimization problem that returns the optimal amount of PV to be installed in order to maximize the net present value of the investment, taking into account the constraints of a hybrid power plant. The viability of installing a battery to make use of the curtailments of energy is also going to be analysed.

Another way of improving grid usage is to overpower wind power plants by installing more capacity of which can be injected to the grid. In this chapter it is also going to be analysed the performance of overpowered wind power plants. For doing so the expected curtailments of energy and the increase of grid usage are going to be analysed.

2.2 Synergies between wind and PV power plants

Co-locating wind and PV can make both projects more profitable by sharing some of the infrastructures needed to develop the plants, or by splitting some of the costs between the two projects.

2.2.1 Grid infrastructure

The main saving that co-locating wind and PV have is sharing the connection line. If it exist complementarity between the generation profiles of both power plants, this means that if one of the technologies is not producing electricity the other technology is, both plants could share the connection line to inject energy to the grid. This would entail an important saving for the project.

Both wind and PV technologies have similarities when producing electricity, they both need to use power electronics to connect to the grid.

Wind produces electricity as alternating current (AC), this current is converted into direct current (DC) through a rectifier, and lastly is converted again into alternating current. All this process guarantees that the wind power plant injects the energy at the correct voltage and frequency. In the case of PV, the electricity is generated directly as direct current, so it only has to be converted into alternating current through an inverter. This process is done again through power electronics.

As it has been mentioned before, both wind and PV need power electronics to convert the electricity generated into alternating current with the correct voltage and frequency specifications. Depending on how the connection of wind and PV is done we can distinguish two types of connections, AC-coupled and DC-coupled.

In AC-coupled mode, each of the technologies has its own power electronics, and the electricity is integrated after being converted into AC and before going to the substation, as depicted in figure 2.1. In this mode, the technologies share the substation, the transmission line and the grid connection. The vast majority of projects carried out to date have been realized in AC-coupled mode.

In DC-coupled mode, the technologies share part of the power electronics, the DC electricity coming from PV is connected with the wind DC electricity from the rectifier, once the DC electricity is integrated it is converted to AC through and inverter adapted to deal with two different DC power sources, as shown in figure 2.2. In DC-coupled mode, the technologies share the inverter,

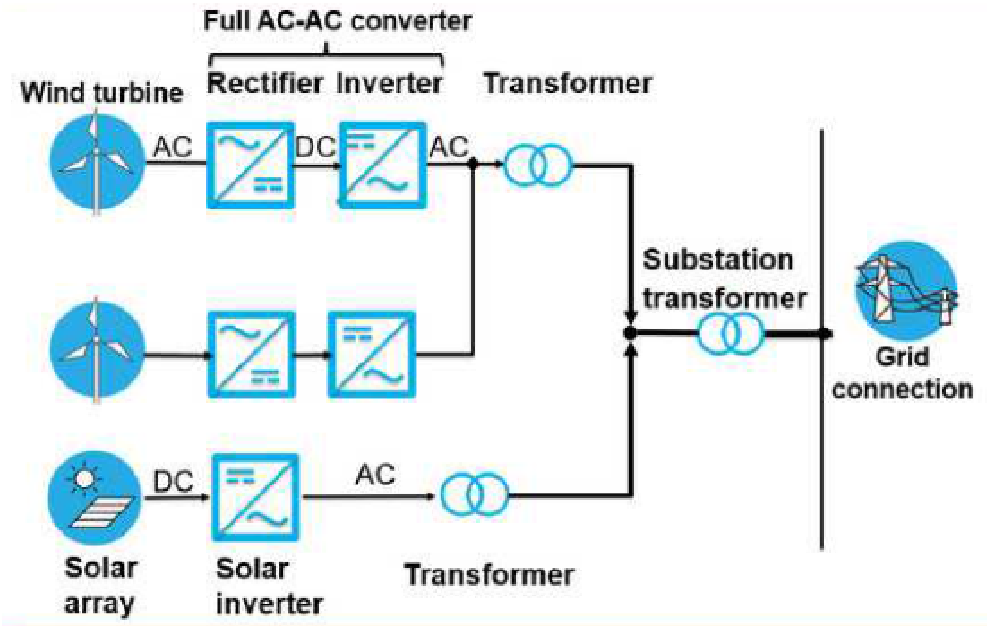

Figure 2.1: Scheme of a AC-coupled installation. Source BNEF [11].

the transformer, the substation, the transmission line and the grid connection. The DC-coupled mode is not usual nowadays, this is due mainly to the technical complexity as the inverter of the wind turbine should be adapted to deal correctly with the DC power coming from two different sources. There are only few small-scale demonstrator projects at the moment.

As it has been said, sharing grid infrastructure is one of the main savings that co-locating wind and PV could have, right now most of the hybrid wind PV projects that are being done worldwide are done in AC-coupled mode, but if companies continue research and find a way to correctly coupled both installations in DC-mode, this could entail further benefits for hybrid wind and PV projects.

2.2.2 Permits

If the wind power plant is already constructed, the project owners should have done already the processes to obtain all the permits, therefore they already know which are the procedures to be done. Also, they should have done studies to obtain the environmental impact assessment, so they can reuse part of the information to obtain the PV environmental impact assessment. If the project is built greenfield (new wind and PV installation), the cost could be share between the two technologies.

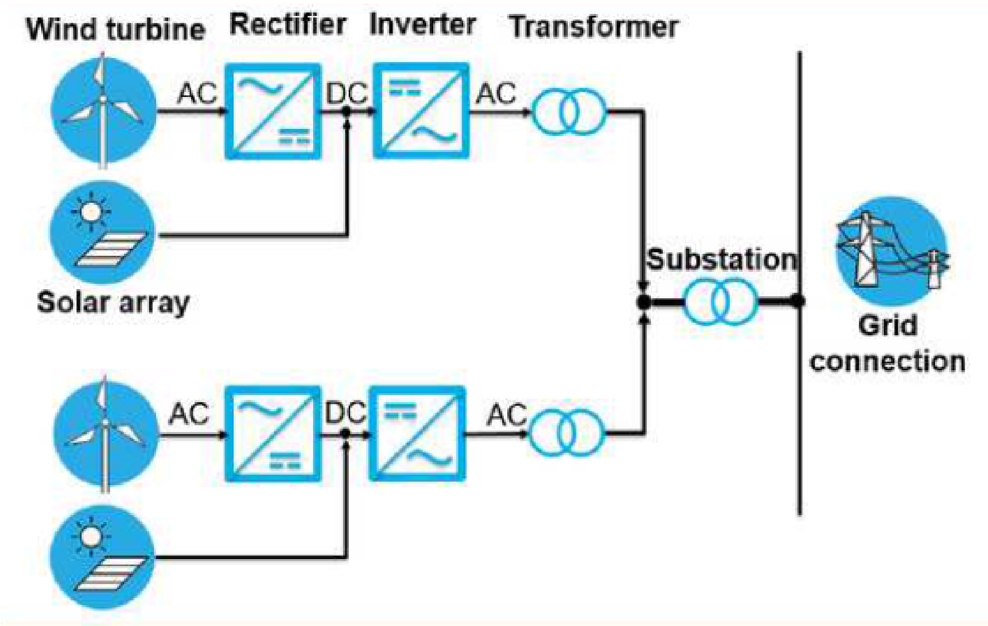

Figure 2.2: Scheme of a DC-coupled installation. Source BNEF [11].

2.2.3 Land lease

The project owner would have probably carried out some geotechnical studies of the place, and maybe have already climate studies of the place, that could be useful to design the PV power plant.

As the project owner has already a land agreement, it could be easier for him to renegotiate the terms of this agreement with the landowner to place the PV power plant in the same terrain close to the wind power plant.

If the place is far from roads or even it is a place of difficult access, the project owner may have done civil works like roads or bridges. This civil works could be useful to transport the PV material to the place.

2.2.4 Operation and maintenance costs

PV plants require a simpler operation and maintenance procedures compare with a wind power plant. If existing wind staff can be trained to realize the PV operation and maintenance, Opex would be reduced.

Other possibility is that the project owners get an operation and maintenance contract with the same company, if this happens they may get a better price.

2.3 Methodology

In order to establish if a hybrid wind-PV power plant project is going to be profitable, the first step is to study the power production profiles of both technologies and analyse the overlaps between them.

For the wind production profiles, a set of wind power plants have been selected. These plants covers different locations in Spain, and have different nominal power. The available data for these plants is the hourly generation of each plant for a typical design year.

In the case of the PV production profiles, a profile from a PV power plant has been chosen. This profile would be corrected depending on the irradiation of each of wind power plant location. Also, for the PV profile the data available is the hourly generation of the plant for a year.

Once all the data of the profiles is ready, the overlaps between both production profiles have been analyse. The objective of the analysis is to infer some kind of correlation between the power production of wind and PV.

Once the profile of both power plants have been analyse and there is some complementarity between both profiles, an optimization problem is formulated to obtain the optimal amount of PV that should be installed in order to maximize the return of the investment. The optimization problem aims to maximize the net present value of the investment, taking into account all the restrictions of this hybrid power plants.

After all this the energy curtailed in each hour is analyse to study if it could be profitable to install a battery for making use of that energy curtailed.

2.4 Hybridization of already existing wind power plants with a new photovoltaic power plant

In this section, an analysis of a wind-PV hybrid power plant, where the wind power plant is already in place is going to be made. It is important to remark that the grid capacity would not be increased.

2.4.1 Analysis of the wind-PV complementarity

The first step, as it is said in the previous section, is to analyse the complementarity of the wind and PV production profiles. To do so two different complementarities are going to be studied, the seasonal complementarity and the intraday complementarity. The former is how wind and PV production profiles complement each other along the year, as it is known, the PV production is higher in summer, so if the wind production is lower in summer and higher in winter, the wind profile will complement the PV profile and probably the hybridization will be profitable. The latter refers to how wind and PV compensate each other during the day, this means that while the PV is producing at maximum power during the central hours of the day wind should be producing more during the hours without sun to compensate PV profile and occupy the grid connection most of the time and with low excess energy.

Firstly, an analysis of how is the distribution of the production during the year of each of the wind power plants is going to be made. To analyse this, the percentage of the energy produce in each month over the production along the whole year is calculated, as shown in figure 2.3.

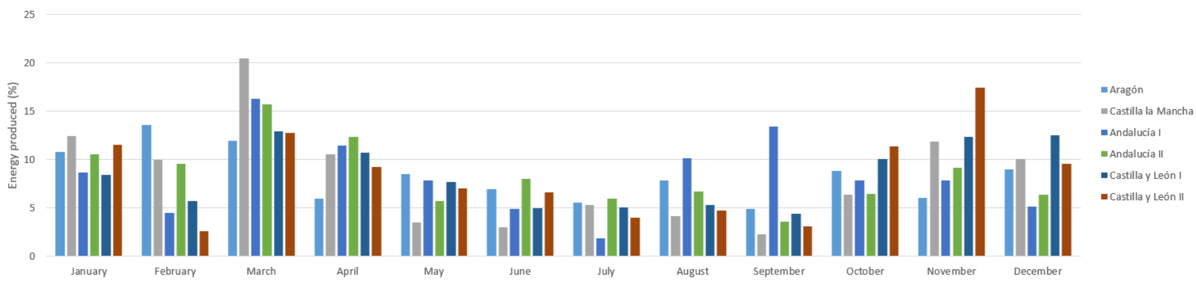

Figure 2.3: Percentage of energy produced in each month for the wind power plants.

In figure 2.3, it can be observed that the majority of the wind power plants selected have a higher production during November, March and winter. The lower production period occurs during summer, that are the months where solar irradiation is maximum and therefore PV produce more energy. So, with the results shown, the wind power plants selected seem to be good candidates to hybridize with PV.

Continuing with the analysis, now a deeper study on the seasonal and intraday complementarity of wind and PV production is going to be carried out. For this purpose, the data is going to be represented in a boxplot chart. The boxplot, or box and whiskers plot, is a kind of chart used for representing the dispersion within a data set. As it is depicted in figure 2.4, the box part of the chart is composed by the extreme of the box that are the first quartile (25th percentile) and the third quartile (75th percentile), and the line between the extremes that is the median (50th percentile); the first quartile is the value that is higher than the 25% of the data, the median is the value that is higher than the 50% of the data and the third quartile is the value that is higher than the 75% of the data. The "whiskers" that come out of the box represent the "minimum" and "maximum" of the data set, meaning the values that are no further than 1.5 times the interquartile range (third quartile - first quartile) from the first quartile and from the third quartile, respectively. The dots outside this "whiskers" are the outliers, the data that is numerically speaking far from the rest of the data. The width of the box indicates the range that is occupied by the 50% of the data, and depending how close is the median from each of the extremes of the box it can be deduced how concentrate is the data in one or other side of the box. With the whiskers it can be known with are the extreme values of the data set, and the outliers indicate the values that occurs but are not close to the rest of the data.

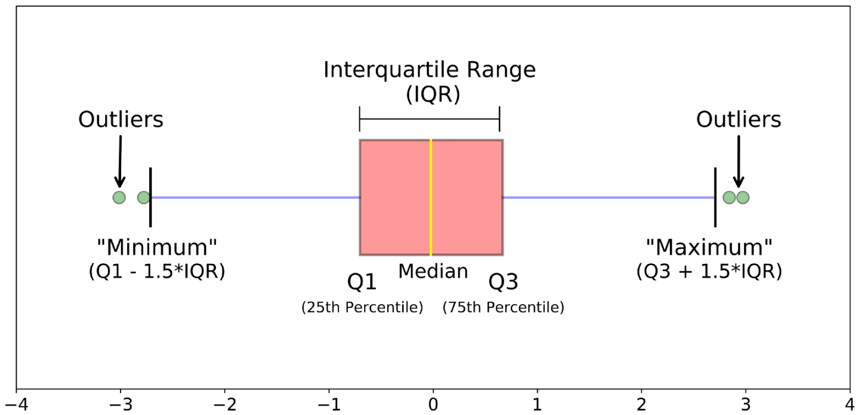

Figure 2.4: Scheme of a boxplot chart. Source [10]

In figure 2.5 is depicted the dispersion of the wind and PV production for the wind power plant located in Aragón in each season and during each hour of the day. In addition to the boxplot of each technologys production, a line that represents the mean for each of the hours is also depicted. In order to compare accurately both technology the production values are going to be represented in per unit (pu), on the one hand because the amount of PV to install has not been calculated yet, and on the other hand because in this way is easier to observe what is the level of production of the PV depending on the level of production of the wind.

As it can be observed in figure 2.5, in summer, there is high complementarity between the profiles, the PV is producing most of the time at almost peak power while during that hours the wind production is concentrated around low values, nonetheless, when the PV production is reduced or during the night when the PV does not produce at all, the wind production increases compensating the low

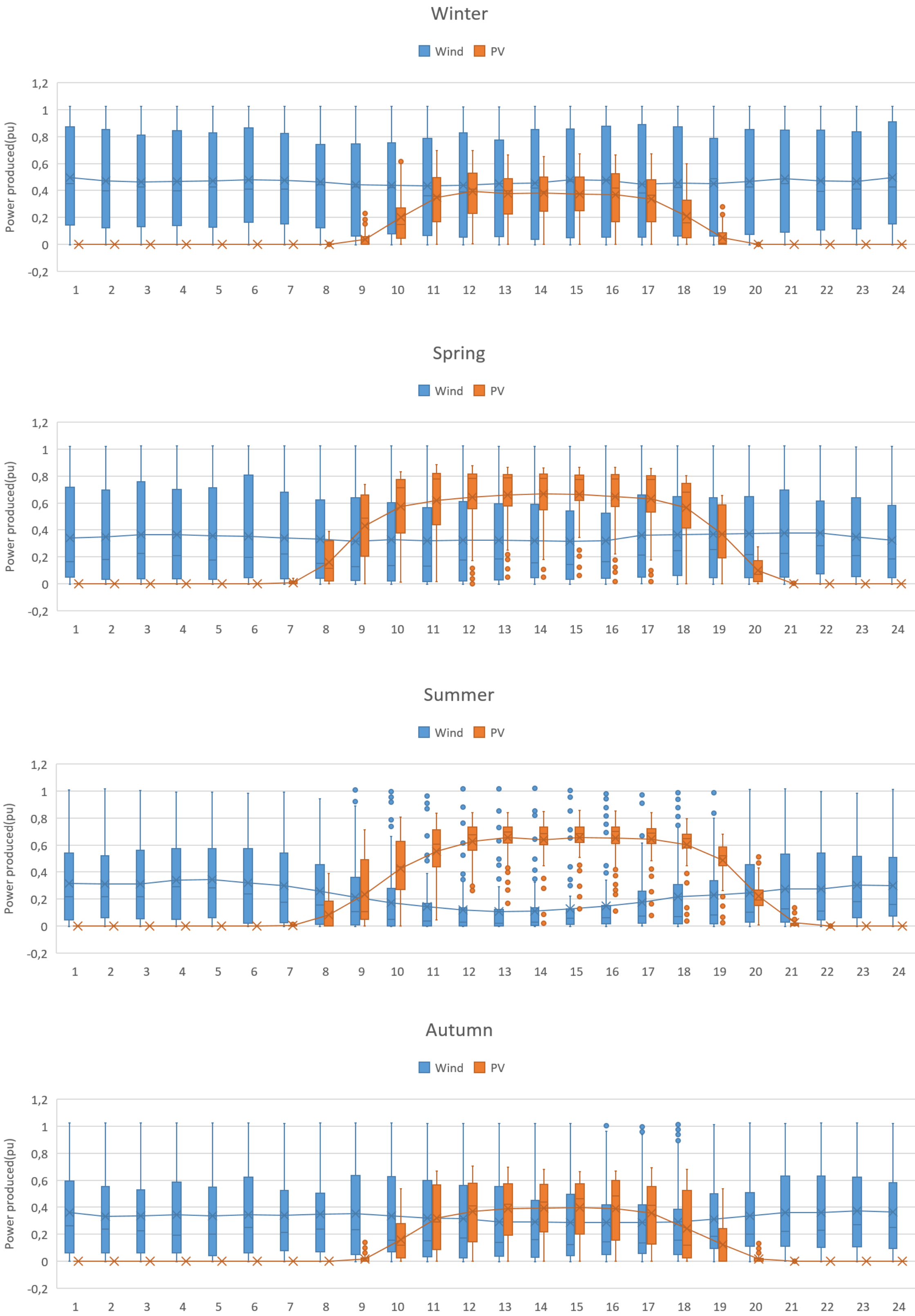

Figure 2.5: Dispersion of wind and PV production in each season and during each hour of the day.

production of PV. Contrary to summer, in winter the production of PV is the lowest of all year as the irradiation along that months is the minimum; the wind production achieves in winter its maximum values but with high dispersion of the data. In spring, the PV production is high but has more dispersion in the data than summer, the wind production is lower than winter but achieving also high values. In autumn, the PV production present values a bit higher than the values of winter and the wind production have values similar to the values of spring.

With the observations made of figure 2.5, the month with higher complementarity is summer so there should not be a lot of excess energy during this period. Winter is also a month with high complementarity and the excess energy is not expected to be much. Talking about autumn, this period has lower complementarity of profiles than winter and summer, but as both wind and PV production concentrate in low-middle values the excess energy should not be a problem. Spring is the period with less complementarity and, therefore, the period where is expected to have more excess energy.

2.4.2 Analysis of the performance of the new PV power plant

The project to be studied is the installation of a PV power plant together with an already existing wind power plant. Therefore, as this two plants would share the interconnection capacity, that was designed for the already existing wind power plant, there would be hours where the combined production of both power plants would exceed the interconnection capacity, and there would be curtailment of energy. The amount of curtailed energy would depend not only on the complementarity of the production profiles of both technologies, as it has been already explained, but also on the amount of PV installed. So, before starting with the computation of the optimal PV capacity that should be installed, the expected used energy (the energy that would finally be injected to the grid) and curtailed energy (the energy that could not be injected to the grid because of achieving the grid interconnection limit) are going to be studied in order to have a first idea of which could be the performance of the PV power plant installed.

To realize this study the used and curtail energy are going to be computed depending on the ratio PV/wind. The PV/wind ratio expresses how much PV capacity is going to be installed, in MW, per each MW of wind already installed. The used and curtailed energy are going to be expressed in equivalent PV hours so it can be easily compare with the original PV plant. The equivalent hours is the ratio between the energy produced by a power plant (usually during a year) divided by the peak power of the plant, the result is the hours that the plant should have worked at full power to achieve the same energy produced during the whole year. The results of the simulation are the ones shown in figure 2.6.

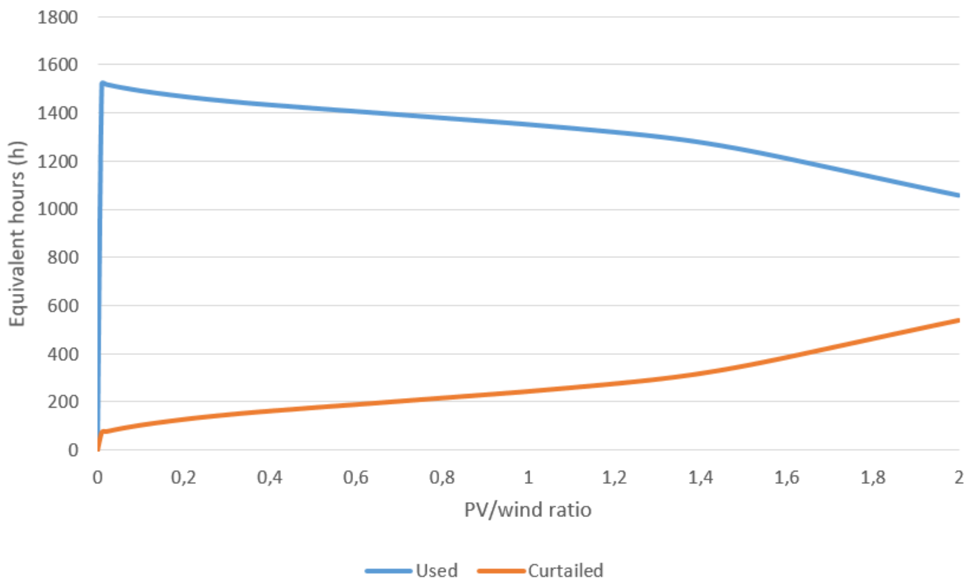

Figure 2.6: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind.

As it can be observed in figure 2.6, the curtailed energy does not rise up to an excessive value as it remains almost constant in 200 equivalent PV hours even if the amount of PV installed is the same as the amount of wind already installed, therefore the same as the grid interconnection capacity. Also, if the ratio PV/wind is lower than 1, the energy used remain in the range of 1500/1390 equivalent PV hours, this is due to two factors, one of them is that if the PV/wind ratio is increased there would be more energy curtailed in the hours where already had energy curtailment, and more hours where the energy is curtailed would appear. By contrast, if the PV/wind ratio is increased to values greater than 1, the energy used starts to decrease quicker, as well as the energy curtail also increase quicker, this is because even in hours where there is no wind production the PV by itself could exceed the grid interconnection limit. That is why, usually the maximum PV capacity installed would be the one corresponding to 1 PV/wind ratio, as it could be difficult to curtail the PV production. As it has been studied in the previous subsection, the high complementarity between the PV and wind production profile makes it possible to realize a installation of PV within a wind power plant taking advantage of the already built grid interconnection and without having to curtail much energy production.

Another study that could be interesting is to know how much curtailed energy with respect to the total production of the hybrid plant there would be, and how the usage of the grid is going to improve when adding the PV power plant. In order to estimate this two aspects, two indexes have been defined [11].

The first of them is the one that measures the curtailed energy with respect to the total production of the hybrid plant. To measure it, it has been created the index %curtailed energy, that calculates which percentage of the total energy that the hybrid power plant would be curtailed. The total energy is the sum of the energy that is used plus the energy that has to be curtailed due to overlaps in production profiles that exceeds the grin interconnection limit. The formulation of the %curtailed energy index is represented in equation 2.1.

$$\%curtailed\ energy = \frac{E_{curt}}{E_{total}} \cdot 100 = \frac{E_{curt}}{E_{used} + E_{curt}} \cdot 100 \tag{2.1}$$

The other information that could be useful to know is how the grid connection usage increase when installing PV capacity in the same grid connection of the wind power plant. In order to measure this, the index %grid usage has been established, for knowing how much grid has been used, it compares the amount of energy that has gone through the grid interconnection (the used energy from the hybrid power plant) with total energy that could have gone through the grid if the grid were working at full capacity the whole year. This index could also be seen as the capacity factor of the hybrid power plant. The formulation of the %grid usage index is represented in equation 2.2.

$$\%grid\ usage = \frac{E_{used}}{8760 \cdot \overline{\overline{grid}}} \cdot 100 \tag{2.2}$$

Once that both indexes have been defined, some calculations could be performed with them. Firstly, for the wind power plant located in Aragón, the percentage of curtailed energy is going to be calculated depending on the PV/wind ratio, figure 2.7.

As it is shown in figure 2.7, the percentage of curtailed energy increases when the PV installed increases, as it could be expected. This is due to the fact that, even when there is high complementarity between production profiles, the more PV installed the more hours where the combined production is going to exceed the grid capacity. Also, it could be observed in figure 2.7, that when the PV capacity installed is lower than the wind capacity already installed (PV/wind ratios lower than 1), the increase in the curtailed energy is more or less constant, whereas when the PV capacity installed is higher than the wind capacity already installed (PV/wind ratios higher than 1), the increase in the curtailed energy does not continue to be constant. This is due to the fact that when the PV/wind ratio is lower than 1, the high complementarity between profiles allows that the PV production could be injected to the grid in the same ratios than before, but when the PV/wind ratio is higher than 1 there appear hours when even if there is not wind production, some of the production of the PV power plant should be

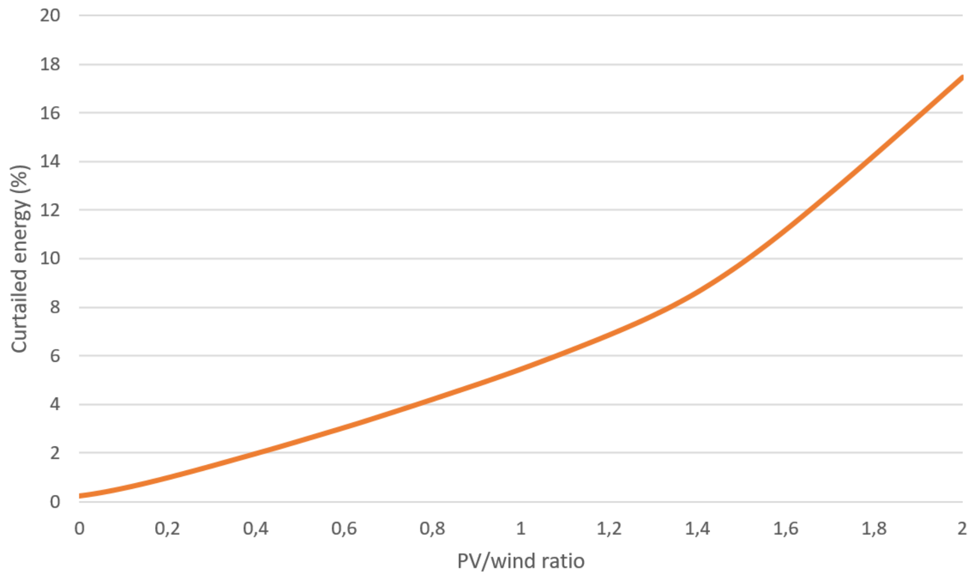

Figure 2.7: Percentage of curtailed energy depending on the ratio PV/wind.

curtailed in order to not overload the grid interconnection. The figure 2.7 also shows that even though the amount of PV capacity installed would be the same as the amount of wind capacity already installed, the curtailed energy would not be more than a 5% of the total production of that hybrid power plant.

In the same way than before, now the percentage of grid usage is going to be computed depending on the PV/wind ratio, for the same wind power plant located in Aragón, figure 2.8.

In figure 2.8, it is depicted how the percentage of grid usage would evolve when increasing the PV capacity installed. As it is shown in the figure, the percentage of grid usage increases when the PV/wind ratio increases, this is obvious as the more PV capacity installed, the more energy used that is going to be produced by the hybrid power plant, and therefore, the more time that the grid connection is going to be used. Also, it can be observed how with high PV/wind ratios the percentage of grid usage curve starts to flatten and if more capacity is installed there is not going to be a significant increase in the grid usage. This is due to two factors, on the one hand, similar to what happened in the percentage of curtailed energy, the more PV capacity installed the more curtailed energy there is, so the used energy does not increase proportionally with the PV capacity installed; on the other hand, the PV can only produce in sunlight hours, this means that even if a lot of PV capacity is installed there is not going to be production of this PV at night. This reasons makes it impossible to increase the percentage of grid usage to a 100%, because of the lack of PV production during night hours and because of the wind not producing at full capacity during all the night hours of the year.

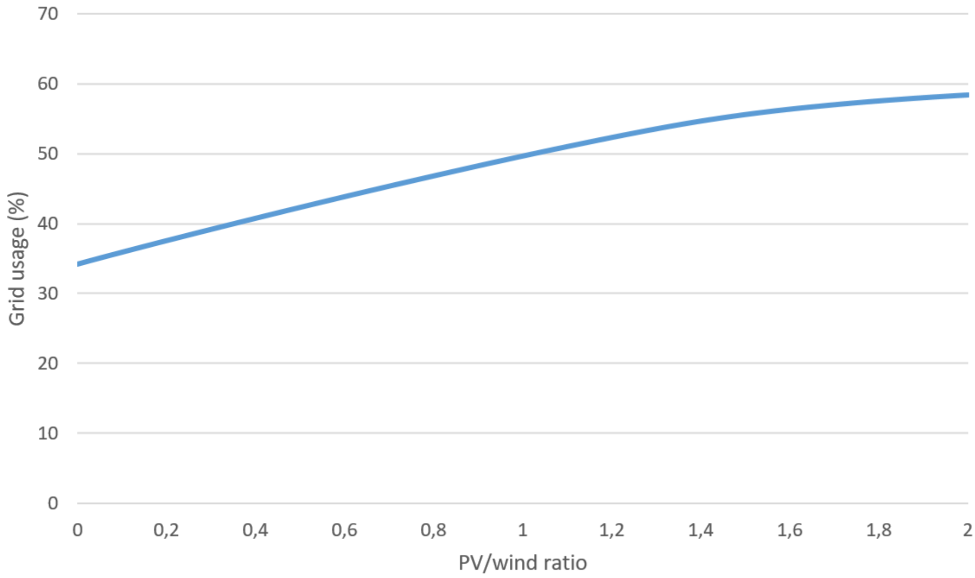

Figure 2.8: Percentage of grid usage depending on the ratio PV/wind.

Finally, this process is repeated for all the wind power plants selected. The figures for the rest of wind power plants not appearing in this section are located in the Annex A of this document.

2.4.3 Optimal PV capacity to be installed

Once that the wind-PV profiles from all the wind power plants selected have been studied, and it is observed a high level of complementarity of both profile, and the possible performance of the hybrid plant has been analysed, the optimal amount of PV that should be installed together with each of the wind power plants is going to be calculated. In order to compute this optimal capacity of PV, an optimization problem has been developed. This optimization problem finds the PV capacity to be installed that maximizes the net present value of the investment taking into account the constraints of a hybrid power plant, its formulation is the following.

$$\text{Maximize} \qquad \sum_{n} \frac{CF_n}{(1+k)^n} - I_0$$

subject to

$$\begin{aligned}
&W_t + PV_{hib,t} \leq \overline{grid} && ;\forall t \\
&0 \leq PV_{hib,t} \leq \frac{PV_t}{\overline{PV}} \cdot \overline{PV_{hib}} && ;\forall t \\
&CF_n = \sum_t \Big[(1-GT) \cdot p_{n,t} \cdot PV_{hib,t} - PV_{hib,t} \cdot (O\&M + GAT) \Big] && ;\forall n \\
&I_0 = \overline{PV_{hib}} \cdot C_{PV}
\end{aligned} \tag{2.3}$$

The description of all this abbreviations are explained in the Nomenclature section, at the beginning of this document.

The value of the parameters used for performing this optimization problem are reflected in table 3.1. The number of years n that the PV power plant is suposed to generate cash flow is assumed to be 20.

Table 2.1: Data of the parameters of the PV wind optimization problem. Source Endesa internal data.

PV cost (€/MW)	600000
Grid infrastructure cost (€/MW)	110000
Interest rate (%)	7,09
Generation tax (%)	7
O&M cost (€/MWh)	4
Grid access tariff (€/MWh)	0,5

The objective function to maximize is the net present value of the investment, as it has been said before. The first constraint, is the core of the problem and it means that the production of both power plants cannot be higher than the interconnection capacity in any of the hours. The second constraint means that the production of the PV power plant in the hour t should be greater than or equal zero, and lower than or equal to the maximum production of the PV power plant for that hour, this is because the PV power plant should adapt its production to the remaining space available in the connection grid; the maximum production of the power plant is determined with the production profile of the reference PV power plant selected in pu and then multiplied by the optimal PV

Table 2.2: Classification of hours depending on the season. Source [12].

	Winter	**Summer**
Peak	18 − 22	9 − 13
Shoulder	8 − 18 , 22 − 24	8 − 9 , 13 − 24
Off-Peak	0 − 8	0 − 8

capacity for the hybrid plant. The next equation is the cash flow of each year, where it is taken into account the generation tax, the price of the market for each hour of that year, the production in each hour, the operation and maintenance costs and the grid access tariff. The final equation is the investment cost of the PV power plant.

The new PV power plant constructed within the wind power plant is thought to sell its energy directly to the market, to recreate the prices of the market in the time the PV is expected to produce, it has been taken the prices of future markets, the data has been take from OMIP [13]. As the future market OMIP only provides data until the year 2026, the prices for the following years have been supposed to remain constant. Also the different hours of the year have been classify in Peak, Shoulder and Off-peak hours, as shown in table 2.2.

OMIP has available yearly price data for peak and off-peak hours, but not for shoulder hours. For computing the price in the shoulder hours it has been supposed that the price in the shoulder hours is the weighted average of the price in the peak and in the off-peak hours taking into account the number of peak and off-peak hours, this is shown in equation 2.4.

$$p_{shoulder} = p_{peak} \cdot \frac{h_{peak}}{h_{peak} + h_{off-peak}} + p_{off-peak} \cdot \frac{h_{off-peak}}{h_{peak} + h_{off-peak}} \tag{2.4}$$

So the price for each type of hour and for each year computed are the ones shown in table 2.3.

So once the model has run the optimization problem it provides the optimal amount of PV to install in the wind power plant of Aragón, the model returns a 0.53 PV/wind ratio to install. This result means, that the optimal amount of PV to install is a 53% of the already installed wind capacity. For this 0.53 PV/wind ratio, the percentage of energy curtailed of the total output of the hybrid plant is a 2.65% and the percentage of grid usage is a 42.74%. This results show that it is possible to enhance the grid usage by only curtailing a little amount of energy. Also, the production profile for a whole year of this hybrid power plant is represented in figure 2.9.

Table 2.3: Future energy prices depending on the type of hour. Source own elaboration with data from OMIP [13].

	Peak	Shoulder	Off-peak
2020	60,32	57,46	55,83
2021	56,32	53,69	52,18
2022	53,29	50,78	49,35
2023	52,01	49,58	48,19
2024	51,03	48,64	47,27
2025	50,49	48,12	46,77
2026	50,47	48,12	46,77
2027	50,47	48,12	46,77
2028	50,47	48,12	46,77
2029	50,47	48,12	46,77
2030	50,47	48,12	46,77
2031	50,47	48,12	46,77
2032	50,47	48,12	46,77
2033	50,47	48,12	46,77
2034	50,47	48,12	46,77
2035	50,47	48,12	46,77
2036	50,47	48,12	46,77
2037	50,47	48,12	46,77
2038	50,47	48,12	46,77
2039	50,47	48,12	46,77

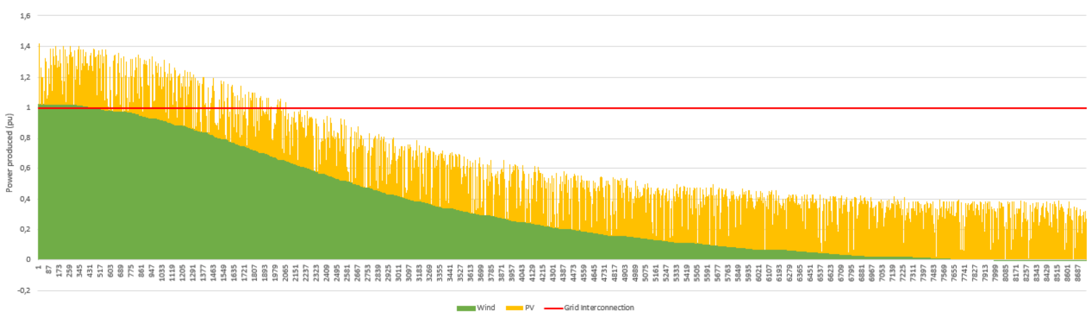

Figure 2.9: Yearly production for the optimal PV/wind ratio hybrid plant.

In figure 2.9 is shown the interconnection capacity and the wind and PV production of a whole year ordered from the hours with higher wind production to the hours with lower wind production, the PV and wind production are expressed in per unit (pu) both with respect to the wind power plant capacity that is also the grid connection capacity. As it can be observed in figure 2.9, the PV production exceeds the interconnection capacity in some hours, but as the complementarity of both wind and PV production profiles is high, this energy that should be curtailed only represents a 2.65% of the total production of the hybrid power plant. Also, it can be observed in the figure that there are a lot of hours where the wind power plant is not using all the interconnection capacity and in some of this hours the PV is using it achieving a grid usage of 42.74%.

Now that the optimal amount of PV is calculate, a comparison that could be interesting is to evaluate which would have been the net present value of the investment in the case that the PV power plant is constructed hybrid with the wind power plant, and which would have been the net present value of the investment if the PV power plant is constructed separated with its own grid infrastructure. For doing this the PV plant alone is assume to have the same costs that the PV plant hybridized, the only difference is that the PV plant alone has to construct its own connection to the grid infrastructure. The comparison is shown in figure 2.10.

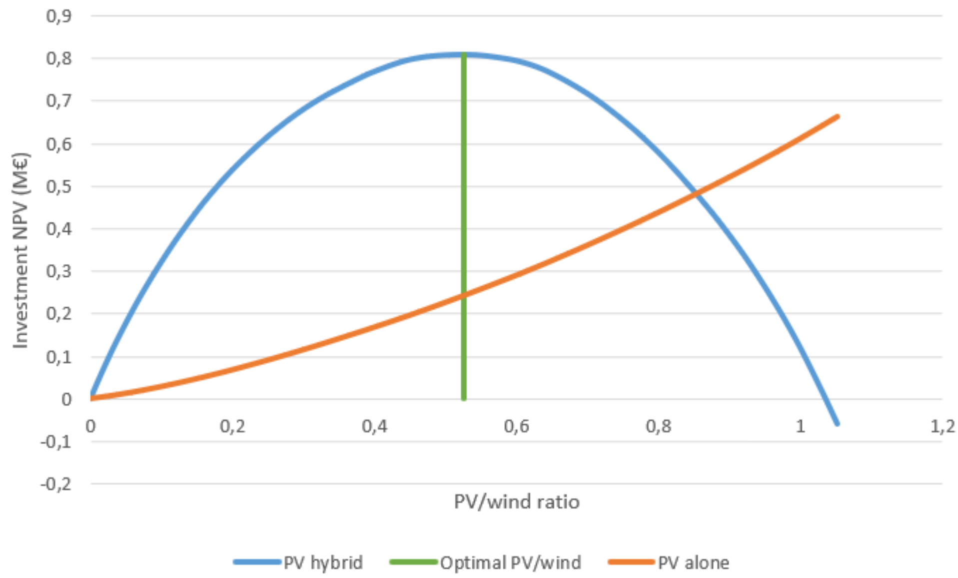

Figure 2.10: Comparison of hybrid PV and alone PV power plant net present value.

In figure 2.10 is depicted the evolution of the net present value of the investment for the PV constructed in hybridization and the PV constructed alone depending on the PV/wind ratio. As it can be observed in the figure, for the optimal amount of PV calculated the net present value is higher in the case of

Table 2.4: Summary of the simulation results for all the wind power plants.

Wind Plant	**Aragón**	**Castilla la Mancha**	**Andalucía I**	**Andalucía II**	**Castilla y León I**	**Castilla y León II**
Wind Equivalent Hours (h)	3000,17	2596,41	1879,52	1854,44	1316,97	1615,44
Wind Capacity Factor (%)	34,33	29,76	21,5	21,17	15,03	18,47
PV Capacity Factor (%)	18,21	16,95	21,96	21,11	16	16,68
Optimal PV/windratio	0,53	0,38	0,98	1,02	0,96	0,77
NPV of the Investment (M€)	0,81	0,31	3,09	2,76	0,93	0,5
IRR of Investment (%)	7,76	7,57	9,9	10,29	7,52	7,7
Curtailed Energy (%)	2,65	1,41	7,39	4,47	0,4	1,56
Grid Usage (%)	42,74	35,67	39,77	40,73	30,28	30,9

hybridization than in the case of constructed this same capacity but alone. Also, there is point where constructing the PV power plant in hybridization is less profitable than constructing the PV power plant alone, this is due to the fact that with higher PV/wind ratios, the amount of energy curtailed is also higher, therefore the revenues would be constant or lower but with a higher investment cost; there is even a point where installing the PV hybridized is not profitable.

Lastly, the model is run to calculated the optimal amount of PV to be installed in all the wind power plants studied. In table 2.4, apart from the optimal PV/wind ratio, the wind equivalent hours, the wind capacity factor, the PV capacity factor, the net present value of the investment, the internal rate of return of the project, the curtailed energy and the grid usage are also shown.

As it can be observed in table 2.4, there are a lot of factors that have influence in the optimal PV/wind ratio. In the case of the wind power plant located in Castilla la Mancha, the wind power plant have a high capacity factor of 30% and a low PV capacity factor of 17%, this makes that the PV/wind ratio to be installed is only a 0.38, as the wind have a lot of production it becomes difficult for the PV power plant to inject power in a lot of hours and therefore there is not profitable to install a lot of PV capacity. The contrary happens with the wind power plant Andalucía II, in this case the wind power plant has a capacity factor of 21% and a PV capacity factor of also 21%, the low wind production leads and the high PV capacity factor leads to a high complementarity of profiles making than the optimal amount of PV to install even exceed the already install wind capacity, this is due to the fact that, as the PV power plant is not producing at full capacity during the whole year, it is profitable to install more PV capacity using that energy during the low production periods, knowing that during the high production periods there would be excees energy even when the PV is producing and the wind is not.

2.4.4 Profitability of installing a battery

As in all the hybrid power plants there would be energy curtailed, this energy could be stored in a battery so that it could be injected to the grid in other hours where there is grid capacity available.

