UNIVERSIDADE DA BEIRA INTERIOR
Engenharia

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

Renata Filipa Morais Martins

Dissertação para obtenção do Grau de Mestre em
Engenharia e Gestão Industrial
(2º ciclo de estudos)

Versão Final após Discussão

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

Covilhã, julho de 2015

This work was supported by FEDER funds (European Union) through COMPETE and by Portuguese funds through FCT, under Projects FCOMP-01-0124-FEDER-014887 (Ref. PTDC/EEA-EEL/110102/2009) and PEst-OE/EEI/LA0021/2013. Also, the research leading to these results has received funding from the EU 7th Framework Programme FP7/2007-2013 under grant agreement no. 309048.

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

COMPETE
PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

SEVENTH FRAMEWORK
PROGRAMME

Acknowledgements

I would like to express my gratitude to my supervisor Professor Doctor João Paulo da Silva Catalão. I am grateful for the opportunity he gave me to develop this dissertation under Sustainable Energy Systems Laboratory (SES). His trust, support and motivation were crucial for the success of this dissertation.

Also, I would like to express my gratitude for the Professor Doctor João Carlos Oliveira Matias, for its support and trust not only during this phase but during my path in the master.

I would like to express my deepest gratitude to Doctor Agustin Alejandro Sánchez de la Nieta López. His patience and support were important during the course of this work. Also, I am thankful for the knowledge that he passed me. I considered his inputs significant and of importance for the success of this work.

I am very thankful for my friends help, showing me how blessed I am. Their support were crucial in this work development, especially during difficult times. I would like to express my gratitude to Iliana Pappi for her support, patience and contribution. A special thanks goes to my friend Miguel Medeiros for all his support, trust and the knowledge that were always helpful.

Finally, I would like to express my gratitude to my parents. There are no words to describe their support during these years. I am grateful for their support, patience and trust which without them this important mark would not be possible.

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 estes problemas ambientais. Uma das soluções encontradas para estes problemas passa pela introdução de fontes renováveis no sistema elétrico. As energias renováveis, não só contribuem para os objectivos ambientais, como também, apresentam-se como uma oportunidade de reduzir as pressões económicas que os países têm enfrentado no que respeita à dependência dos combustíveis fósseis.

No entanto, existem desafios com a introdução de energias renováveis na produção elétrica, nomeadamente com a introdução de tecnologias como a fotovoltaica e a eólica. Este tipo de tecnologias, caracterizadas como energias de produção variável por serem fortemente dependentes das condições climatéricas podem ter impactes negativos quando integradas no mercado de eletricidade, uma vez que a produção deste tipo de renováveis traz muitas vezes incerteza para o mercado, desencorajando a sua utilização. Contudo, se a produção a partir de fontes renováveis for bem sucedida, modelos de decisão mais sofisticados 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 de electricidade. Ambas as tecnologias oferecem a produção de energia a partir do sol e do vento com o objectivo de chegar a uma mais benéfica oferta ao mercado de electricidade.

Palavras-chave

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

Abstract

Electrical energy sector has been changing over the past years due to economic and environmental causes.

The climate changes over the last decades have led to the Kyoto Protocol agreement in order to address these environmental concerns. The appointed solution which is proposed as an answer to these concerns is the production of electrical energy through renewable energy sources (RES).

RES not only contribute to these environmental goals, but also are an opportunity to reduce the economic challenges that countries face due to fossil fuel dependence.

However, it is important to address the challenges that come from adopting RES as a means of energy production. Several RES such as wind and solar production, which are strongly dependent on weather conditions, could have a negative impact on market structures. The production from these types of sources can introduce significant uncertainty to electricity markets, which could further hinder their use. If the investments on RES production units such as wind and solar are to be successful, decision-making models could help the investors to be confident regarding the investment, increasing the promotion of the use of these technologies.

In this dissertation, two bidding strategies in the day-ahead market are presented. The proposed strategies maximize the profits from offering the wind and photovoltaic production in the day-ahead market, improving the production management.

Keywords

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

Contents

List of Figures

List of Tables

Relevant Acronyms

CNE	*Comisión Nacional de Energia*
DA	Day-ahead Market
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 operator
Mtoe	Million tonnes of oil equivalent (1 Mtoe = $11,63$ TWh)
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 Rources
SMILP	Stochastic Mixed Integer Linear Programming
SO	System Operator
VIC	Vertical Integrated Companies

List of Symbols

A. Sets

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 electric energy consumption over the past years, especially in emergent countries. However, this rapid electrical demand growth brought a significant problem, the Climate Change. The use of fossil fuels as a means of energy production, led to an increase of greenhouse gas emissions that is compromising the planet sustainability. In order to maintain the planet 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 gas emissions in order to promote the planet sustainability for future generations. This protocol was active until December 2012, but its principles were continued. The *DOHA amendment* came with the intent of further addressing the climate issues by extending the efforts to 2020.

To preserve the planet from climate changes, there is a need to change the energy paradigm, especially regarding the production. There is a need to reduce the use of fossil fuels as a means to produce electrical energy, to prevent the gas emissions and the risk of depleting this resource. Facing this paradigm, the Renewable Energy Sources (RES) became an attractive option to tackle this challenge. This alternative way of producing energy, guarantees the sustainability by reducing the consequences of energy production through fossil fuels, providing its contribution in addressing the climage changes.

The European Union (EU) has already started addressing this climate change issue. Therefore, an European directive has rose, being widely known as the “20-20-20” Directive [2], which has the objectives of promoting the increase of renewable energy production and energy efficiency. Hence, 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 climate challenge made RES a strong candidate to fit the European 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. Moreover, this presented itself as a good opportunity to improve the energy efficiency in countries that are highly dependent on fossil fuels.

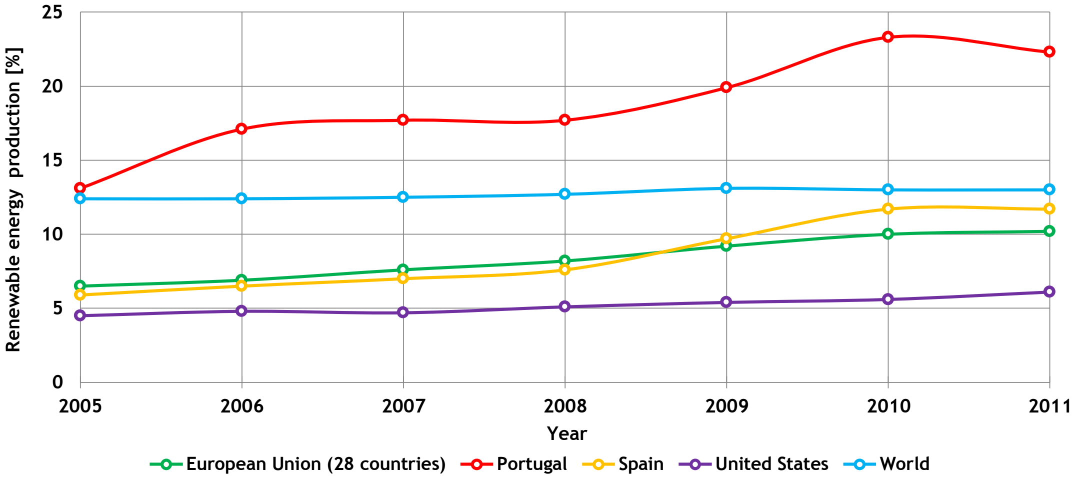


Figure 1.1 – Evolution of renewable energy production.

For a country like Portugal, the RES can significantly improve the country economic situation. This country is highly dependent on fossil fuels and suffers economic struggles from its dependence. However, Portugal started focusing its policy on promoting the use of RES as a mean of energy production. 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%, being the set out goal of 31% by 2020 [3]. On the other hand, Spain has lower levels of RES penetration when compared to Portugal, with a share of renewable generation of 12%, having a goal of 20% by 2020. The EU set different goals for each state member by 2020, regarding the contribution of renewable energy production. This is mainly attributed to the fact that each country differ from the available types of energy production sources.

Considering the goals of Portugal and Spain, it can be expected the goals of Spain are significantly less since this country relies on nuclear energy production. The Portuguese government did not follow this course of action, leaving the option of focusing on the investments in RES. Countries like Portugal have significant opportunities regarding the use of RES. Its geographical location is considered a significant key point to effectively exploit favorable weather conditions [4].

According to [5], the wind energy production in Portugal has been increasing as it is observable in Figure 1.2. In 2013, the installed wind 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 [6]. Also depicted on Figure 1.2 is the CO_2 emissions of this country in the past years. It is noticeable a decrease of CO_2 emissions especially after 2005. Moreover, after this period (2005) the wind and photovoltaic installed capacity increased. This CO_2 reduction could be related to the fact of increased investments in RES. Considering these values, Portugal is fulfilling its objectives regarding the increase of RES while reducing its greenhouse gas emissions.

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.

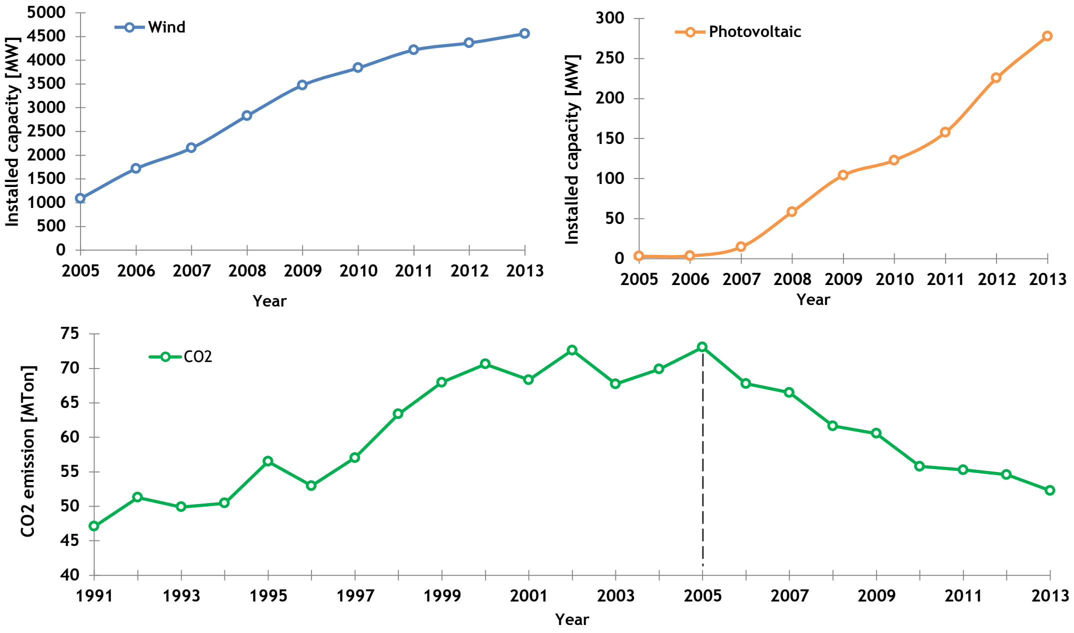


Figure 1.2 – Portugal status: installed capacity (Wind and PV) and CO_2 emissions.

1.1 Background

It is important the integration of RES, in order to accomplish the European environmental and efficiency goals. According to [7], in 2020 it is expected that 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.

It is noticed in Figure 1.3 the 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 [7].

In terms of the value of investment, it is expected 1 trillion of dollars of RES [8]. The photovoltaic (PV) rooftop installations expects an investment of 339 billions of dollars, while wind has a 250 billions of dollars. It is a considerable investment regarding the deployment of both RES technologies (wind and PV).

However, an additional challenge is created in current times. According to the last report on renewable energy progress [3], it is expected that several countries could have serious difficulties in accomplishing the initial goals of RES share if the pace of investment is maintained. It is pointed out that current economic crisis is responsible for slowing down the process of investments in RES. Additionally, the low carbon price did not provide a sufficient incentive, into adopting technologies that contributes to the low carbon policy (e.g. RES).

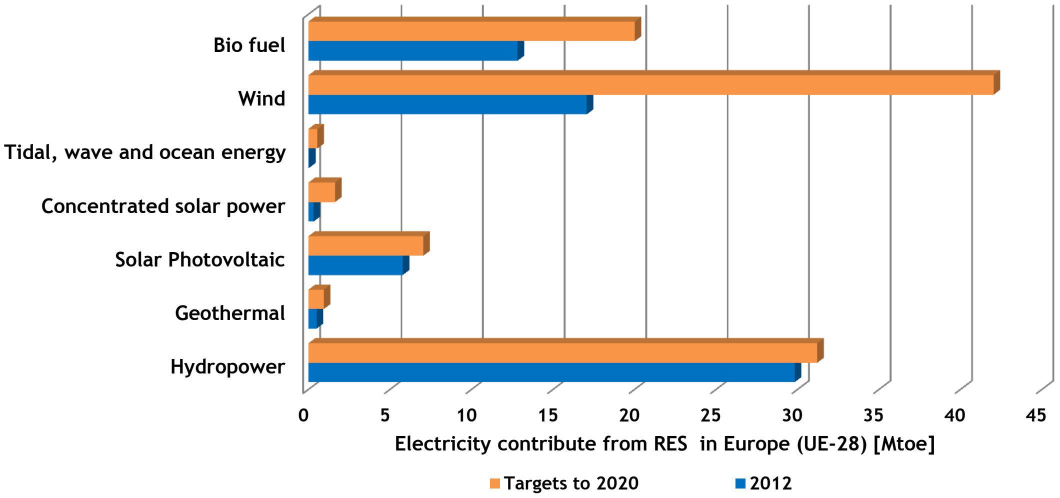


Figure 1.3 – Distribution of different RES technologies for Europe (Data source: [1]).

There is a need to encourage the investments in RES technology. Nevertheless, 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, which places them under the category of 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 especially regarding the RES price. Due to its resource properties, these technologies are considered to have almost zero price of production. On the other hand, the RES technologies have high costs of initial investment that contributes to the increase price when compared to the fossil fuel energy. Therefore, the goal is to bring the RES generation closer and more competitive against the use of fossil fuels, by lowering its selling price, increasing the revenue to the investors reducing the payback period.

1.2 Motivation and Objectives

In order to fulfill the efficiency goals, the RES need a robust electricity market to make it 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 energy production. This can be achieved by developing prediction techniques which aids the bidding of these technologies in electricity markets. Moreover, it could aid to attract possible investors in the use of RES, reducing the risk associated with these technologies by increasing the revenue. This ultimately leads to development of market competitiveness by lowering the electricity prices.

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.

The main goal of this dissertation is to give a contribution in the decision-making under uncertainty to bid into electricity market. Prediction tools can be helpful in determining optimal offers to the market, increasing the revenue of participants.

In short, 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.

It expected that comparing the two offering approaches, the decision-maker could have a better understanding of the possible outcomes of introducing the RES in the electricity market.

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 electric sector is presented. It is explained the restructuring of the electric systems in Europe, explaining the liberalization process 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 resulted 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 sector has been changing over the past years mainly due to the increased energy consumption globally and other factors such as environmental, political and economic reasons. The importance of these factors led to a significant restructure of the electrical system all over Europe.

Therefore, this chapter starts by highlighting the importance of these factors and their contribution to the restructuring of the power system. Additionally, the impacts of this restructure regarding the electricity markets are presented. The contributions of adopting a 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 the 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 totally destroyed. There was a need to rebuild the electric infrastructures after the war, in order to accelerate the development of each country.

In order to facilitate the management of the electrical system, the focus was placed on creating a structure that gave permission to certain large-scale companies in order 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 and distribution of the electrical system [9].

Inside the aforementioned structure, the production was considered to be at the top of this vertical structure. The production of electrical energy was mainly characterized by centralized power plants that used fossil fuels as a way to produce energy. In this vertical structure, the production was planned and scheduled in order to guarantee that the entire system demand is satisfied, without compromising with the system stability. Apart from production, the responsibility for the energy delivery to the consumers through transmission and distribution systems was also entitled to the VIC. Hence, these companies had to sustain the costs of production, transmission and distribution in overall.

Being the fully responsible for the electrical system, the VIC companies had several opportunities that could be exploited. This vertical structure allowed these companies to acquire the full control of the system, even of the price regulation. Therefore, being able to define the electricity price, these companies grew economically faster. A large scale centralized production, allowed these companies to reduce their operational costs. The consumers paid these companies a bill by an electricity price determined by these companies. As a consequence, these companies could better manage their production in order to profit from this fixed pricing scheme.

The consumer was considered to be at the bottom of the vertical structure. In this structure, the consumer had no choice regarding the selection of the energy supplier. Moreover, the electricity bill paid by the consumers was not easily criticized, since the actual costs of production, transmission and distribution were not known at that time [10].

Even with a relatively stable and secure electrical system, emerged a need to improve this structure. The energy supply through the VIC, constitutes a monopoly that can be exploited regarding the prices [10]. This low transparency policy towards the consumers for the actual electricity prices raised concerns about the price fairness. Furthermore, the VIC system is more volatile to political and economic changes that can further jeopardize the efficiency of this system [11]. These changes could even deteriorate the terms and conditions of electricity billing.

Besides the facts stated previously, another important event reinforces the idea of improving this structure. The excessive use of fossil fuels for the electrical energy production brought severe consequences regarding the climate changes. There is 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 had an impact on rethinking the forms of electrical energy production. The energy production through RES was the appointed path to help towards achieving these goals. RES is a new form of energy production that could face the current challenges of an economically and environmentally sustainable electrical energy system.

The use of RES could be of benefit for countries that rely on energy production from fossil fuel sources. Despite its benefits, the implementation of RES is a challenging target. The structure of a vertical electrical system can no longer support these new sources of production. Certain types of RES (e.g. Wind and PV) support the possibility of producing electrical energy in small-scale installations. The nature of RES production can transform the production system from a centralized to a decentralized approach.

Several RES technologies are available to residential consumers that have the reverse ability of supplying with energy the electrical grid under certain circumstances. However, several technical and economic complexities need to be solved. In the technical part, the main problem that rises with this introduction is the shift of energy flow. It evolves from a single-flow to a bidirectional flow of energy. This is especially important for designing protection system equipment in the case of system failures.

However, the economic part of the implementation of RES could be a serious setback. The RES will need to be applied into a robust market structure that can address the market offerings from any producer. Moreover, a regulation frame will need to be deployed in order to prevent further drawbacks related to VIC structures.

Therefore, a market structure is needed in order to promote the several benefits of RES against the production from fossil fuels. Regarding the basic principles of liberalization, the electricity market has to be based in some factors that will mainly determine its success. A better understanding will be given in the following section, Section 2.3.

2.3 Market Liberalization

Liberalization is a necessary process for the market evolution. The market cannot be competitive if it is not well-organized.

In order to promote the competitiveness of energy production, the liberalization of the electricity market is necessary. This market, through liberalization, is able to include several participants (buyers and sellers) to further develop in terms of competitiveness. Hence, a liberalized structure relies on three important factors:

- Open access;
- Restructuring;
- Deregulation.

Electricity markets can only be competitive if are open to everyone without discrimination. Thus, electricity production and pricing can be freely negotiated between countries. Moreover, this point is of help for the power system in order to lower the electricity prices, due to the large number of participants into the electricity markets.

The second important point stated before is the restructuring. This aims to design new regulations in order to abolish the VIC monopoly, and the total control ceased by the companies in a VIC scheme because of this, and in parallel simplify the market structure. This process, also known as deregulation, intends to change the existent regulatory frame with the main goal to facilitate the introduction of a new electricity market. Moreover, this change in the strict regulatory frame prevents from unfair competition, by increasing the participants into the electricity market. In this way, it is an opportunity to work with private interaction, without influence of regulated structures that will facilitate decentralized trading. At the same time, investment decisions are required due to the necessity of separating the electricity companies, by a privatization process in order to promote competitiveness [9].

However, this separation of companies, requires independent control mechanisms to continuously supervise and follow the market, in order to guarantee its security and reliability in manner of transparency and increasing competitiveness, since it removes the VIC price control [12].

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 or through a strictly regulated system. The trade is done in different basis, depending on the type of market. In the European Union section, Section 2.4, the Iberian market will be presented with more detail.

Regarding transmission and distribution systems, it is expected that these systems will not be liberalized since they are physical monopolies, in order to serve everyone. Companies responsible for these systems are require to maintain their operation and technical considerations [10].

Therefore, the liberalized electricity market has two sides: technical and economic side. On the technical side, these markets 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 avoidance of energy congestion in transmission lines).

On the other hand, the market operator is responsible for the regulation of the prices between the different energy producers, by 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 [13].

Different approaches have been suggested in order to achieve a liberalized market. The different approaches of electricity market models [12] are:

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

The first approach to create a competitive market was the single buyer model. In this model, the producer is able to make contracts 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 a unique company.

In order to overcome the problems of this model, two others were proposed: the wholesale market model, designed for electrical energy producers; the retail market model, designed for energy retailers, resellers. For the scope of this work, the wholesale market is explored in the context of European Markets.

2.4 The Liberalized European Market

The European Union has already started the liberalization of the electricity market, with the purpose of reducing the greenhouse gas emissions and increasing the energy efficiency with the use of RES [14]. In Figure 2.1 the evolution process of the European electricity market models is presented.

The process of market change started in 1996, by the Directive 96/92/CE [15]. This first approach consisted of adopting the single-buyer in each state-member of the European Union. In this market model, there is only one single-buyer of energy for producer companies, where this single-buyer is responsible to buy all production and was also the only one responsible to sell this energy to the final consumers.

On the other side, production companies are Independent Power Producers (IPP) from the regulated system. Competition is possible with long-term contracts between IPP with single buyer companies. These contracts protect the producer from investment risk. Moreover, revenues are paid in a fixed price base, independent of its production. This risks are supported by final consumers, not by the producers [16], as an incentive to attract new RES investments due to the strong necessity to meet the European goals. This appears to be a costly solution for the final consumers.

In the end, this market model does not put an end to the monopoly, since these companies have the full control of final consumers. Additional costs are applied to the final electricity price for the final consumers. One more time, final consumers have no right in choosing their supplier. The selling is done by single-buyer companies, having one more time, total access to the electricity price determination. That was the reason of EU countries to adopt other market models.

It was in 2003 that the Directive 2003/54/CE [17] 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 [14]. 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.

It is noticeable that the main purpose of this Directive is the separation of power producers in older VIC schemes. 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 with continental regions. Therefore, these companies are responsible for maintaining the entire electrical system.

The last package, Directive 2009/72/CE, was created for 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 help towards bigger price competitiveness [18]. This is an important step into developing the liberalized market shaping into the IEM.

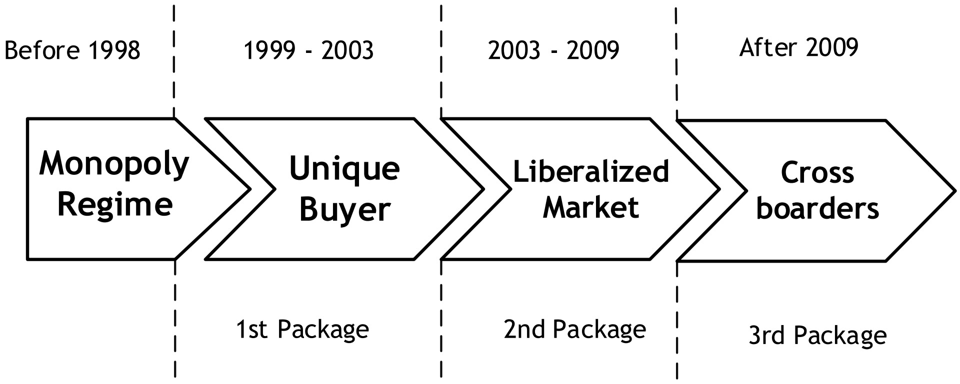


Figure 2.1 – European market models evolution.

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 in a second step. In this philosophy, small markets have been emerging, following the same principles of the competitive electricity market. Currently, it is expected that Europe will be divided into several markets, being the most relevant [19]:

- 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).

Despite the market separation, it is the ultimate goal of the liberalized market to combine all these market structures into a single European market structure. The working principles of each of these market structures are similar, adopted in different regions. Therefore, in the context of this work, the working principles of MIBEL are explored.

2.4.1 Iberian Electricity Market (MIBEL)

In Iberian space, Spain and Portugal made an agreement that led to the creation of the Iberian Electricity Market (MIBEL) in 2004 [20]. In 1997, Spain started its liberalization process by the implementation of 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 the Iberian area could buy electrical energy from any energy supplier or retailer operating in Portugal or Spain. In order to do it, new policies were needed in order to establish the energy exchange between both countries.

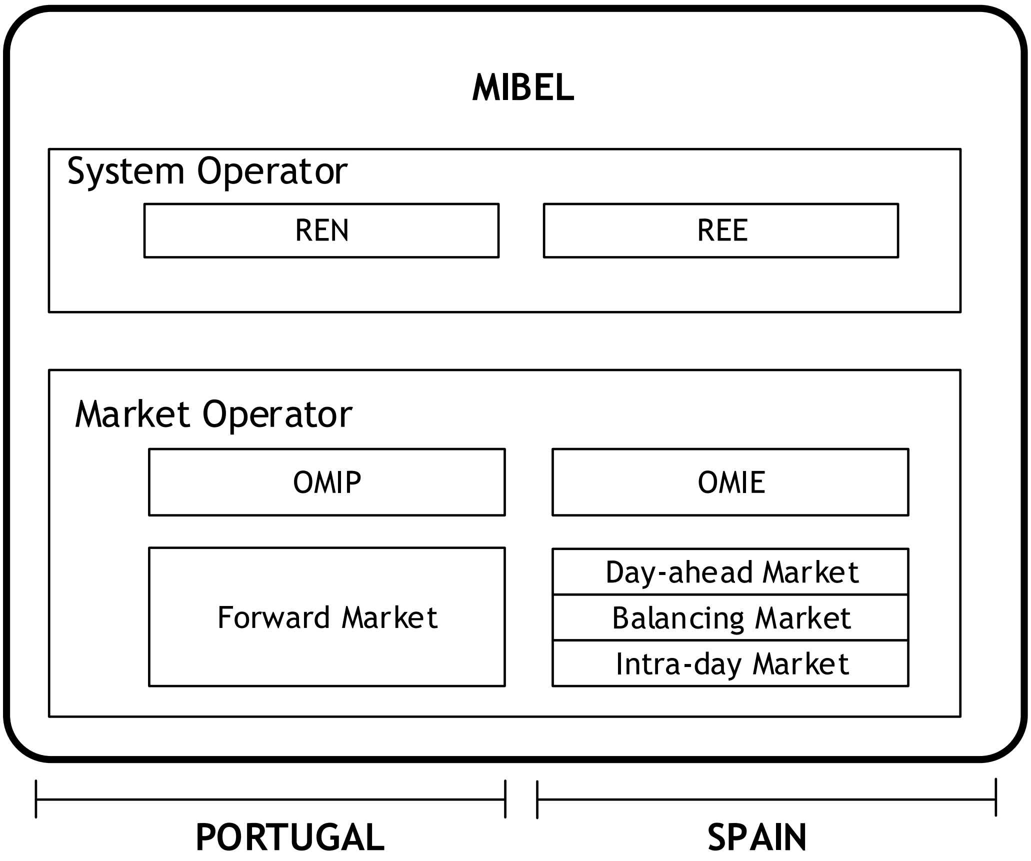


Figure 2.2 – Principles of MIBEL structure.

Evidently, each country still has its own regulation system. In Portugal, this regulation is managed by an independent company, ERSE [21]. In Portugal, licenses are required in order to gain access to production in this market. Despite this fact, small producers can be found in Portugal that have no direct access to the market structure.

These small producers are obligated by law, to sell the energy to the last-resort market company. If small energy amounts could be easily introduced in the market it could create disparity in offers [22]. The costs of entering in the electricity market, is not profitable, since costs are higher than benefits [23]. Last-resort market company is trading this energy with more profitable offers into electricity market.

The MIBEL is organized and managed by two countries as can be illustrated in Figure 2.2. Portugal is responsible for the forward market where Portuguese market operator (OMIP) is the system operator. On the other hand, the management responsibility of the short-term market is guaranteed by Spanish market operator (OMIE). As stated before, market operators are responsible to determine the price by guaranteeing its transparency. There are also system operators in each country responsible for the technical structures: Portugal: Rede Eléctrica Nacional (REN); Spain: Red Eléctrica de Espanã (REE). Since the market structure is relatively new, independent entities are responsible for supervising the market competition and guarantee the consumers' rights [24]. In Portugal, the responsible entity is Entidade Reguladora dos Sistemas Energéticos (ERSE), while in Spain this function is held by Comisión Nacional de Energia (CNE).

Bilateral contracts are also available in both countries. Bilateral contracts are signed between sellers and buyers, in which they can freely negotiate energy. It is to be noted that each country still has public entities where regulation exists. The ultimate goal is the migration of these entities to the electricity markets. However, the migration is a slow process due to its complexity.

Still, every year the number of market participants is increasing, especially in the short-term. By March 2015, Portugal had 3,9 million of clients in MIBEL [24]. The Day-Ahead market is a type of short-term market that is available and widely used in MIBEL [25]. This market type is presented in section 2.4.2.

2.4.2 Day-Ahead Market

Short-term transactions in MIBEL are done in the Day-Ahead Market, which deals with short-time period exchanges. The main goal is to make use of management mechanisms in order to create equilibrium between production and consumption supported by participants, eligible consumers and producers. In day-ahead market, participants have to decide the quantity and the price of energy that intent to sell/buy in the previous day of the dispatch. According to [26] the bidding strategy principles are:

- The 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.

Trading action 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 have to take place in the twelve hours before the first hours of previous day. After the submission, the market operator will determine the price of energy. This generic behavior can be observed in Figure 2.3. In the intersection of both curves (supply & demand) it is presented the market price for a single period (1 hour). The marginal price is the mechanism of achieving the price of energy to be delivered in each hour (period). For example, in 24 hours of day-ahead market this process happen 24 times. The decision on taking the fair price is determined by disposing in an ascending order the supply offers. In a descending order the demand. The market price, in a given period, is determined by the lowest price given, for which the supply can satisfy the demand.

These prices are settled in both sides, sellers and buyers. Hence, all participants will trade based on the same price value. Marginal price is achieved considering the lower bid price to avoid disparities in the market, and the risk of having bids so higher than the marginal price. This could comprise the production dispatch. On the other hand, very low offer indications would increase the probability of being dispatched, resulting in lower price than production costs [22]. Market must be functional with a marginal price system. After the energy negotiation takes place, in the day of delivering, marginal prices are determined for those periods.

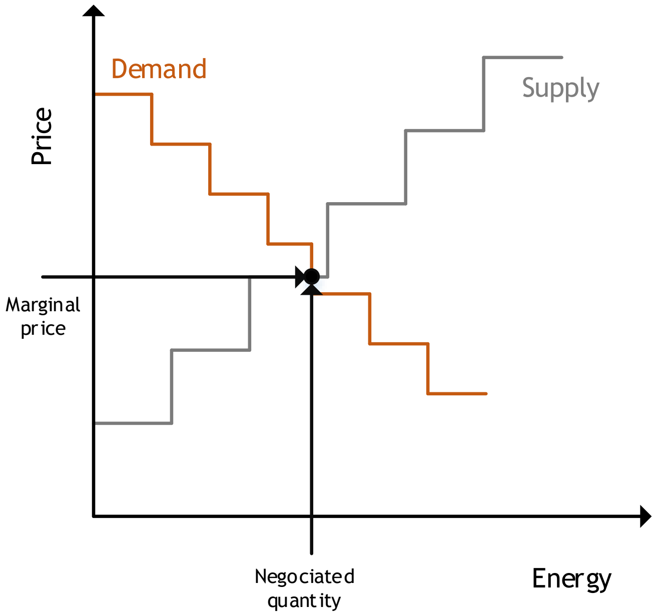


Figure 2.3 – Generic curve of demand-supply.

In the Iberian Day-ahead market, a considerable share of uncertain RES is already tradeable [27]. This type of highly uncertain energy resource introduces uncertainty in general in the market operation, especially concerning the energy price. In order to control this volatility caused by uncertain RES, the balancing market is introduced as a safety mechanism by the SO.

The Balancing market is not considered a real market, but rather acts as a set of mechanisms of adjustments to the undelivered part of “promised” energy delivery due to equipment failure or lack of production by uncertain RES (e.g. Wind and PV). The use of this market may force sometimes the use of spinning reserve units with higher energy prices [28]. These balancing mechanisms take place minutes before the actual energy delivery. In case of production deviation (positive or negative), producers will need to take balance trading in order to compensate this deviation.

There are important considerations to be taken into account, especially when integrating RES into the market. By bringing more variable RES into the market, the system has a direct influence in market price. The marginal cost of RES is very low, being zero or even negative in some cases. The zero prices can occur for periods during which the RES production exceeds the energy demand. During these periods, the market price decreases. Thus, if a large fluctuation of RES generation is to be balanced by the conventional generation methods, it could result in the use of less efficient power plants, a fact which is a barrier for the possible beneficial behavior of RES, especially regarding the emissions [28].

The Figure 2.4 aids to explain the production deviation concept. For example, we can consider a market participant that announces to deliver a specific energy amount of wind power. However, due to weather conditions the participant is unable after all to supply the announced amount.

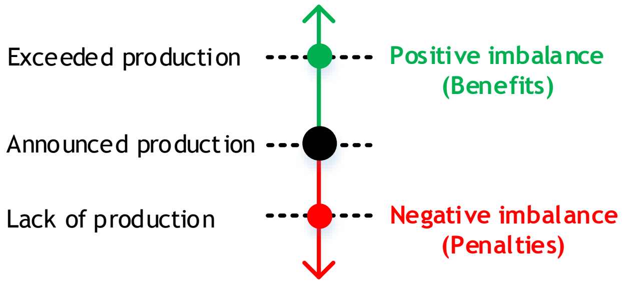


Figure 2.4 – Generic illustration about the balancing market mechanism.

In case of higher production, this is granted as a positive deviation of the production. In this case the participant will receive extra benefits for the delivery of more energy into market, based on its contribution to system stability.

On the other hand, if the participant comes up short on its announced amount, a penalty is applied for this imbalance. In this situation, the market operator will have to compensate the non-delivered energy, by the use of reserve units (e.g. spinning reserves).

Another important decision to be made after the bid submission is the technical operation. The SO needs to guarantee the electrical system conditions to sustain the energy trading in a secure and reliable way. It is a responsibility of SO to guarantee the limit capacity of the transmission lines and prevent, at the same time, energy congestion problems. In the beginning of MIBEL, the interconnection capacity between Spain and Portugal was difficult to match resulting in difference between electricity prices.

In Figure 2.5 a comparison of marginal prices between 2008 (the year that Portugal entered MIBEL) and 2014 is presented. These prices that are discussed are related with both countries in the day-ahead market. In 2008 the price disparity is observable between the two countries. When Portugal marked its presence in the day-ahead market, the prices where different assuming higher values when compared to Spain. One of the reasons that contributed to this price disparity was the interconnection capacity. In the beginning, this infrastructure was fragile and was not supporting effectively the energy trading between countries. However, observing the price in 2014 the price relation is closer, being the energy prices harmonized between the two countries.

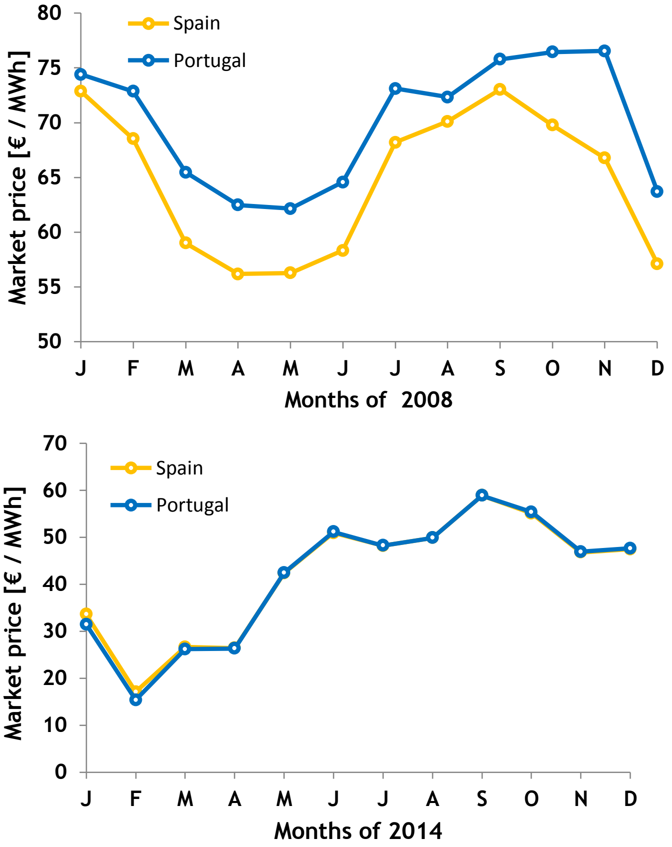


Figure 2.5 – Marginal prices comparison in Iberian Day-Ahead Market.

2.4.3 Challenges of Integrating RES in Electricity Markets

Despite the benefits that RES could have for the economy and the environment, the relevant challenges cannot be neglected. It is important to understand that electricity is not a typical tradable commodity, since once it is produced it needs to be consumed at the same time. When producing energy with a countable quantity of fuel it is easy to determine the price of production. The resource is well quantified and the operation costs can be determined. However, the production situation changes with the use of uncertain RES production units such as wind and PV. These types of RES are only available when favorable weather conditions exist. The resource is difficult to quantify when compared to the quantified fuel sources. Therefore, these technologies are non-dispatchable and cannot be controlled by the operator.

The volatility of this production brings uncertainty to the electricity markets. Typically, the market price is determined by calculating the marginal price, taking into account all the production offers and respective prices. To ensure the electric system stability, there is a need for the market participants to report the amount of energy to be delivered into the electricity market in order for the supply to match the demand. However, this is aggravated by the production units that introduce uncertainty in the procedure.

To overcome these unpredictable fluctuations, it is required from the market to have backup systems [29]. This is guaranteed by the use of spinning reserves, which are units that are ready to immediately answer to the lack of energy supply.

However, the use of these units requires higher operational costs, and this has a direct impact on the electricity price. These units are considered as emergency units and are priced substantially. If the introduction of uncertain RES is not carefully planned, it could lead to a significant increase of the electricity price.

With the high integration of RES, the electricity price could become more volatile. On the other hand, the increase of RES in the electricity market could lower the electricity prices. As it was stated before, a significant advantage of the RES is the low cost of production. This could result in a cheaper energy injection into the market, when compared to the production from fossil fuel sources. Moreover, it is expected in some cases the energy production could result in low prices (e.g zero euros), due to excess RES production compared to the overall demand of the system.

Considering this production volatility, these types of RES are usually tradeable in short-term market structures. The difficulty of prediction in a long period, forces the decision to offer these production in shorter periods (e.g Day-Ahead market). However, trading in short-term market does not solve the problem of uncertainty. This fluctuation causes uncertainty and it represents a risk for the investor. Since the RES holder/investor cannot control the production, it could be difficult to maximize the benefits in order to force the initial investment into a payoff. As non-dispatchable technologies, RES introduce difficulties to sell this energy when it is more profitable. The RES require high initial investments that could slow down the payback period.

The goal of an investor is to invest in a profitable business. In the case that RES technologies do not bring a fast return of investment, the investors are discouraged to adopt these types of technologies. From a business point of view, these investments are considered to be risky, since they are affected by a considerable amount of factors. Evidently, the lack of investments regarding RES do not bring competition to the market and do not fulfill the environmental goals.

There are some challenges in having these liberalized markets to trade energy. The integration of RES in these markets brings several concerns regarding the selling prices. An important point that the liberalized structure must address its transparency. It is required that the electricity market is transparent in order to avoid the market manipulation. Big production companies (formerly VICs) could try to manipulate the market price. This could be achieved by removing or adding capacity from the market, which directly affects the electricity price when compared to small participants [30]. Additionally, if all the market participants are trying to have the most profitable benefits from selling in higher price periods and buy at lower price periods, it will have side effects especially on the first steps of market liberalization. In practice, even the market could be significantly manipulated due to aggressive trading strategies of the participants, especially regarding wrong information regarding reported energy production [29]. If the settling rules are not correctly designed, this manipulation could jeopardize the market structure.

Apart from market manipulation by big companies, small producers face serious challenges. For example, in some market structures (e.g MIBEL) the small producers are required to make power purchase agreements with intermediate representatives (utilities or independent retailers) to sell electricity in the liberalized market.

In some cases, such intermediate representatives can even achieve better prices when compared to the energy owners, by keeping a share of the sales profit for their trading services [31]. Hence, the small producers have no flexibility seeing that they cannot freely negotiate their energy into the market, since they require agreements with other companies.

One of the European Liberalized market principles, is the ability to trade energy between countries. Evidently, it could be useful since energy from RES that is not to be absorbed by one country can be consumed by another country, in order to prevent production waste. However, the price harmonization between countries could be challenging. Different countries have different energy production sources. Depending on each technology adopted by each country the actual cost of production can differ between countries [22]. For example, a country that relies heavily on fossil fuels will have different production prices than a country that contains a significant share of RES or even nuclear production. Additionally, there is also a challenge on how to price the ageing of the interconnection infrastructure due to its expected use [11].

However, important challenges rise with the liberalization process. There is not a role model to follow and the market can only be improved by experience and failure. Hence, its development phase is a time consuming process. In addition, there are still some concerns about the consolidation of the liberalized electricity markets, especially after blackout events that happened (e.g. in USA: California). In 1970's the USA was motivated to adopt a liberalized electricity market, mainly due to the increase of fossil fuel price caused by political changes/factors. The purpose was to reduce this fossil fuel dependence in order to restore the economy. However, this market implementation was not successful which led to several blackouts, being the most famous in 2003 affecting the entire electric system for a four hour period [10]. Careful attention is needed, in order to avoid the mistakes that could jeopardize the European electric system [11].

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, the RES could be an attractive option for investors. As a result, an increased number of market participants is expected, 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. Uncertain 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 against fossil fuels. It stated the challenges of integrating RES in electricity markets, especially focusing on the variable production of RES such as wind and solar.

Hence, this chapter starts by addressing typical tools used in Decision-Making process under variable assets. It starts by addressing the importance of decision-making regarding the variable production of RES in market offerings. At the end of this chapter, a literature survey on market offering strategies is presented.

3.2 Decision-Making Under Uncertainty

Optimization is a reality in engineering domain and it has an increasing importance, since it can significantly affect typical everyday decisions [32]. This was one of the reasons that led to the creation of the operational research field. Operational research was developed in Second War World due to need to address several logistic problems [33]. With the pass of the years operational research has evolved in order to address further problems in the engineering world. Nowadays, it is used also as a tool to support decision-making processes. The use of these tools support the decision-maker with the information that best describes the problem that wants to address.

However, in many fields of industry the decision-making process has to be made taking into account possible future outcomes that are not known at the given time. Decisions that consider possible future outcomes brings uncertainty and several variables that cannot be known by the decision-maker. A process where the vector of decision variables can change the value over the time is known as a stochastic process. Stochastic process relies on random variables with the main goal to describe phenomenons that cannot be easily predicted due to the uncertainty of the process.

Typically, to evaluate the randomness of a given process scenarios are used. A scenario provides a possible path of occurrence of a given event. In Figure 3.1 a scenario scheme is illustrated. Each node in the tree represents a possible decision and each arc the probability of occurrence of the event. These nodes represent the possibles stages that a process can have given by the set of variables.

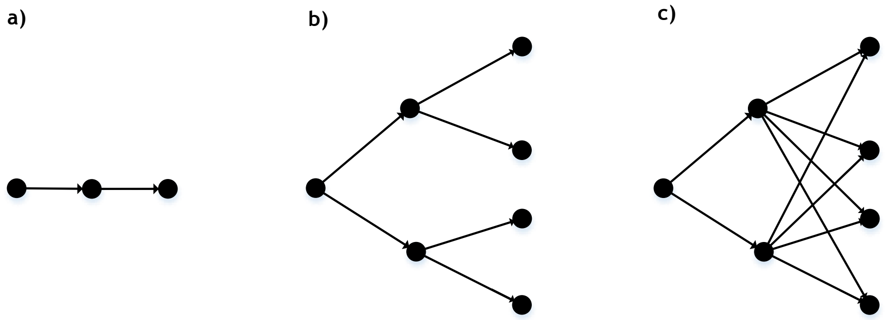


Figure 3.1 – Types of scenarios.

There are several ways to build scenarios to describe a random process. Peter in [34] mentions that the three types of scenario schemes are:

- Linear;
- Scenario Tree;
- Dynamic.

Due to the nature of these process, these stages can or cannot be independent and the scenario scheme needs to be chosen according to the application in question. The linear scenario scheme assumes that the process that is describing is deterministic, meaning that the future outcome will follow a similar relation that was existent in the past. Therefore, there are no unpredictable variables, leading to no uncertainty in the process since the future is well known and precise.

The scenario tree scheme is normally used in classical stochastic programming, since the process it describes there is uncertainty present and one cannot predict the future outcome of an event. These types of scenarios take into account different possible outcomes, presenting a range of possible future outcomes.

The last scenario type presented is the dynamic scenarios. This type relies on the approach to recombine several scenario trees. In this approach, each decision (node) can modify the probability of the next stages (nodes). It is considered dynamic scenario tree, since the decision developments can affect the probability of possible scenario outcomes.

Typically, in industry applications the desired method to predict future outcomes is the scenario tree scheme [34]. For instance, the use of linear scenarios assume that the future outcome will have high degree of certainty and cannot be significantly affected by external factors. This is one of the reasons why this method is used in quantifiable instances. For example, the expected quantity output of a production line in a typical factory, since the inputs are well defined. The dynamic scenario scheme is the most complex approach of the presented schemes. However, its complexity is also a setback in terms of computational burden. For instance, a dynamic scenario that adapts at each period to several external factors requires a significant computational support to tackle the increased number of variables, due to the randomness of the process [34].

The scenario tree scheme allows the decision-maker to predict possible future outcomes according to a direct relation with the probabilities of occurrence. These probabilities can be shaped based on the information available to the decision-maker. According to the nature of the problem in question, some scenarios could have higher probability of occurrence when compared to others. This scenario scheme is widely used in short-term prediction models, since in a long term the probability of occurrence is difficult to quantify.

Hence, the use of scenarios is commonly used in the field of stochastic programming. The stochastic programming concerns with problems that requires a decision based on current information and the uncertainty of the process that is trying to study [35] [36].

Due to the nature of the process the variables of this type of programming can take any possible value in a range of possible outcomes. Therefore, in a decision-making process to determine the best possible outcome, all scenarios need be considered [37].

The optimization process focus on maximizing or minimizing the objective function of the problem. Additionally, to a typical optimization problem several constraints are applied in order to guarantee the feasible region of possible solutions.

In stochastic programing problems it is common to categorize these problems in two types: two-stage and multistage decision process. In a two-stage type of programming there are two levels of decisions [38]. In the first stage, the decision is made before the realization of the stochastic process. As a consequence they are not dependent of each instance of the stochastic process. In the second stage are decisions that have been influenced from the previous stages. In this case, this stage starts to be dependent on the stochastic process. A process is considered to be multistage when it comprises more than two decision stages. In this work, a combination of different stages represents a possible scenario outcome.

In many practical applications it is important to state the decision of the decision-maker in the stochastic optimization problems. This is typically achieved by the use of binary variables that represent possible discrete decisions from the decision-maker. Hence, the optimization problem is considered to be a Stochastic Mixed-Integer Linear programming (SMILP). This type of programming is characterized by an objective function, a linear set of constrains and a set of decision variables.

This kind of optimization is used when solving practical logistic problems such as transportation and production scheduling, but can also be used in economical problems.

3.2.1 Importance of Prediction

Due to variability of renewable energy, it is important to predict the availability of resource to help in the decision-making process. The new approach of energy production (distributed generation), caused by integration of RES brings different benefits. However, prediction tools are needed [39].

A high integration of RES could lead to problems regarding congestion, since the electrical grid still relies on an outdated infrastructure [40]. Moreover, other serious problems could happen due to the lack of or bad prediction (e.g. system blackouts) [41]. This is one of the reasons why prediction techniques are used to predict the availability of production assets (e.g unit commitment). Unit commitment is the schedule of power generation in order to meet the supply with the least costs possible. Hence, prediction tools are important in this field, especially when dealing with large scale resources [42].

Prediction is essential when integrating RES in the electricity market, especially in making them more competitive against fossil fuel sources. This kind of energy is non-dispatchable since it depends on weather conditions. The production by the use of RES is cheaper when compared with the production through fossil fuels, since the latter is significantly affected by global conflicts and economic pressures. However, due to the variability of production RES still do not have a competitive price. This problem have encouraged researchers to intensify their efforts in the development of better predicting techniques [43]. It is necessary the improvement of the predicting methods to better support the decision-making process.

With the prediction of price and weather conditions, producers can achieve better offers in order in the electricity markets that leads to a maximization of their revenue. Taking into account the producer point of view, a good prediction will help in deciding the amount of energy to be offered in electricity market. This is important, especially in the day-ahead market, since the market participants are obligated to announce the amount of energy to be delivered in the previous day of the energy dispatch.

Many markets work with balancing mechanisms. In case of a producer cannot satisfy the production that was announced, to the producer is applied a penalty for the noncompliance. This market working principle presents a challenge to variable RES such as wind and solar, where the production is not controlled. Additionally, this market balancing system can further demotivate the use of RES due to the long period of return of investment. Additionally, the lack of government incentives further demotivates the use of RES. However, the use of prediction techniques allows the decision-maker to get a better understanding of the possible outcomes of the intended offer. Moreover, the use of these techniques can motivate the investments in RES by encouraging the investors by granting them a certain degree of confidence, by not only preventing the penalties but also exploit possible benefits.

Therefore, prediction techniques are required to support the RES in both technical and economic fronts [28]. Evidently, these techniques vary between the resource it wants to predict and different factors are taken into account. For the context of this work, these techniques are explored in the context of wind and PV production. Typically, weather conditions are difficult to predict seeing that it depends on a combination of a several non-controllable factors. Hence, these prediction techniques rely on probabilistic scenarios that represent possible future outcomes [44].

Wind power production depends on wind speed. The wind movement forces the rotation of a turbine, leading to the conversion of mechanical energy to electrical energy by the use of a generator. However, this energy conversion process have technical limitations and inefficiencies. 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 speeds of operation to guarantee useful production. Additionally, at a high level of wind speed the wind production is shutdown for safety reasons to prevent possible equipment damage.

Wind is considered the most developed renewable energy and also the most available in literature in electricity market. Many integration studies have been performed to assess the integration costs of wind or to determine the impact of this technology in electricity market operators [45]. The same problems are also explored in European studies [46].

However, there are some important characteristics to take into account when trading wind energy in electricity market such as wind speed curve [47]. This is an important point since it can affect the bidding price, leading to economic consequences to the producer. Therefore, for the wind power producer it is important to perform predictions. According to [48], several factors can affect the wind variability:

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

Other factors can affect the wind speed variation such as tower shadow, wind shear and turbulence [49]. Considering the presented factors, it is challenging to effectively predict the full behavior of wind production. Therefore, the probability of occurrence of a given event if important for predictions. These probabilities determine the possibility of a specific event to happen. This can be done by using distributions that support on historical data, in order to quantify the expected behavior of the event.

In Figure 3.2 the curve of wind speed distributed by hourly basis is presented. The most common distribution that is used to predict the wind speed curve is the weibul distribution [50], [51], [52], [53]. As it is observable, the shape of the weibul distribution better fits the data when compared to the other distributions. Wind is more available during nigh periods due to the air mass that becomes colder with the sunset. During the day period, despite existing wind that is useful for production it has lower wind speeds to the heating of air mass. Therefore, the weibul distribution better approximates these periods of production.

Solar energy is the most abundant clean energy source available. The received power from sun by the Earth is about 1.8×10^{11} MW, which is far superior to the present rate of world energy consumption [54]. To produce electrical energy through PV systems there is a need to quantify the effective sun hours [55]. These sun hours change with seasonality due to sun's trajectory around earth. Typically in summer, more sun hours are available when compared to winter as it is depicted in Figure 3.3. Additionally, the latitude of the place of production can affect the effective sun hours available for production.

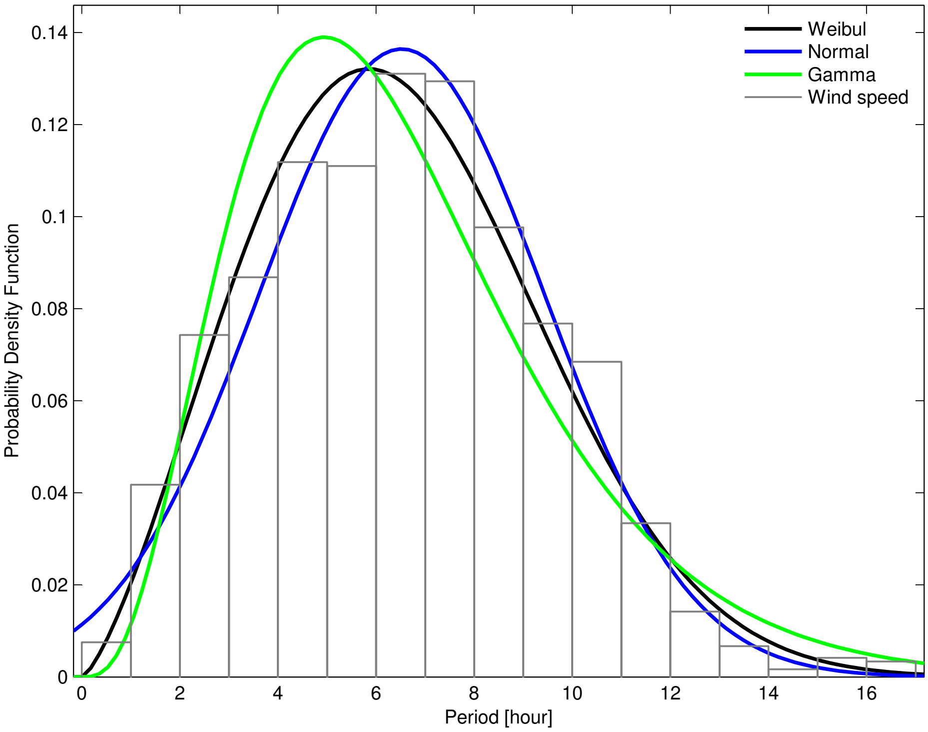


Figure 3.2 – Wind Speed density with different distributions.

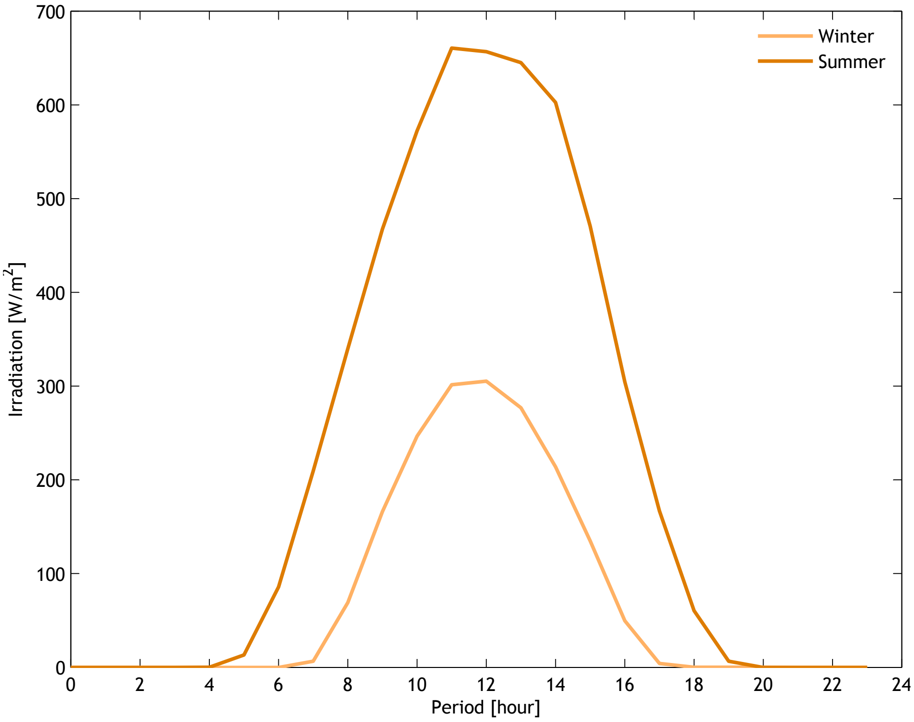


Figure 3.3 – Seasonality represented by lower limit (winter) and upper limit (summer).

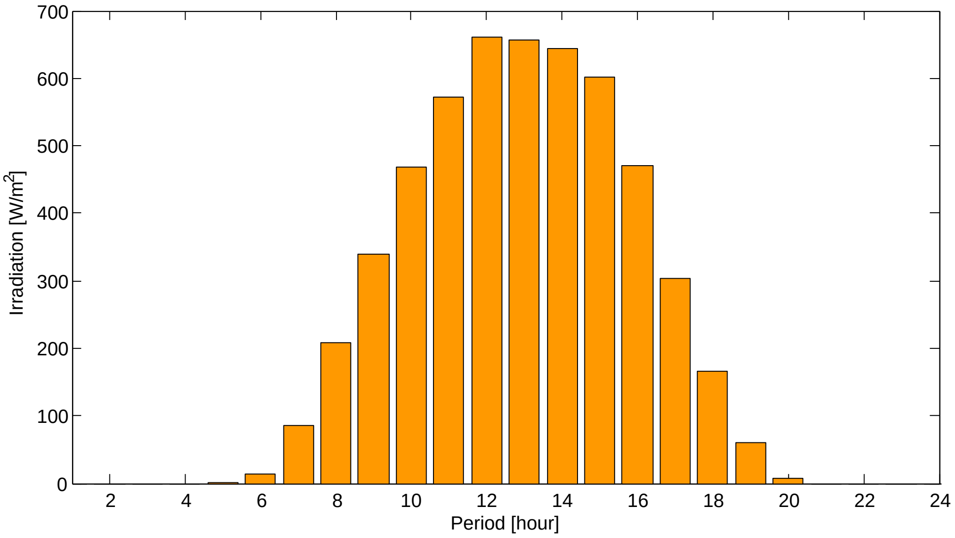


Figure 3.4 – Typical distribution of solar irradiation.

To prediction the shape of the available irradiation, distributions are used. In Figure 3.4 a typical day of solar irradiation is presented. Typically, the most typical distribution used to approximate this data are Gauss or Normal distribution [56]. Typically, the mean of the normal distribution is considered to be at midday hour since it is when the sun is in a perpendicular position relative to the Earth (with the exception of 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. Hence, a good prediction will help the decision-maker and will also contribute to the system equilibrium. In the next section a literature survey about the subject is presented.

3.3 Literature Survey

Regarding optimization RES have been receiving a significant attention. The RES integration face several challenges being one of them in the technical side. Due to the nature of production of variable RES, any improvement made is a step forward to the efficiency goals. There is a wide topic the increase of power output of these technologies.

For instance, regarding wind technologies studies exist that try to maximize the production output of a park by optimizing the production of individual production of each turbine [57]. This is achieved by adjusting the pitch angle of each turbine according to the wind speed and direction in order to maximize the production output. Other studies try to associate turbines to explorer non-optimal points in order to minimize costs associated with logistics and the interconnection between Another method is associated turbines are studied in [58] exploring the non-optimal points in order to reduce the losses and minimize the costs of logistics and electrical interconnection between turbines. Several technologies and developments are presented in [59] and [60] that address the strategies on how to explore the maximum energy potential output of the wind generation.

Of the variable RES, wind technology is not the only production type that gets the research attention, since PV technology is widely explored. 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, being most commonly used for supplying hot water to houses and swimming pools. The solar PV production seeks to convert directly into electricity through a process known as photovoltaic [61]. The photovoltaic effect is further explored in [55] and the current developments on photovoltaic cells is presented in [62]. Nowadays, electrical energy from PV systems play a limited role in global power generation, supplying not more than 0,4% of global electrical demand [63]. One of the most significant challenges of the PV technology its the poor energy conversion efficiency. Typically, the available commercial panels of multi-crystalline silicon has an efficiency between 14% to 19% [54]. These low efficiencies represent a significant setback for its investment. This is one of the reasons that this type of technology is used as small-producing centers, especially in domestic users.

These low efficiencies motivated researchers and engineers to find mechanisms to improve the power output in the best possible way given the current conversion efficiency. A typical PV system needs to be sized in order to address the optimal position angle, in order to maximize its irradiate capture. In [64] is analyzed the optimal angles of solar panels in different geographical locations. Additionally, several automated mechanisms have been proposed to track the sun movement in order to maximize this capture. These systems are also called maximum power point tracking (MPPT) and have been proven that posses better production outputs when compared to stationary systems. In [65] this technology is used in order to adapt the PV orientation based on solar irradiation. Additionally, in [65] a strategy is developed to optimize solar arrays according to variable radiance conditions.

Besides the technical limitations that are being addressed by the scientific community, the operation RES rises concerns. As stated before, one of the problems of variable RES is the inability of energy production control. Since the energy production through these technologies cannot be controlled, opens the field to the prediction of the production. There are studies that supports on historical data in order to approximate a future predictions [66] [50].

Other studies address the prediction based on weather models [67]. Numerical weather prediction (NWP) make use of atmosphere models and computational techniques in order to provide an expected production output. Additionally, studies have been performed using NWP for a long prediction horizon [68]. However, the use of this technique requires a considerable amount of data, which presents a computational burden since wind speeds change in short time periods. Hence, the use of this prediction is typically associated with short periods. In [69] a probabilistic wind power prediction considering geographically information was proposed.

The use of weather prediction techniques is also adopted in irradiation values [70]. In [71] historical weather data was used in order to determine the output production. Accurate prediction of PV production can reduce the impacts on the electrical grid due to the uncertainty, improving system reliability and power quality. In [72] an intelligent energy management strategy that relied on forecasting the PV generation was presented. The aim of this study was the minimization of the operational cost and the environmental impact of a microgrid. In [73] a model aimed to study the correlation between solar radiation and timescale-related variations of wind speed, humidity, and temperature.

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.

Due to the uncertainty of wind production, many strategies have been proposed in the literature in order to achieve the maximum benefits in bidding in short-therm electricity markets. In [74] a strategy to offer wind power production in Nordic short-term market is proposed. This strategy tries to maximize the profit of the wind park owner, based on statistical methods relying on historical data. In [53] models are applied to a wind farm located in Iberian Peninsula.

In [75] a strategy to maximize the profit of wind production in Day-ahead market was presented. In several countries, the market infrastructure operate with balancing systems. There are studies that start to take into account the risk of not producing the expected amount [60]. In [76] a model for optimal trading of wind power in day-ahead (DA) electricity markets under uncertainty is presented. It relied on probabilistic estimations of wind power and considered also the uncertainties associated with the DA market. In [77] an equilibrium model of short-term market to address the impact of wind operation is proposed. This model is formulated for several prices and is considered a two-stage stochastic optimization problem.

Other possibility of trading RES into electricity market is to combine different types of technologies. The combination of different technologies can reduce the imbalances of production, leading to more profitable offers. In [78] a coordinated trading strategy of wind and thermal power plants is presented. The aim of this study is to mitigate the risks due to uncertainty. It is assumed that both wind and thermal plants are exposed to the same energy price and both technologies are owned by the same producer. In [68] the uncoordinated and combined offer using wind and hydro technologies is explored. The pumped-storage plant is used to pump water during the off-peak periods, in order to sell the energy in peak periods. Similarly, in [52] three models of combined offers between wind and hydro plants in day-ahead Iberian Market for 168 hours periods are presented. The first model assumes that both production centers operate separately, providing separate offers. The second model focus on combining both production centers in separate offers. Finally, the last model proposed in [52] assumes that both production centers make a combined offer to the electricity market.

Despite all the efforts done in this field there is still a research gap exist. The studies presented mainly focused on offering wind technologies separately and some even proposed combining it with storage systems. However, none of these studies presented the possible benefits of combining wind power production with PV production centers. There is a gap existent regarding the market offers of both technologies (wind and solar), in order to determine the possible improvements on the offer by the decision-maker. Therefore, this work will study the combination of these two technologies by designing two offering approaches: both productions offered separately; combined production into a single market offer.

3.4 Summary

In this chapter, the importance of prediction techniques in aiding the decision-making process was presented. The process of how to design scenarios was explored and well as its importance in stochastic programming. At the end of this chapter a literature survey was presented highlighting the research gap existent on the field, regarding the combination of wind and PV into market offers.

Chapter 4

Proposed Methodology

4.1 Introduction

In this chapter the proposed methodology is presented. It starts with the problem description and a brief explanation of the bidding strategies used. Additionally, the mathematical formulation of PV and wind models are presented, explaining the applied objective functions as well as the constraints required to design offering strategies in the day-ahead electricity market.

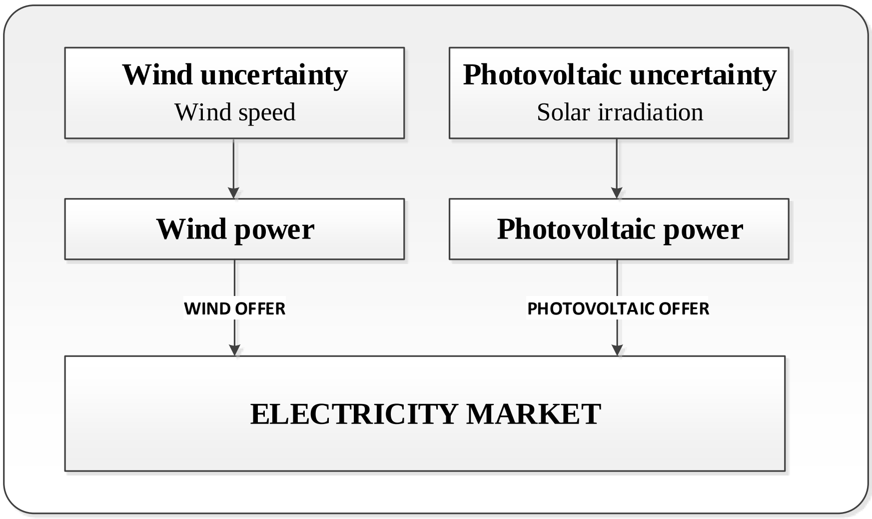
4.2 Problem Description

The uncertainty of volatile RES production are challenging for researchers, since it is a necessity to create strategies that reduce the bidding risk of the announced production from RES holders in order to increase their profits. At the end of the previous chapter (Chapter 3.3), a literature survey highlighted the advantages of combining RES technologies into a single offer to electricity market. A combined offer of different technologies can lead to a more solid market offer, with a possible lower deviation of production leading to more profitable offers.

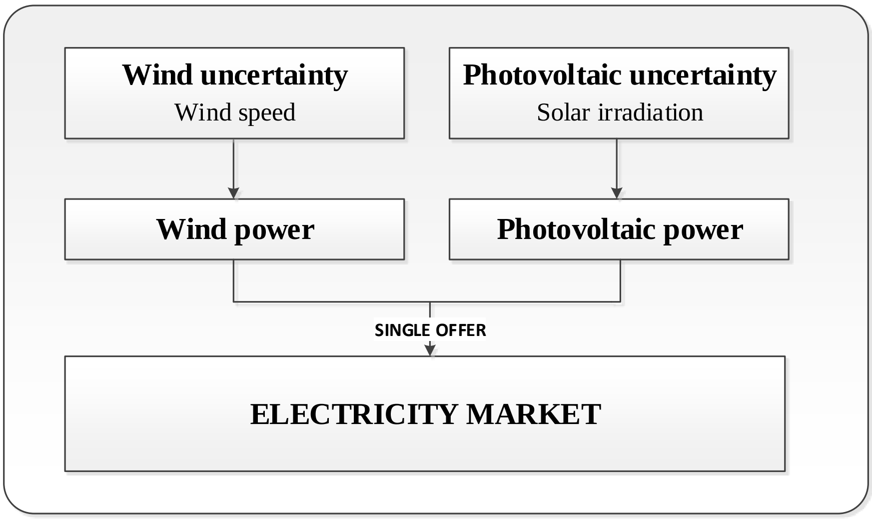
Therefore, two strategies are proposed: i) Separate offering model for each technology (Wind and PV); ii) Combination of PV-wind production into a single offering strategy.

In separate offer (Figure 4.1a) into electricity market, PV and wind production are analyzed individually. As a consequence two different optimizations are done in order to guarantee the best possible offer from each individual technology. The second strategy consists of using both technologies to create a combined production package to make a combined offering. The combined offer strategy is depicted in Figure 4.1b. In order to consider a combined offer, both productions are merged into the same scenario generation. Despite of the fact that there are different technologies in separate offering, they are part of the same offer in the end.

Due to the challenge in predicting the uncertain production, a wide range of possible scenarios are generated to mitigate this uncertainty. The scenarios are disposed as a tree (scenario tree) with two nodes. The first node starts by defining the market prices which are generated with the support of real data (real market prices) and the second node the power production (PV and wind). In combined strategy there is also a third node to integrate both production into the same scenario prices. Moreover, due to the possibility of deviation in RES production, the balancing market is also considered (positive imbalance price and negative imbalance price).



(a) Separate offer strategy.



(b) Combined offer strategy.

Figure 4.1 – Separate and combined Wind-PV offering strategies.

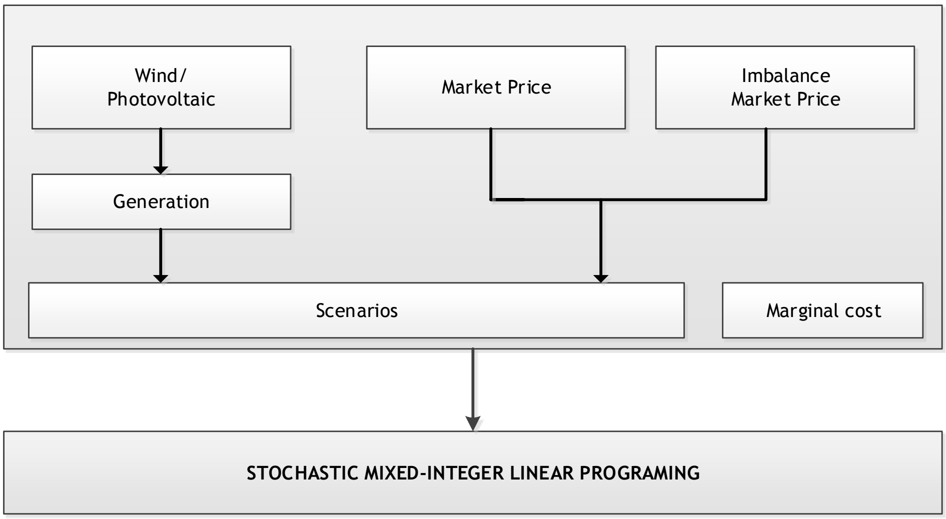


Figure 4.2 – Schematic of simulation process.

The optimization process is done through SMILP. The input data (wind & PV production) and market prices (including imbalance prices) are approximated by stochastic processes (scenarios) as it can be observed in Figure 4.2. This data input represents a strong source of uncertainty and is described in discrete periods of time.

Due to the nature of the optimization problem, imbalances of production are characterized through the problem constraints. Additionally, these imbalances are determined by the use of binary variables, when a deviation of production occurs. In separate offer, two binary variables are needed (one for each technology).

On the other hand, considering a combined offer only one binary variable is required, since they are related under the same offer into the Day-ahead market. As a result, only one combined deviation is considered.

The optimal solution is achieved after taking into account all variables resulting from power production with the possible scenarios.

4.3 Photovoltaic Model

Photovoltaic power depends on solar irradiation. This irradiation reflects the volatility of the resource which represents a source of uncertainty when selling/buying in electricity market. Typically, the highest solar irradiation occurs during the day. During the day, the time series of the solar irradiation can be characterized by the normal distribution [56], 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.

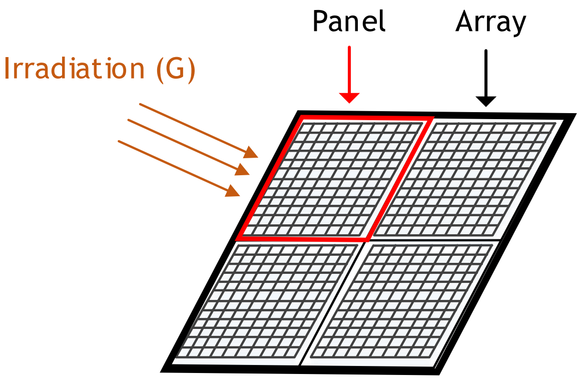


Figure 4.3 – Irradiation caption phenomena from a PV system.

Solar energy is directly dependent of the area surface of the panel as presented in Figure 4.3. A wide area in surface increases the capacity of production since the total efficiency of the panels is cumulatively bigger. However, due to technical limitations, PV panel efficiency is still relatively low. Therefore, the total power output (P [W]) of a PV system [56] is given by:

$$P(G) = \eta \cdot A \cdot G. \tag{4.1}$$

Where, G is the solar irradiation from known data in [W/m^2] and presents the global incidence of solar light. A is the panel area [m^2], which is the surface area capable of transforming the solar irradiation into power. Evidently, this is one of the most important factors in PV power production, where a bigger area can lead to a higher expected production. In terms of practical applications, these panels are connected into arrays as portrayed in Figure 4.3.

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

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

The main interest of producers is to sell the energy and get the maximum profit revenue possible. Considering this, the objective is to maximize the profits of selling energy of PV power production in the offer to day-ahead market.

Solar irradiation is the input, the uncertain source in study. Photovoltaic power has a range of possible production and it is distributed by a number of production scenarios with a specific probability of occurrence. These scenarios will be designed by taking into account real data and the uncertainties of production. Additionally, these scenarios are combined with the price scenarios.

The expected profit is determined considering the previous parameters and they are presented in the following equation (4.3):

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

The expected profit is given taking into account three components. The first one, is the energy bid presented by b_t^{PV}. This energy is a revenue multiplied by its current market price $\lambda_{t,w}$.

However, this revenue is a function of production, being subtracted by the total cost required to produce this energy presented by c^{PV} multiplied by 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).

Considering the PV production as an uncertainty source, imbalances must be considered in order to compensate the deviation caused by unexpected production (under- or overproduction). Therefore, $\lambda_{t,w}^{+}$ and $\lambda_{t,w}^{-}$ are multiplied by the deviation of production whenever the deviation is an excess ($\Delta PV_{t,w}^{+}$) or a lack of energy ($\Delta PV_{t,w}^{-}$).

As mentioned before, failure can lead to penalties for the producer to comply the announced production. 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 $\lambda_{t,w}^{+} \cdot \Delta PV_{t,w}^{+}$.

On the other hand, if the production supplies less energy than the scheduled announcement, the producer receives a penalty given by $\lambda_{t,w}^{-} \cdot \Delta PV_{t,w}^{-}$.

Since the producer objective is to maximize the profit of bidding the PV production into the electricity market, the higher profit has to be chosen following all constraints and depending on the parameters. It is only possible taking into account a different number of possible scenarios. The profit of bidding PV power production (represented by PF_{PV}) has to be considered for each scenario w.

The PF_{PV} is represented as a summation 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, thus 24 bid offers have to be integrated in PF_{PV} equation.

The expected profit is maximized taking into account all scenarios, w, by evaluating the offers, imbalances and costs of production. Additionally, this function is limited by constraints of the problem in order to get feasible solutions. These constraints are explained later in Section 4.4.1.

4.4 Wind Model

The wind model is based on the works of [52]. This model addresses the analysis of wind and hydro as separate offers as one of the three strategies presented. In spite of the different bidding structures and proposed objectives, the principles on which the wind model is based are similar. However, they incorporate risk-hedging 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 of a given region is used.

As it demonstrated on Figure 4.4, an air mass in motion represents a wind force in terms of kinetic energy stated in equation (4.4):

$$E_k = \frac{1}{2} \cdot m \cdot v^2. \tag{4.4}$$

This principle derives from the classic physics (the second Newton's law), given by $F = m \times a$. Since it is not practical to estimate the amount of mass crossing 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 formulation that relates to the wind power output [48] is given by the equation (4.5):

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

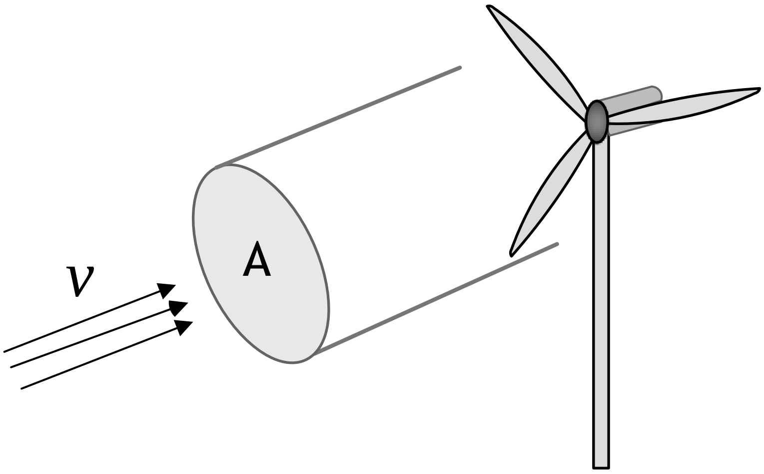


Figure 4.4 – Wind power production under the influence of air mass through the turbine.

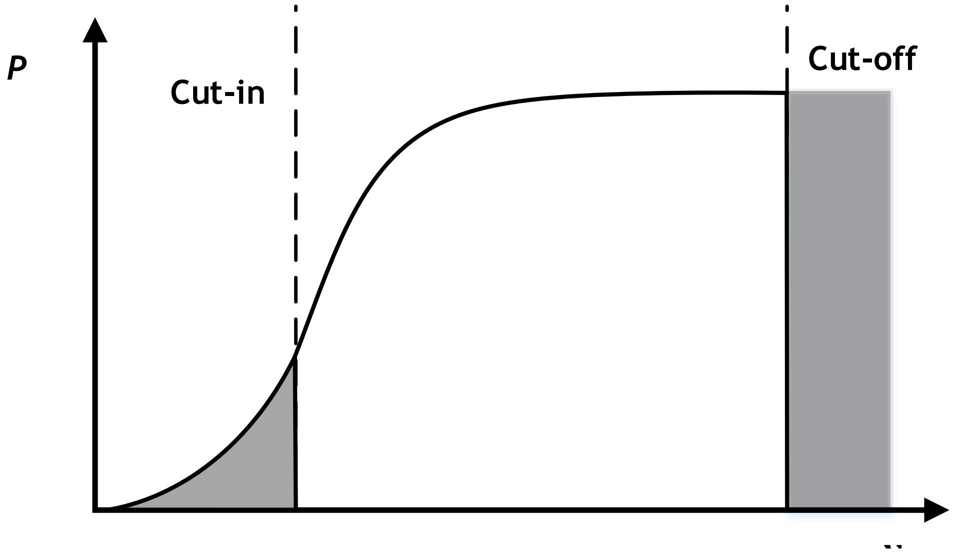


Figure 4.5 – Wind production region.

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. Nonetheless power of generator (P) is limited from technical constraints, represented by the following Figure 4.5.

It depends on manufacturer specifications in defining this value. In fact, there is a starting point (cut-in) where the turbine starts operating and producing energy. Additionally, a point of maximum production is achieved given the technical limitation responsible to cause damage on equipment from higher rotation [79]. There are other important factors to determine the wind speed such as terrain rugosity which is considered in [48]. Any irregularities on surface can modify the wind speed, and consequently compromise the production.

Wind power production is the input in decision making process. After, the power output is adjusted following a Weibull distribution. This distribution as shown in the previous Chapter 3.2.1 in Figure 3.2, provides a good characterization of the wind power availability. Hence, wind power follows this distribution for a specific number of scenarios of wind per hour. This results in a probability of an event, for each time (hourly base).

Another component of scenarios is the prices. Moreover, balancing market must be considered due to the uncertainty of wind production when offering in Iberian DA market.

The objective 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 in equation (4.6).

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

Wind power offer is considered in function of the amount bid into DA market represented by $\lambda_{t,w} \cdot b_t^W$. However, production has costs associated, characterized by c^W ($c^W \cdot g_{t,w}^W$) 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 taken into account in this function, where exceeded production will have an extra profit ($\lambda_{t,w}^+ \cdot \Delta W_{t,w}^+$) and a not-satisfied production will represent a cost ($\lambda_{t,w}^- \cdot \Delta W_{t,w}^-$).

Due to the uncertainty represented by wind uncertainty, wind power production will be different considering the period t and the number of scenarios w. The best solution is made by taking into account the range of generated scenarios.

4.4.1 Mathematical Constraints

There are different types of constraints to take into account for both models: offer constraints and imbalance constraints.

4.4.1.1 Offer Constraints

In day-ahead Market, the producer has to submit 24 bids, one bid per hour. The producer has to take into account the quantity of production and the minimum selling price. Hence, for each period, the producer has to determine the bid considering the wind and PV power production capacity.

The minimum value of production is zero when weather conditions are not enough for having production. In the case of a wind turbine it will be zero for values of speed before the cut-in value, since the available speed is insufficient to produce power (Figure 4.5). In the case of irradiation, this can be achieved at night which 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 capacity limit of each power plant production, represented by P_{max}^{PV} and P_{max}^W to offer into electricity market. Hence, the PV bid (b_t^{PV}) is limited in equation (4.7) and wind bid (b_t^W) in equation (4.8).

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

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

4.4.1.2 Imbalance Constraints

Imbalance constraints have to be considered in the DA market which gives the deviation of an expected production, since the wind power production is a more volatile RES than PV. These imbalances are considered when having uncertainty energy productions (wind or PV). In this case the balancing market is also needed to consider these deviations. There are two possible options of having deviation: negative or positive deviation.

Negative deviation occurs when the delivery amount is lower than the scheduled in the DA market, and positive when the quantity of production is higher than scheduled. When negative deviation occurs, the producer has a penalty for not delivering the announced amount. More expensive energy has to be injected to balance the non-delivered energy from the producer.

Otherwise, if production is higher than the offered, the producer will receive a payment lower than in the DA market. These imbalances are presented in equations (4.9) - (4.12).

As mentioned before, when the binary variable ($j_{t,w}^{PV}$ ou $j_{t,w}^{W}$) takes value 0, there is no negative imbalance. On the other hand, when the binary assumes the value 1can exist a negative imbalance. When the production is lower than the offer, i. e. negative imbalance, the producer has to pay the difference for the amount of energy not delivered (negative imbalance $\Delta W_{t,w}^{-}$). In the other hand, when the injected energy is higher than the offer given, the producer will receive more money for the exceeding energy amount (positive imbalance $\Delta W_{t,w}^{+}$).

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

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

$$0 \leq \Delta PV_{t,w}^{+} \leq P_{max}^{PV} \cdot \left(1 - j_{t,w}^{PV}\right). \tag{4.11}$$

$$0 \leq \Delta W_{t,w}^{+} \leq P_{max}^{W} \cdot \left(1 - j_{t,w}^{W}\right). \tag{4.12}$$

The total imbalance is decomposed in ($\Delta PV_{t,w}$) for PV power and ($\Delta W_{t,w}$) for wind power. These imbalances are presented in equation (4.13) and equation (4.14).

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

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

The imbalance is defined as the difference between PV production ($g_{t,w}^{PV}$) and the offer in the electricity market (b_{t}^{PV}).

$$\Delta PV = g_{t,w}^{PV} - b_{t}^{PV}. \tag{4.15}$$

$$\Delta W = g_{t,w}^{W} - b_{t}^{W}. \tag{4.16}$$

The mathematical formulation of the several models are summarized as equation (4.17) for the PV formulation and equation (4.18) for the wind formulation.

$$\begin{aligned}
\text{maximize} \quad & PF_{PV} = \sum_{w} prob_{w} \sum_{t} \left(\lambda_{t,w} \cdot b_{t}^{PV} + \lambda_{t,w}^{+} \cdot \Delta PV_{t,w}^{+} - \lambda_{t,w}^{-} \cdot \Delta PV_{t,w}^{-} - c^{PV} \cdot g_{t,w}^{PV} \right) \\
\text{s.t.} \quad & \Delta PV_{t,w} = g_{t,w}^{PV} - b_{t}^{PV}; \\
& \Delta PV_{t,w} = \Delta PV_{t,w}^{+} - \Delta PV_{t,w}^{-}; \\
& 0 \leq \Delta PV_{t,w}^{-} \leq P_{max}^{PV} \cdot j_{t,w}^{PV}; \\
& 0 \leq \Delta PV_{t,w}^{+} \leq P_{max}^{PV} \cdot (1 - j_{t,w}^{PV}); \\
& 0 \leq \ b_{t}^{PV} \leq P_{max}^{PV}.
\end{aligned} \tag{4.17}$$

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

4.5 Combined Wind and PV Model

The main goal of this strategy is to optimize the profit of selling wind and PV power together as a combined offer, lowering the uncertainty of the generation. The Figure 4.6 presents a generic example of the combination of both technologies [80]. As can be observed, the wind power is more available typically in night periods, and PV during the daylight. