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Decision-Making Under Uncertainty for Market Bidding Strategies of Wind and Photovoltaic Technologies

Renata Filipa Morais Martins

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Orientador: Doutor João Paulo da Silva Catalão
Coorientador: Doutor Agustin Alejandro Sánchez de la Nieta López

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Resumo

O sector de energia elétrica tem vindo a sofrer alterações ao longo dos últimos anos devido a pressões ambientais e económicas. As alterações climáticas levaram à criação do Protocolo

de Quioto de modo a controlar os problemas ambientais. Uma das soluções encontradas para estes problemas depara-se com a introdução de produção renovavel na produção de energia eléctrica. As Energias renovaveis não só contribuem para os objectivos ambientais como também apresentam-se como uma oportunidade de reduzir as pressões económicas que os países tem enfrentado no que respeita à dependencia dos combustíveis fosseis. No entanto, existem

desafios com a introdução de energias renováveis na produção elétrica, nomeadamente com a introdução tecnologias como o vento e a fotovoltaica. Este tipo de tecnologia são caracterizadas como energia de produção variável por serem fortemente dependentes das condições climatéricas podem ter impactes negativos quando integrados no mercado de energia elétrica, uma vez que a producção deste tipo de renováveis traz muitas vezes incerteza para o mercado, desencorajando a sua utilização. Contudo, se a produção apartide de fonted renováveis for bem sucedida, melhores modelos de decisão serão necessários para permitir, ao investidor, um maior grau de confiança necessária à promoção do uso destas tecnologias. Nesta dissertação

serão apresentadas duas estratégias de oferta ao mercado diário. Ambas as tecnologias oferecem a produção a partir do vento e da fotovoltaica com o objectivo de chegar a uma mais benéfica oferta de mercado.

Palavras-chave

Mercado de eletricidade; Tomada de decisão; Programação estocástica, Fontes de energias renovaveis; estratégias de oferta ao mercado.

Abstract

The electrical energy sector has been changing over the past years due to economical and environmental pressures. The climate change paradigm has led to the creation of the Kyoto Protocol

in order to address these environmental concerns. The appointed solution to address these concerns is the production of electrical energy through renewable energy sources (RES). The RES

not only contribute to these environmental goals, but also are an opportunity to reduce the economic pressures that countries face due to fossil fuel dependence. However, it is important to

address the challenges that come with adopting RES as a mean of energy production. Variable RES such as wind and solar production, are strongly dependent on weather conditions, could have negative impacts on market structures. The production from these types of sources can bring significant uncertainty to electricity markets, further discouraging their use. If the energy production from RES such as wind and solar is to succeed, better decision models are needed, in order to provide the investors the degree of confidence necessary to further promote the use of these technologies. In this dissertation two bidding strategies in the Day-Ahead market are

presented. Both strategies offer the production from wind and photovoltaic technologies. In this work, the objective is to achieve a more profitable market offer for the holder of these technologies.

Keywords

Electricity market; Decision-making; Stochastic Programming; Renewable energy sources; Bidding strategies.

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Relevant Acronyms

CO	Combined Offer
DAM	Day-ahead Market
DO	Different offers
ERSE	Empresa Reguladora dos Sistemas Energéticos
EU	European union
IEM	Internal Electricity Market
IPP	Independent Power Producers
Mibel	Mercado Iberico de Energia Electrica
MO	Market operater
Mtoe	Million tonnes of oil equivalent $(1Mtoe = 11,63TWh)$
NWP	Numerical Weather prediction
OMIE	Operador del Mercado Ibérico de Energia - Polo Espanhol
OMIP	Operador de Mercado Ibérico Português
PV	Photovoltaic Technology
REE	Red Eléctrica de Espanã
REN	Rede Energéticas Nacionais
RES	Renewable energy sources
VIC	Vertical integrated companies

List of Symbols

A. Sets

n	Index referring to the number of photovoltaic panels.
t	Index referring to a period [hour].
w	Index referring to a scenario.

B. Parameters

c^{PV}	Photovoltaic marginal cost [€/MWh].
c^{W}	Wind marginal cost [€/MWh].
$g^{PV}_{t,w}$	Power produced by the photovoltaic park in period *t* and scenario *w* [MW].
$g^{W}_{t,w}$	Power produced by the wind park in period *t* and scenario *w* [MW].
$\lambda_{t,w}$	Day-ahead market price in period *t* and scenario *w* [€/MWh].
$\lambda^{+}_{t,w}$	Positive imbalance market price in period *t* and scenario *w* [€/MWh].
$\lambda^{-}_{t,w}$	Negative imbalance market price in period *t* and scenario *w* [€/MWh].
P_{Max}	Maximum installed power capacity of the combination of photovoltaic and wind parks [MW].
P^{PV}_{Max}	Maximum installed power capacity of the combination of photovoltaic and wind parks [MW].
P^{W}_{Max}	Maximum installed power capacity of the combination of photovoltaic and wind parks [MW].
$prob_w$	Probability of each scenario w.

C. Continuous Variables

b_t	Power offer in the day-ahead market associated to the photovoltaic and wind park in period *t* [MW].
b_t^{PV}	Power offer in the day-ahead market associated to the photovoltaic park in period *t* [MW].
b_t^{W}	Power offer in the day-ahead market associated to the wind park in period *t* [MW].
$\Delta_{t,w}$	Imbalance between actual photovoltaic and wind production and offer in period *t* and scenario *w* [MW].
$\Delta_{t,w}^{+}$	Positive imbalance between actual photovoltaic and wind production and offer in period *t* and scenario *w* [MW].
$\Delta_{t,w}^{-}$	Negative imbalance between actual photovoltaic and wind production and offer in period *t* and scenario *w* [MW].
$\Delta PV_{t,w}$	Imbalance between actual photovoltaic production and offer in period *t* and scenario *w* [MW].
$\Delta PV_{t,w}^{+}$	Positive imbalance between actual photovoltaic production and offer in period *t* and scenario *w* [MW].
$\Delta PV_{t,w}^{-}$	Negative imbalance between actual photovoltaic production and offer in period *t* and scenario *w* [MW].
$\Delta W_{t,w}$	Imbalance between actual wind production and offer in period *t* and scenario *w* [MW].
$\Delta W_{t,w}^{+}$	Positive imbalance between actual wind production and offer in period *t* and scenario *w* [MW].
$\Delta W_{t,w}^{-}$	Negative imbalance between actual wind production and offer in period *t* and scenario *w* [MW].
PF	Profit of sales energy in the day-ahead market [€].
PF_W	Profit of sales wind energy in the day-ahead market [€].
PF_{PV}	Profit of sales photovoltaic energy in the day-ahead market [€].

D. Binary Variables

$j_{t,w}$	0/1 variable, that is equal to 1 if the imbalance in period *t* is negative, otherwise it is 0 for a positive imbalance.
$j_{t,w}^{PV}$	0/1 variable, that is equal to 1 if the photovoltaic imbalance in period *t* is negative, otherwise it is 0 for a positive imbalance.
$j_{t,w}^{W}$	0/1 variable, that is equal to 1 if the wind imbalance in period *t* is negative, otherwise it is 0 for a positive imbalance.

Chapter 1

Introduction

The world industrialization and population growth has contributed to the increase of electrical energy consumption over the past years, especially in emergent countries. This rapid electrical demand growth, contributed to the increase of greenhouse gas emissions due to the use of fossil fuel as a means of energy production. In order to maintain the sustainability and prevent further damages from the greenhouse gas emissions, an agreement was created, the Kyoto Protocol. This international protocol supported by several countries, envisioned the reduction of greenhouse gases and the increase of energy efficiency. This protocol was active until December 2012, but its principles were continued with the DOHA amendment.

The European Union (EU) started addressing this climate change issue. Therefore, an European directive has rose, being widely known as the "20-20-20" Directive [1], which has the objectives of promoting the increase of renewable energy and energy efficiency. Therefore, the overall goals of this directive can be summarized as follows:

- Reduction in 20% of EU greenhouse gas emissions;
- Increase in 20% of EU energy share of renewable energy resources;
- Improve 20% of EU energy efficiency.

This challenge made renewable energy sources (RES) a strong candidate to fit the European Directive policy. The RES would play a key role in the reduction of fossil fuel dependence by contributing in the process to the reduction of greenhouse gas emissions. This presented itself as a good opportunity to improve the energy efficiency in countries that are highly dependent on fossil fuels.

For a country like Portugal, the RES can significantly improve the country economic situation, since this country is highly dependent on fossil fuels. Depicted in the Figure 1.1 is Portugal status regarding the renewable energy production. One can note that, regarding the energy balance the production from RES in 2011 was 22%. On the other hand, Spain has lower levels of RES penetration when compared to Portugal, with a share of renewable generation of 12%. However, Spain is not so dependent on fossil fuels, since it rely on nuclear energy production. The Portuguese government did not follow this course of action leaving the current option of focusing on the investments in RES.

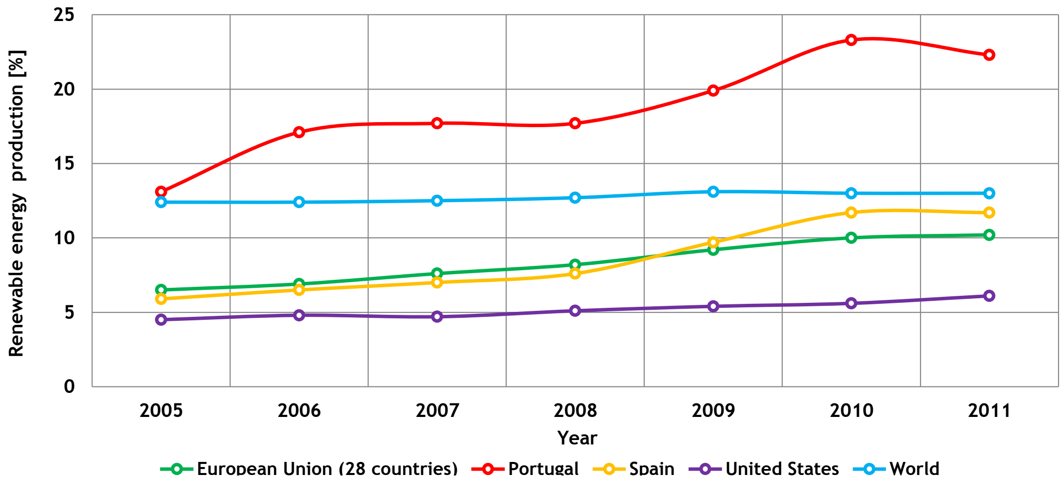


Figure 1.1 – Evolution of renewable energy production.

Countries like Portugal, due to its geographical location [2], have a great opportunity to effectively exploit favorable weather conditions facing the current economical crisis. The RES could contribute to the energy efficiency of this country, since it could reduce on this country high rates of fuel importations.

According to [3], the wind energy production in Portugal has been increasing as it is observable in Figure 1.2. In 2013, the installed capacity was approximately 45 000 MW. If weather conditions were favorable to produce the maximum installed capacity, it would be enough to satisfy 80% of total energy consumption in the country in this year REN. Moreover, it is evident the relation between CO_2 emissions reduction and installed capacity of wind and photovoltaic capacity. The certain is that emissions have been lowering at the same time of increased installed capacity of both renewable technologies. It means that Portugal is on its way to meet the european goals to 2020.

Despite of the increase penetration of RES in past years, the RES still require a considerable cost of initial investment. The uncertain production and the low incentive policies present itself as a setback to attract possible investors. The appointed solution is the development of a market framework that makes the RES more competitive against fossil fuels.

1.1 Background

It is important the integration of RES in order to accomplish the European environmental and efficiency goals. It is expected in 2020, according to [4], that an expected 90 MToe, approximately 1048 TWh, of RES share make a contribution of 36 % of the Europe energy balance. In Figure 1.3 the current and the target energy share is presented.

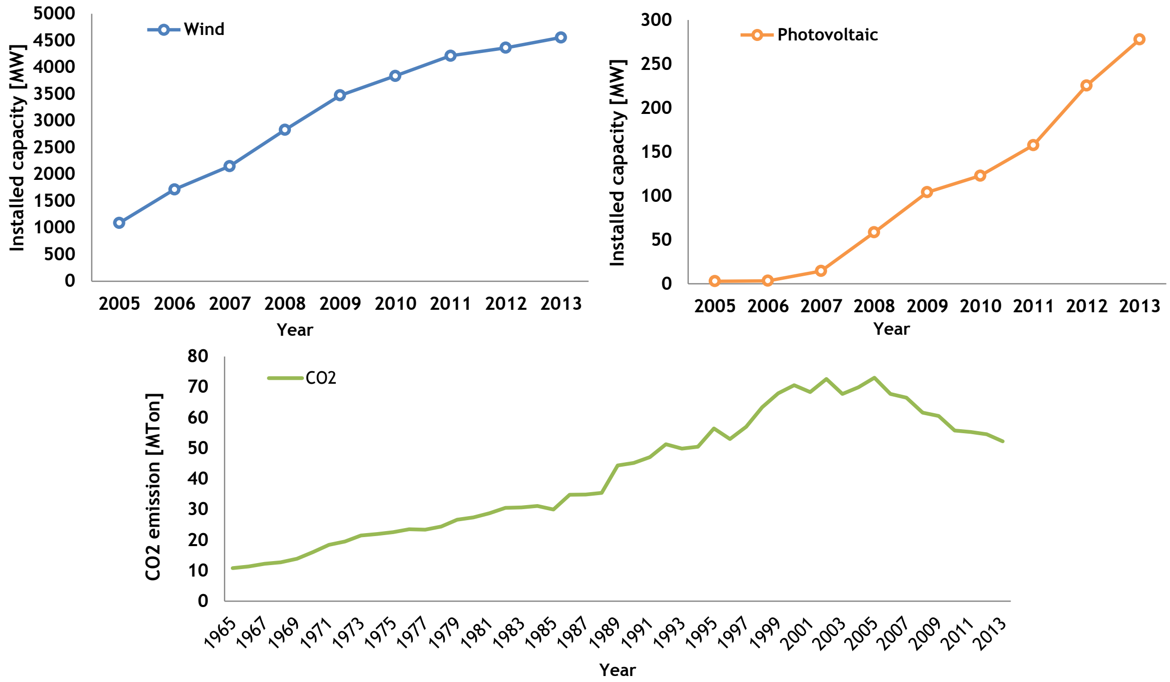


Figure 1.2 – Wind and photovoltaic installed capacity of Portugal over the years

It is noticed in the Figure 1.3 that wind power production projections for 2020. Of all the RES, wind has the most ambitious goal. It is expected by 2020, the integration of RES such as wind and solar will have a 30 % contribution to electricity sector in the order of 38 Mtoe (442 TWh). Comparing these projections to the last year of the available data (2012), this represents an increase of 209 TWh [4].

The use of RES such as solar and wind, bring several uncertainties with respect to the production side. For instance, RES such as solar and wind production are highly dependent on weather conditions, in which it is considerable non-dispachtable energy production. Thus, it becomes a challenge in integrating these technologies in the electrical system due to its unpredictability.

Additionally, this aggravates in the electricity market. Another problem is with the price of energy because renewable have almost zero price of production but otherwise has an higher cost of initial investment that made the price higher than fossil fuel energy. Therefore, the goal is to bring the RES closer and more competitive to the generation of energy through fossil fuels, by lowering its selling price, increasing the profit from the investor, by reducing the payback period.

One way to make the RES more competitive, is selling in liberalized market structure. However, the variable production can be challenging in settling the production price. Several resources have been explored in order to predict the market price and also the RES production.

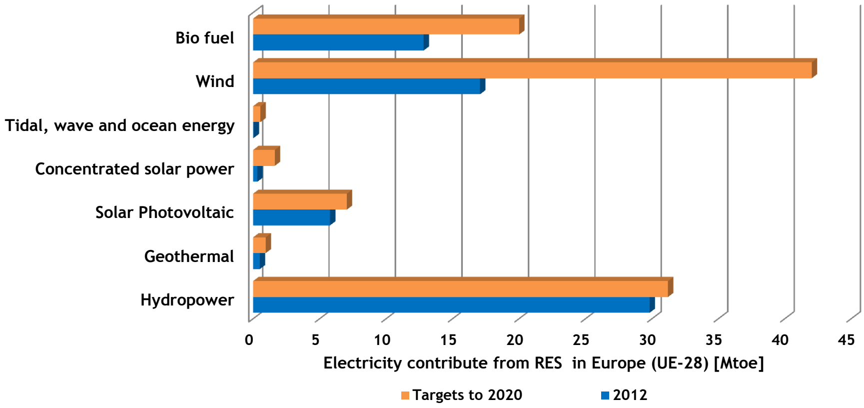


Figure 1.3 – Distribution of different RES technologies for Europe

1.2 Motivation and Objectives

In order to fulfill the efficiency goals, the RES need a robust electricity market, in order to make them more competitive against the traditional way of energy production through fossil fuel. However, the challenges of integrating RES cannot be neglected. It is expected that RES such as wind and photovoltaic production will increase in a near future. Although these types of RES have several setbacks mainly due to its variable production output that could be catastrophic in the electricity markets.

Therefore, there is a need to address this concern by designing better market integration strategies that prevents the consequences from the variable production. This can be achieved by developing prediction techniques which aids the bidding of these technologies in the electricity markets. Moreover, it could aid to attract more investors in the use of RES, reducing the risk associated and increase the revenue. This ultimately leads to an increase of market competitiveness and in the process, the lowering of the electricity prices.

Although market prices are characterize by higher level of volatility, making market less predictable in studying its behavior. A good market price prediction as well as RES production is essential on determine the optimal offer to the market, increasing the profit of participants.

The main goal of this dissertation aim to make use of decision-making under uncertainty to bid into electricity market. Bidding variable energy is a as well as the participant profit decrease in level of uncertainty.

The contribution of this work is to propose a bidding offer strategy in the Iberian Electricity Market, by maximizing the revenue from a holder of a RES production. The objective is to consider the two types of variable RES (wind and solar) into offering strategies in order to determine the best possible offer. Moreover, it is the purpose of this dissertation to study the possible outcomes between the two offering strategies. A strategy that consists in offering these technologies as a single independent offer; A strategy that combines both productions and make a single combined offer.

1.3 Dissertation Structure

This dissertation is divided into 6 chapters. The current chapter, **Chapter 1** , started by introducing the research question and the contribution that this work aims to provide in addressing the problem of integrating variable RES in electricity markets. The following chapters are structure as follows:

In **Chapter 2** an overview about the evolution of the electrical sector is presented. It is explained the restructuring of the electric systems in Europe, explaining the liberalization of the European Electricity market. At the end of this chapter, the working principles of the Iberian Electricity Market (MIBEL) are presented, highlighting the Day-Ahead Market.

In **Chapter 3** the importance of the decision-making process is presented. It starts by addressing the production prediction techniques that are required to aid in the integration of RES in electricity markets. It is also explored in this chapter, the importance of different possible outcome scenarios in the decision-making process. At the end of this chapter, a literature survey regarding the market bidding strategies of RES is presented.

In **Chapter 4** the mathematical formulation is presented. It starts by explaining the wind and photovoltaic model, presenting the objective function and the considered constraints. Moreover, it is presented the bidding strategies used in this work (Single offer and Combined offer)

In **Chapter 5** the obtained results and their discussion is presented.

In **Chapter 6** the final conclusions and the contributions that result from this work are presented. Additionally, the future work possibilities are also presented.

1.4 Summary

In this chapter, a brief introduction of the research work was provided. It started by addressing the research question, presenting afterward the motivation that leads to the development of this dissertation.

The following chapter will address the principles of electricity markets. It starts by explaining the changing process to the liberalized market. The European market structure is presented, stating its challenges with respect to the integration of RES.

Chapter 2

An insight in Electricity Markets

2.1 Introduction

The electrical energy production has been changing over the past years mainly due to the increased consumption and other factors such as environmental, political and economic pressures. The importance of these factors led to a significant restructure of the electrical system all over Europe.

Therefore, this chapter starts by addressing the importance of these factors and their contribution to the restructuring of electrical system. The contributions of adopting an European Liberalized Market are explored, focusing mainly on the Iberian Liberalized Electricity Market (MIBEL).

2.2 The vertical approach

The world industrialization and the increased population growth, have significantly contributed to the changes in the electrical system.

However, this was not the only reason that led to the change of this system. An important historical event shaped this sector, the Second World War. At the end of this period, European electrical systems were significantly damaged and even destroyed. There was a need to rebuild this sector in order to promote the developments of each country after the war.

To facilitate the management of the electrical system the approach focused on creating a structure that envisioned the use of large companies to take full responsibility of the electrical system. This structure was also known as Vertically Integrated Companies (VIC). Basically, these companies were responsible for the Production, Transmission, Distribution of the electrical system [5].

The production was at the top of this structure. The production mainly relied on the use of fossil fuels to produce energy. In this vertical structure, the production is planned and scheduled in order to guarantee that the entire system demand is satisfied, without compromising the system stability.

Additionally, the responsibility for energy deliver to the consumers through Transmission and Distribution systems was also entitled to these companies. Therefore, the VIC had to sustain the costs of production, transmission and distribution.

Being the fully responsible for the electrical system, the VIC companies had several opportunities that could be exploited. This structure allowed these companies the full control of the system even on the price regulation. By this price regulation, it provides the occasion for these companies to grow economically faster. A large scale production, allowed them the reduction of the operation costs. The consumers paid these companies a fixed bill by an electricity price that was stated by these companies. As a consequence, these companies could manage better their productions in order to profit from this fixed pricing scheme.

In this structure, the consumer has no choice regarding the selection of the energy supplier. Moreover, the electrical bill paid by the consumers was not transparent since they do not know the actual costs of production, transmission and distribution [6].

Despite of the electrical system was relatively secure and stable for decades, there is a need to change this structure. The energy supply through the VIC, constitutes a monopoly that can be exploited regarding the prices [6]. The low transparency to the consumers of the real electricity prices raises concerns. Additionally, these VICs are more susceptible to political and economic pressures, that can further compromise the efficiency of this system [7].

Besides the reasons stated before, another important event contributed to the aggravation of this situation. The excessive use of fossil fuels for the electrical energy production brought severe consequences regarding the climate changes. There was a need to reduce the consequences from the use of the fossil fuels by reducing the greenhouse emission gases that contribute to these environmental problems.

This contributed to the rethinking of electrical energy production. The energy production through Renewable Energy Sources (RES) was the appointed path to help achieve these goals. It presented as a new form of energy production that could level the scales in the economic and environmental front.

The use of RES could benefit the countries that rely on the energy production from fossil fuel sources. However, the RES have several challenges that need to be addressed in order for it to succeed. The structure of a vertical electrical system can no longer support these new sources of production. The availability of the RES will increase the number of possible small-scale producers. This will contribute to the change of production from a centralized to a decentralized approach.

Several RES technologies will be available to residential consumers that could have the ability of supplying energy back to the electrical system when it is most needed. Despite of the environmental benefits of electrical energy production from RES, several technical and economic complexities needs to be addressed. In the technical part, the main problem that rises with this introduction is the shift of energy flow. It will cease to be in a single-flow to be a bidirectional flow of energy. This is especially important when designing protection equipment in case of system faults. However, the economic part of the introduction of these RES could be a serious setback. The RES will need to have a robust market structure that can address the market offerings from any producer. Moreover, regulation will need to be deployed in order to prevent further pressures from the VIC. Thus, a market structure will be needed in order to promote the competitiveness of the RES against the production from fossil fuels.

2.3 Market Liberalization

An appointed path to address these concerns is through the liberalization process. This process requires new regulations to abolish the VIC, splitting them in different activities in order to remove their total control. This process, also known as deregulation, intents to reduce the existent regulation in order to facilitate the introduction of a new electricity market that works with private interaction, decentralized trading and investment decisions [5]. However, this diversity into separate companies requires control mechanisms to continuous follow the market in order to guarantee the security and reliability in operation [8].

In order to promote the competitiveness of energy production, a liberalization of the electricity market must occur. This market needs to be liberalized, in order to include several participants (buyers and sellers) to further promote its competitiveness. To achieve this liberalized structure, it needs to rely on three important factors:

- Open access;
- Restructuring;
- Deregulation.

Electricity markets can only be competitive if opened to everyone without discrimination. It is expected with this openness, that electricity can be freely negotiated between each country. Moreover, this point contributes to the lowering of electricity prices due to the large number of participants, making it more competitive.

The second important point stated before is the restructuring. This aims to design new regulations in order to abolish the VICs monopoly, separating them in different activities. By this, their monopoly power is removed and transparency is guaranteed. Moreover, this separation will prevent disloyal competition, by bringing more competitors into the electricity market. However, this separation of companies, requires independent control mechanisms to continuously supervise the market, in order to guarantee its security and reliability [8].

It is the purpose of the deregulation to simplify the market structure. This is accomplished by abolishing the price control that was associated with the VIC and the promotion of decentralized trading and investment decisions [5].

This process can be expensive due to the necessity of separate companies (e.g privatization process). However, the disintegration is benefic to the electricity market system in manner of transparency and increase competiveness, since it removes the VIC price control.

In a liberalized electricity market, the energy production activity is open not only for large scale producers but also for retailers. In production, participants can freely negotiate energy without interference of other companies and regulated system. The trade is done in different basis, depending on type of market. In the European Union section, more detailed Iberian market will be presented.

Regarding transmission and distribution systems, it is expected that these systems will not be liberalized since they are natural monopolies, cannot be competitive in order to serve everyone. Companies responsible for these systems are require to maintain their operation and technical considerations [6].

Therefore, the liberalized electricity market stands on two principles: technical and economical. On the technical side, these markets will have a system operator that is responsible to guarantee the electrical system stability. It ensures the secure trading of energy while maintaining practical considerations (e.g avoid energy congestion in transmission lines).

On the other hand, the market operator is responsible for the harmonization of the prices between the different energy producers. Handling offers and bids while assuring the transparency of the price to further motivate the producers. These two entities (market and system operator) can operate in an individual or in a combined manner [9]. Different approaches have been suggested in order to achieve a liberalized market. The different approaches of electricity market models are :

- Single-buyer model
- Wholesale market model
- Retail market model

The first approach to create competition was the single buyer model. In this model, the producer is able to make contrasts with only one buyer. However, this model had its limitations. The competition was created between producers, leaving no advantages for the final consumers since they were obligated to buy the electrical energy only from unique buyer company.

In order to address the problems of this model, two others were proposed: wholesale market designed for electrical energy producers; retail market designed for energy retailers, resellers. In the next section these models are explored in the context of European Markets.

2.4 The Liberalized European Market

The European Union already started to address these concerns regarding the liberalization of the electricity market. An important Directive [?]tated the purpose of the liberalization and its core principles. These goals stated by, ¤20-20-20¤ European Directive, consist in a reduction of the greenhouse emission gases and the further integration of RES into each country energy production [10]. In Figure 2.1 the evolution process of the European electricity market models is presented.

The main goal of IEM is give the opportunity of consumers to choose their suppliers with reasonable and similar price in any part of Europe. Hence, inter-ligation transmission lines are required to connect countries.

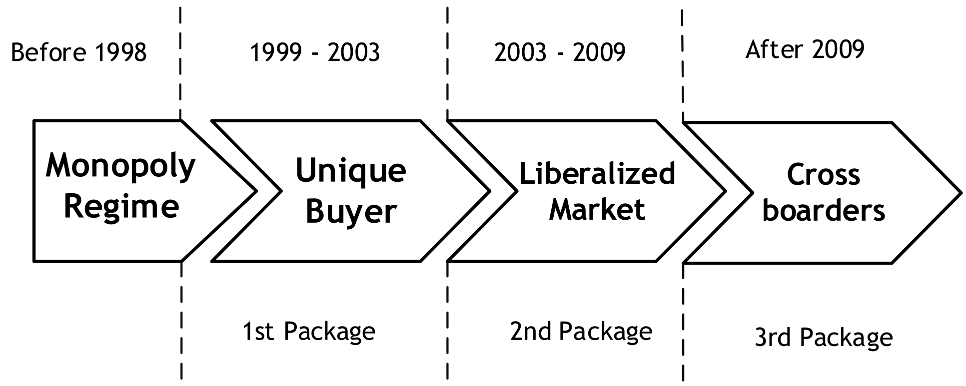


Figure 2.1 – Market Models Evolution.

The process of market change started in 1996, by the Directive 96/92/CE [11]. This first approach consisted on adopting the single-buyer in each state-member of the European Union. In this model, there is only one single-buyer of energy for producer companies. These companies are independent power producers (IPP) from regulated system. Competition is done in long sell contract to operate this IPP with the single buyer companies.

This contracts protected producer of investment risk. Moreover, revenues are paid in a fixed price base, independent of its production. This risks are supported by final consumers, not only by the producers [12]. This model is not an abolishment of the monopoly, once they have the full control of final consumers. Additional costs are applied to the final electricity price to the final consumers. One more time, final consumers had no right in choosing their supplier. The sell is done by single-buyer companies, giving one more time, total access to electricity price determination.

Later in 2003, the Directive 2003/54/CE [13] was created to replace the single-buyer market model. This document had the intention to promote the creation of an internal electricity market (IEM), in where all buyers and sellers could choose their energy suppliers [10]. At the same time, there was a need to create an independent entity responsible to regulate this market model, in order to ensure its transparency.

The main goal of IEM is to give the opportunity of consumers on choosing their energy suppliers. Hence, the central objective is to connect different countries with interconnection transmission lines.

Note that the main purpose is the separation of powers of the VICs. However, there are still monopoly companies. For example in islanded systems where it is impossible to create an open market (e.g. EDA in Azores). The isolation due to the geographical properties is one of the most important limitations, since it is difficult to establish an electrical connection to continental regions. Therefore, these companies are responsible for maintaining the entire electrical system.

The last package, Directive 2009/72/CE, was created with the main reason of introducing the interconnection regulation. There was a need to open the cross-borders to new energy suppliers in order to further increase the price competitiveness [14]. This is an important step into developing the liberalized market shaping into the IEM. However, developing an European IEM is challenging. It requires an organized structure, supported by strong policies. The IEM is a complex process and the approach starts by decomposing into smaller markets that can be connected later. Following this philosophy, small markets have been emerging, following the same principles of the competitive electricity market. Currently, it is expected that Europe is divided into several markets, being the most relevant [15]:

- Nord pool (includes north European countries, Norway, Finland, Denmark);
- MIBEL (Portugal and Spain);
- APX-ENDEX (Netherlands and Belgium);
- EPEX (France and Germany);
- APX-ENDEX (Britain);
- IDEM and GME (Italy).

For the context of this work it is relevant to address the working principles of MIBEL.

2.4.1 MIBEL

In Iberian space, Spain and Portugal made an agreement that led to the creation of the Iberian Electricity market in 2004 [16]. In 1997, Spain started its liberalization process by the implementing the market operator (MO) and system operator (SO).

The main objective was the equalization of the tariffs between both countries by promoting competition in a transparent way. Hence, every consumer in Iberia space could buy electrical energy from any energy supplier or retailer operating in Portugal or Spain.

Evidently, each country still has its own regulation system. In Portugal, this regulation is managed by an independent company, ERSE [17]. In Portugal, to gain access to production in this market licenses are required. Despite small producers can be found in Portugal, they have no direct access to the market structure. These small producers are obligated by law, to sell the energy to the last-resort marketing company. [18].

The Iberian Electricity Market is organized and managed by two countries. Portugal is responsible for the forward market where Portuguese market operator (OMIP) is the system operator and Spain is responsible to manage the short-term market supervised by Spanish market operator (OMEL). Bilateral contracts are also available in both countries. There are also system operators in each country responsible for the technical parts: Portuguese case, Rede Electrica Nacional REN; Spain, Red Electrica de Espanã, REE.

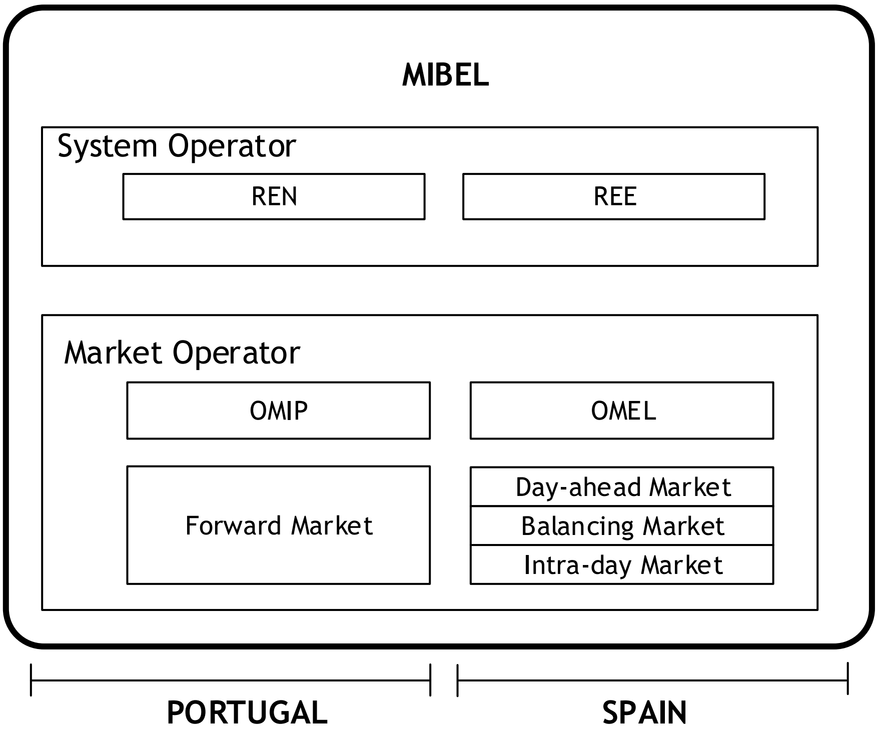


Figure 2.2 – Mibel structure.

It is to be noted that each country still has public entities where regulation exists. However the goal is to migrate all entities to electricity market, but the change is slow. It is a complex process and require a gradually migration due to the necessity of create good interconnection capacity between countries.

2.4.2 Day-ahead Market

Short-term transactions in electricity market are done in Day-ahead Market. This market is a typical spot market or pool market that deals in short-time period. This market has the main goal to make use of management mechanisms in order to create equilibrium between production and consumption supported by participants, eligible consumers and producers.

Every year the number of players in short-term market rises. Still, it is not a perfect competition market due to the number of participants. Thus, big companies are obligated to have a percentage of participation in market. If not, the market price would fluctuate significantly due to the lack of market participants. In day-ahead market trading takes place one day before the delivery of energy. This is done in an hourly basis, meaning that 24 submissions have to be made in order to complete 24 hours. These 24 submissions has to take place in the twelve hours before the first hours of $d-1$ day.

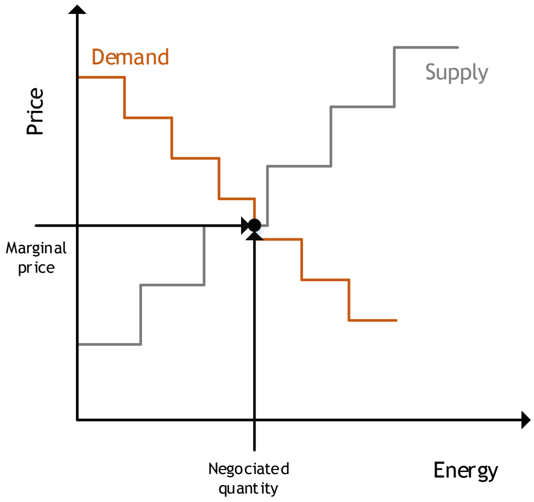


Figure 2.3 – Curve of demand supply

A producer has to decide the amount and the price of energy that intents to offer the market. Hence, these bids can have two components: price and quantity [19]. Regarding this bidding structure the principles are[19]:

- Bid cannot be changed after submission;
- The bid is unknown by other participants;
- Daily market bid has a limited number of hourly block with different prices for each period.

After submission, the market operator will determine the price of energy. This behavior can be observed in Figure 2.3 . In the intersection of both curves it is the marginal clearing price, represented by λ. It is because some decisions have to be made in order to take some variables and also to determine the marginal price of energy. Different sources of energy have different prices and it can be reflected on market price.

Marginal is achieved considering the lower bid price to avoid disparities in the market, risk of having bids so much high than marginal price. This could comprise the generation dispatch. On the other hand, very low offer indications would increase the probability of being dispatch, resulting in lower price than production costs. So market must functional with marginal price system.

After the energy negotiation time in day d, marginal prices are determined for those periods. So price, in this type of market is more volatile.

The balancing market and intra-day market, is not a real market but a mechanisms of adjustments to the undelivered of promised energy. It takes place minutes before the actual energy delivery. These adjustments are required in order to ensure the constant balance between energy supply and demand.

The existence of both these market are important. The day-ahead market is used by energy providers in which they state they plan on energy delivery amount and its price. In cases of deviation of unexpected production (positive or negative), producers will need to take balancing trading in order to compensate this deviation.

In positive deviation, is achieved when more production is being supplied to the market than the one that was reported. In this case, producers will receive extra payments to bring more energy, helping in the equilibrium of the market. On the other hand, if production is not enough to match the reported supply, to the producers a penalty is applied for this imbalance [20].

In some cases, there is a need to compensate the energy match when the energy delivered is lower than the system demand. This energy is more expensive, since this is achieved through the use ancillary services which constitute energy reserves to be introduced in the system in case of need.

Balancing market is needed due to technical issues of transmission, struggled cheap energy in some areas may result, sometimes a force of using other units of energy more expensive, against liberalized market goals [20].

Another important decision to be made after the bid submission has to deal with technical operation in order to guarantee the electric energy supply with secure and reliability. Its system operator job to guarantee the limit capacity of transmission and check constrains in order to prevent congestion problems. In the beginning of MIBEL, the interconnection capacity between Spain and Portugal was difficult to match resulting in difference between electricity prices.

Although, there are some important considerations to be taken, especial when integrating RES into the market. Marginal cost of renewable is very low, zero or even negative depending on cases. Zero prices occur for hours in while the renewable and hydro production exceeded energy demand. Periods with higher renewable energy production, the amount of schedule production and consumption increase and market price decreases. Thus, if a large variation of renewable generation are to accommodate by conventional generation, this may result in conventional power plants operations in a less efficient way, thus reducing the emissions savings bought about by the contribution of renewable to the electricity supply [20].

The higher RES generation, the lower is the market supply and the lower is the spot price [21]. Adequate economic incentives for electricity producers to invest in conventional generation, in particular, in the flexible production technologies required to continue integrating larger amounts of renewable without jeopardizing the security of supply [20].

2.4.3 Challenges of integrating RES in electricity markets

There are still some concerns about the consolidation of electricity market, especially after the blackout that happened in America.

USA motivated by volatility of the price caused by political conflicts of fossil fuel owner countries, in 1970's, adopted an liberalized electricity market. United states, pressed by the fossil fuel dependence, lead to introducing the liberalized market in order to restore the economy devastated by volatility of fossil fuel price. Although, this market was not well succeed ending with a complete blackout of the whole electric system. Carefully attention has to be done to this system in order to solve this challenge without compromise the whole Europe electric system [7].

Electricity is not a typical tradable commodity. Once produced, it has to be consumed at the same time which further complicates its economics. When producing energy with fuel it is easy to determine the price of production. There are some challenges in having these liberalized markets to trade energy. First of all, the big production companies could try to manipulate the market price by removing or adding capacity from the market, having a direct influence in price face compared to small participants [22]. Secondly, if all participants were trying to have benefits from selling in higher price period and buy at lower price periods, it will have the side effects, especially on the first steps of market liberalization.

The reason is at the beginning, market do not have enough participants to develop low prices [23]. All market participants are paid with the marginal price. For instance, if the supply becomes higher than demand, the marginal price will be lower. This is a situation than producers do not want for the reason that they will have less benefit in those cases.

With the liberalized market, it will be more difficult to determine degradation on the electrical grid and choose the right tariff that present the actual cost of using the interconnection [7].

It is evident that with a liberalized market that renewable energy waste is prevented. Energy that is not absorved by one country can be consumed by another country. However, problems rise with the increase of RES in electricity market. Due to uncertainty of production from variable RES (e.g. wind and solar production), these types of RES are non-dispatchable. Evidently, it has significant influence in prices due to the consequences regarding price volatility. This is one of the reasons why these types of RES are traded in pool markets.

In order to minimize the risks from integrating RES in electricity markets, decision methods need to be developed. Decision-making methods can be used in order to predict variable productions. By this prediction, better market offerings can be made which leads to a reduction of possible imbalances associated with the offer. Additionally, by reducing the possible consequences of a mismatch between the reported and the actual production, makes the RES an attractive option for investors. With this, it is expected an increase number of market participants, leading to a more competitive market.

2.5 Summary

Electricity market has been changing due to a series of important factors. The previous monopoly structure is changing to the liberalized approach in order to meet the efficiency goals by supporting the integration of RES.

However, the RES integration became a complex for electricity markets. Variable RES present serious setbacks in the market due to the possible consequences of the mismatch between the actual production and the reported production.

Thus, better decision methods are required in order to develop better offering strategies for the electricity market. In the next chapter, the prediction tools that could aid in the integration of RES in electricity markets are presented.

Chapter 3

Prediction Tools in Decision-Making

3.1 Introduction

The previous chapter presented the typical market frameworks and its benefits in making the RES more competitive in face of fossil fuels options. This chapter starts by addressing the most common tool used in Decision-Making process of variable assets.

It starts by addressing the importance of making-decision the production of energy from RES in making good predictions and market offerings. For the context of this work, it will be demonstrated two types of approaches: Wind and Photovoltaic. Later this chapter, a literature survey on the market offering strategies is presented.

3.2 Decision-Making

Optimization is a reality in engineering solving problems, because everyday decisions has to be made and optimization is a extremely useful tool in making-decision problems. However, making-decision is associated with future decisions that most of the time are uncertainty because is future, so there are a lot of variables that cannot be known. In making-decision they are assumed as a vector of random variables that the value change over the time. This are also called stochastic processes.

Optimal methods has been knowing as a part of operational research problems. Operational research was developed earlier in Second War World [24] as a need to solve problems. Nowadays, operational research is used in a lot of field, as for example engineering.

Stochastic process is considered random process due to the support in random variables. Random variables are a vector of countable numbers displayed in a random sequence. The main goal of this variables is to describe phenomenons that cannot be predict with one under percent sure, due to the uncertainty of the future events. The dependent variables to future events in most of the cases are so large that make it impossible to predict. So each value is associated with a probability, which could be discrete or continuous. For the relevance of this work continuous probability will be explored. In electricity market, making decision should be decide in a continuous base due to the nature of the resource previously explored. Continuous probability it means to work with periods of interval. Probabilities such as probability density function (PDF) and cumulative density function can be used associated to a set of data.

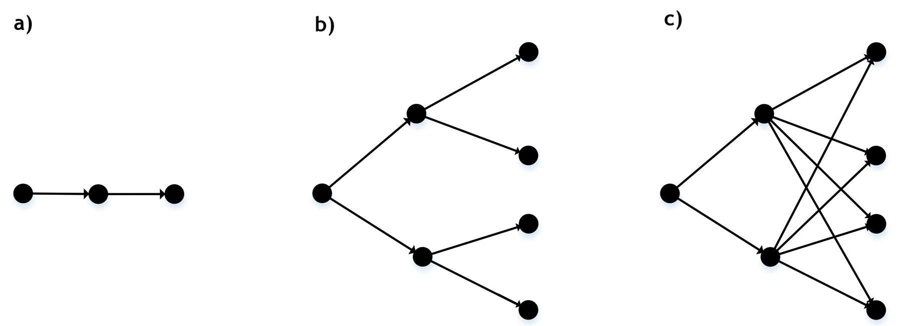


Figure 3.1 – Types of scenarios.

To evaluate this random variables, probability assumptions are made, as a distribution of random variables to occur. Usually it can be evaluate as scenarios illustrated in figure 3.1.

3.2.1 Scenarios

Each node represent a decision and each arc probability of an event to happen. Those nodes represent the possibles stages that a process can be shaped given by a set of variables, presenting by probability. Peter in [25] mentions 3 types of scenario schemes. They are:

- Linear;
- Scenario Tree;
- Dynamic.

Due to the nature of these process, these stages can or cannot be independent. Linear scenarios assume that the process is deterministic. It means that the future will follow a similar relation that was present in the past, there are no unpredictable variables, no uncertainty in the process, the future is well known and precise. Other scenario schemes, such as scenario tree, are normally used in classical stochastic programming, since in the process it describes there is uncertainty present and one cannot predict the future outcome of the event. These type of scenarios, takes into account different possible outcomes, displaying a range of possible future realizations. In the other hand, it can be used a different kind of scenario that recombine scenarios tree. This type is used in dynamic process and take into account that each decision (node) can modify the probability of the next stages (nodes). It is considered dynamic scenario tree, since the future revealed developments can recombine scenarios. In both approaches, regards the same only a single realization from the initial to the final state. Typically,[25], scenarios tree are more appropriate to used with short-therm models. On the other hand, dynamic scenarios with recombination of scenario tree is a more complex process and requires more time consuming [25].

In mathematical statistics, it is mostly the analysis of 'wait-and-see' solutions that is of interest. Stochastic programming is mostly concerned with problems that require a 'here-and-now' decision, without making further observations of the random variables [26].

According to the number of stages considered it can distinguish between two-stage and multistage stochastic programming problems. In two-stage programming there are two levels of decisions [27]:

1. The first is called here-and now and it is a correspondent of a first stage. This decisions are made before the realization of stochastic process. As a consequence they are not dependent of each realization of stochastic process.
2. wait-and-see is for the second stage of decision. This decisions are made after the previous stage had determined. In this case, they are dependent of stochastic process. Being a second stage, each value is defined for each scenario.

Multi-stage problems comprise more than two-stages. It has an identical process as the previous one but with more decisions states and as a consequence it will has more scenarios determination.

3.2.2 Importance of prediction

Due to variability of renewable energy, it is important to predict the availability of resource to help in making-decision process.

Because of the change of matter that cross electricity field and its complexity, there are two main areas of study, technical issues from electric network and electricity market issues.

The new approach of electric network, distributed generation, caused by integration of renewable energy and the possibility of having different direction of energy flow, shown in previous chapter, becomes with different benefits as presented in [28], but it needs prediction techniques to help in technical issues. First of all, the high integration of renewable energies will increase the problems in transmission lines because the network is still keep the old structure as before, when it used to use only fossil fuel, and it will provoke the degradation of electric grid due to variability of renewable energies. In other hand, it could cause network constrains if the injection is more than the network supports [29]. More serious problems could happen because of lack of prediction or bad prediction as having black outs that force the stop[30].

There are different studies that predict methods are used to solve problems such as, save fossil, to schedule maintenance and equipment conditions. There are also important prediction when dealing with unit commitment. Unit commitment is a method to lower the costs of power plant, scheduling units of generation to meet the demand. In order to satisfy the total demand with the most precise prediction, so it is important because in large scale resources and issues can be optimize without lose electric energy as well as costs result from bad prediction [31].

Prediction is essential when integrating renewable generation into electricity Market. It is a wide step for renewable become with more competitive prices as fossil fuel. As known, renewable energies still have higher costs of implementation, initial investment and maintenance comparing with production because power generation come only when wind blows or the sun shine, and this production is variable and uncertain. This variability, there are not such competitive as fossil fuel energy, resulting in a higher price. Due to this fact, electricity market development was a strategy of integrating renewable electricity with other kinds of technologies in order to lower the cost of production and be more competitive than fossil.

But this kind of energy is non-dispatch because it always depend of weather condition that make it intermittent. This becomes a problem that have encouraged researchers to intensify their efforts in the development of better predicting techniques [32]. It is necessary improve the predicting methods to have a better support in making-decision situation with a lower risk, reduced unexpected profit. The challenge is a higher penetration of renewable in electricity market and and more competitive energy than fossil fuel, with a similar price. Great challenge from fossil dependent countries as incorporating european union, such German and Spain that take this position to face the crises [22].

With price prediction and weather prediction, producers can achieve the best offer in order to reduce risk of having a bad prediction, maximizing the profit. Thinking into account a producer point of view, a good prediction will help in deciding the amount of energy to be sold in electricity market. This is important in Day-ahead market due to the necessity of deciding this amount in the previous day of delivery. In case of the producer cannot satisfy the announced amount, in some markets, it could be penalized with extra payment.

Although, electricity market has to be transparent and well structured to lead a good will. But market is still vulnerable.There are some disadvantage in having markets to trade energy. First of all, the big companies can do a tricky game to manipulate the market price by removing or adding capacity from the market and having a direct influence in price face to small participants [22]. Second, if all participants were trying to have a benefice for selling in higher price period and buy at lower price it will have the side effect, the more profitable period before to sell it will become the less profitable after playing with the prediction and the market price.

It is expected the increase of RES, such as wind and solar, for replacing the traditional fossil fuel production. However, due to the nature and the variability of these resources, rises the necessity of having a good prediction techniques, if the RES want to strive in the electricity markets.

It is important to predict the availability and the production output of these resources. And also with integrating RES, electric system will have other behavior, since electricity stopped being unidirectional but distributed [28]. It will result in the technical issues. First of all, the high integration of renewable energies could lead to an increase problems in transmission lines, since the network still keeps the old vertical structure.

RES integration could lead to the degradation of the electrical grid due to variability of production output. Moreover, it could lead to network injection problems in situations that the electrical grid does not support the the energy introduction [29] due to variable production of RES-E. A reasonable prediction can prevent this problem, but if neglected it could represent more injection than grid is able to accommodate. As a consequence grid may become overloaded and in extreme cases provoke electrical system blackouts [30].

The RES have higher costs of implementation, bigger initial investment and maintenance costs when compared to the fossil production. This fact is because of the higher price of technology that is an negative point of RES implementation, requiring a big initial investment. Investments of this nature, are not favorable, since the pay-back is still high due to uncertainty of production and also the lack incentive of governments.

Although, prediction can reduce the return period of investment, once they will have a better prediction of production that allow decision-maker to get a better decision in order to get a better profitable revenue when selling in electricity market. It is an incentive to encourage new investors coming into RES business and it is also an opportunity to make extra money.

However, in terms of production these RES could be considered cheaper due to the variability from oil prices, due to global conflicts or economic pressures. Although, this kind of energy is considered, due to their variability, non-dispatchable since it is strongly dependent from weather conditions. This nature creates a major setback for the RES and prevents them of having a more competitive price.

Probability provides different ratios of probabilities and do not have one single value, but it can take a range of probabilities that may represent the future prediction. This type of prediction make use of probability density functions (PDF)[33].

For the context of this work, it will be focus on probability due to characteristics of RES such as wind and photovoltaic Probability is used in RES power production, since it is dependent on weather conditions. Typically, weather conditions are difficult to predict, seeing that it depends on a combination of a several non-controllable factors. These conditions also vary with time. For instance, if a renewable power plant has to be operational, it can only do it in times of favorable weather, making it a non-dispatchable energy. Because it is not available in time of need, so can not satisfy the required demand all time.

So, it is requires techniques to put renewable more technical and economic efficient [20], solving the problem of non-dispatchable with prediction techniques that helps in making-decision problems in dispatching energy. Having a RES-E predicted, it is easier to manage the technical and the economic problems, network is well organized and money can be save in selling green energy more cheaper than conventional one and not have penalties in market due to undelivered scheduled RES-E.

Evidently, these techniques vary between the resource it wants to predict and different factors are taken into account. In the next sub-sub-sections 3.2.3 and 3.2.4, two cases of different sources requiring different approaches.

From a producer point of view, a good prediction will aid in deciding the amount of energy to be sold in electricity market. This is important in Day-Ahead market due to the necessity of deciding the amount of energy previous the day of the delivery. It gives an certain degree where producer schedule the production, with a more predictable injection and also it will save the penalty balances from the unscheduled energy. For the market it is advantageous because they can easily equilibration of the market energy trading. Jeopardizing more expensive energy sources to meet the undelivered energy promised by producers. So prediction is a gain for each part and system safety, allowing markets to works better, well structured.

3.2.3 Wind Power Production

Wind production sites are directly dependent of the wind strength. Although, there are maximum limits of operation due to mechanical and electronic constrains. Wind's power is primary converted into mechanical power trough the wind turbine where wind is crossing the turbine and make a force that allow turbine to rotate and produce mechanical energy. After, this mechanical energy is connected to a generator that it is connected to the electrical network. Those processes of conversion has mechanical and electrical inefficiencies. Several technologies and developments are presented in [34] and [35] that address the strategies on how to explore the maximum energy potential output of the wind generation. So a system control is important in machine operation and power production, existing then an optimization field in mechanical and electrical losses that can be found in [36].

Wind is considered the most developed renewable energy and also the most available in literature in electricity market . Many integration studies have been done, in United States, on a prospective basis, looking at the potential future power system with wind in order to determine the integration cost of wind or to determine the impact of wind on electricity market operators[37]. The same problems are also taking into account in European studies [38].

Although, there are some important characteristics to take into account when trading wind energy in electricity market, such as shape of wind speed curve as [39]. This characteristics will be important because they can affect the bidding price, having strong impacts on receiving amount for selling in market. So a deviation of scheduled wind production will have economic impacts for producer. Having a lower production is bad to producer, because he will have to take penalties resulting from balancing market, specially designed for RES traders. So for wind power producer, predicting wind power availability requires a carefully factors of interest. Other many factors are relevant for wind variability that it can be found in [40], there are:

- Variations from direction;
- Variations from seasonality;
- Variations from local;
- Variations from time;
- Atmospheric conditions such as pressure forces and Coriolis force.

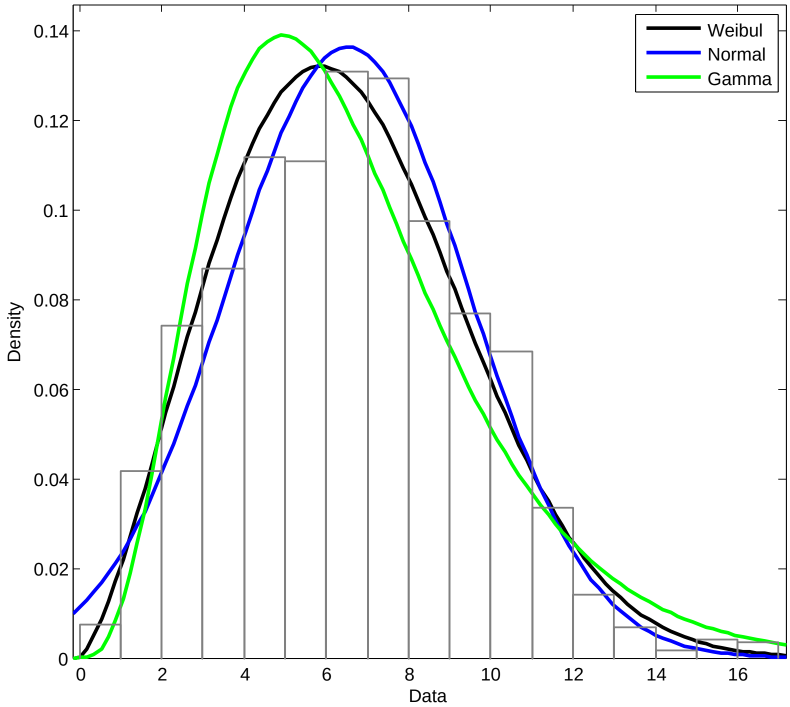


Figure 3.2 – Wind Speed density with different distributions.

Probabilities count events and see how many times they happened in the passed and it convert in a percentage that will define the probability of having an specific event. Using distributions supposed statistical parameters such as variance and covariance of historical data. This data is important to get statistical parameters that can quantify and characterize the shape behavior. This is useful to work with a little data set and is easier to modulate, getting only parameters that can represent the general behavior. With higher density of data, processes become more complex and slow.

Looking at the figure below, can be observed the characteristic curve of wind speed, distributed by hourly curve. The most used method to predict this curve is a weibul distribution [41], [42], [43], [44] and it is noticed in graph that the shape is near to the wind power curve, because weibul is the probability density function that best approach the behavior of wind distributed for different hours of a day as can be observed in figure 3.2. With this distribution, it can be seen that wind is more available at night and in fact it is true due to the sunset, air mass become more cold starting their movements, resulting in more windy region. At day, air mass become more warm and the probability of having wind is lower.

As it can be seen, the most availability is observed at night, when there is a temperature drop in which results in more movements of cold mass of air. The variation in wind speed is also due to a combination of: tower shadow, wind shear and turbulence [45].

To operate a wind turbine there are some equipment characteristics by the fact all wind available is not good for wind production. There are a minimum speed defined to get an output production and above this is not possible to operate. As well with a certain speed, it has a maximum power and and higher of this value that wind turbine is forced to shut down. This is also a safety procedure due to wind turbine dimensions and the possibility to explode and cause serious dangers.

3.2.4 Solar Power Production

Solar energy is the most abundant energy available, inexhaustible and clean of all the renewable energy resources till date. The power from sun received by the Earth is about 1.810^{11} MW , which is many times larger than the present rate of all the energy consumption [46].

The use of solar energy is usually divided into two main areas: Solar thermal and solar photovoltaic electrical production. The first uses the sun as a direct source of heat energy and is most commonly used for supplying hot water to houses and swimming pools. The solar electrical energy production seeks to convert light from the sun directly into electricity through a process known as photovoltaic [47]. The photovoltaic effect is developed in [48] and its present on photovoltaic cells [49]. Electric limitations are considered in photovoltaic once conversion factors are very low. There are some developed technologies that allow panels to follow the sun path, tracking system, maximizing the power extraction in every day hour.

Although, the main challenge of photovoltaic is to develop material capable of improve the maximum possible energy that can be extracted from the irradiation there are achieve using advanced chemical and metallurgical rout [46]. More efficient panel has to be developed in order to increase the conversion efficiency to maximize the possibility of power production and it also an mechanism to become more cost effective, once photovoltaic is still expensive due to low development of technology, representing a large initial investments once returns rate are very very long face to capacity of production. Giving an example, the most typical panels commercially available are made of multi-crystalline silicon that has an efficiency between 14% to 19% [46]. It is a small amount considering the total power potential that comes from the sun. Depicted on the figure, is difference of available and the possible amount of energy that can be extracted. It is still a small amount considering the total power potential that comes from the sun.

To produce electricity is required, as mentioned efficiency of but also the number of effective sun hours [48], once technology is not so developed to create so efficient materials than can produce at lower light, as night period. So, sun hours changes with seasonality due to sun trajectory around earth, that means that in summer it has more sun hours available than in winter, and because sun is closer to earth in summer, the temperatures increases, as it can be observed in figure. As the same way with Latitude that change the angle of hours available.

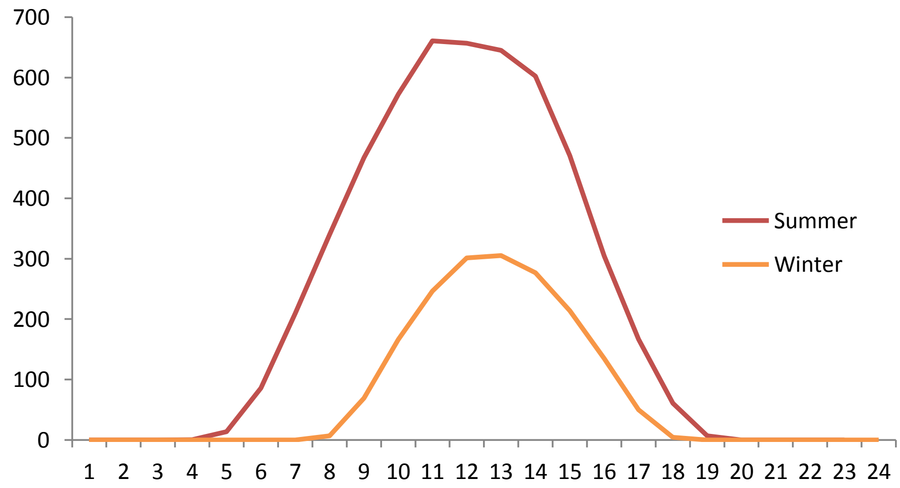


Figure 3.3 – Seasonality represented by lower limit, winter, and upper limit, summer.

Irradiation prediction, with wind prediction are the most variable energy and by the way the most difficult to predict. In order to achieve a good prediction some methodologies and improvements has to be developed. To prediction the shape of irradiation, the most similar distribution used is the Gauss or normal distribution[50], shown in figure. The shape of sun availability fits with a normal distribution. It means the sun shape can be represented by an normal distribution with a specific mean variance and mean value. In fact, this distribution simplify the use of so extensive data, allow it to be modulate as an characteristic normal distribution, with mean of midday hour, once is the most perpendicular position of the sun trough local position, except north and south poles.

Wind and photovoltaic power prediction are important when considering an offer to electricity market. Once its are uncertain sources it has to be planned, because electricity market works with scheduled production made in the previous day of delivery as characteristics of the market system in order to guarantee that demand will be satisfied and the system reliability. So a good prediction it will help decision-maker to has more accurate prediction and also to help the system through equilibrium.

3.3 Integration of Renewable Energy into Electricity Market

In electricity market different strategies are assumed to get the best offer. There are different offer strategies proposed in literature to conventional units. Although with integration of renewable energy into electricity market as a competitive strategy of take a better advantage of renewable energy and achieve the goals of renewable energy and energy efficiency. But due to renewable characteristics there are two main studies as an offer to the market in order to get the best benefit with the minimum risk of unpredicted production. The first kind is studies an separate offer as a strategy of integrate the production of one only technology. After, it will be seen that join different types of energy could be benefit because it combines different characteristic of each technology and it results in a more profitable offer.

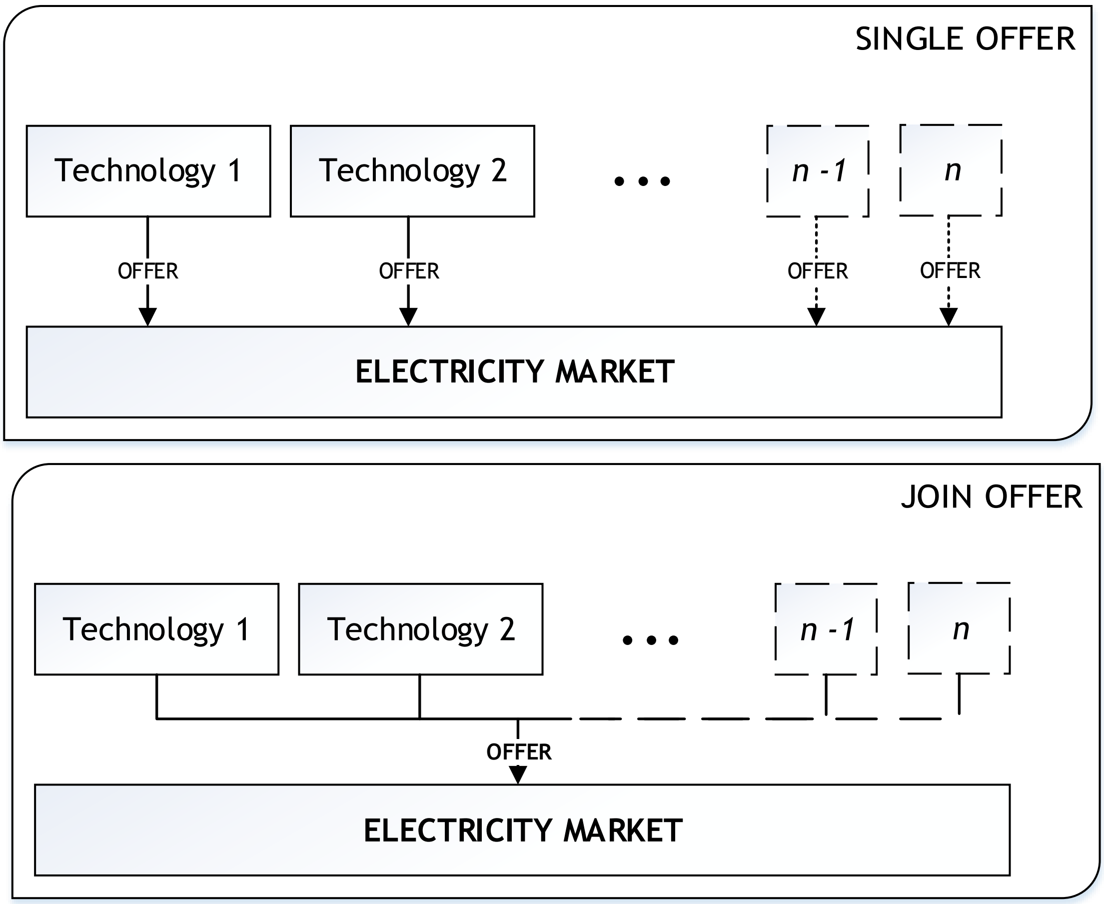


Figure 3.4 – Bidding strategies into Electricity Market.

3.3.1 Separate offer

Integrating wind production into electricity markets is the most available technology on the literature. Due to variability and uncertainty of wind production, many strategies have been proposed, in producer point of view, in order to achieve the maximum benefit in bidding in short-therm electricity market and minimize the costs incurred in the balancing market.

The generation of wind farms cannot be managed through time so it requires efficient prediction techniques. There are many examples of stochastic programming applied to power systems[51]. [52] proposes a Mixed integer programming strategy to generate an optimal wind power production bid into nordic short-term market, maximizing the profit of the owner of wind farm. Different scenarios were generated using statistical methods as ARMA, based on historical wind speed data, from Denmark and error forecast using least-square fitting.

In this paper,[44], uses ARIMA models applied to a pensula iberica wind farm to generate prices because these models provide appropriate accuracy for moderate effort. It also consider risk averse associated with adjustments. Conejo [44] proposes a technique to derive offering strategies for a WP considering different trading floors.

But proposed a strategic WP with power market to maximize the profit when exercising in Day-ahead market, WP is able to define the price and wind power level to offer. It was solved with stochastic MPEC [53].

In some countries, the market is operated taking into account the risk of not produced the expected amount bidded. For this reason some imbalances are considered using CVar and Var as risk manage control [35].

This [54] presents a new model for optimal trading of wind power in day-ahead (DA) electricity markets under uncertainty in wind power and prices. they used kernel density estimation to produce a probabilistic wind power forecast, whereas uncertainties in DA and prices are assumed to be Gaussian.

[55] propose an equilibrium model of the short-term market to address the impact of wind operation under different structural assumptions. The model is formulated for several price taking and formulated as a stochastic equilibrium problem. The problem for each firm consists of a two-stage stochastic optimization problem. Due to price taking assumptions the model is a single stage complementarity problem.

In all above, participants were considered as a price-taker. But there are some literature studding the possibility of having a huge penetration of wind generation capable of having a direct influence on market price. It is called Price-Makers.

The high penetration of wind energy has developed another research field related to market power and the impact of renewable energies in the market price. [56] presents a pool strategy of a price-maker wind producer. The electricity market is studied in these papers for the short-term.

3.3.2 Joint different technologies

Other possibility of trading Renewable energy into electricity market is join different types of technologies. As known, renewable energy such wind and photovoltaic are non-storage energy and are dependent of weather conditions, so the uncertainty associated is high. But join different kinds of energy can lower the gap of production and be more profitable. This types of strategies are also available in literature. Storage systems characteristics are developed [57]

Some authors combined wind with thermal energy, thermal is a conventional energy and easy to manage, because the production is controlled by humans and in time of lack of wind production, fossil fuel are easy to put in charge to compensate this gap. So [58] proposed a coordinated trading of wind and thermal energy to mitigate risks due to those uncertainties, using a mixed-integer stochastic linear program. It is assumed that both the wind and thermal plants are connected to the same bus, exposed to the same energy price, and owned by one producer.

[51] propose to study tow different strategies, uncoordinated and join offer using wind and hydro technologies. The pumped-storage plant considered is composed of an upper reservoir and a lower reservoir and can be pumped in off-peak hour and sold in peak hour. the model allow different pumping and discharging limits. In join model, energy is sold as a single offer.

Similarly, [43] propose three models of join offers between wind and hydro plants in day-ahead Iberian Market for 168 hours periods. The first model assume both plant separately and with separate offers. The second model suppose both plant connected but with separate offers, it means that the exceed production of wind goes to pump. The last one, is similar to the previous one, but now the two technologies are treated as a single offer. Introduce in the optimization model some risk-aversion measures. There is not available in literature wind with photovoltaic strategies, neither as separate or joint strategies.

3.4 Summary

The chapter give a better understanding of whats this work propose to do. It was seen the importance of having a good prediction to get a good prediction about the future as a mechanism of supporting a better decision-making. Although due to renewable characteristics it is useful to escalate in different scenarios to get a better visualization of the limits of uncertainty as well as make use of mathematical programming. Stochastic programming seems to fit offer optimization problems and a very used tool to solve it. Seeing all strategies considered in literature, opting for combining technologies is a good strategy to get a more profitable situation when offering to electricity market. But combining more types of technologies could be studies.

Chapter 4

Proposed Methodology

4.1 Introduction

In the current section the proposed methodology is presented. It starts with the problem description and a brief explanation of the bidding strategies used. In this chapter the mathematical formulation that models the photovoltaic and wind power production is presented, explaining the applied objective functions and constraints required to design the offering in the day-ahead electricity market.

4.2 Problem description

Wind and photovoltaic production is characterized by its uncertainty of production that presents serious problems in integrating in Electricity Markets. This becomes a challenge to researchers, since there is a need to create strategies that reduce the bidding risk of the announced production from RES holders in order to increase their revenue.

In this work a bidding strategy that combines both photovoltaic and wind production to achieve the most profitable offer is developed. Therefore, two strategies are proposed: i) Separate offer model for each technology (Wind and Photovoltaic); ii) Combination of Wind-Photovoltaic production into a single offer strategy.

There are studies that show the advantage of combining technologies into a single offer, presented in the literature survey of the last chapter 3.3.2. The combination of each technology could present its advantages in terms of market offerings, since it could reduce the risk of under- or overproduction. Moreover, a combined offer could lead to a more solid market offer since it includes the expected production output of both technologies. In fact, the combination of different technologies, could balance the uncertainty existent of each technology that could lead to a more profitable offer.

The individual single offer of each technology is depicted on Figure 4.1. In this strategy, two different optimizations are done in order to guarantee the best possible offer from each individual technology.

In this case, to make an offer to the electricity market, wind and photovoltaic production is analyzed individually and the offer is made separately. Starting by collecting data samples of wind speed and irradiation from a given region.

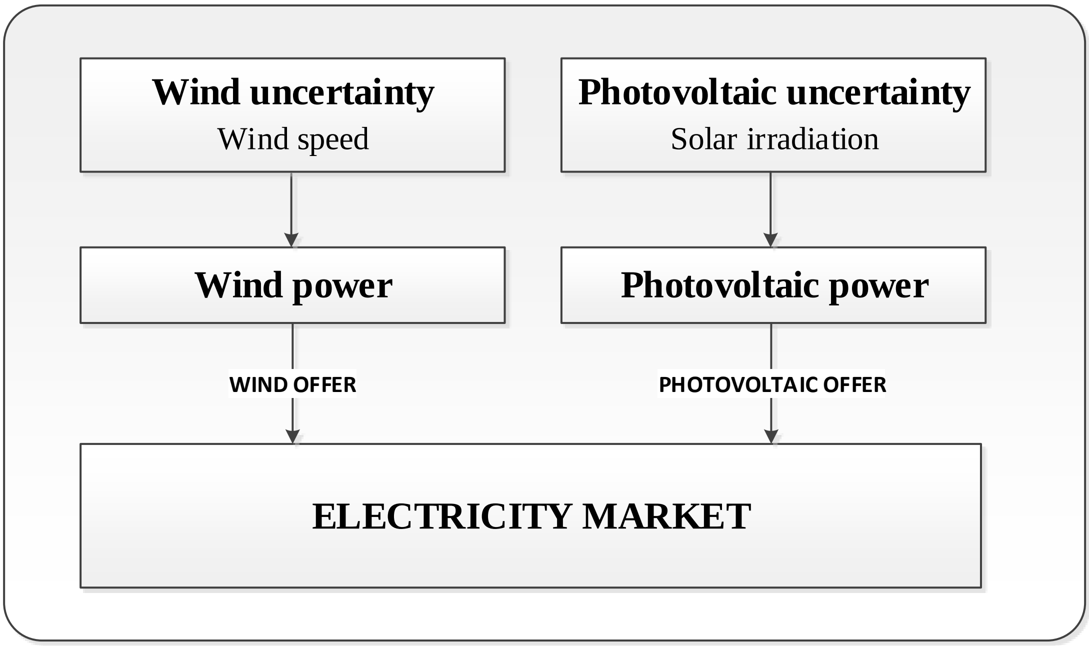


Figure 4.1 – Separate wind-photovoltaic strategy.

As one cannot predict the behavior of each technologies due to its high dependence of weather conditions, a wide range of possible scenarios will be generated to account for the uncertainty of each technology.

Is with this determined values that simulations will be make in order to achieve the optimal solution, using Stochastic Mixed-Integer Linear Programing. This type of programming is used in this case, since is dealing with variable energy outputs that presents a strong source of uncertainty, that needs to be taken into account in order to represent the imbalances. Imbalances are considered in Day-Ahead market to incorporate the uncertainty of production. On development of the formulation, binary variables will be explained in context of this problem as variables that characterize the certain types of uncertainties. These variables are important in the decision-making process, to decide whether or not to offer to the electricity market, and can also describe the level of power production deviation.

Prices are generated with the support of real data (real market prices), in order to achieve a more profitable offer. These prices have three components: real price market as it is depicted in Figure 4.2, ascending price and descending price representing the imbalance of market price. This prices are set in different wind and photovoltaic productions in order to get different possible production.

The ascending and descending prices are important to determine the price variation resulting from balancing penalties. Several scenarios will be created in order to classify a wide range of probable future predictions. Finishing this process, the simulated data will be optimized in order to achieve the profits of wind, photovoltaic and the deviations costs of each production.

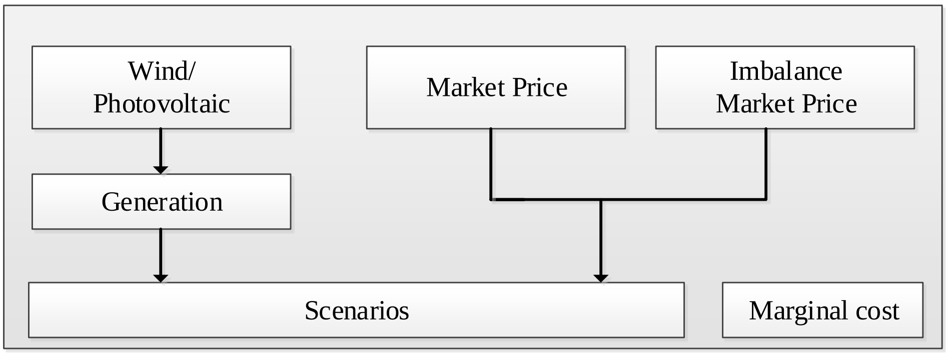


Figure 4.2 – Scenarios input schematic.

The second strategy consists of using both technologies to create a combined production pack, to make a single market offer. The main purpose is to compare this case with the previous one presented and verify which one is the most profitable. The single offer strategy model is depicted in Figure 4.3. However, it has some changes that are responsible to allow a different offer, as it will see with details in subsection 4.6.

To consider a combined offer, both productions are merged into the same scenario prices. Despite of being different technologies in separate they will be combined for a single offer. So the binaries variable mentioned above is now connected under the same decision variables of offering into the Day-ahead market, because production of wind power and photovoltaic power will be bidding into one only offer to the electricity market. The optimal solution is achieved after taking into account all variables resulting from power production resulting from the possible scenarios.

4.3 Photovoltaic Formulation

Photovoltaic power depends on solar irradiation. This irradiation reflects the variability of the resource that represents a source of uncertainty when selling/bidding in electricity market. Typically, the solar irradiation that is used to produce energy is concentrated at day, and no production at night periods. During the day, the irradiation follows a normal distribution pattern [50] by the shape be so similar to a normal distribution that can be characterized by this probability distribution, with a specific mean value and standard deviation of a representative set of historical data.

When the irradiation incidence is perpendicular to the panel, the maximum capacity of power production from panel is achieved being the maximum production achieved in midday. Typically, these panels are set in fixed positions properly oriented to maximize the production. There are disadvantages associated, being fixed make it limited to the maximum production for a whole day. In each changing season there is a need to reposition its orientation, in order to maximize its production.

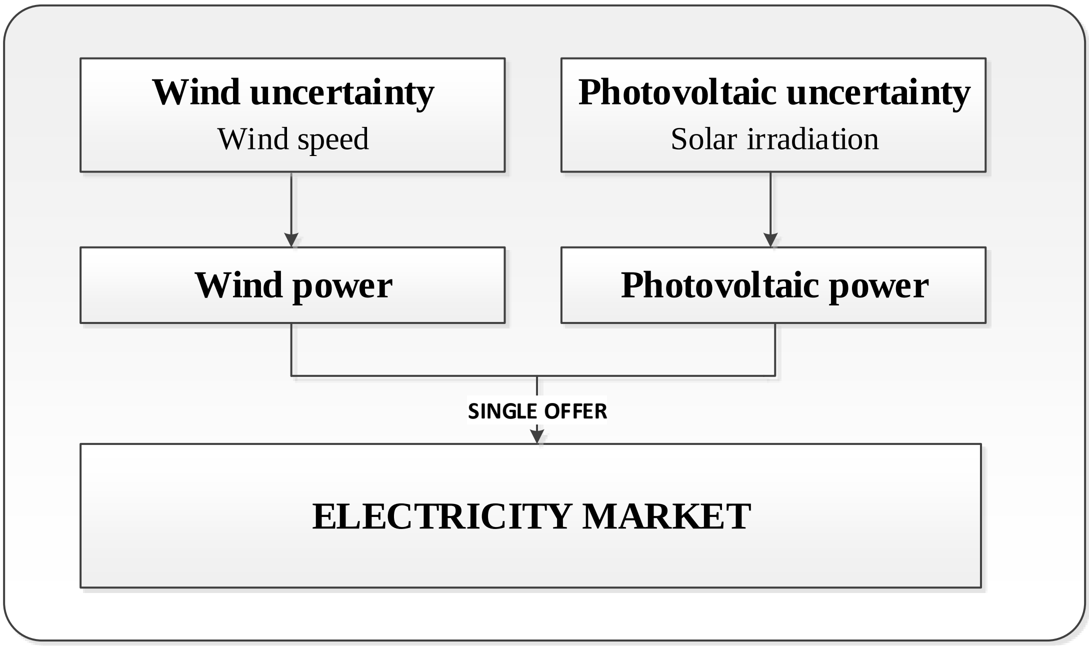


Figure 4.3 – Single wind-photovoltaic strategy.

However, there are technologies available in the market that allow panel to track the sun trajectory since the sun to sunset [48], it allows panel to have at every moment the maximum production possible for each time and improve the return investment.

Solar energy is directly dependent of area surface of panel, so high surface area, bigger is the capacity of production since the panel can collect more solar energy. However, due to technical limitations, these efficiencies are still low and are important to take into account in quantifying the total power output.

The total power output (P [W]) is represented by equation [50]:

$$P(G) = \eta \cdot A \cdot G. \qquad (4.1)$$

Where, G is the solar irradiation from known data in [W/m^2] and present the global incidence of solar light. A is the panel area [m^2], the surface area capable of transforming light into power. Evidently, this is one of the most important factors in photovoltaic power production, since the bigger the area, the higher is the expected production. In practice, work with panels is not appropriate, being these panels connected into arrays as portrayed in the Figure 4.4.

However, regarding the PV production cannot be considering only area, once transforming energy always implies efficiency of conversion due to technologies limitations. The PV efficiency can be described by expression (4.2), in which η_{panel} is the panel efficiency; $\eta_{inverter}$ is the inverter efficieny; η_{others} are other efficiencies that are dependent on each system setup.

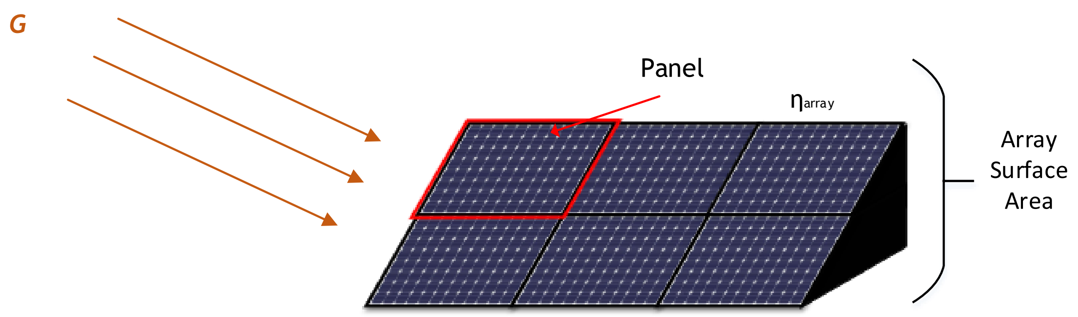


Figure 4.4 – Irradiation caption phenomena from a photovoltaic system.

$$\eta_{pv} = \eta_{panel} \cdot \eta_{inverter} \cdot \eta_{others}. \tag{4.2}$$

It is the producer interest in selling the energy and get the maximum profit revenue possible. Considering this, , the objective is to maximize the profits of selling energy of photovoltaic power production in an offer to day-ahead market.

Solar irradiation is the input, the uncertain source in study. Photovoltaic power has a range of possible future production, so it will be distributed by a number of production scenarios with a probability of occurrence. These scenarios will be designed by taking into account real data and the uncertainties of production. These scenarios will be combined with prices that will vary according to the production.

Three different set of prices are considered. λ is the market price determined for a specific with a determined period. When the production is different of the expected on, different prices will be added to the global trading amount. If the producer achieved more power than scheduled, λ^+ price is an applied price for a bigger amount of energy delivered. The same principle is applied for a lower production than previously scheduled, λ^-, is a penalty applied to the producer for delivering less energy than expected. So these considerations are important to aid in the decision-making process.The expected profit is then determined considering the previous explained parameters and presented in the following expression:

$$PF_{PF} = \sum_{w} prob_w \sum_{t} \left[\lambda_{t,w} \cdot b_t^{PV} + \lambda_{t,w}^{+} \cdot \Delta PV_{t,w}^{+} - \lambda_{t,w}^{-} \cdot \Delta_{t,w}^{-} - c^{PV} \cdot g_{t,w}^{PV} \right]. \tag{4.3}$$

The expected profit is given taking into account three factors. The first one, is the amount of energy bid presented by b_t^{PV}. This energy is a profit multiplied by its current market price. However, this revenue is in function of production, so it has to be subtracted by the total cost required to produce this energy presented by c^{PV} multiplied by the the total amount of production $g_{t,w}^{PV}$. These costs are related to operation and maintenance procedures and can differ depending on each technology.

In this case, the $g_{t,w}^{PV}$ is actually the $P(G)$ presented in the previous equation (4.1). Since the PV production is an uncertainty source, imbalances must be considered in order to compensate the deviation caused by unexpected production (under- or overproduction). Therefore, λ^+ and λ^- are multiplied by the deviation of production $\Delta PV_{t,w}^+$ $\Delta PV_{t,w}^-$ whenever the deviation is in excess or in by default.

As mentioned before, failure to comply the announced production, can lead to penalties for the producer. Therefore, these penalties and benefits must be included in the optimization process. If the producer supplies more energy than he previously announced, he gets an extra payment given by $\lambda^+ \cdot \Delta PV_{t,w}^+$.

On the other hand, if the producer is short on the production that he previously announced, he receives a penalty given $\lambda^- \cdot \Delta PV_{t,w}^-$.

As the producer objective is maximize the profit of bidding into the electricity market, the higher profit has to be chosen. It is only possible taking into account a different number of possible scenarios. So the profits of bidding photovoltaic power production represented by PF_{PV} has to be considered for each scenario w. The PF_{PV} is represented as a sum of all generated scenarios for all periods t once an offer means all periods of a delivery transaction, in DA market, 24 periods are considered, so 24 bid offers has to be integrated in PF_{PV} equation.

Only the most profitable scenario w, taking into account profit, offer and imbalances between them is chosen. Additionally, this function is limited by constrains of the problem in order to get feasible solutions. These constrains are explained later in subsection 4.5.

4.4 Wind Formulation

The wind model is based on the works of [43]. This model addresses the analysis of wind and hydro as a separate offers as one of the three strategies presented. Despite of bidding structure and the proposed objectives be different, the principles that rule the wind model are similar. However, they incorporate risk based on CVar on the bidding offer, which it will not be used for the purpose of this work. This results in an optimization problem that is considered to be risk-neutral. Wind power uncertainty is mostly associated with wind speed. For the sake of simplicity, historical data from wind production in a given region is used.

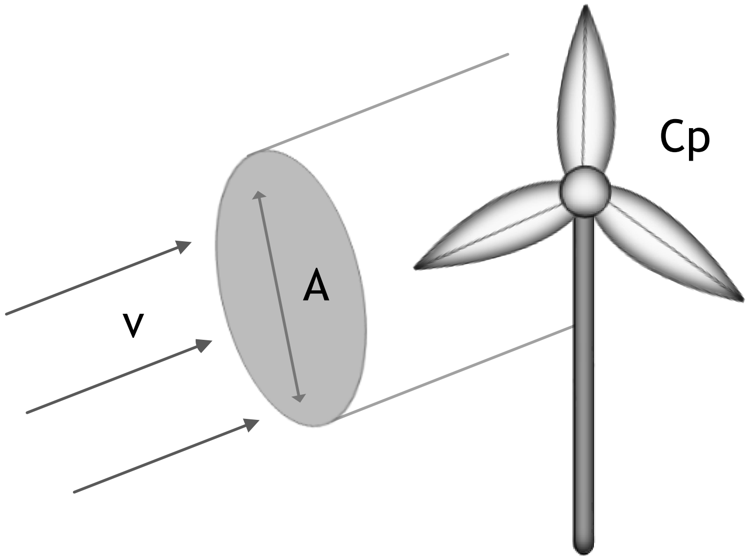


Figure 4.5 – Wind power production under the influence of air mass trough the turbine.

As it demonstrated on Figure 4.5, an air mass in motion representes a wind force in terms of kinetic energy:

$$E_k = \frac{1}{2} \cdot m \cdot v^2. \quad (4.4)$$

This principle comes from the Newton's law, given by $F = m \times a$. Since it is not practical to estimate the amount of mass that is passing the turbine at a given point, a relation must be established in order to become more practical, relating in terms of wind velocity. Considering that a mass of air is $m = \rho \times A$, the new formulation that relates to the wind power output is given by [40]:

$$P(v) = \frac{1}{2} \cdot c_p(v) \cdot \rho \cdot A \cdot v^3. \quad (4.5)$$

Where A is the area of turbine rotor $A = \pi \cdot \frac{d}{2}^2$; d is the diameter of the turbine; ρ is the air density. One of the most important characteristics of air mass and $c_p(v)$ is the overall efficiency of wind turbine in order of wind speed. Power of rotor is power of generator and P is the equation explained in equation (4.5). Although, wind production is limited from technical constrains. The following figure is an example of this (figure 4.6).

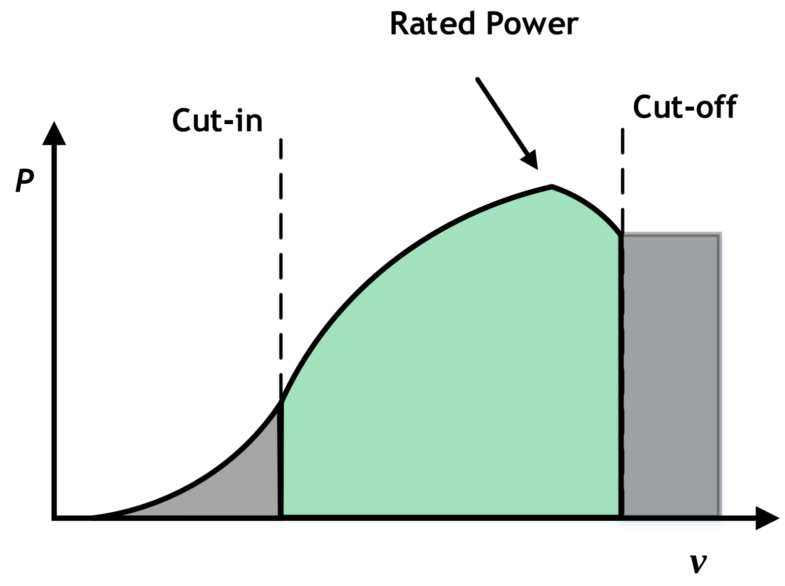


Figure 4.6 – Wind production region.

For a very low wind speed, turbines are not able to produce any energy. It depends on manufacturer specifications in defining this value. In fact, there is a starting point called cut-in, where turbine starts operating and producing energy. Additionally, a point of maximum production is achieved given the technical limitation, such as damage caused on equipment from higher rotation [59]. There are other important factors to determine the wind power production such as rugosity of the terrain considered in [40]. Any irregularities on surface can modify the wind flow, and consequently compromise the production.

Wind power production is now the input in making-decision process. After, the power output is adjusted following a weibul distribution. This distribution has shown in the previous chapter 3.2.3 in figure 3.2, it is good to characterize the wind power availability. So wind power will be follow this distribution for a specific number of scenarios of wind per hour. This will result in a probability of an event, for each time, in this case hour. The same type of prices explained before in are contemplated in wind formulation. This it means that wind, as a source of uncertainty is also included into balancing market where different prices are considered in case of deviation on promised scheduled production in DA market.

So the objective here is to maximize the profits of selling energy of wind power production considering an offer to day-ahead market. This benefit is presented by PF_w that represents:

$$PF_w = \sum_w prob_w \sum_t \left(\lambda_{t,w} \cdot b_t^W + \lambda^+ \cdot \Delta W_{t,w}^+ - \lambda^- \cdot \Delta W_{t,w}^- - c^W \cdot g_{t,w}^W \right). \qquad (4.6)$$

Wind power offer is considered in function of the amount bid into day-ahead market represented by $\lambda_{t,w} \cdot b_t^W$ minus the cost of production $c^W \cdot g_{t,w}^W$ where $g_{t,w}^W$ is given by equation (4.5). In case of deviation on scheduled production an extra payment or penalty will be also taking into account in this function, where exceeded production will have an extra profit represented by $\lambda^+ \cdot \Delta W_{t,w}^+$ and an not satisfied production will represent a cost given by $\lambda^- \cdot \Delta W_{t,w}^-$.

Because of the uncertainty represented by wind variability, wind power production will be different considering the period t and the number of scenario w. Takes giving to the mixed-integer linear programming, the best scenario w in a range of generated scenarios will be considered as the best offer for a day, with 24 periods. But there are some constrains to make this problem to be solved (feasible) in linear programming context. Constrains that limit the problem are explained above, in next section 4.5.

4.5 Mathematical Constraints

There are different types of constrains to take into account for both models: offer constrains and imbalance constrains. Both are bidding constrains because the objective is to make an offer to the electricity market.

4.5.0.1 Offer constraints

In day-ahead Market, producer has to submit 24 bids, one bid per hour. In order to do this, he has to take into account the quantity of production and the minimum selling price. So, for each period, producer has to determine the bid considering the wind and photovoltaic power production capacity. The producer cannot sell more energy than can be produce by each plant. So, the maximum power production is achieved in that value. The minimum value of production is zero when weather conditions are not enough for having production. For wind turbine it will be zero for values of speed above cut in value, represented in previous figure 4.6, where the speed of wind available is insufficient to produce power. For irradiation, this can be achieve ate night, when sun is out. So it is assumed zero as the minimum value, avoiding negative values due to impossibility of having negative production. Then, for each period it is considered a value in a range of zero to the maximum limit capacity of each plant production, considering the quantity energy production. Photovoltaic bid is limited in equation (4.7) and wind bid by (4.8)

$$0 \leq b_t^{PV} \leq P_{max}^{PV}. \tag{4.7}$$

$$0 \leq b_t^{W} \leq P_{max}^{W}. \tag{4.8}$$

4.5.0.2 Imbalance constraints

Imbalance constrains have to be considered in day-ahead market which gives the deviation of an expected production, since the wind power production has higher degrees of uncertainty. These imbalances are considered when having uncertainty energy producers as wind or photovoltaic by the impossibility to predict their production level before the closing of the market, one day before the production. So producer has no control of this production, having times when they cannot delivery the previous schedule production. In this cases balancing market is also needed to contemplate this deviations. So, in formulation some considerations has to be defined in time of production.

In formulation, it can only considered one deviation. Negative if the delivery amount was above of scheduled in DA market, and positive if the quantity of production was higher than scheduled. This is important to take into account because the two action has different impacts on electricity market. When negative, the producer has a penalty to not delivery the schedules, most of the time, another more expensive energy as to be injected to balance the non delivered from producer. Otherwise, if production is bigger than the expected, it is good for both, producer and market system, producer will receive an extra payment and at the same time, bringing more energy into the market will helped in restoring the system.

The optimization problem is a mixed-integer linear programming due to use of binary variable $j_{t,w}$, because of the product of variables presented in equation (4.10) and (4.9). When this variable take value 1, negative deviation is considered, it means the production has above than expected. In this case, the producer has to pay the difference for not to delivery the amount of energy supposed (negative imbalance $\Delta W^{-}_{t,w}$). In the other hand, when the real energy is higher than the offer given, the producer will receive more money for the exceeding energy (positive imbalance$\Delta W^{+}_{t,w}$).

$$0 \leq \Delta PV^{-}_{t,w} \leq P^{PV}_{max} \cdot j_{t,w}. \tag{4.9}$$

$$0 \leq \Delta W^{-}_{t,w} \leq P^{W}_{max} \cdot j_{t,w}. \tag{4.10}$$

$$0 \leq \Delta PV^{+}_{t,w} \leq P^{PV}_{max} \cdot (1 - j_{t,w}). \tag{4.11}$$

$$0 \leq \Delta W^{+}_{t,w} \leq Pmax^{W} \cdot (1 - j_{t,w}). \tag{4.12}$$

The total energy imbalance, is decomposed in $\Delta PV_{t,w}$ for photovoltaic power production and $\Delta W_{t,w}$ for wind power production deviation, as difference of two parts, the positive and negative imbalances presented in equation (4.22) and equation (4.14), respectively and represents the total deviation of selling in DA market.

$$\Delta^{PV} = \Delta PV^{+}_{t,w} - \Delta PV^{-}_{t,w}. \tag{4.13}$$

$$\Delta^{W} = \Delta W^{+}_{t,w} - \Delta W^{-}_{t,w}. \tag{4.14}$$

Total deviation is also defined as the difference between photovoltaic production, $g^{PV}_{t,w}$, and the power offer in electricity market, b^{PV}_{t}. The same assumption for wind total deviation.

$$\Delta PV = g^{PV}_{t,w} - b^{PV}_{t}. \tag{4.15}$$

$$\Delta W = g^{W}_{t,w} - b^{W}_{t}. \tag{4.16}$$

In short way, the formulation regarding in previous lines are summarized as the following mathematical structure. The first one, equation (4.17) is the photovoltaic formulation, and the second introduce the wind formulation, equation (4.18).

$$\begin{aligned}
\text{maximize} \quad & PF_{PV} = \sum_{w} prob_w \sum_{t} \left(\lambda_{t,w} \cdot b^{PV}_{t} + \lambda^{+} \cdot \Delta PV^{+}_{t,w} - \lambda^{-} \cdot \Delta PV^{-}_{t,w} - c^{PV} \cdot g^{PV}_{t,w} \right) \\
\text{s.t.} \quad & \Delta PV = g^{PV}_{t,w} - b^{PV}_{t}; \\
& \Delta PV = PV^{+}_{t,w} - \Delta PV^{-}_{t,w}; \\
& 0 \leq \Delta PV^{-}_{t,w} \leq P^{PV}_{max} \cdot j_{t,w}; \\
& 0 \leq \Delta PV^{+}_{t,w} \leq P^{PV}_{max} \cdot (1 - j_{t,w}); \\
& 0 \leq \ b^{PV}_{t} \leq P^{PV}_{max}.
\end{aligned} \tag{4.17}$$

$$\begin{aligned}
\text{maximize} \quad & PF_W = \sum_w prob_w \sum_t \left(\lambda_{t,w} \cdot b_t^W + \lambda^+ \cdot \Delta W_{t,w}^+ - \lambda^- \cdot \Delta W_{t,w}^- - c^w \cdot g_{t,w}^W \right) \\
\text{s.t.} \quad & \Delta W = g_{t,w}^W - b_t^W; \\
& \Delta W = \Delta W_{t,w}^+ - \Delta W_{t,w}^-; \\
& 0 \leq \Delta W_{t,w}^- \leq P_{max}^W \cdot j_{t,w}; \\
& 0 \leq \Delta W_{t,w}^+ \leq P_{max}^W \cdot (1 - j_{t,w}); \\
& 0 \leq \ b_t^W \ \leq P_{max}^W.
\end{aligned} \tag{4.18}$$

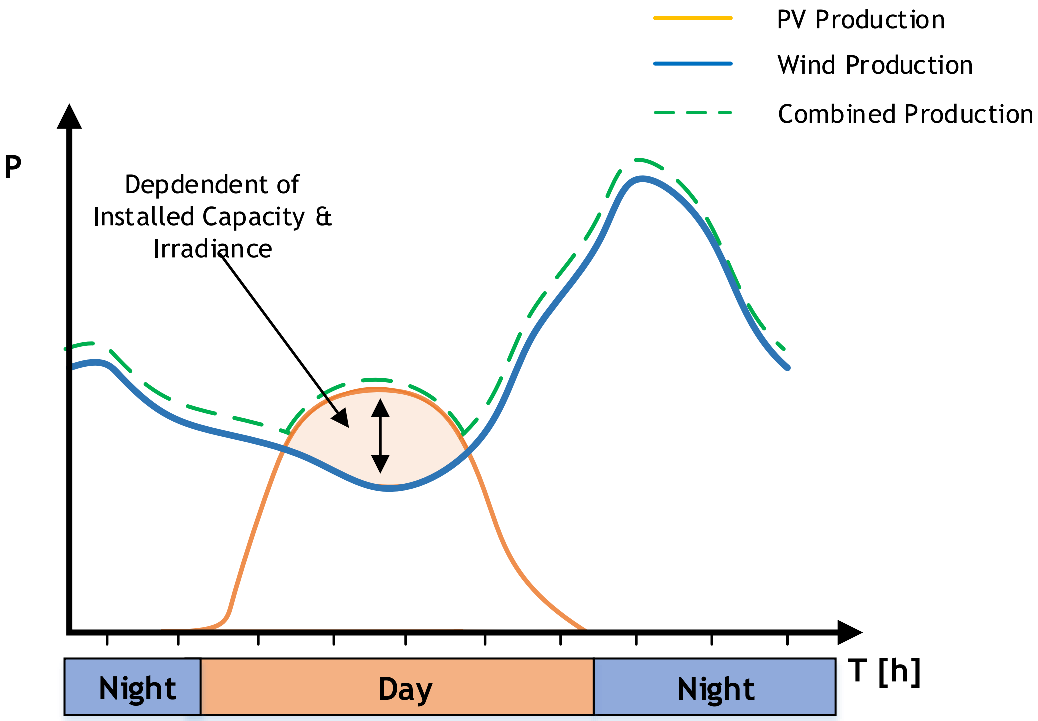
4.6 Combined wind and photovoltaic model

In the combined model, the main goal is to optimize the profit of selling wind and photovoltaic together as a single offer of energy. The figure 4.7 presents a generic example of the pretended approach of combining both technologies. It can be observed as already mentioned, wind power is more available typically in night periods, and photovoltaic during the daylight. Hence, to a producer perspective, combining both technologies will let photovoltaic compensate the variable production of wind in day period. Additionally, in the night periods wind can support all the production, since PV production is not available.

In a general way, the one depicted in this figure, the general line of production will have not a big valley, for example on wind production, because photovoltaic will be there to up the dome. Imbalances of wind production will be low in time of photovoltaic is available to produce by reducing the uncertainty associated of wind.

Although, this example is not true for all circumstances, because as it was explored in the last chapter, Chapter 3, wind and solar sources are dependent on a large number of factors, illustrated in 3.2.3 and 3.2.4, it make it easier to understand the goal of combining both technologies.

So, in this formulation, wind model is now connected to the photovoltaic model and both will be generated as dependents for each scenario w. Previously in other strategy, this scenarios were calculated in separate as independent technologies. Now they will be submitted to the same scenario production in order to get the same variables of decision in objective function to determine the best combine offer of selling both technologies together, photovoltaic production and wind production, as a single offer in the day-ahead market for each period t. Following the same philosophy, three set of prices will be added also into scenarios production with wind and photovoltaic production.



[h]

Figure 4.7 - Illustrative example of combining production (Photovoltaic and Wind).

Profits are determined by the following equation:

$$PF = \sum_{w} prob_w \sum_{t} \left[\lambda_{t,w} \cdot b_t + \lambda^+_{t,w} \cdot \Delta^+_{t,w} - \lambda^-_{t,w} \cdot \Delta^-_{t,w} - c^W \cdot g^W_{t,w} - c^{PV} \cdot g^{PV}_{t,w} \right]. \tag{4.19}$$

The working principle is similar to the previously presented approach. However, the variable b_t is an offer that includes both technologies. If the offer is combined, cost of both technologies have to be considered c^W and c^{pv}. Imbalances are determined by $\Delta_{t,w}$ assuming a negative value $-\lambda^-_{t,w} \cdot \Delta^-_{t,w}$ if the scheduled amount in DA market was lower than expected or $\lambda^+_{t,w} \cdot \Delta^+_{t,w}$ if exceeded production was delivered. Although, the decision-maker needs to analyze a different number of scenarios. So in formulation, objective function will be a sum of offer $\lambda_{t,w} \cdot b_t$ plus imbalances minus costs of production wind power and costs of producing photovoltaic power $c^W \cdot g^W_{t,w} - c^{PV} \cdot g^{PV}_{t,w}$ for each scenario w.

4.6.1 Constraints

4.6.1.1 Offer constraints

Both producers have to offer their energy in the day-ahead market at each hour. All productions are combined and offer to the market with the range that goes to the maximum power production since the value zero, that means not sell energy to the market. These equation is represented in equation (4.20).

$$0 \leq b_t \leq P_{max}. \tag{4.20}$$

4.6.1.2 Imbalance constraints

Since both technologies are uncertain sources deviation has to be taking into account (equation 4.22), this types of technologies is easy to get deviation on scheduled production. This constrains are important in balancing market to equilibrate the market from variable production of renewable. Imbalances are calculated as the difference between production and offer of both technologies equation (4.21).

$$\Delta_{t,w} = (g^{W}_{t,w} + g^{W}_{t,w}) - b_t. \tag{4.21}$$

$$\Delta_{t,w} = \Delta^{+}_{t,w} - \Delta^{-}_{t,w}. \tag{4.22}$$

The imbalances have an upper limit, although in this case the upper limit will be the given by the sum of both technologies production equation (4.23) and equation (4.24).The lower limit of the imbalances is zero.

$$0 \leq \Delta^{-}_{t,w} \leq P_{max} \cdot j_{t,w}. \tag{4.23}$$

$$0 \leq \Delta^{+}_{t,w} \leq P_{max} \cdot (1 - j_{t,w}). \tag{4.24}$$

Therefore, the proposed optimization can be simplified as follows:

$$\begin{aligned}
\textit{maximize} \quad & \mathrm{PF} = \sum_{\mathrm{w}} \mathrm{prob_w} \sum_{\mathrm{t}} \left[\lambda_{\mathrm{t,w}} \cdot \mathrm{b_t} + \lambda^{+}_{\mathrm{t,w}} \cdot \Delta^{+}_{\mathrm{t,w}} - \lambda^{-}_{\mathrm{t,w}} \cdot \Delta^{-}_{\mathrm{t,w}} - \mathrm{c^W} \cdot \mathrm{g^W_{t,w}} - \mathrm{c^{PV}} \cdot \mathrm{g^{PV}_{t,w}} \right] \\
\text{s.t.} \quad & 0 \leq b_t \leq P_{max}; \\
& \Delta = \Delta^{+}_{t,w} - \Delta^{-}_{t,w}; \\
& \Delta_{t,w} = (g^{W}_{t,w} + g^{PV}_{t,w}) - b_t; \\
& 0 \leq \Delta^{-}_{t,w} \leq Pmax \cdot j_{t,w}; \\
& 0 \leq \Delta^{+}_{t,w} \leq Pmax \cdot (1 - j_{t,w});
\end{aligned} \tag{4.25}$$

4.7 Summary

The electricity prices in the day-ahead and adjustment markets are characterized as stochastic processes. The prices in the day-ahead market are considered to be independent of the producer. The producer objective function was presented. This optimization problem tries to maximize the expected profits from offering energy in the day-ahead, minimizing the cost incurred in the balancing market due to energy deviations. In Chapter 5 several simulations will be depicted in order to demonstrate the benefits of each offering strategy.

Chapter 5

Results and Discussions

5.1 Introduction

The current chapter presents a case study based on the previous chapter formulation. Some results are presented with graphical support.

5.2 Input data

The case study comprises a wind farm and a photovoltaic park located in Navarre, Northern Spain. The objective of this study is to present bidding strategies into Iberian day-ahead electricity market, managed by Spain market operator.This strategies were explained in previous chapters in order to select the best one between combined PV and wind and combined offer. As mentioned before, two technologies, wind and photovoltaic, are studied and evaluated if they are more profitable to be delivered together or as a separate offer.

Solar irradiation is a source of uncertainty. It has to be predicted before considering in market offer. For determine the power output, a set of historical data of 10 in 10 minutes of solar irradiation was required. This data were collected from [60].

The power output was determined using equation 4.1 with η_n^{PV}=0.143, A_n^{PV}=1.6*12, G is the solar irradiation from previous data [W/m^2] and N=18200 is the total number of arrays present in the solar park. Every parameters where considering a typical commercial PV array.

The irradiation is simulated with a Normal distribution fixed per hour. Adjusting irradiation with normal distribution it will be generated by a range of scenarios.

Wind is another source of uncertainty. For determine the power output, a set of historical data of 10 in 10 minutes of wind speed is required. This data were also collected from the same meteorological base, available in [60]. The conversion to WP is given by 4.5, where A is the area of turbine rotor of $80m$ of diameter, ρ^W is $1,2kg/m^3$ and $c_p(v)$ is 0.59 of value and N represents the number of turbines of 25 turbines.

Wind will be represented by a weibull distribution. After the adjustment, PV and WP output are simulated using the Monte carlo method for a specific number of scenarios of irradiation per hour in a range of 168 hours.

The photovoltaic park has a total capacity of 50 MW and a marginal cost of 23.6 €/MWh. The total wind capacity is 50 MW and the wind marginal cost equal to 17 €/MWh. Costs values of both technologies came from [61]. The simulations are for the Spanish electricity market, and for a time frame of 24 and 168 hours.

The uncertainty is introduced through the parameters such as the wind generation, the photovoltaic generation. Also prices are sources of uncertainty. Market prices, the positive imbalance market prices and the negative imbalance market prices. Market prices came from iberian day-ahead market prices available in [62]. Imbalance prices, otherwise from [63] from temporal periods of July to September, 2014.

All this parameters are stochastic processes that can be describe through scenarios. Scenarios will show up possible alternatives that a decision-maker can have. So this processes has to be dependent of scenarios. For this case scenario tree are aplied to describe the stochatic variables. It means that Wind and PV have to be distributed in hourly base, once the bidding, the iberian day-ahead market, is taking for each hours of a day.

Depending on number of decision, it can be considered two-stage decision or multi-stage decision. In this specific decisions, two-stages decisions will be presented. The first stage is carying about market prices, the second is the considered generation scheduled. For this case, are presented three two-stage scenario trees, two for the separated model and one for the coordinated model as presented in figure 5.1. In separated offer case, scenario tree is divided into two trees. The first tree comprises the price node and the second node, photovoltaic generation is distributed.

The total scenario are 36, considering 6 market price scenarios and 6 photovoltaic production scenarios, it makes $w = 6 \times 6 = 36$ scenarios.

The second tree has the price node and after the wind generation node, as a second node. The procedure is the same of the previous one, with photovoltaic. Remaining the same number of scenarios for market prices and wind power generation, total of scenarios are 36 scenarios.

For both scenarios, containing or PV or wind generations, the probability for each scenarios happen is: $w = P1 + PV1$ $w = 0,01 \times 0,027$. $w = P1 + W1$ $w = 0,01 \times 0,027$.

Scenarios have the same probability of happening, in fact, by the probability property, the sum of all probabilities have to make 1. So dividing 1/36, where 36 is the number of each uncertainty source scenarios, it ill give the $0,027$. In the total, each scenario with two decisions will give $0,027 \times 0,027 = 0,000729$.

The third tree is considered in offering PV and wind as a single offer. A two-stage scenario tree has now, the market price as a first node that match with first stage decision and the photovoltaic generation with wind generation as second and third nodes, and this both are a second stage of decision.

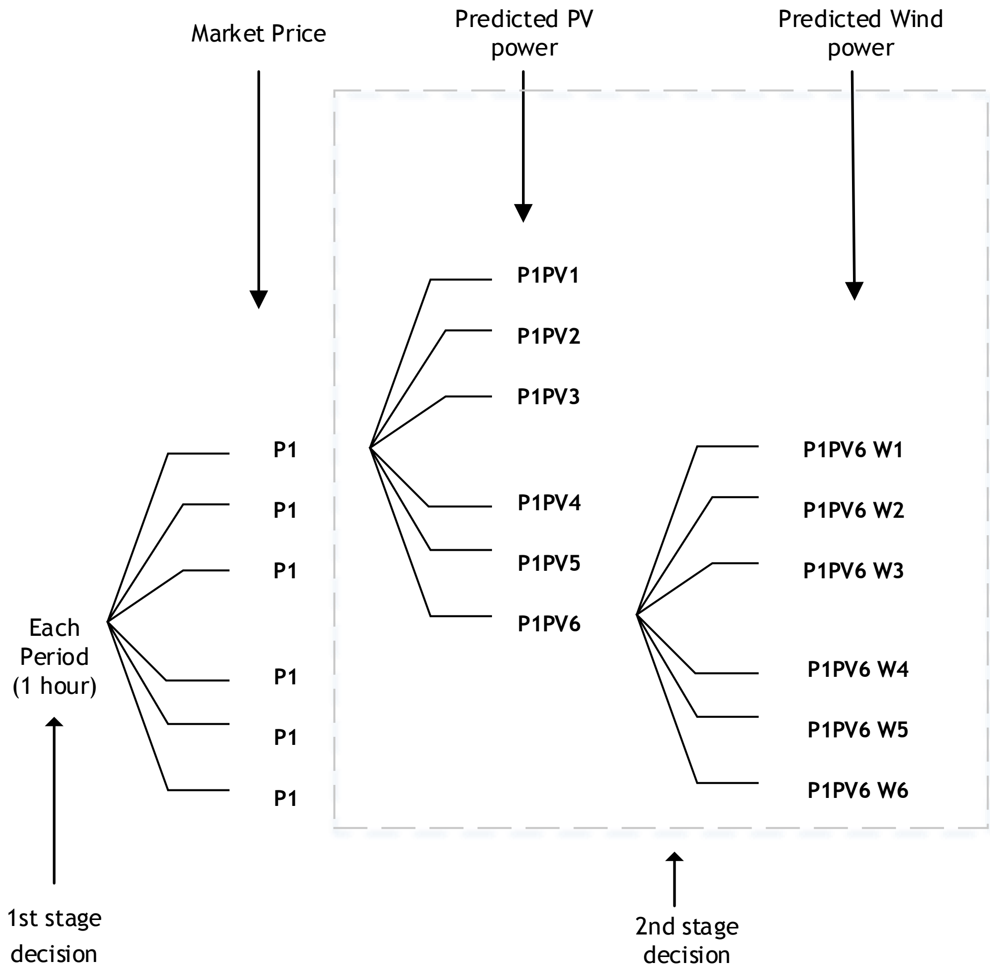


Figure 5.1 – Scenario schematic of Two stage decision.

In this second model of bidding, the same number of scenarios for each source will be remain the same. However, the number of scenarios will make a total of 216 scenarios. This result from the connection of market prices, PV and wind generation scenarios, each one with 6 scenarios. So the total is given by $6 \times 6 \times 6 = 216$ possible scenarios.

The probability now of each possible scenario is smaller. The same property is respected again. the probability it will be given by $1/216$, witch 216 is the number of total scenarios divided by total number of generated scenarios.

The modulation of scenarios was solved through Matlab sotfware [64]. All the input data are managed into Matlab.

After the application of scenarios, stochastic mixed integer linear programming is applied to determine the best profitable offer into the electricity market. The best result is achieved regarding all scenarios.

This optimization stochastic problem was solved trough Matlab/GAMS interface, using CPLEX solver. CPLEX can solve stochastic problems with binary variables. Binary variables are used to determine the RES generation, as random variables. Although, some constrains are needed to limit this uncertainties and make it solver. For each technology generation the maximum limit of production is the total installed capacity of each park, as presented in previous chapter.

Its are also generated though GAMS [65]. For the first case xx constrains xx binary variables and xx variables were used. For the second case xx constrains xx binary variables and xx variables were used.

5.3 Results

5.3.1 Market price and Imbalances

Price scenarios are demonstrated in figure 5.2. It is visible volatility in market price for Day-ahead market. Volatility is represented by soft grey color line, and variations are represented by different demand energy required and the amount and type of energy bringing to electricity market.

Usually, prices are lower at night, after midnight, because of lower consume. In iberian countries, the consume is lower at morning and afternoon, in times people are at work, so consume is more concentrated in companies and services. At night and in the first hours in the morning is when consumption comes bigger because of the human activity is more concentrated in that periods. And at night, after midnight the prices drop due to the lower demand. Evidently prices are bigger when are more needed. The mean value is presented at black color closer to 50 €/MW. At night, this value drops to 22 and at day can achieve 60 €/MW.

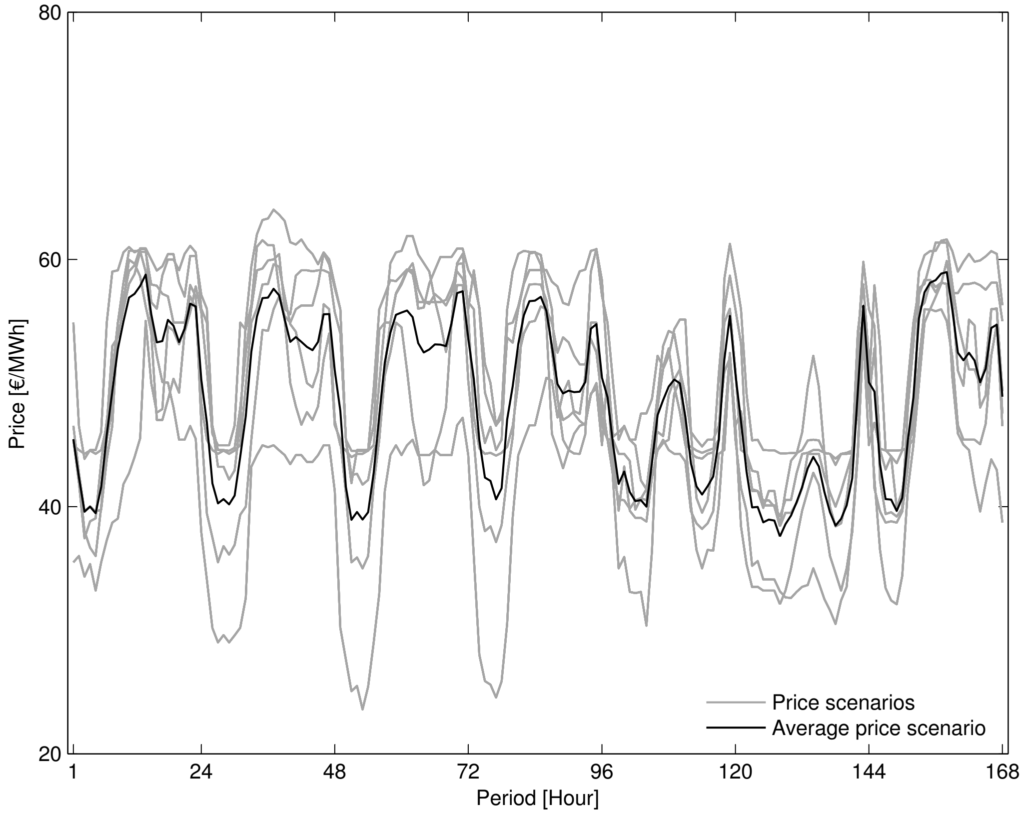


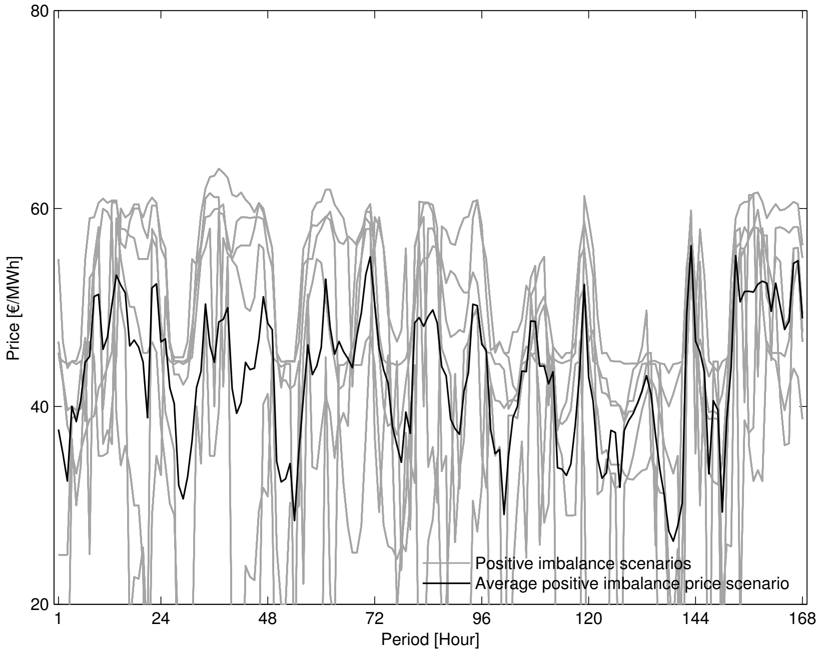
Figure 5.2 – Price scenarios, in €/MWh and average price scenarios from July to September 2014.

According to the prices curve. The most profitable time to sell energy is in higher spot of price, where prices are higher, and producer can have more benefit from selling at that time.

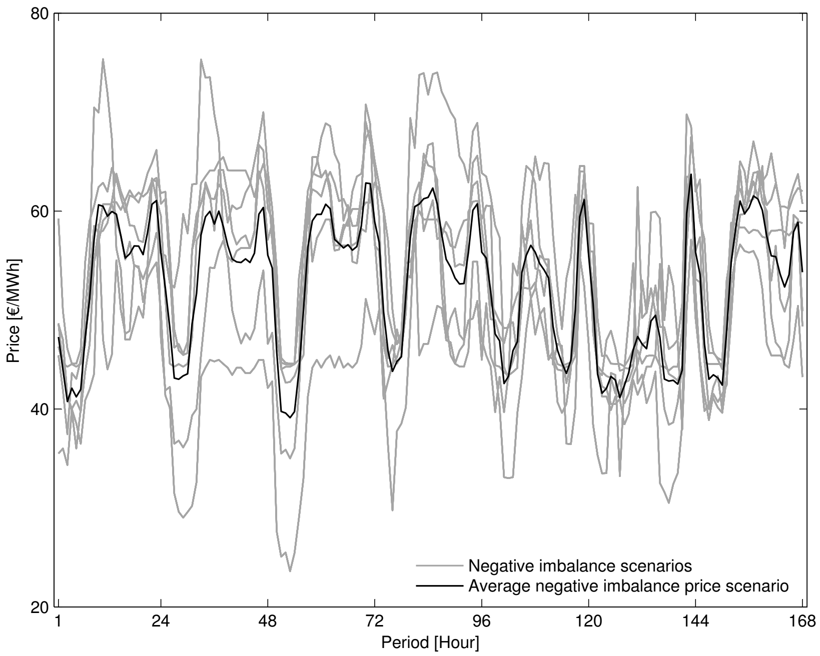
Figure 5.2 presents the marginal price scenarios of electricity DA market of iberian market. Prices are higher during peak hours and lower and out of it. Higher volatility in peak hour is expected, being the time of the most required energy.

Looking at the first four days, the prices follow the same pattern, with similar prices and shape. As a behavior cycle. However, the last three days something happened to get the price dropped. Market prices are achieved by crossing the demand and the supply. If one of these two become lower, it has direct influence on market price. Human habits in general remain the same, but not generation, specially if has RES integration. The higher production of this type of energy will lower the market price.

The next figure introduce imbalances prices for 168 hours. Positive imbalances is lower than negative imbalance prices, analyzing the next figure 5.3. This means, in proportion, having a deviation of production unscheduled it not represent the same amount, received and paid. With this figure, if a producer has an negative deviation will have to pay more that in a receiver case, where the received amount is less. So in general having a deviation is more risky to be negative than positive, because the imbalances will present a higher ratio to penalty than benefit.



(a) Positive imbalance price scenarios and average price scenarios.



(b) Negative imbalance price scenarios and average price scenarios.

Figure 5.3 – Prices, in €/MWh, from July to September, 2014.

Comparing both imbalances, it easily identified than both depends of market prices due to variation. When positive imbalances are higher, the negatives are also high. Otherwise, when the positive drops, negative imbalances are lower too. Moreover, and following the same previous idea, prices of imbalances are lower in the last three days, as a direct influence of market price dropped.

Bidding in lower prices, the revenue will be lower but in the other side will have less risk of having high penalties if scheduled production were less than promised. In the other hand, if the producer have a positive deviation, it means to bring more energy into the market, the extra profits will be lower than expected

5.3.2 Production

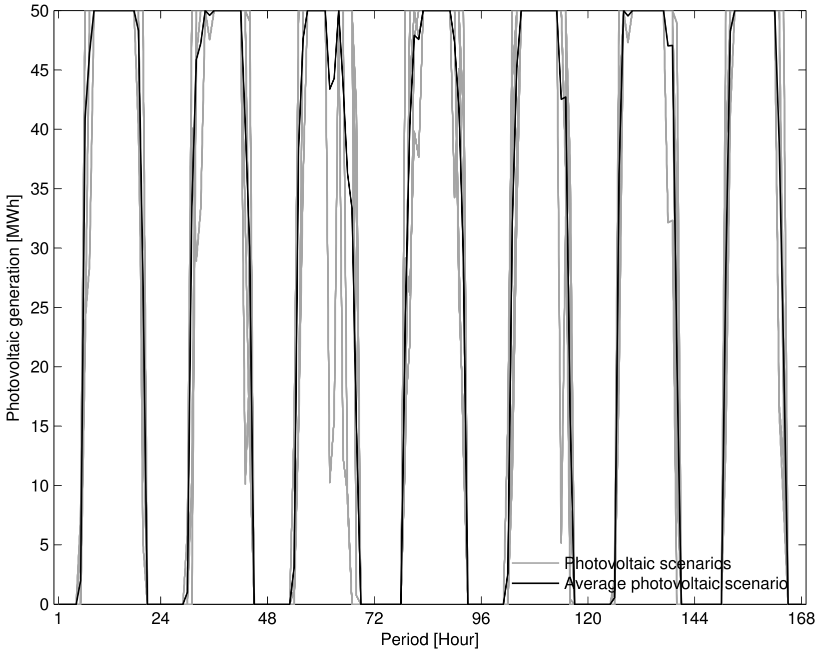
In figure 5.4a, photovoltaic generation scenarios is presented in Mwh. There are always some values with zero value in approximately 24 hours interval. This period is characterized by night period where sun is not available and then photovoltaic production is not possible. In a light grey color, 10 photovoltaic scenarios are presented and they are very close to the mean value. Although, the third day, depicted between 48 and 72 hours period, is the most variable period with more variable scenarios, achieving at one scenario a production of 10 MWh.

Wind generation scenarios is presented in the next figure, figure 5.4b. The wind data sets comprise ten minute averaged speed measurements that have been aggregated into hourly time intervals. These data were collected between 1^{st} of July and 30^{th} of September of 2014. In a different position of photovoltaic, wind speed is not usually normally distributed. It follows a Weibull distribution. Wind speed frequency distribution of historical data and the corresponding probability density function (pdf) of the fitted Weibull is presented in figure.

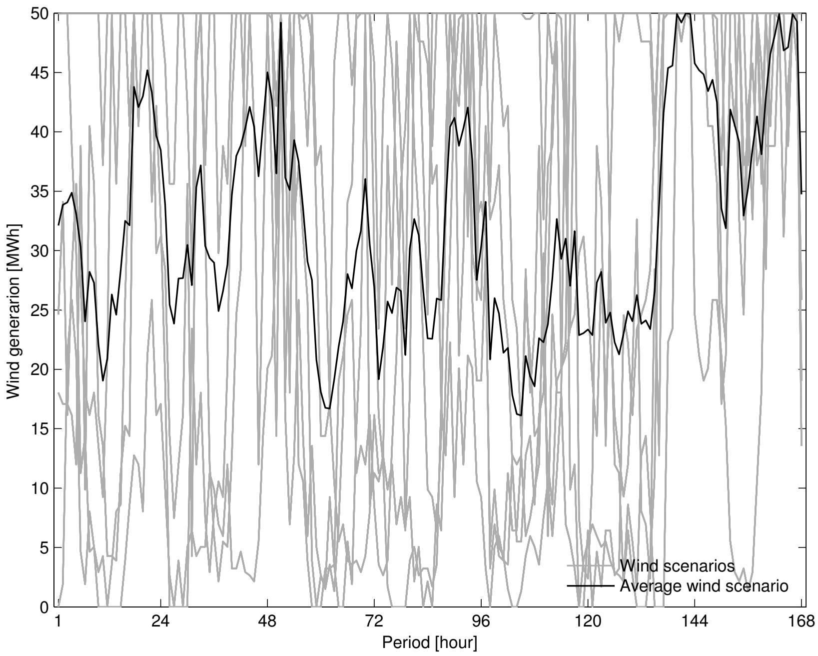
In a opposite way of photovoltaic, wind generation scenario are more volatile, due to variable of wind in during a period. It is much more oscillatory, being more profitable at some times and worst in other, gaining more but also loosing more.

5.3.3 Separate offer and combined offer

Separate and combined offer were simulated in order to achieve the best results. In Table 5.1, profit and deviations are determined in values. To get a better precision analysis. Evaluating the results, the conclusion is in profit manner, the participant will receive the same amount of selling both together or in separate offer. Although, analyzing deviation is evident the differences. For this week, almost 5.000 € are saved from combining offers than bidding as a separate offer. witch means a better prediction of combined offer in achieving the same profit as separate offer, with less deviation. Deviation is not always a bad call, but is more risky, resulting in a bad prediction in losses for the participant.



(a) Standard deviation and average of standard deviation of PV generation.



(b) Standard deviation and average of standard deviation of wind generation.

Figure 5.4 – RES generation, in MWh, from July to September, 2014.

Moreover, analyzing the imbalances, separate offer has less negative imbalances comparing to combined offer and more positive imbalances. Positive imbalances are good because they represent an extra profit for bringing more energy into the market. The reason is simple, besides having a lower deviation, combined achieved the same profit witch mean the prediction is less risky than with separate offer.

Focusing on production, wind was, for this week, ans in general more profitable than photovoltaic, witch means a better integration of wind technologies than photovoltaic. So there is a future work in try to create strategies for photovoltaic integration be more profitable. Additionally, being photovoltaic a limited technology does not help in this process, by not having enough capacity to produce energy at night.

In this specific situation, in analyze of separate offer (SO), profits of selling solar was 43.344 € less profitable than wind. This value is less disparity because, between wind and photovoltaic, photovoltaic has in this week less deviation. In MW values, wind has a total deviation of 2.320 MW while PV had almost 0,380 MW. It is simply explained by being an summer pick week, so the sun irradiation indexes are, in generally, higher at day time, but at nigh too. At night there is no deviation by the incapacity of photovoltaic produce at this time. No production, no deviation. It allowing to have, in general, a lower deviation than wind. It is more significant in analyzing the extra amount from deviation delivery. Only, approximately, 16% of standard deviation is caused by photovoltaic. It presents a 8.210,57 € out of 49.804,20 € of standard deviation.

Comparing the separate offer with combined offer, it is evident that the profit is not so different, having a difference of almost 500 € favorable to combined offer. However, in manner of standard deviation, combined offer had less deviation than as a separate offer. It is not so much but observing the both profit and standard deviation parameters, combined offer got a more profit of 500 € for a less 7.066 € of standard deviation and also less 0,463 MW delivered.

Table 5.1: Total profits, standard deviation of the total profits, average positive imbalances and average negative imbalances for both strategies.

	Wind power	PV power	Total SO	Combined
Profit [€]	163.205,54	118.861,55	282.067,08	282.519,11
Standard deviation [€]	41.593,63	8.210,57	49.804,20	42.738,24
Total offer [MW]	5.910,77	4.690,89	10.601,66	10.137,59
Average Positive imbalance [MW]	878,07	77,24	955,31	1.167,13
Average Negative imbalance [MW]	1.422,90	303,20	1.726,10	1.473,85

5.3.3.1 Comparison between SO and Combined offer

The next Figure 5.5 is a short vision of the previous on. Actually it is more simple to check some differences in bidding. It is presented the two offers strategies, in separate offer technologies highlight in red color and both technologies together as a combined offer presented in blue color. Comparing both offers it is possible identify periods with the same amount of energy production. The first appears in the first peak. This hours is part of night period, where photovoltaic is not able to produce. So it is sure to say that this generation is provoked only by wind production, representing not variance in offer, once, at that period, only wind is offer as a combined or separate offer. Same thing happen in other period during a week, specially at night for the same reason.

Most of the time, separate offer is more capable to deliver more energy that combined strategy. At some periods, as, for example, between 60 to 72 hours, big different amount is delivered by each strategy, being higher with an increment of 30 MWh of difference. The same disparity can be detected in hour 130 and between 144 and 168 hour period. Although, combined offer is witch present more profits with less energy bidden, as presented in table below, Table 5.1. Hence, bring more energy to the market is not synonymous of making more money. It is because of the volatility of the price. In peaks with more energy bidden from combined technologies, became more profitable because with less energy the amount received was higher than in periods with more separate offer bid.

Moreover, it is possible to find same periods with zero MW of bid. In this cases, at this periods the energy produced will not give enough profit in selling energy. Or because of insufficient energy produced or because this energy will have an nonviable return, it is not enough to cover the costs of production. But into day-ahead market a participant is obligated to offer in every period. Even if not profitable. So in this analysis the decision is to offer the less energy as possible.

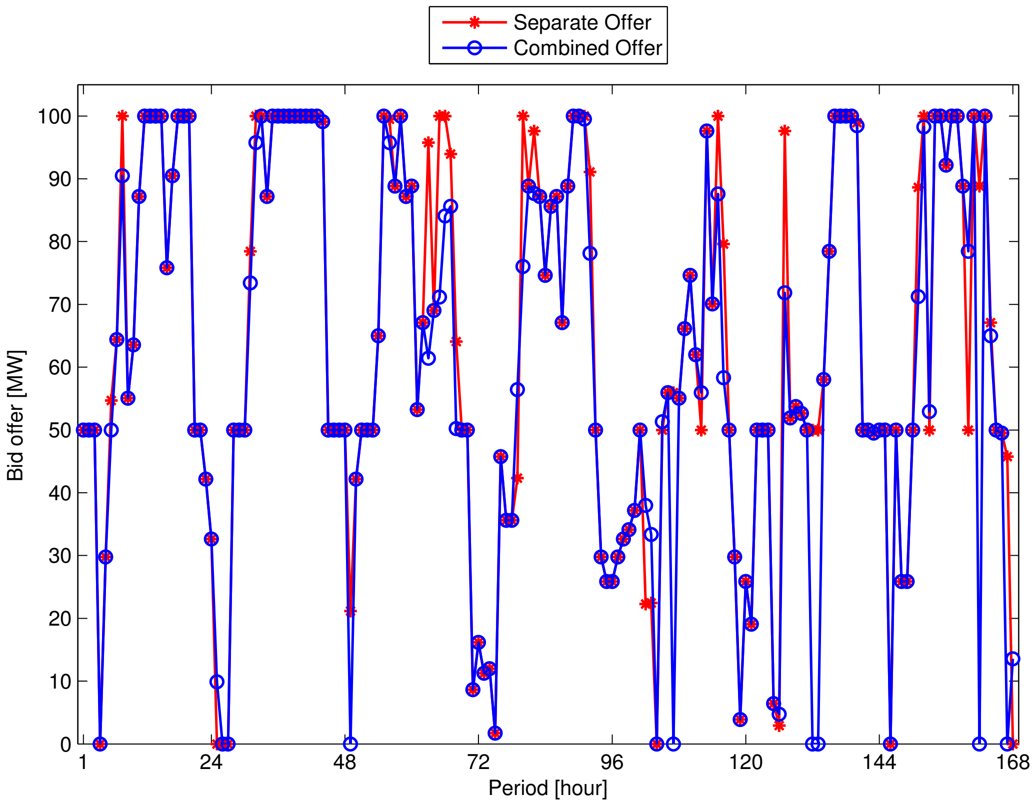


Figure 5.5 – Comparison between SO and CO of PV and Wind power generation, in MWh.

5.4 Summary

This chapter presents a stochastic programming model to allow producer in derivative optimal offering curve into day-ahead market. By the nature of wind and photovoltaic plants, producer is considered in balancing market.

The balancing market prices and market prices are characterized as a stochastic processes, as well as wind and photovoltaic power generation. But prices are considered independent of producers action.

Stochastic model used is well known as mixed-integer linear programming and can be solved using commercial software.

Chapter 6

Final considerations

Choosing the best approach is not optimization models decisions, but decision-makers. Optimization is an helpful tool to show possible ways to take, specially, in stochastic processes, where multiple random variables are unpredictable. At the last result, can give an idea of how is the system behavior and what should be the answers in taking some decisions.

The case explored in this dissertation was predict the market prices and imbalances and also the uncertain production of PV and wind power. The optimal solution between a range of scenario demonstrate the more benefit of bring combined offer to the market, once it presents less deviation and more profit. Also imbalances are lower.

Thus, in an investors point of view, he wanted to have a higher return of investment as possible. In RES, investments are expensive and requires tied money, once returns are slow. Although, with prediction techniques, it is possible to make returns faster.

In the other hand, decision-maker may opt for a more defense position of to have lower risk, because renewable energy, specially photovoltaic and wind, are extremely difficult to predict, and in a last case, they can loose more money if they have to pay the penalty.

This technique is only one tool of prediction. There is no certain in predicting the future decisions due to the uncountable unexpected variables that future imply. There why the development of different techniques.

The present dissertation proved with this technique that combined PV with Wind technologies can be not so profitable but can reduce the standard deviation of selling in Iberian day-ahead market.

6.1 Future work

Photovoltaic energy is a gap in literature, so there is an wide possibilities to explore in future work. The technique presented is a neutral-risk perspective, but it could be interesting in explore the incorporation of some risk position. On the other hand, additional forecast techniques can be used to improve the accuracy of the model and study the impact of incorporating new techniques.

In market participation, as presented before, some strategies were adopted in order to increase the profit of bidding RES technologies. One way to improve the profit and lower the risk is combined different RES technologies with similar or different characteristics and study the difference and impact on the electricity market.

In the same philosophy, it could be interesting combined PV with other technologies (e.g. storage, hydro) because its have another characteristic of being more dispatchable technologies. Explore the differences between them may lead to a higher profits and maybe an strategy to encourage more investment in RES in electricity market. Other possibility is also combine this technologies with wind.

6.2 Research Contributions resulting from this Work

A.A.S. de la Nieta, T.A.M. Tavares, **R.F.M. Martins**, J.C.O. Matias, J.P.S. Catalão, J. Contreras, "Optimal generic energy storage system offering in day-ahead electricity markets", in: Proceedings of the IEEE Power Tech 2015 Conference, Eindhoven, Netherlands, 29 June - 2 July, 2015 (accepted).

A.A.S. de la Nieta, **R.F.M. Martins**, T.A.M. Tavares, J.C.O. Matias, J.P.S. Catalão, J. Contreras, "Short-term trading for a photovoltaic power producer in electricity markets", in: Proceedings of the 2015 IEEE Power Energy Society General Meeting — PESGM 2015, Denver, Colorado, USA, July 26-30, 2015 (accepted).

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