The first step for analysing if it would be profitable to install a battery is to study the excess energy of each hour, for making such study a boxplot chart has been used to represent the dispersion of the excess energy of each hour of the year, the results are the ones depicted in figure 2.11. This figure represents the values of excess energy of the hybrid power plant of Aragón.

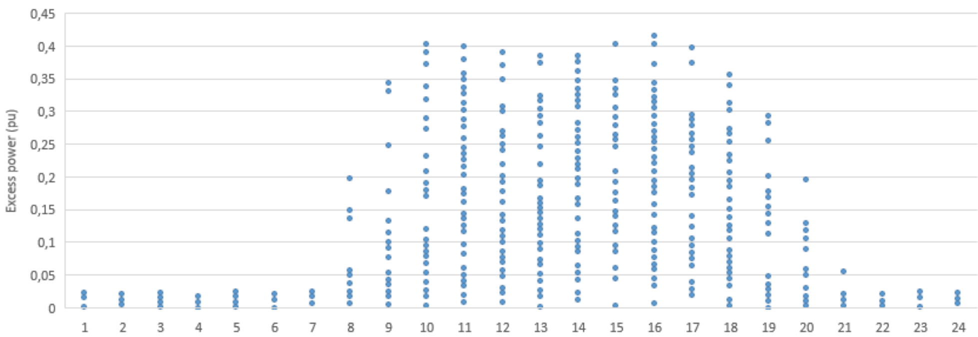

Figure 2.11: Dispersion of the excess energy in each hour of the year.

In figure 2.11 there is no box represented, this means that the whole box is located in 0, meaning this that during the majority of the hours of the year there is no excess energy in the hybrid power plant. Also, this means that the points represented in the figure are outliers, this outliers are only 805 hours of the year and the majority of them present lower values, another factor is that the excess energy occurs mainly in the hours where the PV is producing that are the peak and shoulder hours, so the battery would be obliged to sell in the lower price hours of the day. With all this factors and the high prices that the batteries still have nowadays, it does not seem to be profitable to install a battery together with the hybrid power plant.

The fact that a battery would not be profitable or needed, shows that the hybrid power plant is well designed and, as it has been said before, the energy curtailed does not represent a huge amount.

2.5 Overpowerment of wind power plant

As it has been explained in the introduction of this Master's Thesis, overpowerment is another way of maximizing the utilization of grid. The main difference with hybridization is that in hybridization there are two or more technologies that complement each others production profiles to maximize grid usage, while overpowerment consists in installing more capacity from the capacity of the grid interconnection. As renewable technologies, usually, are only producing at peak power some hours of the year, the rest of hours there could be space remaining for more production. In that peak hours there would be an amount of energy that should be curtailed, but it could be possible that the promoter of the installation recovers the investment with the extra production during the rest of the year.

Even if this seems to be strange this is already done in the case of the PV. Speaking about regulation, the power of PV power plants are measured by the power nameplate of the inverter and not by the power nameplate of the sum of all the photovoltaic panels, with this definition there is room for oversizing the solar field.

For analysing the overpowerment, it is going to be considered that the extra capacity installed as if it were other power plant, as in the case of the PV and wind hybridization. This overpowerment is going to be defined as a percentage of the already installed wind power capacity. In order to make the analysis the same six wind power plants are going to be selected, and it is going to be compared the same results obtained for the hybrid project, these are the equivalent production hours of the new technology, the percentage of energy curtailed and the increase in the grid usage. For this chapter the wind power plant located in Aragón has been chosen to analyse all the figures.

In the case of overpowerment, it does not make sense to analyse the complementarity of both profiles, as they are the same technology, the already installed capacity and the extra capacity are going to produce in the same hours.

Now, it is going to be studied how the extra capacity installed would work. For doing this the equivalent hours of the extra capacity are represented depending on the percentage of overpowerment and differentiating the equivalent hours of energy used and energy curtailed. The results of this are shown in figure 2.12.

As it can be observed in figure 2.12, start to loose used equivalent hours faster than the hybrid plant, this is due to the fact that there is no complementarity between profiles, so the hours along the year where the wind power plant has a high production there would be energy that would be curtailed. For a overpowerment of 100%, it can be observed that the equivalent hours of the extra wind capacity decreases by half.

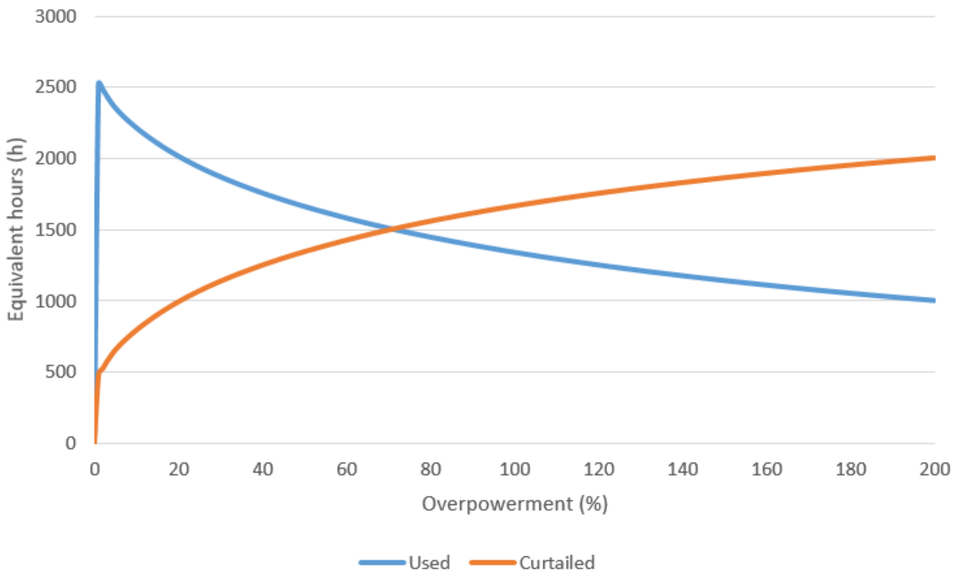

Figure 2.12: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment.

The next step, is to analyse the percentage of curtailed energy that the overpowered plant would have. To do this, the index defined in the equation 2.1 is going to be used, and the results are going to be represented depending on the percentage of overpowerment. The results are depicted in figure 2.13.

As it can be observed in figure 2.13, the percentage of curtailed energy is much higher than in the case of the hybrid power plant. This is due to, again, the fact that there is no complementarity between two technologies in the case of overpowerment, and therefore it is expected that the energy that should be curtailed is higher than in the other case. In the case of having a 100% overpowerment, it could be observed that the percentage of energy curtailed raise to values around 30%.

Now, it is going to be analysed which is the increase in the grid usage that the overpowered plant would achieve. For doing this, the index defined in equation 2.2 is going to be used. The results in figure 2.14, are represented depending on the percentage of overpowerment.

As it can be observed in figure 2.14, the percentage of grid usage present values similar to the ones of the hybrid power plant. This is due to the fact that this index is taking into account only the energy injected to the grid by the power plant, and therefore in both cases the amount of energy injected should be similar. Also it has to be considered that the wind power plant have a capacity factor higher than the PV power plant, hence even if there is higher amount of energy curtailed, there is also higher amount of energy produced, and this compensates

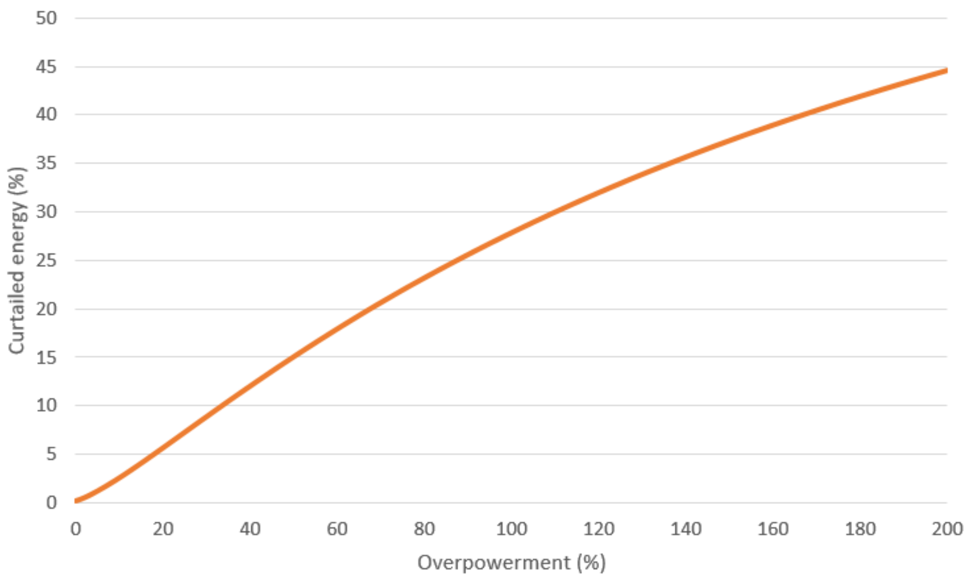

Figure 2.13: Percentage of curtailed energy depending on the percentage of overpowerment.

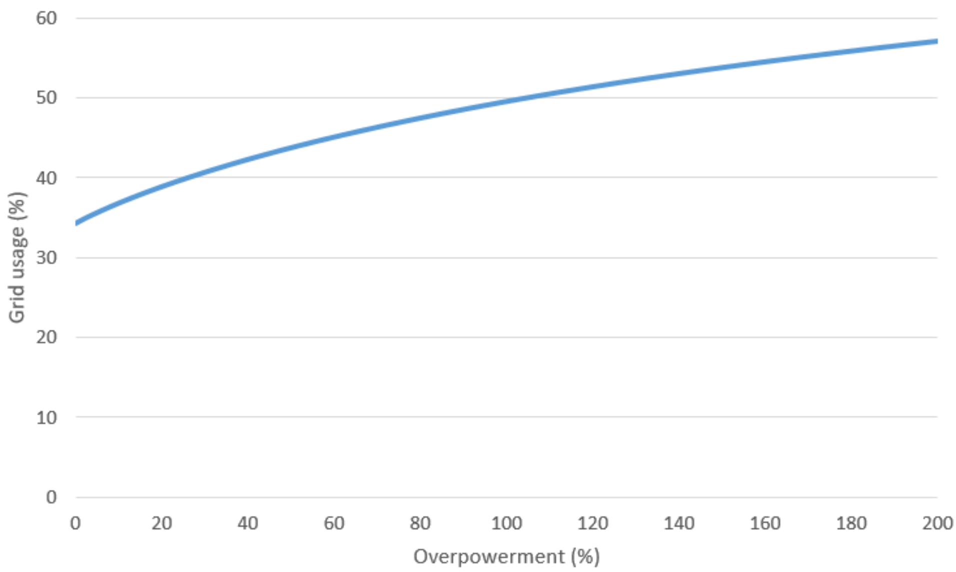

Figure 2.14: Percentage of grid usage depending on the percentage of overpowerment.

the null complementarity of overpowerment. Another factor to take into account is that wind can produce in any hour of the day as long as there is wind blowing, contrary to this, the PV power plant only produces during sunlight hours, this allows that the wind power plant can produce during more hours during the year, and most of this hours could be hours when the wind power plant is not producing at peak capacity.

In the case of the overpowerment the optimal amount of extra capacity to be installed is not going to be calculated, as this should be calculated when the power plant is designed. If there is need to establish the optimal amount to be installed for a new project the optimization problem developed in equation 2.3 can be used by only doing some changes in the constraints.

This process is repeated for all the wind power plants selected. The figures for the rest of wind power plants not appearing in this section are located in the Annex A of this document.

With the results presented here it can be stated that overpowerment is another effective way of increasing grid usage. It is important to analyse the possible energy curtailments as there is not complementarity between production profiles. Even though the curtailed energy is higher than in the case of a wind PV hybrid power plant, the fact that the wind power plant presents a higher capacity factor than the PV power plant compensates the higher percentage of energy curtailed, so the percentage of grid usage is similar to the one obtained with the hybrid power plant.

2.6 Conclusions

The results of this chapter allows to draw several conclusions.

Hybrid PV wind power plants are able to increase the already built grid usage without having to curtailed a high amount of energy. The complementarity of the wind and PV production is demonstrate to be high for the wind power plants studied. The six wind power plants studied in this chapter results to be profitable for installing a hybrid PV wind power plant, achieving an internal rate of return of 8-10% for the project. As the profitability of the hybrid power plants depend on a lot of factors, such as the complementarity between production profiles, the wind capacity factor or the PV capacity factor, it is important to analyse each power plant individually and considering all the factors. The installation of a battery would not be profitable, as there is only excess energy in some hours of the year, this, together with high prices for batteries nowadays, makes it difficult for a battery to recover the investment.

In case of the overpowerment it is demonstrated that, as the complementarity between the already installed power plant and the extra capacity is null, the curtailed of energy is higher than in the case of the hybrid power plant. Furthermore, it is also demonstrated that even if the curtailed of energy is high, the fact that the wind power plant has a high capacity factor allows to achieve grid usage levels similar to the ones obtained in the hybrid power plant.

Chapter 3

Hybridization of hydro and photovoltaic

3.1 Introduction

Hydro power plants are really interesting for the power systems because of their capability to store water and schedule their production. Firstly in this chapter it is going to be explained which could be the synergies between hybridizing hydro and PV power plants that could make hydro PV hybrid power plants profitable.

Furthermore, it is going to be analysed which is the profitability that hydro-PV hybrid power plant could have. For doing so the complementarity of both production profiles is going to be studied. Other study that is going to be carried out is the possible performance of the PV power plant that is going to be installed, for doing so the expected curtailments of energy and the increase of grid usage are going to be analysed. Once that all this studies are done the next step is to build an optimization problem that returns the optimal amount of PV to be installed in order to maximize the net present value of the investment, taking into account the constraints of a hybrid power plant.

3.2 Synergies between hydro and PV power plants

Co-locating hydro and PV can make both projects more profitable by sharing some of the infrastructures needed to develop the plants, or by splitting some of the costs between the two projects.

3.2.1 Grid infrastructure

One of the main savings of co-locating hydro power plants and PV power plants is to share part of the connection to the grid infrastructure.

In case of the PV power plant, it needs power electronics to connect to the grid, as the energy coming out from the PV panels is in DC and have to be converted through the inverter into AC to be able to be injected in the grid. Hydro power plants produce electricity directly in AC.

As the production of both power plants is done in a different way, they should be coupled in AC mode, this means that the electricity of the hydro is integrated with the electricity from the PV after it has come from the inverter and before entering into the substation. In this mode, the technologies would be able to share the substation components, the transmission lines and the grid connection.

3.2.2 Land lease

If the promoter is the owner of the hydro power plant, or if the promoter has an exploitation permit for the hydro power plant, he could also have some terrains near to the dam belonging to him to install the PV power plant.

Other interesting option is to install the PV power plant as a floating PV power plant [17]. In this type of power plants the PV panels are located in a floating structure located in the reservoir. This floating PV power plants utilize unused water reservoir space for energy generation, leaving land for other purposes.

3.2.3 Increase in PV panels efficiency

The efficiency of regular photovoltaic panels depend mainly on the irradiance that it receives, but also other factor that affects the efficiency is the temperature, temperature could make efficiency to drop about a 0.4% for each Celsius degree increase. If the PV power plant is constructed floating in the water reservoir, the efficiency of the panels would be increased as the water beneath the panels would help to refrigerate them. Most of the floating photovoltaic panel are designed with a material that replaces the panel frame and enables the panel to float on a water surface, also, the same material transfers the heat to the back of the panel in contact with water, that helps to refrigerate the panel decreasing its temperature and therefore increasing the panel temperature. Some of the studies done so far [14], shows that floating photovoltaic panels could have a 5.93% increase in energy produced with respect to a normal photovoltaic panel working in same conditions. This increased in the efficiency could lead to reduction in the costs of the project.

3.2.4 Other hydro and PV power plants synergies

Other synergy between hydro and PV power plants is the reduction in the hydro reservoir evaporation [15], even though the reduction in the evaporation is small, the water that is not evaporated could be used to generate electricity [17].

The shadow provided by PV panels could reduce the growth of algae, and in this way increase the quality of the reservoir's water, reducing the costs of treating the water for other uses.

3.3 Possibilities for the hybridization of hydro and PV power plant

There are different types of hydro power plants each of them with different capacity to store water, so depending on the type of hydro power plant with which the PV power plant is going to be hybridize there are different benefits [16].

3.3.1 Run-of-river hydropower plant

A run-of-river hydropower plant is a facility that takes advantage of the flowing water from a river and channels it through a cannal or penstock to spin a turbin. This kind of plants does not have usually storage capacity, so they are usually non-schedulable technology.

If the hybridization is done with a run-of-river hydro plant, it would be similar to the hybridization between wind and PV, the complementarity between production profiles should be studied in the same way.

3.3.2 Storage hydropower

Storege hydropower is a large system that stores water in a reservoir thanks to a dam. Electricity is produced due to the potential energy of the water stored in the reservoir, when the water is released it activates a generator. This kind of hydro power plants can operate as base load or as peaker plants. The storage capacity usually enables them to operate for many weeks independently of hydrological inflows.

When hybridization is done with a storage hydro plant if the PV installation is lower than the evacuation to the grid capacity, there should not be any curtailed of energy, as if the production of PV and the hydro plant exceeds the grid capacity the hydro power plant could reduce the amount of water being turbine, and use that water in other moment.

3.3.3 Pumped-storage hydropower

Pumped-storage hydropower are composed by two reservoirs, the upper reservoir and the lower reservoir. This hydro power plant pumps water, consuming electricity, from the lower reservoir to the upper reservoir in the hours when prices are lower, and then turbines that water, producing electricity, from the upper reservoir to the lower reservoir in the hours when prices are higher. This kind of hydropower plant could be seen as a battery that is not allow to charge from the grid.

If the hybridization is done with a pumped-storage hydropower plant, the PV power plant could be oversized, with respect to the grid connection capacity, in order to use the excess energy to pump water to the upper reservoir, reducing the costs of operation of the hydro power plant. This kind of hybridization could be seen as a PV power plant together with a big battery.

3.4 Methodology

For assessing the profitability of installing a PV power plant together with a hydro power plant, some real hydro power plants have been selected. The five hydro power plants selected are of the type storage hydropower. This hydropower plants have been selected because they present low energy production values, this is because the main objective of this hydropower plants is not to produce electricity, but to provide water for irrigation crops when it is needed. This makes that this hydro power plants are not completly schedulable from the point of view of Endesa as they should follow instrucctions given by the hydrological confederations. Therefore, the plants produce energy when there is a need for irrigation.

So, in order to establish the profitability of installing a PV power plant, the same PV production profile as the one selected for the wind and PV hybridization. Also, the production profiles of the five storage hyrdropower plants are available. The avaible data for the PV and for the hydro is hourly generation data. For the hydro plant there is available the hourly production data of two years, one a dry year and another one a wet year.

Once that both production production profiles are selected, the next step is to overlap them, and analyse which would be the energy that could be used and the energy that would be curtailed.

3.5 Hybridization of already existing hydro power plant with a new photovoltaic power plant

In this section, an analysis of a hydro-PV hybrid power plant, where the hydro power plant is already in place is going to be made. It is important to remark that the grid capacity would not be increased.

3.5.1 Analysis of the hydro-PV complementarity

The first step, would be to analyse if there is some kind of complementarity between the production profiles of both technologies. So, firstly, an analysis on how the production of the hydro plant in the two selected years is distributed along the different months of the year is going to be made. To analyse this, the equivalent hours of energy produced in each month is calculated, as shown in figure 3.1.

In figure 3.1, it can be observed that, except HYDRO III power plant, all the hydro power plants produce a low amount of equivalent hours. Also, it can be seen that the production is mainly concentrated around the summer months, this makes sense as this are the driest months, and therefore the months with the higher need for irrigation for the crops. The fact that the production of the hydro power plants is concentrated in summer could entail a problem for the hybridization with a PV power plant, but as the equivalent hours of production

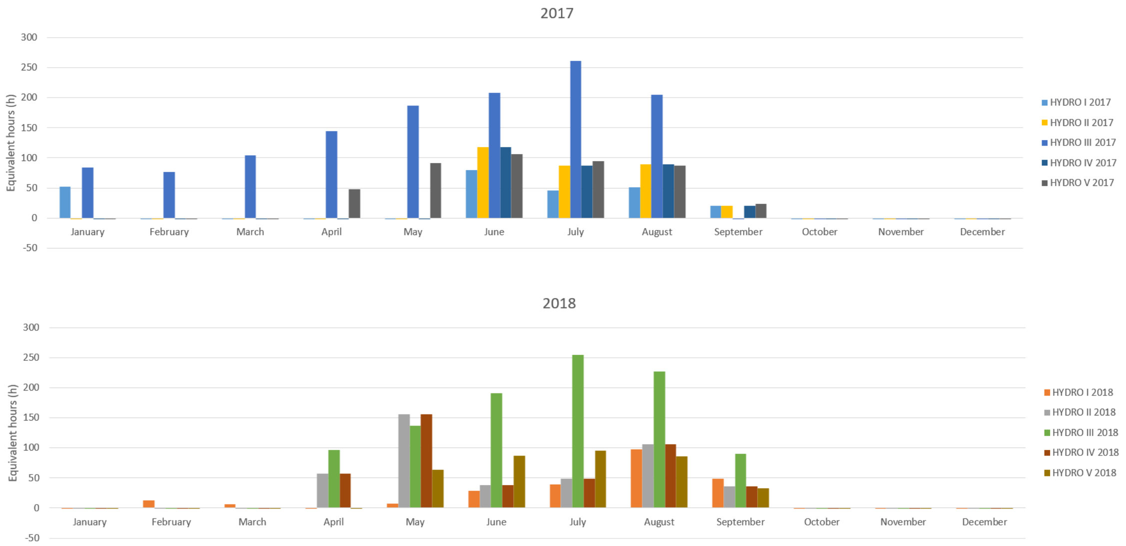

Figure 3.1: Equivalent hours of energy produced in each month of the year for the two study years.

are really low, there could be a big amount of PV integrated with the hydro power plants that would not exceed the grid capacity limit. Even though is supposed that the year 2017 was a dry year and that the year 2018 was a wet year, the production of the hydropower plants does not present a huge difference between that two years, and most power plants, contrary to what could be expected, have a higher production during the dry year; this could be because the actual production of the plants do not depend on the future hydro inflows or in the future price of the production, it mainly depend on when the hydrological confederation say that there is a need of release water for irrigation, is in this moment when this hydropower plants are going to produce.

In order to analyse the overlaps with the PV power plant, the worst of the two years for each power plant is going to be selected, this means that the year with higher hydro production is the one that is going to be chosen. For all the power plants the year with higher production is the year 2017, except for HYDRO IV power plant which year with higher production is 2018. As the decisions to produce do not depend on the plant operator, but on the hydrological confederations, the hydro power plants are going to be considered as if they were run-of-river hydro power plants, so there could be energy curtailed. In order to analyse if there would be a lot of hours where the hydro and PV production exceeds the grid connection capacity, as it was done in the case of wind and PV, the seasonal and intraday complementarity of production profiles between the hydro power plant are going to be studied. For this study, the power plant selected is the HYDRO III, as it is the hydro power plant with higher production hours, and with production in more months along the year. As in the previous chapter the boxplot chart is the type of plot selected to measure the complementarity of both production profiles, figure 3.2.

As it can be observed in figure 3.2, in autumn the production of the hydro power plant is almost null, hence the PV power plant would be able to inject most of its production. Contrary to this, in summer is the month where more curtailed energy could be expected as, as it observed, the PV is producing at its maximum capacity and the hydro is producing during the same hours and also at a high level. In spring, the PV production stills high but also with higher dispersion than in summer, but the hydro production remains at the same levels of summer but with lower overall production, hence some energy curtailed could also be expected during this hours. During winter, the PV is producing at lower values than in spring and summer, and the hydro production is also lower, therefore there should not be a lot of energy curtailed during this period. One curious thing that could be noticed in the figures about the hydro production profile, is that hydro is not producing at its maximum capacity at almost any hour of the year, the maximum power production is about 0.7 pu, this means that when hydro is injecting energy to the grid there would always be a 0.3 pu that is free to be used by the PV production.

3.5.2 Analysis of the performance of the new PV power plant

Similar to the case of the previous chapter, the project here is to install a PV power plant with an already existing hydro power plant to share the interconnection grid. As the grid was designed to only allocate the maximum production of the hydro power plant and now, with the construction of the PV power plant the maximum production of both power plants is going to exceed that amount in some moments, there would be some energy that would have to be curtailed. This amount of energy curtailed would not only depend on the complementarity of PV and hydro production profiles, but also on the amount of PV installed, so in order to have an idea of which could be the performance of the PV power plant installed the expected used energy (the energy that would finally be injected to the grid) and curtailed energy (the energy that could not be injected to the grid because of exceeding the grid capacity limit) are going to be simulated. As in the previous chapter the quantity of PV installed is going to be measured as a ratio, in this case the PV/HY ratio. This ratio expresses how much quantity of PV could be installed in MW per each MW of hydro installed. The results of this simulation are depicted in figure 3.3.

As it can be observed in figure 3.3, there is no curtailed energy until a 0.4 PV/HY ratio, this is because as it has been said before the hydro power plant is

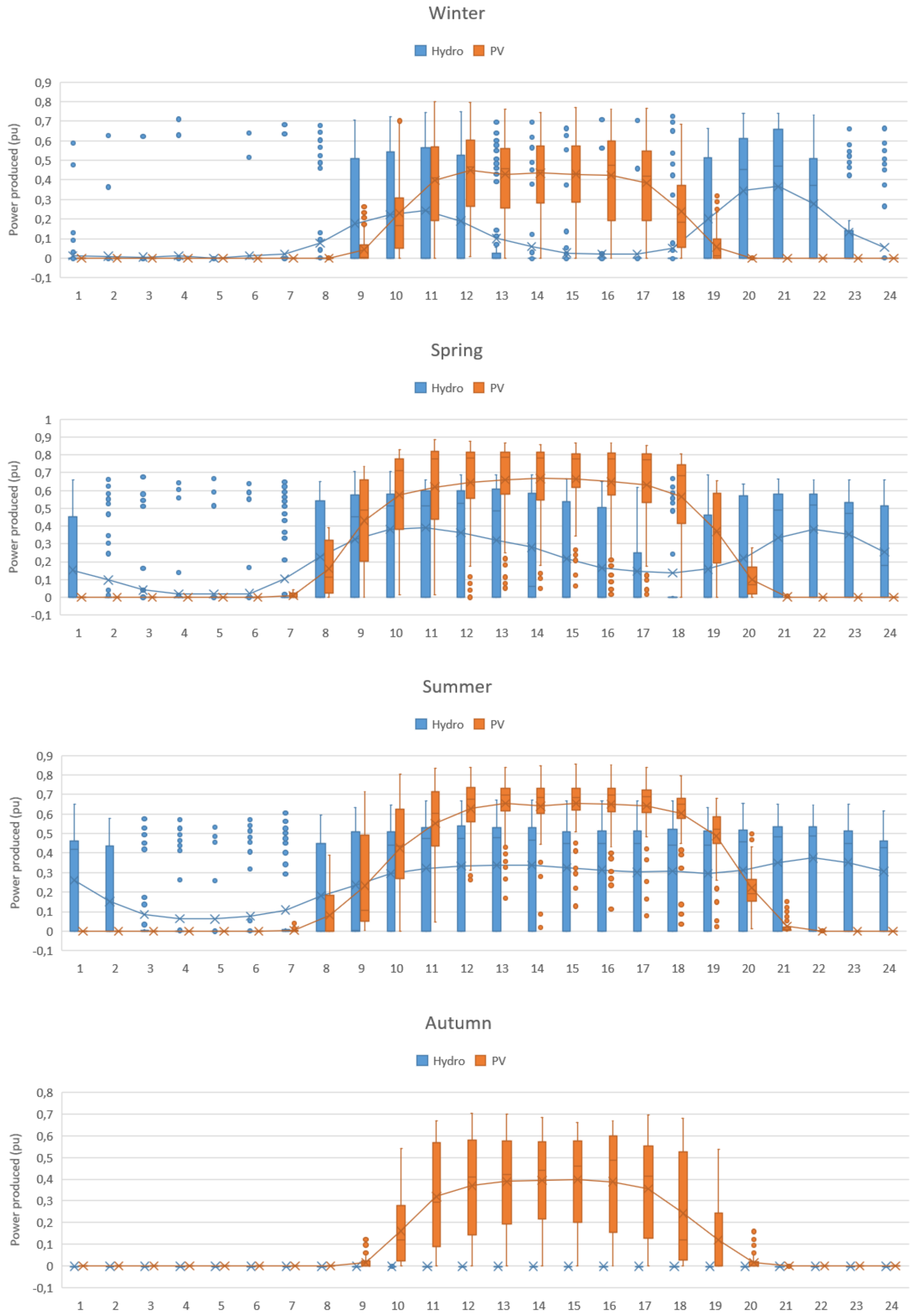

Figure 3.2: Dispersion of hydro and PV production in each season and during each hour of the day.

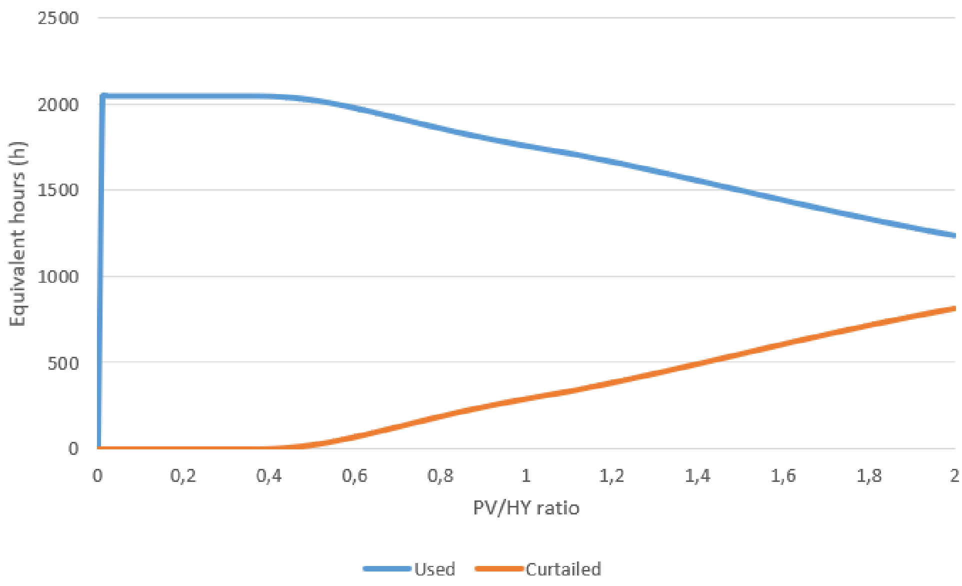

Figure 3.3: PV equivalent hours of energy used and curtailed depending on the ratio PV/HY.

not producing at full capacity in any of the hours, then, if this 0.4 PV/HY ratio is installed it could inject to the grid in almost any hour. When increasing the PV/HY ratio further than 0.4 the PV power plant starts to have curtailed energy but this is not very significant even if the capacity of PV installed is the same of hydro already installed (PV/HY ratio of 1), having in this case 300 equivalent hours of curtailment. Summing up, the fact that the hydro is not producing at full capacity almost any hour allows to install a considerable amount of PV without having any curtailment, then if more capacity is installed, the equivalent hours of used energy remains around 1600 hours.

After simulating the performance of the PV power plant, the possible performance of the hybrid power plant is going to be studied. For doing this the same indexes defined in the previous chapter are going to be used, these are the %curtailed energy (equation 2.1) and the %grid usage (equation 2.2). With this two indexes it could be studied how much the curtailed energy with respect to the total production of the hybrid plant there would be, and how the usage of the grid is going to improve when adding the PV to the already built hydro power plant. The results of the simulation of both indexes for the HYDRO III power plant are depicted in figures 3.4 and 3.5.

As it can be observed in figure 3.4, the results are similar to the ones obtained in figure 3.3, until a ratio of 0.4 PV/HY the percentage of curtailed energy is almost zero, if this ratio is increased it could be observed how the curtailed energy increases in a linear form. For a PV/HY ratio of 1, the percentage of curtailed energy is about 9%. The main reasons for the increase of energy curtailed

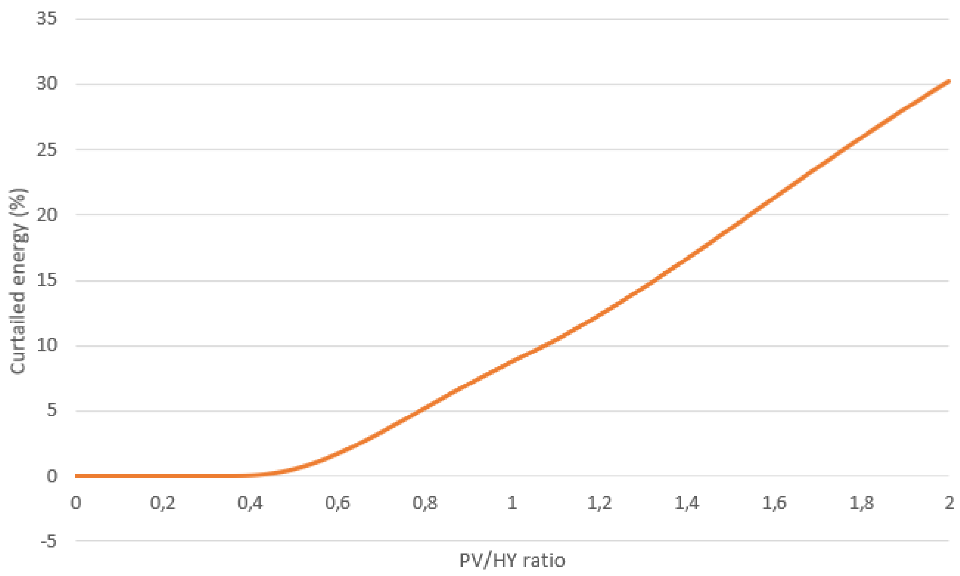

Figure 3.4: Percentage of curtailed energy depending on the ratio PV/HY.

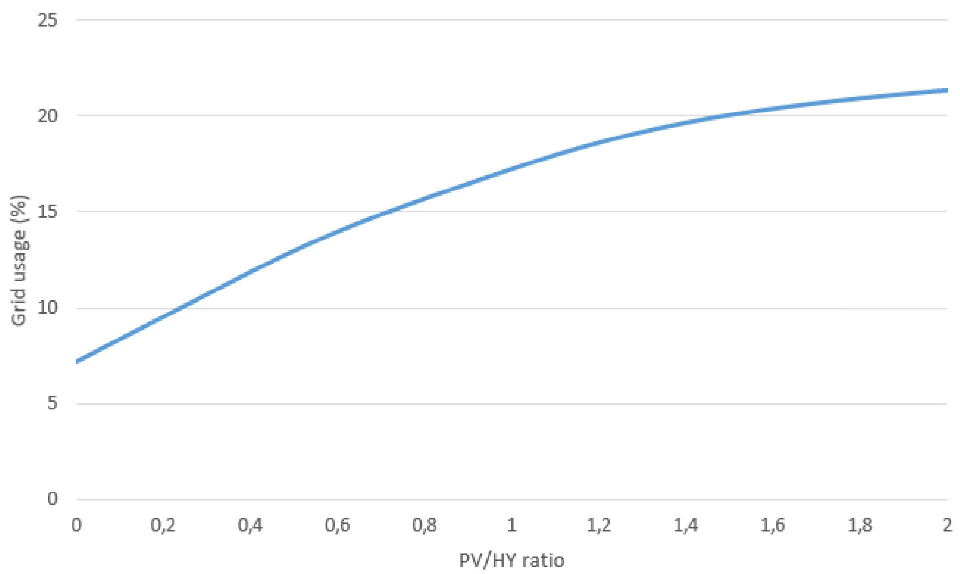

Figure 3.5: Percentage of grid usage depending on the ratio PV/HY.

are that increasing the amount to install increases the amount of energy that exceeds grid capacity and also makes that new hours exceeds the grid capacity, so the amount of PV to install should be sized correctly in order to maximize the investment but taking into account that there are going to be hours that even installing more PV the production does not increase necessary.

In figure 3.5 it is shown the evolution of the grid usage depending on the PV/HY ratio. As it can be observed in the figure the hydro power plant by its own (PV/HY ratio of 0) only has a 7% usage of the grid, it can be observed how this value could be even double without having to install a big amount of PV, with a PV/HY ratio of 0.8 the grid usage could achive a 15%. It can be observed that with high PV/HY ratios, the percentage of grid usage starts to flatten, this have two reasons, the first of them is the same of what has been said for the energy curtailed, the higher the PV installed the higher the energy curtailed, the other factor is that the PV only produce energy during the sunlight hours, therefore even if a high capacity of PV is installed the night hours are going to remain with the same production; therefore, there is a point where increasing the PV installed does not increase the grid usage.

Finally, this process is repeated for all the hydro power plants selected. The figures for the rest of hydro power plants not appearing in this section are located in the Annex B of this document.

3.5.3 Optimal PV capacity to be installed

Once that the hydro and PV production profiles from all hydro power plants selected have been studied, and it is observed a high level of complementarity of both profile, and the possible performance of the hybrid plant has been analysed, the optimal amount of PV that should be installed together with each of the hydro power plants is going to be calculated. In order to compute this optimal capacity of PV, the same optimization problem used in the previous chapter is going to be used. As it has been said, the optimization problem finds the PV capacity to be installed that maximizes the net present value of the investment taking into account the constraints of a hybrid power plant, its formulation is the following.

$$\text{Maximize} \qquad \sum_n \frac{CF_n}{(1+k)^n} - I_0$$

subject to

$$\begin{aligned}
&H_t + PV_{hib,t} \leq \overline{grid} && ;\forall t\\
&0 \leq PV_{hib,t} \leq \frac{PV_t}{\overline{PV}} \cdot \overline{PV_{hib}} && ;\forall t\\
&CF_n = \sum_t \left[(1-GT)\cdot p_{n,t}\cdot PV_{hib,t} - PV_{hib,t}\cdot (O\&M + GAT)\right] && ;\forall n\\
&I_0 = \overline{PV_{hib}} \cdot C_{PV}
\end{aligned} \tag{3.1}$$

The description of all this abbreviations are explained in the Nomenclature section, at the beginning of this document.

The value of the parameters used for performing this optimization problem are reflected in table 3.1. The number of years n that the PV power plant is suposed to generate cash flow is assumed to be 20.

Table 3.1: Data of the parameters of the PV hydro optimization problem. Source Endesa internal data.

PV cost (€/MW)	600000
Grid infrastructure cost (€/MW)	110000
Interest rate (%)	7,09
Generation tax (%)	7
O&M cost (€/MWh)	4
Grid access tariff (€/MWh)	0,5

The objective function to maximize is the net present value of the investment, as it has been said before. The first constraint, is the core of the problem and it means that the production of both power plants cannot be higher than the interconnection capacity in any of the hours. The second constraint means that the production of the PV power plant in the hour t should be greater than or equal zero, and lower than or equal to the maximum production of the PV power plant for that hour, this is because the PV power plant should adapt its production to the remaining space available in the connection grid; the maximum production of the power plant is determined with the production profile of the reference PV power plant selected in pu and then multiplied by the optimal PV capacity for the hybrid plant. The next equation is the cash flow of each year, where it is taken into account the generation tax, the price of the market for each hour of that year, the production in each hour, the operation and maintenance costs and the grid access tariff. The final equation is the investment cost of the power plant.

As in the hybridization of the previous chapter the new PV power plant constructed is thought to sell the energy directly to the market, so the prices of the table 2.3 are going to be used again to estimate the amount that the PV power plant would earn.

Once the model has run the optimization problem for the HYDRO III power plant it returns that the optimal amount of PV to be installed is 0.74. This means that it is optimal to install a 74% of the already installed hydro capacity. For this 0.74 PV/HY ratio the percentage of energy curtailed of the total output of the hybrid plant is a 1.95%, and the percentage of grid usage is a 14.16%, compared with the initial 7.22% usage. This results show that it is possible to enhance the grid usage by only curtailing a little amount of energy. Also, the production profile for a whole year of this hybrid power plant is represented in figure 3.6.

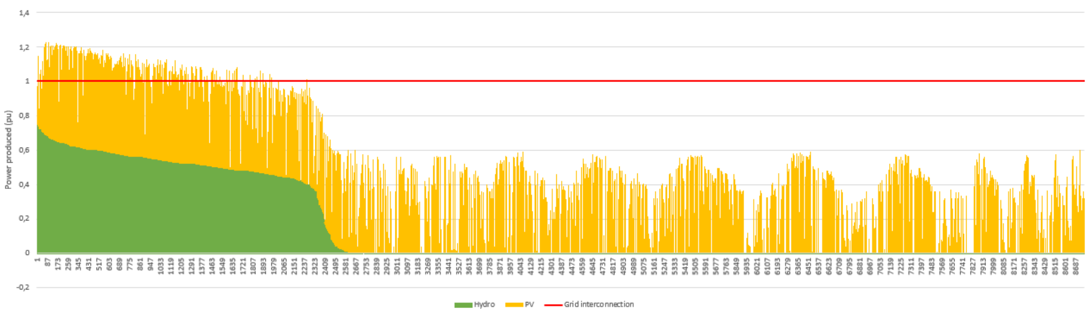

Figure 3.6: Yearly production for the optimal PV/HY ratio hybrid plant.

In figure 3.6 is depicted the interconnection capacity and the hydro and PV production profiles for a year, the production is ordered from the hours with higher hydro production to the hours with lower hydro production, the PV and hydro production are expressed in per unit (pu) both with respect to the hydro power plant capacity that is also the grid connection capacity. Similar to what happened with the wind and PV hybrid plant of the previous chapter, there are some hours where the PV production exceeds the interconnection capacity, but this energy that exceeds the grid capacity only represents a 1.95% of the total output of the hybrid power plant. The figure also shows how most of the year the hydro power plant is not using the interconnection capacity then during this hours the PV power plant is going to be able to inject all the energy produced to the grid, this fact makes profitable the PV power plant to be installed, as even if there are some energy curtailed the PV power plant is saving the grid infrastructure. Apart from the savings the grid that was already deployed also increases its usage up to a 14.16%.

Same as in the previous chapter, now that the optimal amount of PV to be installed is known, it could be interesting to know which would have been the net present value of the investment for the PV power plant if it were constructed alone with its own grid infrastructure. In figure 3.7 it is depicted the evolution of the net present value of the investment done for the PV power plant constructed hybridized with the hydro power plant and the PV power plant constructed alone depending on the PV/HY ratio.

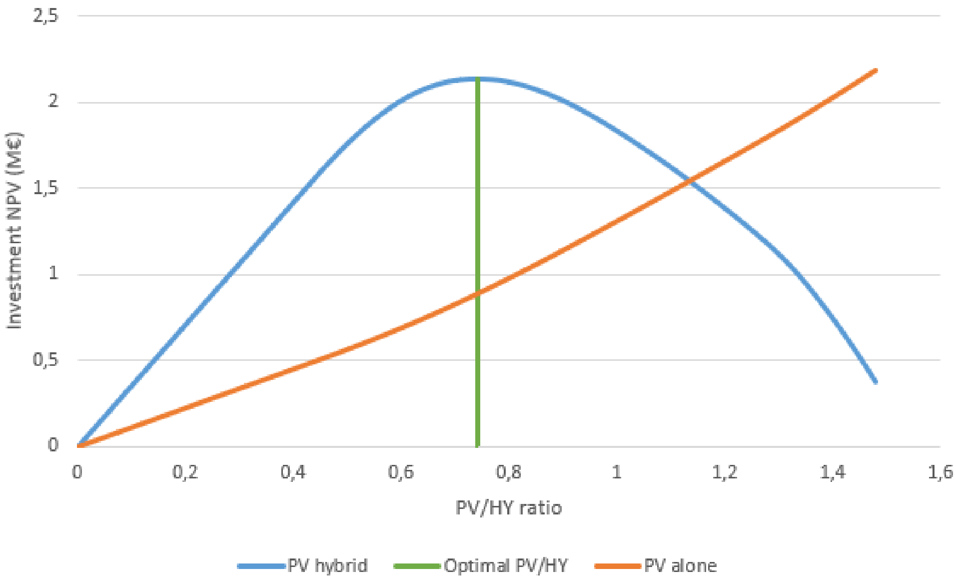

Figure 3.7: Comparison of hybrid PV and alone PV power plant net present value.

In figure 3.7 it can be observed that for the optimal PV/HY ratio calculated (0.74) the net present value of the investment is higher when it is constructed together with the hydro power plant rather than when it is constructed alone. Also it can be observed that with PV/HY ratios higher than 1.2 the PV alone starts to be more profitable than the PV hybrid, this is due to the fact that when installing more PV capacity hybridize the amount of energy that should be curtailed increases and therefore the revenues are lower for a higher investment.

Finally, the model is run to calculate the optimal amount of PV to be installed in all the hydro power plants selected. In table 3.2, apart from the optimal PV/HY ratio, the hydro equivalent hours, the hydro capacity factor, the PV capacity factor, the net present value of the investment, the internal rate of return of the project, the curtailed energy and the grid usage are also shown.

As it can be observed in table 3.2, in the profitability of a hybrid power plant

Table 3.2: Summary of the simulation results for all the hydro power plants.

Hydro Plant	**HYDRO I**	**HYDRO II**	**HYDRO III**	**HYDRO IV**	**HYDRO V**
Hydro Equivalent Hours (h)	243	566,39	1264,88	305,92	439,67
Hydro Capacity Factor (%)	2,77	6,47	14,44	3,49	5,02
PV Capacity Factor (%)	23,24	23,04	19,51	22,88	22,88
Optimal PV/HY ratio	1,18	1,08	0,74	1,19	1,17
NPV of the Investment (M)	32,31	4,24	2,14	15,14	6,27
IRR of Investment (%)	12,62	12,48	9,89	11,86	12,1
Curtailed Energy (%)	3,94	3,39	1,95	6,26	4,81
Grid Usage (%)	14,55	15,12	14,16	14,39	15,17

is conditioned by a lot of factors. Also in the table it could be differentiated two different cases. One of them is the case of the HYDRO III power plant, which has been analysed more in detailed in this chapter, as it can be observed in the table the HYDRO III is the power plant with the higher equivalent hours and the higher hydro capacity factor, this makes that the PV/HY ratio is the lower of all the hydro power plants. The other case is the rest of hydro power plants, as they have low equivalent hours and low hydro capacity factor it is profitable to install a higher PV/HY ratio, in all the cases the PV/HY ratio is higher than 1, this is due to the fact that the PV power plant only produces at full capacity during some months in the year, this makes that as in the other months the capacity to produce is lower it is profitable to install more PV capacity and produce with it during that months knowing that during some moments in the year there could be energy curtailed only coming from the PV power plant.

3.6 Conclusions

The results of this chapter allows to draw several conclusions. Hybrid hydro PV power plants are able to increase the already built grid usage without having to curtailed a high amount of energy. This is mainly due to the fact that the hydro power plants selected had a really low capacity factor. The complementarity of the hydro and PV production is demonstrated to be high for the hydro power plants studied. The result for the five hydro power plants studied in this chapter show that installing a hybrid PV hydro power plant is profitable, achieving an internal rate of return of 9-12% for the project. As the profitability of the hybrid power plants depend on a lot of factors, such as the complementarity between production profiles, the hydro capacity factor or the PV capacity factor, it is important to analyse each power plant individually and considering all the factors.

Chapter 4

Regulatory aspects of Hybrid Renewable Energy Systems

4.1 Introduction

Hybrid Renewable Energy Systems are quite new when referring to utility scale projects, this makes that regulation is not prepared for this new kind of power plants. In this chapter some of the regulatory aspects that prevent or could prevent hybrid power plants deployment are going to be analysed.

4.2 Electricity market regulation

Right now the Spanish regulation defines in the Procedimiento de Operación 3.1 (P.O. 3.1) (Operation Procedure 3.1) [18] what are a *Unidad de Programación* (Schedule Unit) (UP) and a *Unidad Física* (Physical Unit) (UF).

"A schedule unit is the elemental unit of representation for all the different energy programs defined in this Operation Procedure. The schedule unit allows the integration, in the spanish peninsular market, of the different programs of sell or acquisition of energy corresponding to an individual installation, which would be defined as a physical unit, or to a set of them according to the criteria defined in Annex II of this procedure". So, following this definition, in order to be able to participate in the market in Spain, a power plant should be included in a schedule unit otherwise it would not be allow to sell the energy produced.

In the Annex II of the procedure, in the first point *Unidad de programación para la entrega de energía* (Schedule unit for the delivery of energy) in the section *Unidades de generación pertenecientes a instalaciones o agrupaciones de instalaciones renovables (salvo UGHs), de cogeneración y de residuos, de potencia neta superior a 1 MW* (Generation units belonging to a installation or group of renewable installations (except UGHs), cogeneration and wastes, with net power greater than 1 MW) is said that *"Generally, for electric energy production installations that use renewable energy as primary energy source (except UGHs), cogeneration installations and installations that use wastes as primary energy source, and their net power or sum of net powers is greater than 1 MW, it would constitute a single schedule unit for the delivery of energy, for each market agent and type of production UP, "..."In this way, each market agent would have, generally, as maximum, as much units as types of production defined integrate his generation portfolio, in such a way that each schedule unit integrates in the generation market a single kind of production type. Each schedule unit would be composed by one or more physical units with the same type of production than the schedule unit"*.

The section *Unidades de generación pertenecientes a instalaciones renovables (salvo UGHs), de cogeneración y de residuos de potencia neta menor o igual a 1 MW* (Generation units belonging to a renewable installation (except UGHs), cogeneration and wastes, with net power lower or equal than 1 MW) contains the same of what have been said in the previous paragraph, but it changes the last sentences saying *"Each schedule unit would be composed by a single physical unit that would gather all the installations with net power lower or equal than 1 MW of the same production type and market agent"*.

With this current legislation as the two or more technologies participating in the same hybrid renewable energy plant are different physical units, they would belong to different schedule units; this means that it would not be allowed that the production of a hybrid renewable energy plant would be sold as unique, not having to differentiate how much energy has been produce with one technology and how much with the other technology. This may seem as little problem and that would not be a huge inconvenient for the development of HRES, but as it has been explained in section 2.2.1, if the research achieves to develop an inverter that is able to convert the energy coming from the PV power plant and from the wind power plant, it could be difficult to differentiate the amount of energy that is being injected from each of the technologies. If a hybrid renewable energy plant is set today, the different technologies would have to belong to different schedule units as the production type would be different for both technologies, this would mean that also the operation of the plant would be more difficult as also the bids into the market would be differentiated.

4.3 Access and connection to the grid

As it has been said during this Master's Thesis, HRES is a new topic, that is right now under discussion in the electric power systems, therefore there are some regulation currently being drafted that affect HRES. This is the case of the new Circular for Access and Connection to the Transport and Distribution Grid. This circular is written by the Comisión Nacional de los Mercados y la Competencia (CNMC), as it is indicated in the Royal Decree 1/2019 [19] article 3, *"is a function of the CNMC to establish the methodology used to calculate the conditions for the connection and access to the gas and electricity grid"*. The circular, is pending of approval, and right now is in allegation fase. In this circular, in the article 6 about the application for access and connection permits, in the point 3 f), says that it should be submitted a draft of the project where it is included the identification of the production installation, including the technology and the power installed for which the permits are asked for. In this case what is understood by technology is the different kind of production categories defined in the Royal Decree Real Decreto 413/2014 article 3 [20]. As in this Royal Decree is not defined any kind of hybrid plant, it could be supposed that it will not be allow to ask for access and connection to the grid for a hybrid plant at itself.

In the same circular of the CNMC, in the article 3 Definitions, there is a definition of what is called *Potencia Complementaria* (Complementary Power). The definition is the following: *"Additionally to the maximum installed power in a specific point, the system operator could consider to give grid access to a certain additional complementary power that could only access to the grid if the maximum installed power coinciding in the connection point have their grid access completely fulfilled"*. This definition does not refer directly to HRES, as it could be referring only to overpowerment, but in article 11 of the same circular, in the point 2 it says *"As a particular case, the complementary power could be associated to a different technology of the one that got access to the grid previously in the same location. The complementary power would have to get the corresponding access and connection permits"*. This latter point in the article 11, leaves the door open to the installation of HRES, the main problem is that with the definition of complementary power provided in this same circular, the promoter could not decided how to operate the power plant as he wishes, as the rest of power plants connected to the same point have to have full access to the grid for their production in that moment, if after all the power plants having access to the grid there is still some capacity remaining the complementary power could access the grid and evacuate the power produced. This could be an obstacle in the development of HRES as the promoter would have troubles to identify when its complementary power would be allowed to produce, and therefore, how and when is he going to recover his investment.

4.4 Conclusions

As it has been mentioned in this chapter, the fact that the hybrid power plant would not be able to sell the energy in the market as an unique power plant could make more difficult the operation of this hybrid power plants.

The new Circular for Access and Connection to the Transport and Distribution Grid is considering to enhance grid usage by allowing power plants to installed an extra capacity. The main problem with this extra capacity is that its production depends on the other power plants connected to the node to be able to produce, therefore the promoter is assuming a high uncertainty. The fact that the CNMC is thinking about increasing the usage of the already constructed grid, opens the door for the deployment of Hybrid Renewable Energy Systems.

Chapter 5

Conclusions and future working lines

5.1 Introduction

In this chapter a summary of the Master's Thesis is done. Also, the main conclusions of the study are presented. Moreover, some future working lines that could be developed from this study are provided.

5.2 Abstract

Renewable Energy Source power plants are increasingly part of the energy mix in most of the countries. The main problem of these power plants is that they produce electricity when the resource is available, which limits the level of use these power plants are giving to the connection to grid infrastructure. Within this scenario, Hybrid Renewable Energy Systems could be a solution to enhance this low usage of the grid. Hybrid Renewable Energy Systems are the combination of two or more Renewable Energy Source power plants that produce electricity to inject it to the grid while sharing a connection to grid infrastructure. Hence, sharing the grid the usage of it increases. The main problem of sharing that infrastructure is that there would be hours where production of both power plants could exceed the grid connection capacity.

This Master's Thesis studies the profitability of developing certain of the aforementioned hybrid power plants. In order to assess the profitability of hybrid power plants, several key factors have been analysed, such as the complementarity of the production profiles of both technologies that comprise the hybrid power plant, the amount of energy that would be curtailed due to the capacity limit and the share on the increase in the grid usage. Besides, with the input of this analysis, an optimization problem has been built to compute the optimal capacity of the new production technology to be installed, in order to achieve the maximum net present value of the investment to be done.

This study allows to draw several conclusions. Hybridization allows to increase grid usage without having to curtail a high amount of energy. It is profitable to make hybridization in the power plants studied, but this profitability differs depending on each specific power plant. There are many factors that affect the profitability of hybrid power plants, such as the complementarity between the production profiles or the capacity factor of the technologies forming the hybrid power plant, so each hybrid power plant should be analysed individually.

5.3 Conclusions

This study allows to draw several conclusions.

For the two types of hybrid power plants studied, PV wind hybrid power plants and hydro PV power plants, hybridization allows to increase grid usage without having to curtail a high amount of energy, this is mainly to the high complementarity of profiles and the low use that wind and hydro power plants are doing of the grid. It is profitable to make hybridization in the power plants studied, but this profitability differs depending on each specific power plant. There are many factors that affect the profitability of hybrid power plants, such as the complementarity between the production profiles or the capacity factor of the technologies composing the hybrid power plant, so each hybrid power plant should be analysed individually.

In case of the overpowerment it is demonstrated that, as the complementarity between the already installed power plant and the extra capacity is null, the curtailed of energy is higher than in the case of the hybrid power plant. Furthermore, it is also demonstrated that even if the curtailed of energy is high, the fact that the wind power plant has a high capacity factor allows it to achieve grid usage levels similar to the ones obtained in the hybrid power plant.

The regulatory aspects studied, shows that there is concern about the low utilization of the grid made by renewable power plants. This could mean that in the future Hybrid Renewable Energy Systems could play an important role in increasing grid usage.

5.4 Future working lines

With this Master's Thesis as an starting point, there could be further improvements to be done to the models realized, as well as new working lines. Some of this improvements and future working lines are the following.

- The wind PV hybrid model could be improved in order to study the profitability of the battery to sell energy in balancing markets, which profits are usually higher than the day ahead market.
- It could be studied which could be studied which could be the profitability of installing a completely new hybrid renewable energy plant, that could also optimize the capacity of the grid to be constructed.
- The PV hydro hybrid power plant model developed could be adapted, so that the hydro power plant reduces its production in the hours where the combined production of both power plants exceeds the grid capacity, storing that water thanks to the dam. For doing this, it should be taken into account some constraints imposed by the hydrological confederations, as that the amount of water released every day or every week should remain the same. This would allow to have a hybrid power plant that does not have curtailed energy, and therefore, the profitability of the project and the grid usage would increase.
- For the hybridization with hydro power plants it could be interesting to develop models for analysing the performance and operation of hybrid projects with already existing storage hydropower plants or pumped-storage hydropower plants. This would allow to store the curtailed energy increasing the already constructed grid usage.

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[19] Real Decreto-ley 1/2019, de 11 de enero, de medidas urgentes para adecuar las competencias de la Comisin Nacional de los Mercados y la Competencia a las exigencias derivadas del derecho comunitario en relacin a las Directivas 2009/72/CE y 2009/73/CE del Parlamento Europeo y del Consejo, de 13 de julio de 2009, sobre normas comunes para el mercado interior de la electricidad y del gas natural.

[20] Real Decreto 413/2014, de 6 de junio, por el que se regula la actividad de produccin de energa elctrica a partir de fuentes de energa renovables, cogeneracin y residuos.

Annex A

Results from the hybridization of wind and photovoltaic

A.1 Dispersion of wind and PV production

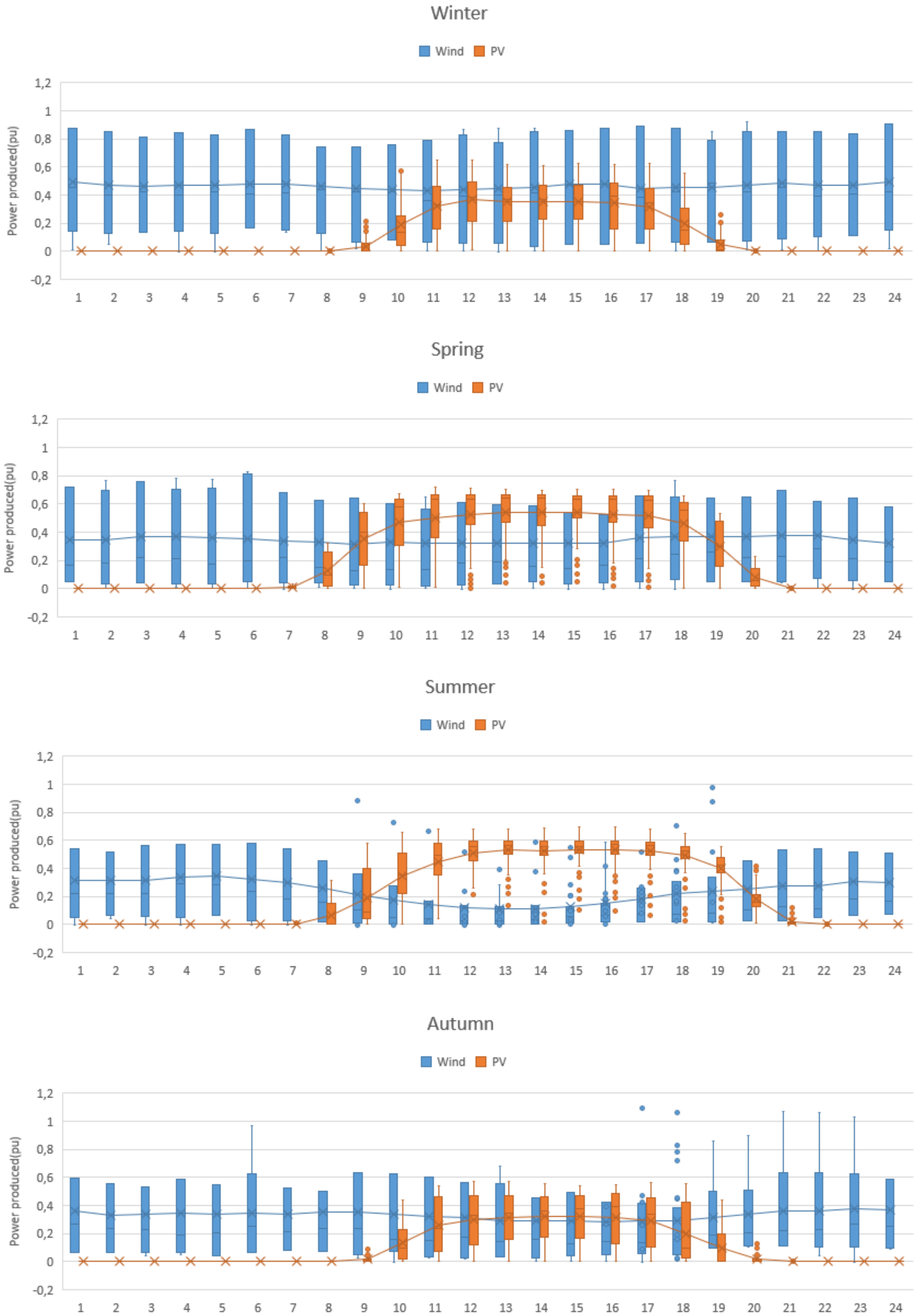

Figure A.1: Dispersion of wind and PV production in each season and during each hour of the day for the wind power plant located in Castilla la Mancha.

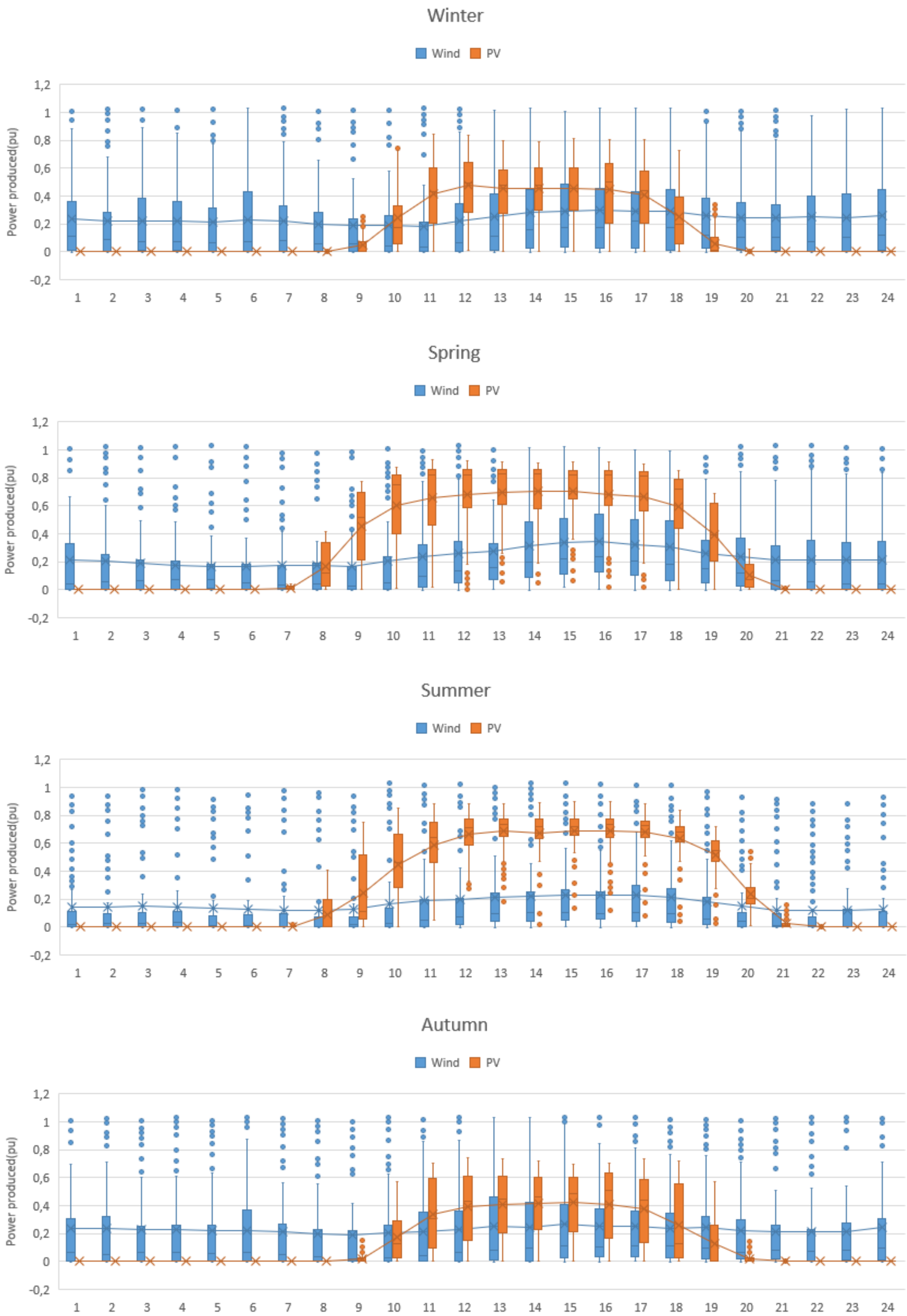

Figure A.2: Dispersion of wind and PV production in each season and during each hour of the day for wind the power plant located in Andalucía I.

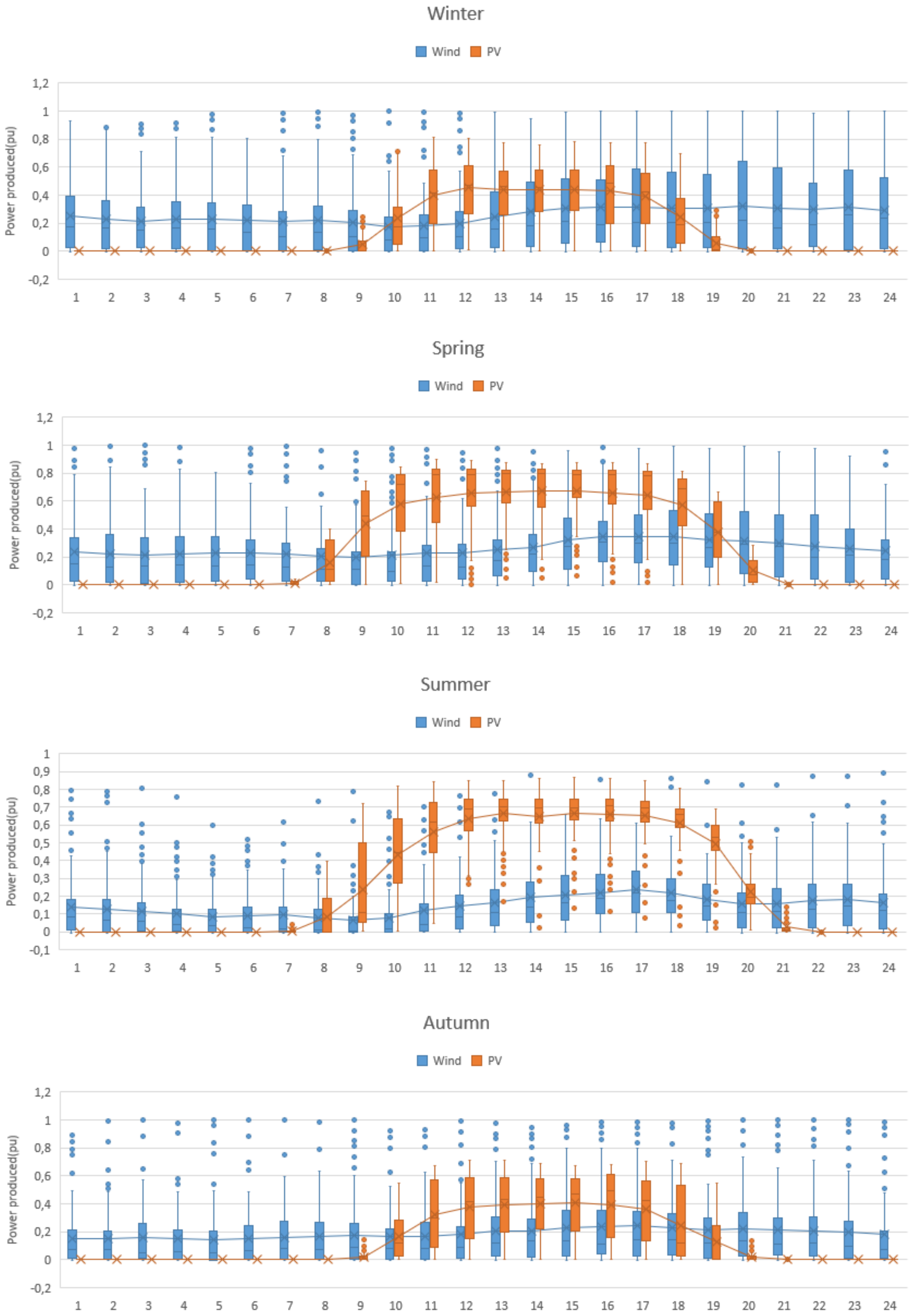

Figure A.3: Dispersion of wind and PV production in each season and during each hour of the day for the wind power plant located in Andalucía II.

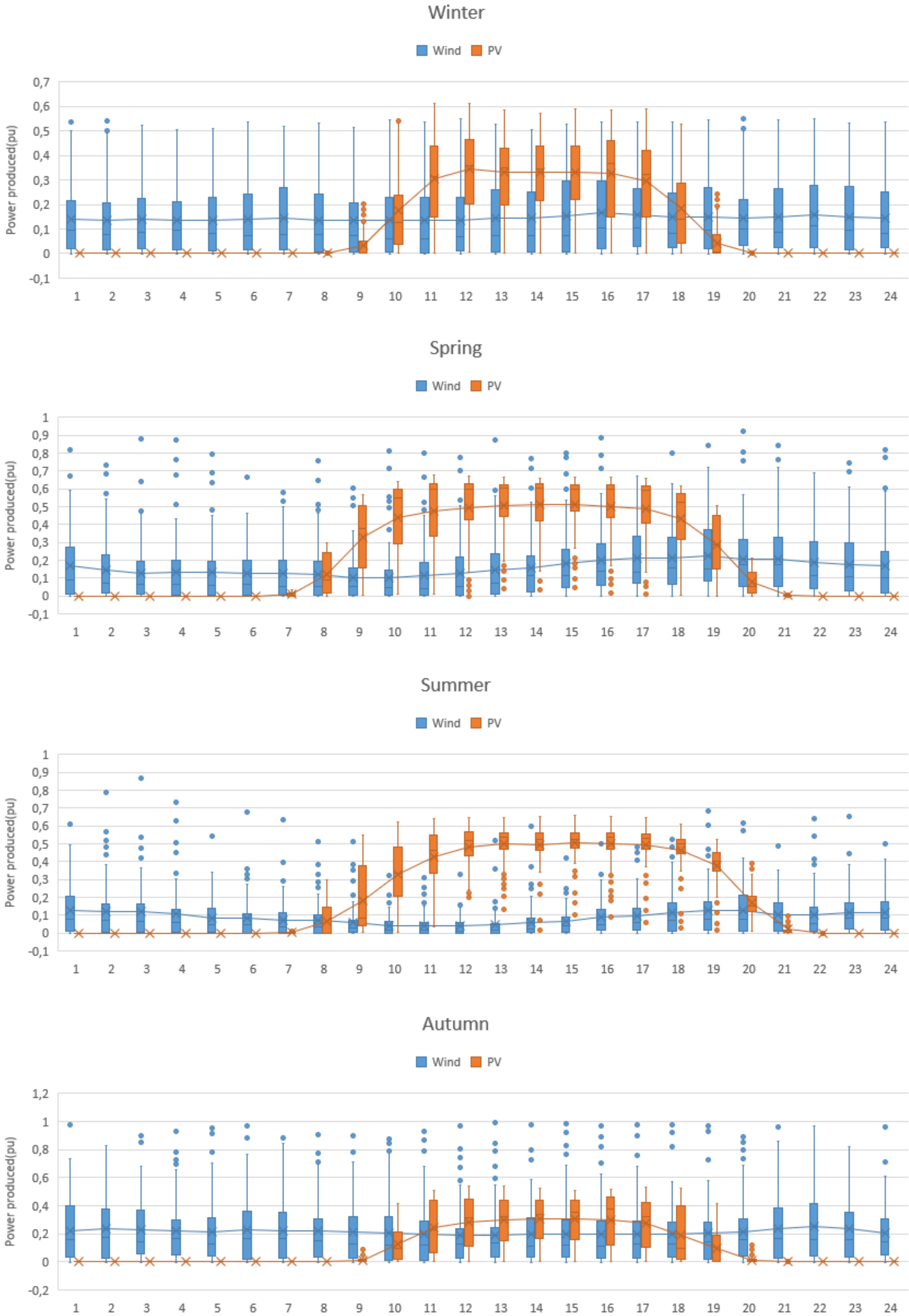

Figure A.4: Dispersion of wind and PV production in each season and during each hour of the day for the wind power plant located in Castilla y León I.

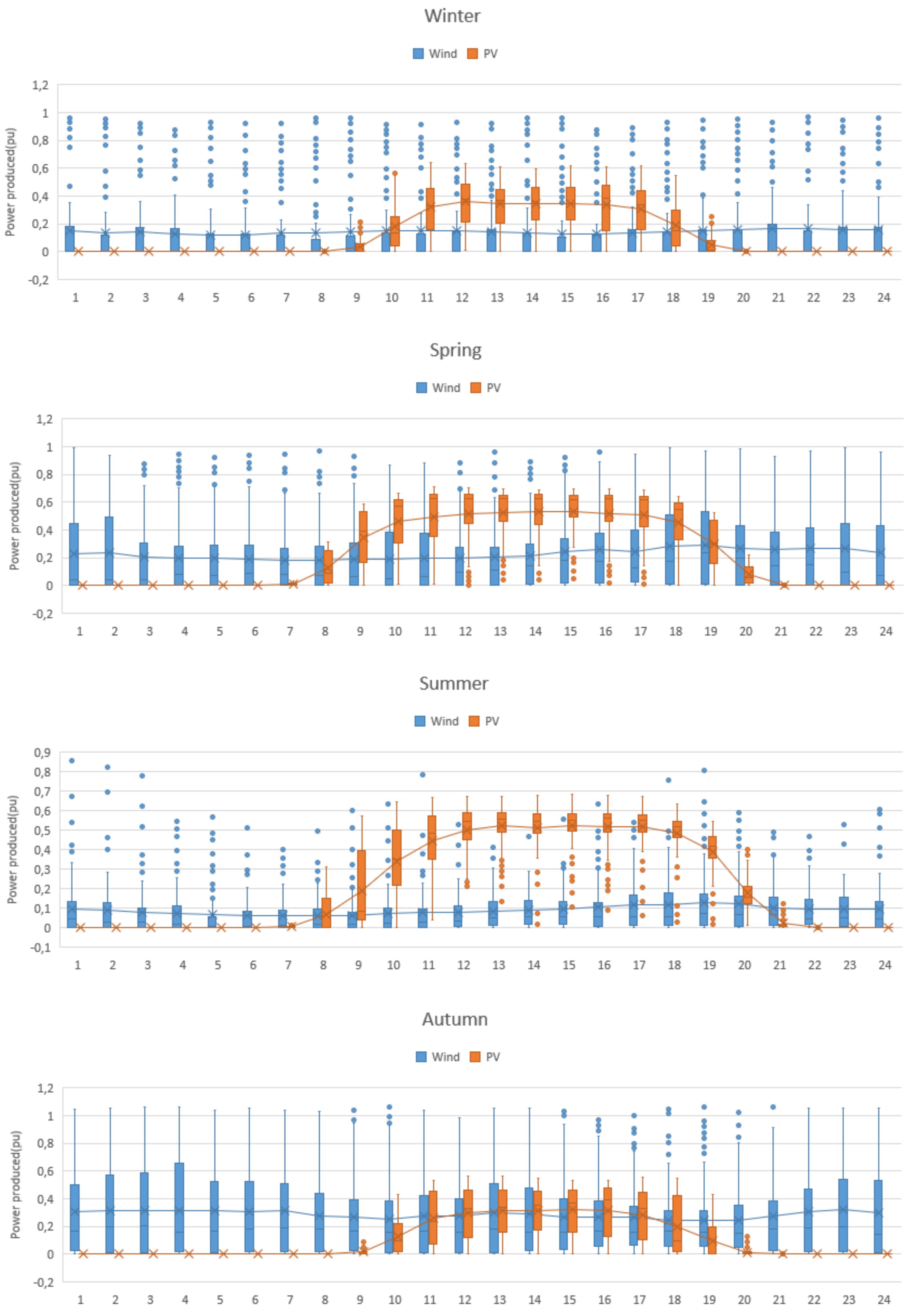

Figure A.5: Dispersion of wind and PV production in each season and during each hour of the day for the wind power plant located in Castilla y León II.

A.2 PV equivalent hours

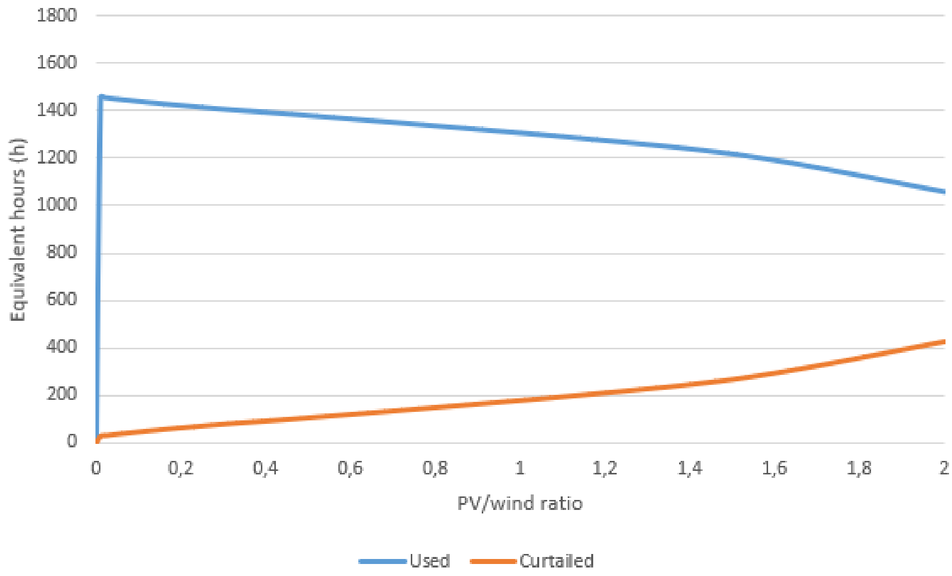

Figure A.6: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind for the wind power plant located in Castilla la Mancha.

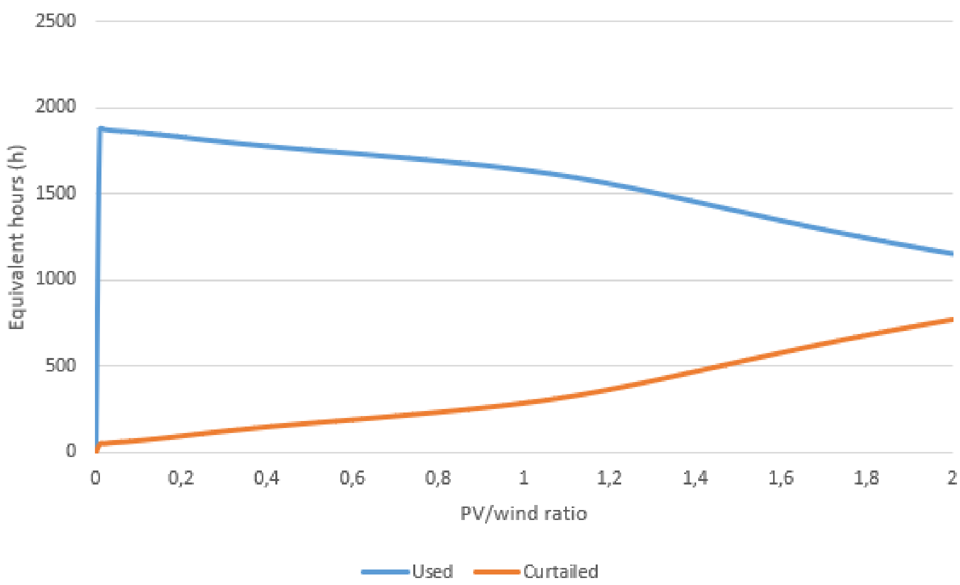

Figure A.7: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind for the wind power plant located in Andalucía I.

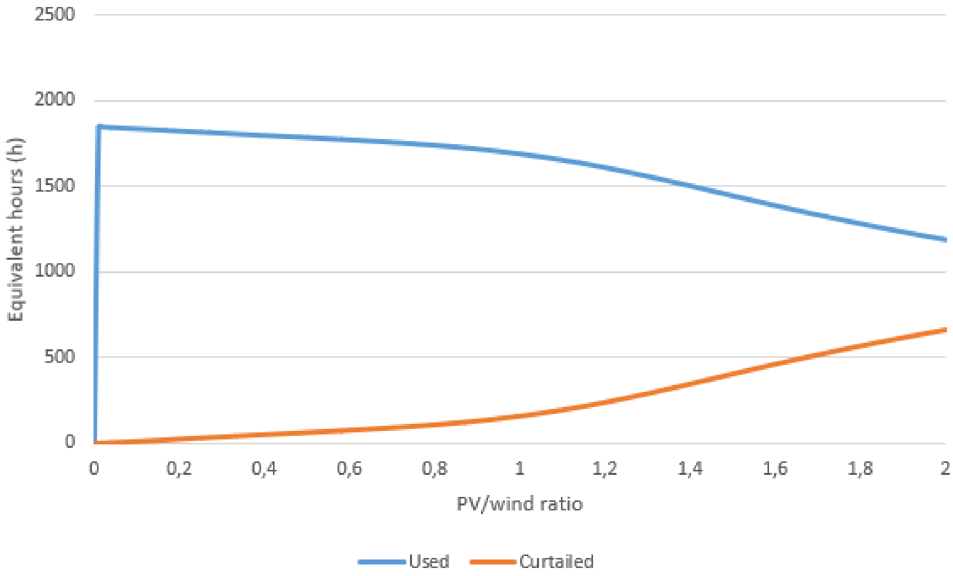

Figure A.8: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind for the wind power plant located in Andalucía II.

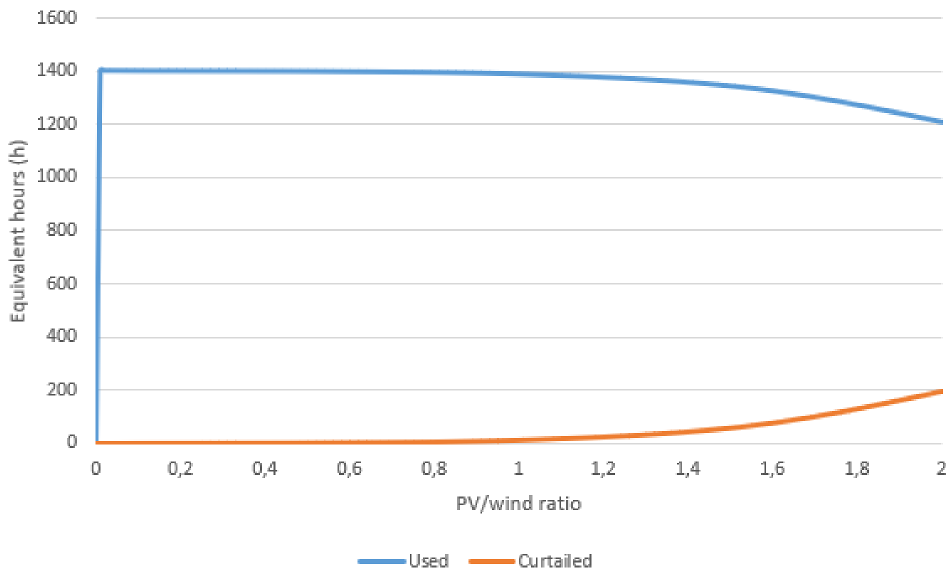

Figure A.9: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind for the wind power plant located in Castilla y León I.

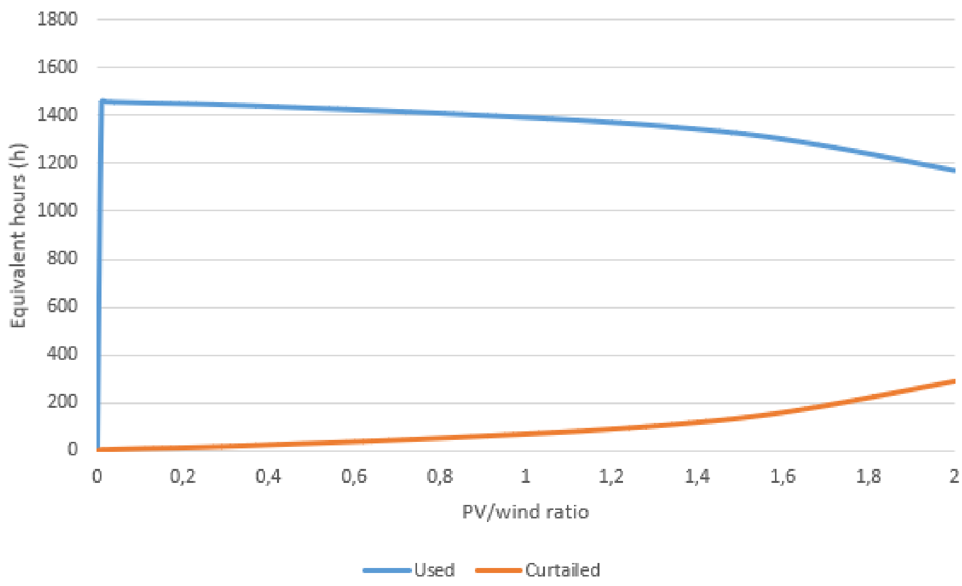

Figure A.10: PV equivalent hours of energy used and curtailed depending on the ratio PV/wind for the wind power plant located in Castilla y León II.

A.3 Percentage of curtailed energy

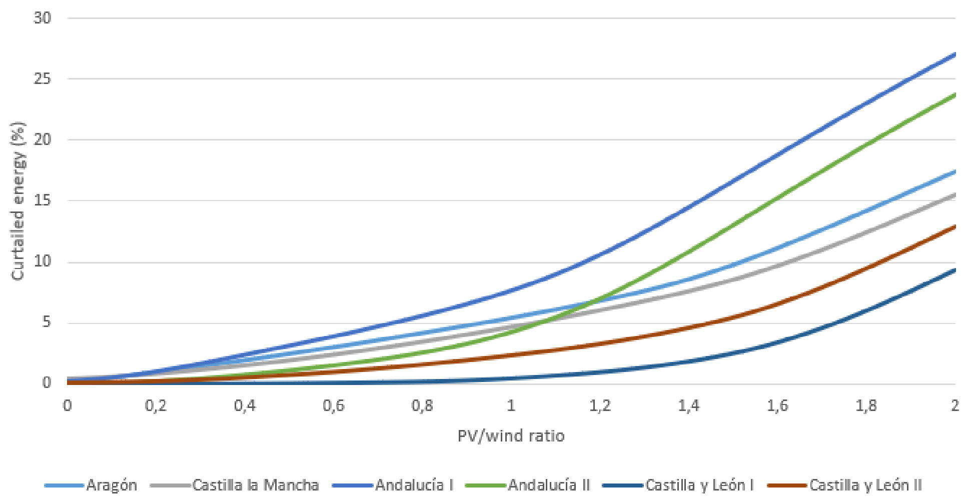

Figure A.11: Percentage of curtailed energy depending on the ratio PV/wind for all the wind power plants.

A.4 Percentage of grid usage

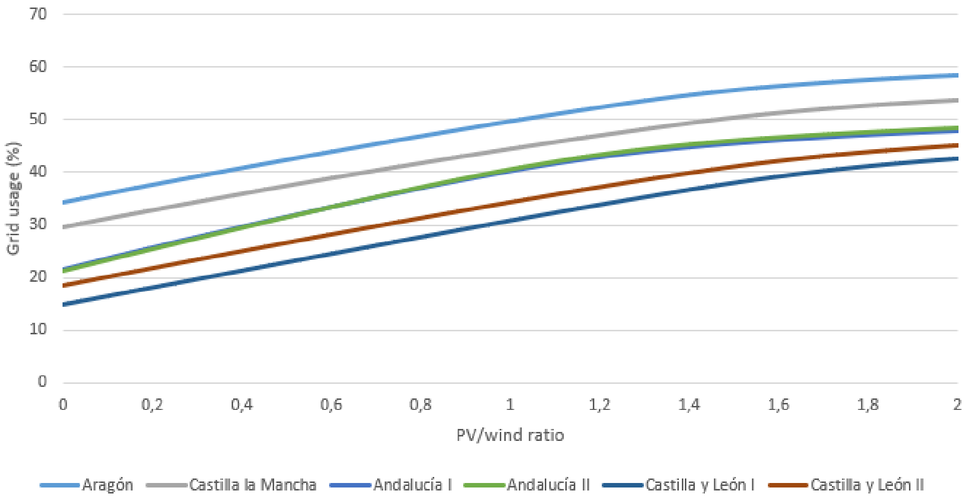

Figure A.12: Percentage of grid usage depending on the ratio PV/wind for all the wind power plants.

A.5 Results from the overpowerment of wind power plants

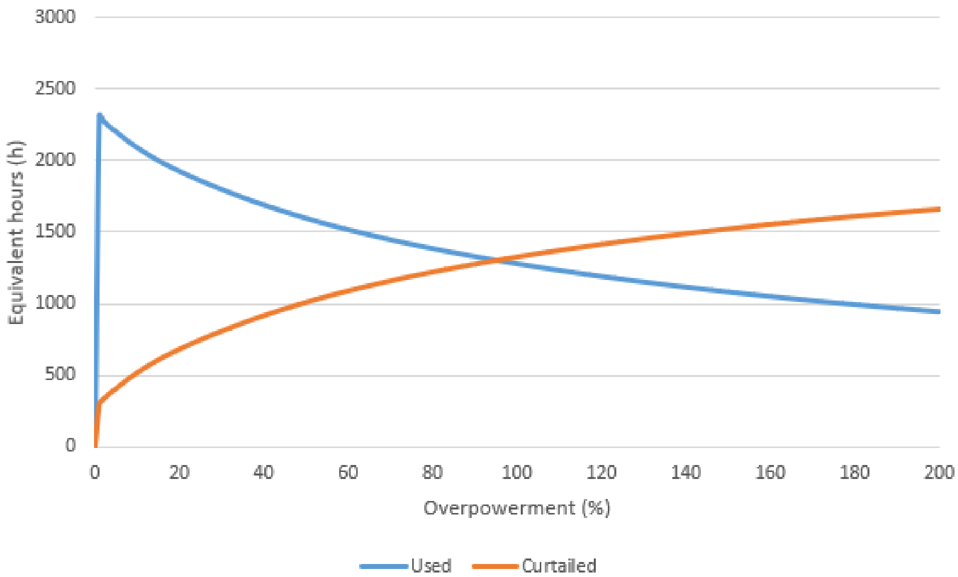

Figure A.13: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment for the wind power plant located in Castilla la Mancha.

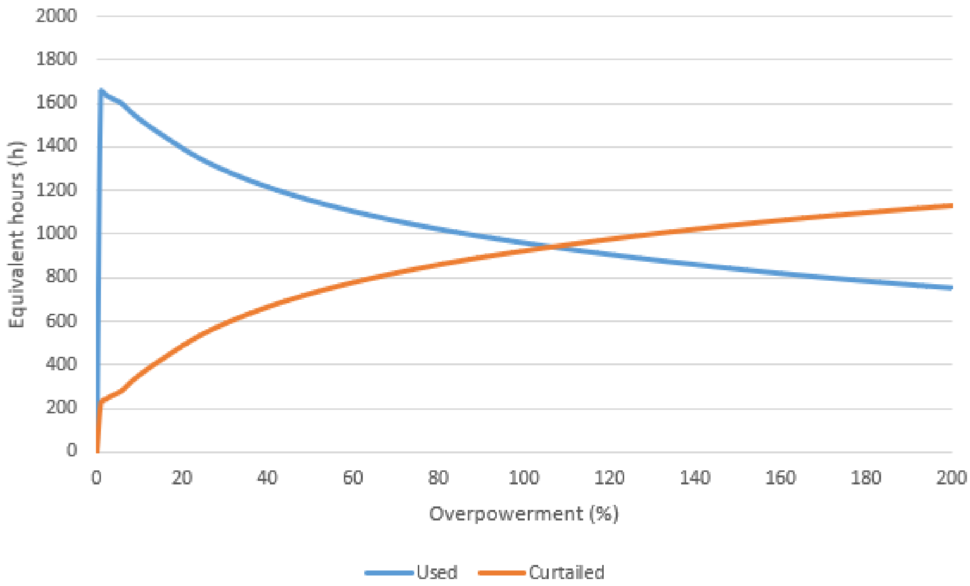

Figure A.14: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment for the wind power plant located in Andalucía I.

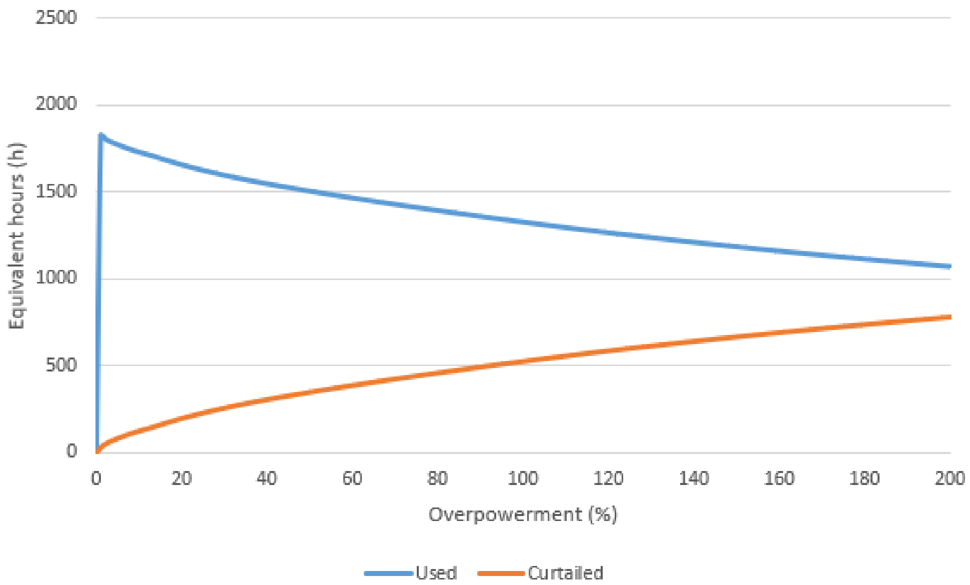

Figure A.15: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment for the wind power plant located in Andalucía II.

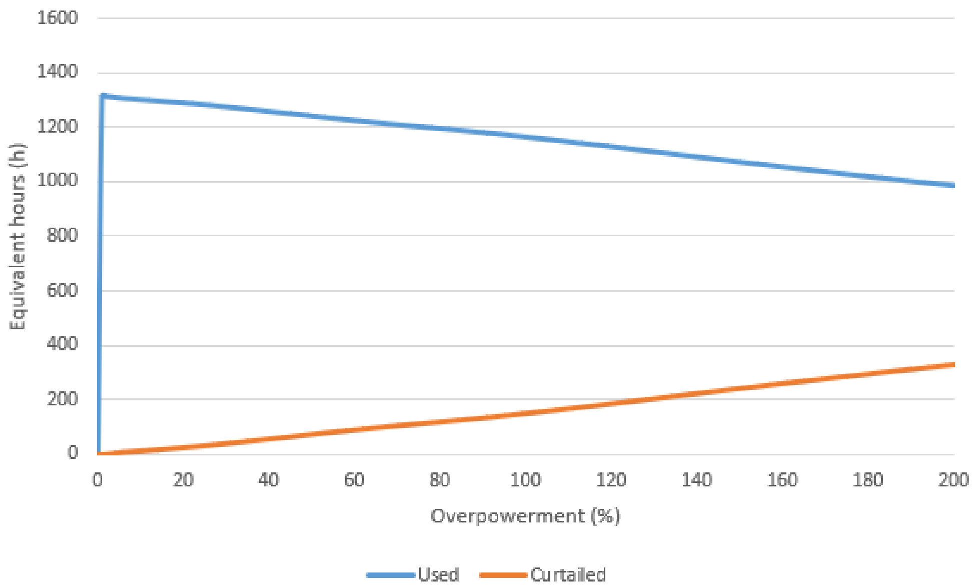

Figure A.16: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment for the wind power plant located in Castilla y León I.

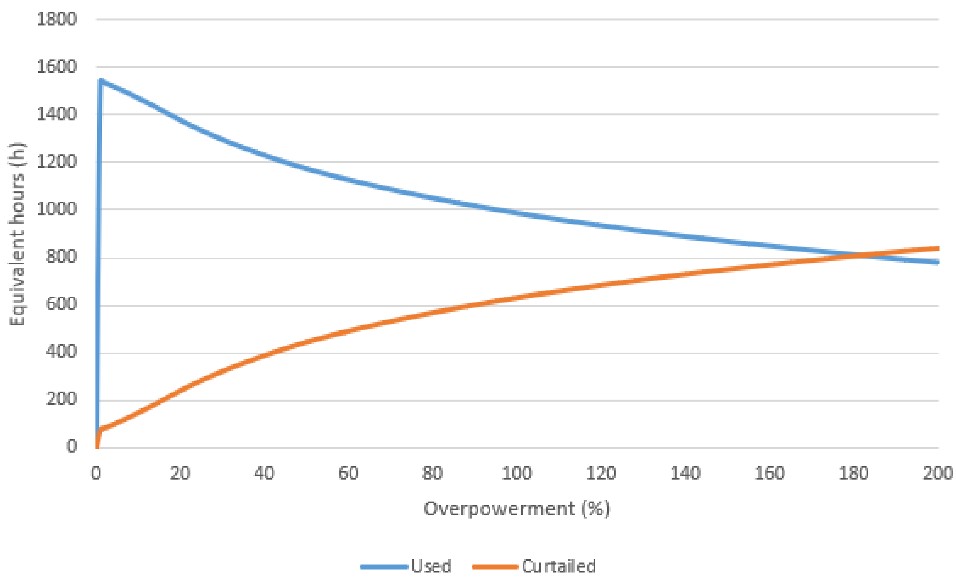

Figure A.17: Extra wind capacity equivalent hours of energy used and curtailed depending on the percentage of overpowerment for the wind power plant located in Castilla y León II.

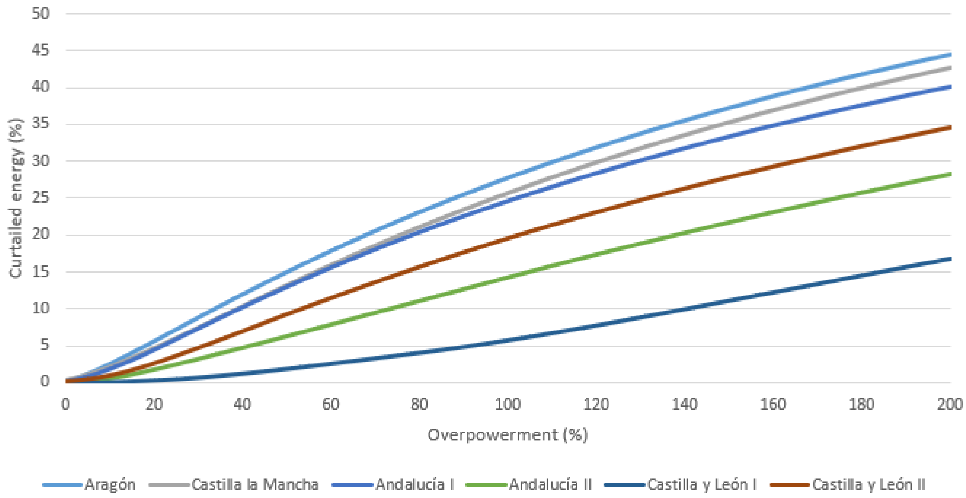

Figure A.18: Percentage of curtailed energy depending on the percentage of overpowerment for all the wind power plants.

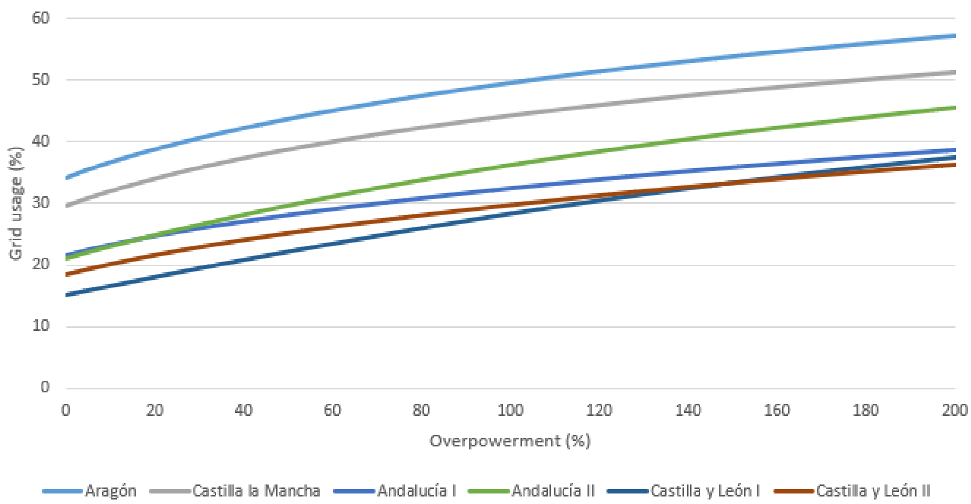

Figure A.19: Percentage of grid usage depending on the percentage of overpowerment for all the wind power plants.

Annex B

Results from the hybridization of hydro and photovoltaic

B.1 Dispersion of wind and PV production

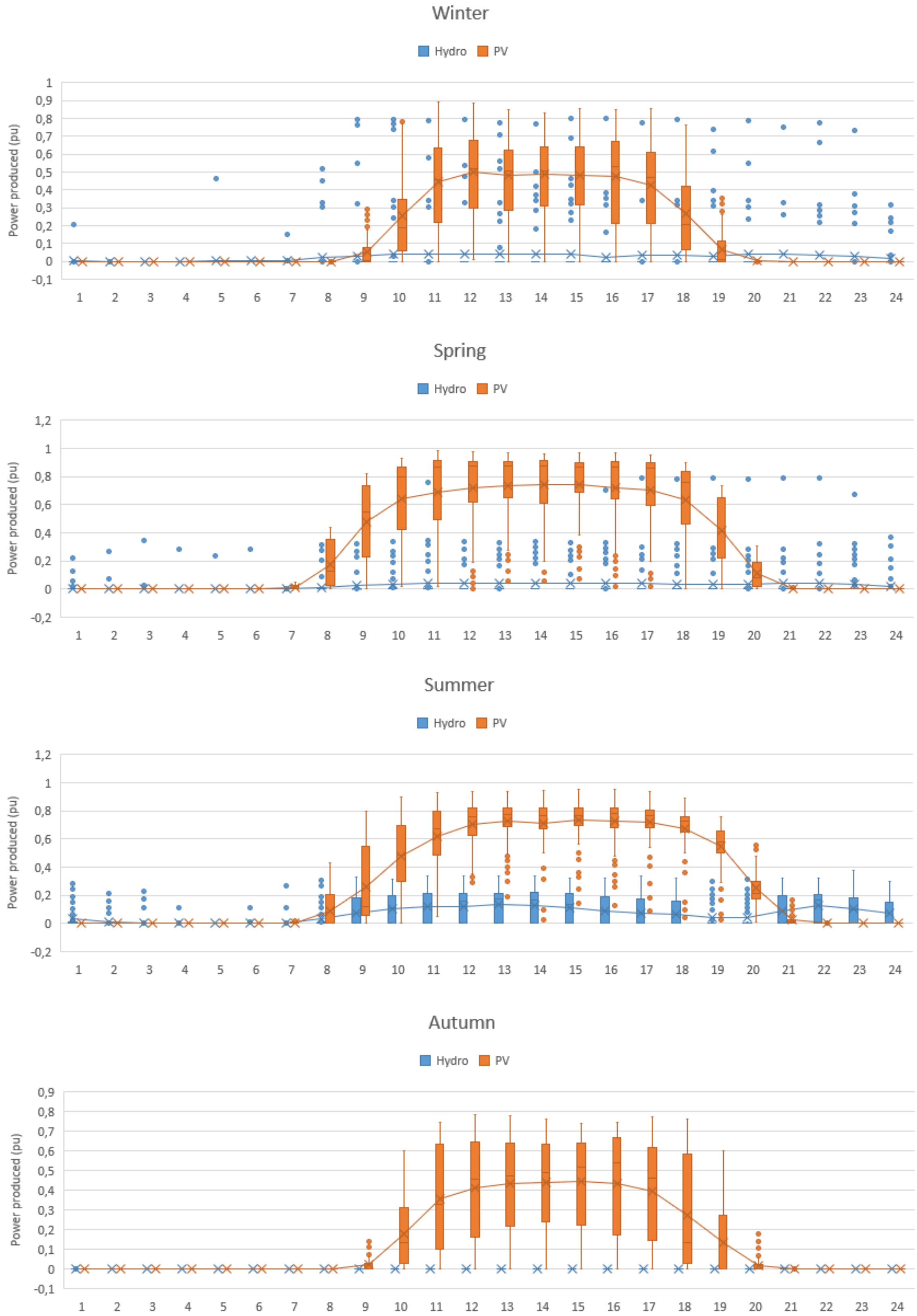

Figure B.1: Dispersion of hydro and PV production in each season and during each hour of the day for the HYDRO I power plant.

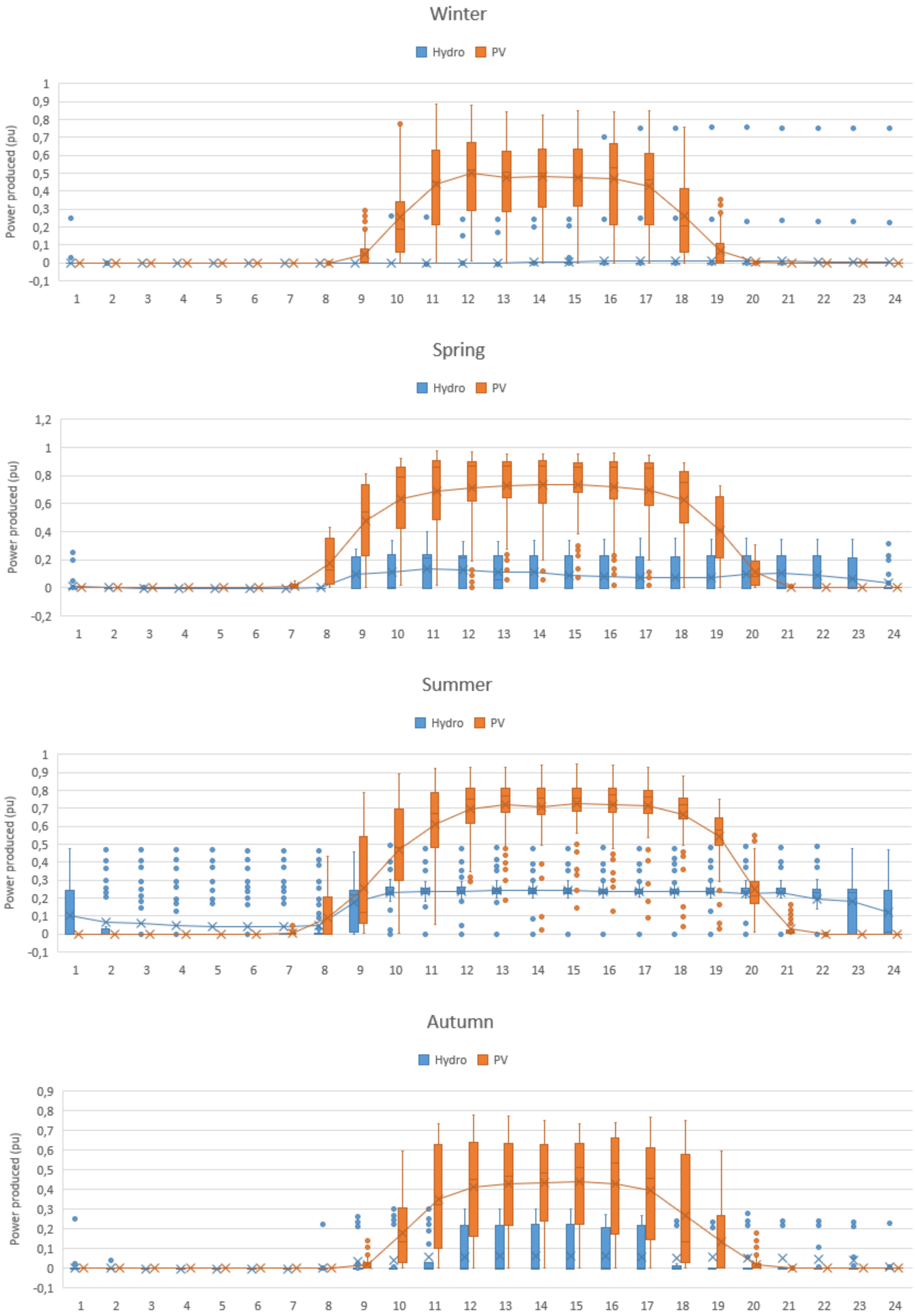

Figure B.2: Dispersion of hydro and PV production in each season and during each hour of the day for the HYDRO II power plant.

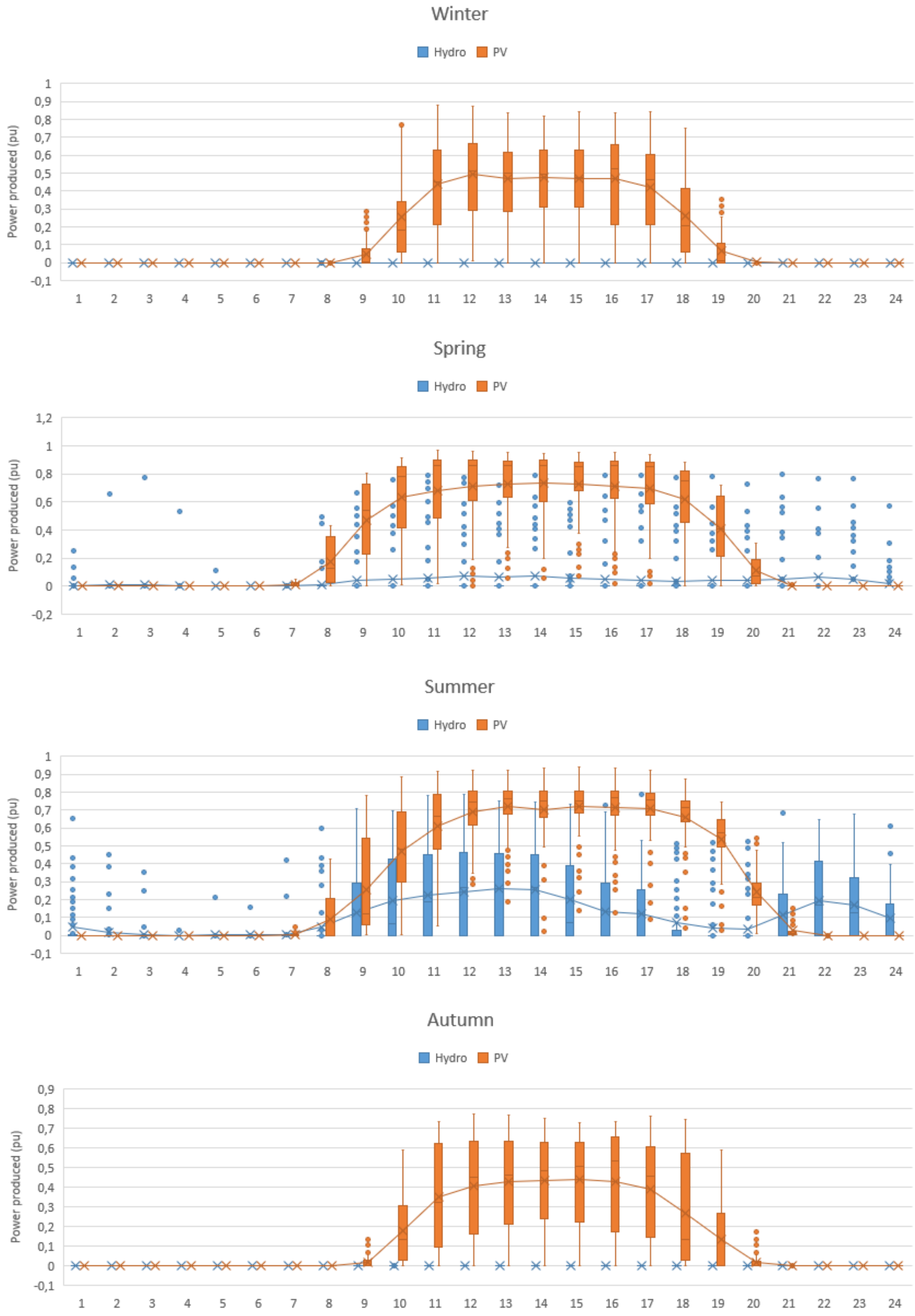

Figure B.3: Dispersion of hydro and PV production in each season and during each hour of the day for the HYDRO IV power plant.

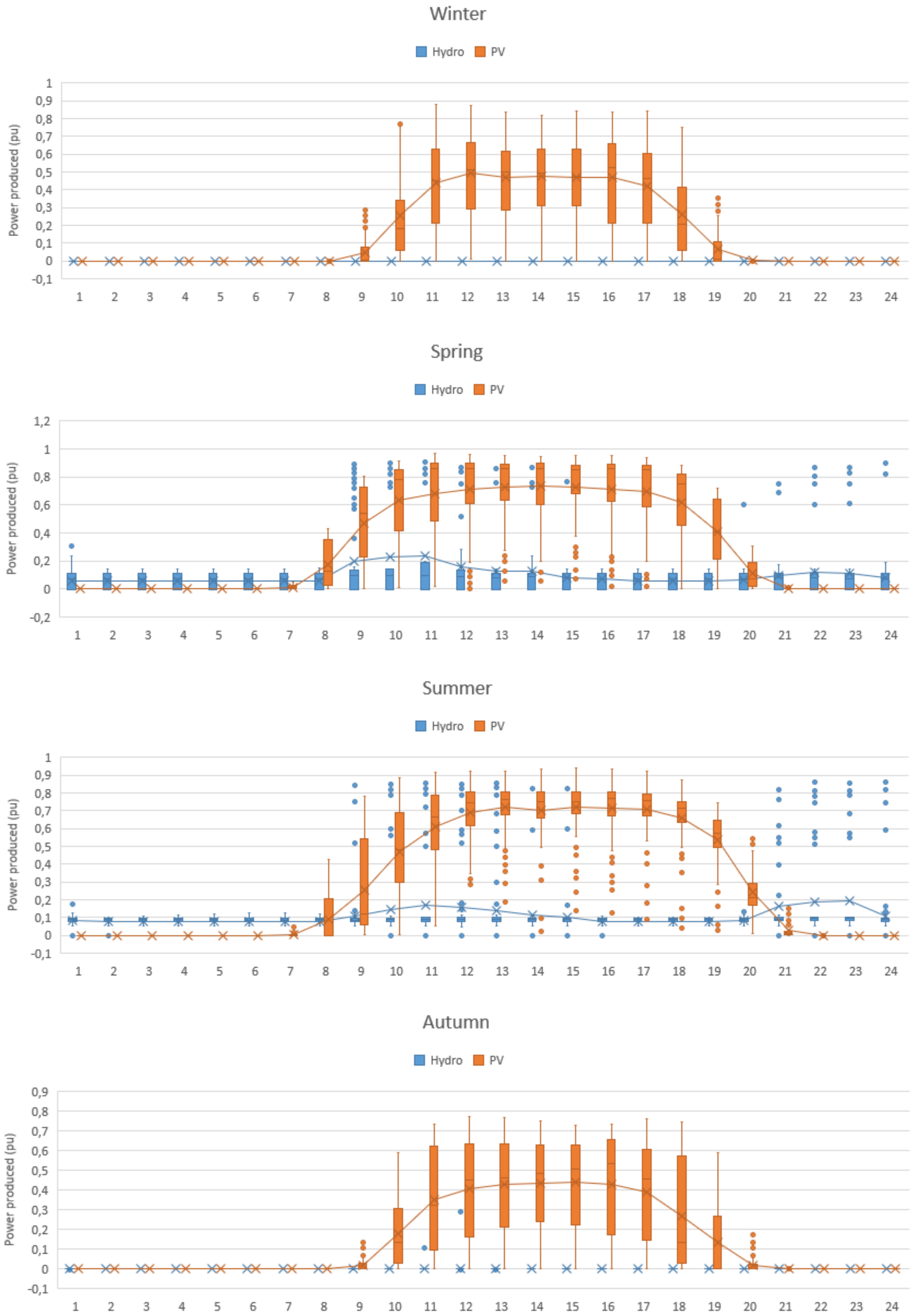

Figure B.4: Dispersion of hydro and PV production in each season and during each hour of the day for the HYDRO V power plant.

B.2 PV equivalent hours

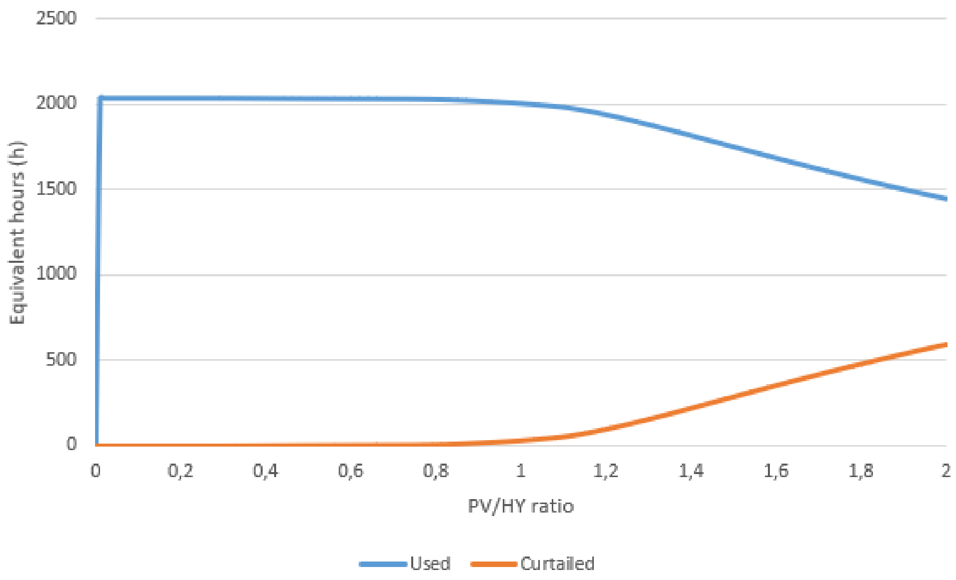

Figure B.5: PV equivalent hours of energy used and curtailed depending on the ratio PV/HY for the HYDRO I power plant.

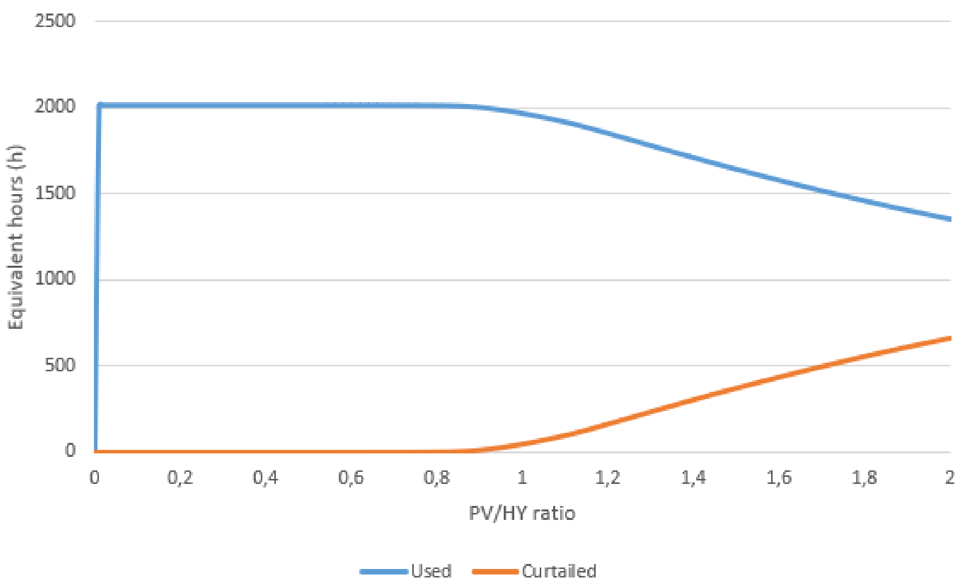

Figure B.6: PV equivalent hours of energy used and curtailed depending on the ratio PV/HY for the HYDRO II power plant.

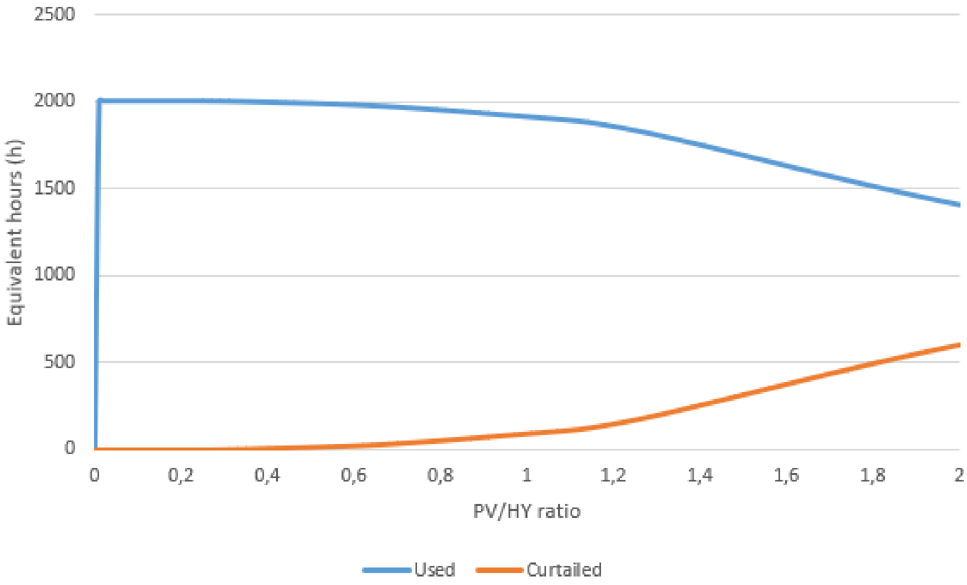

Figure B.7: PV equivalent hours of energy used and curtailed depending on the ratio PV/HY for the HYDRO IV power plant.

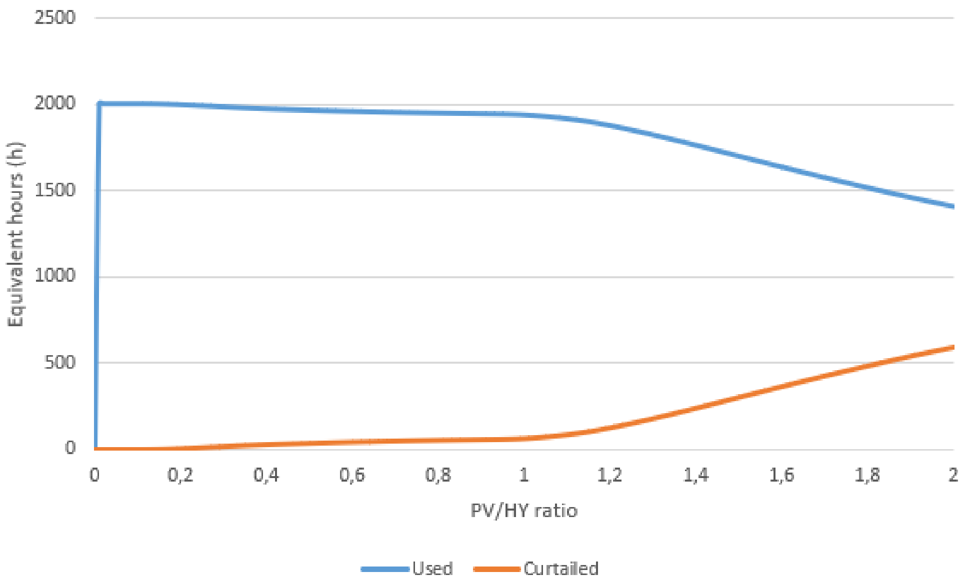

Figure B.8: PV equivalent hours of energy used and curtailed depending on the ratio PV/HY for the HYDRO V power plant.

B.3 Percentage of curtailed energy

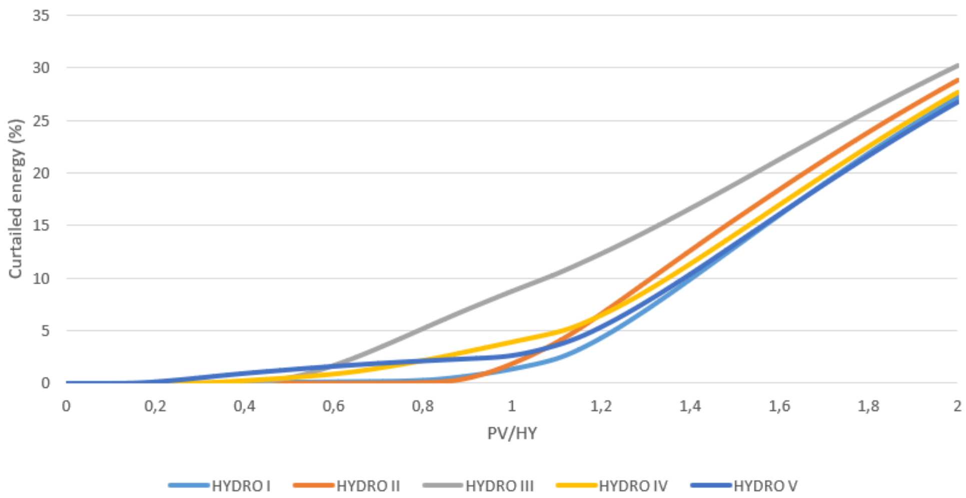

Figure B.9: Percentage of curtailed energy depending on the ratio PV/HY for all the hydro power plants.

B.4 Percentage of grid usage

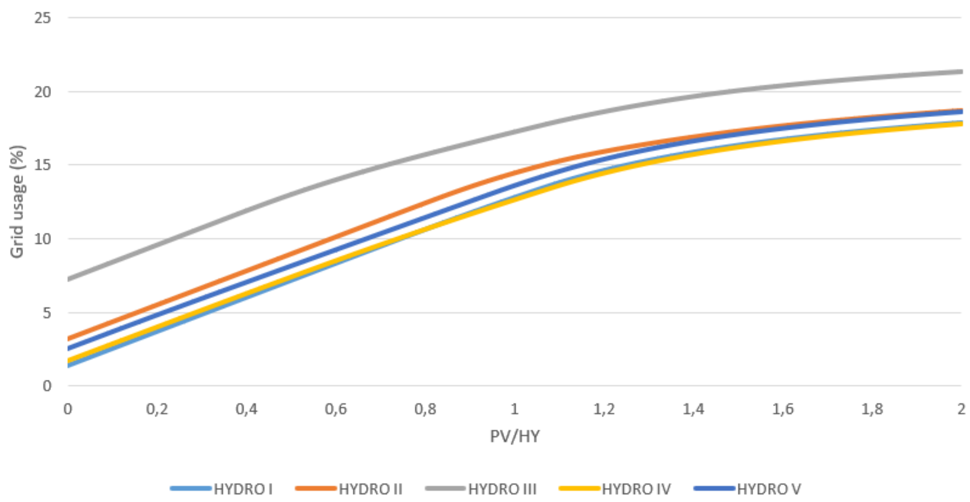

Figure B.10: Percentage of grid usage depending on the ratio PV/HY for all the hydro power plants.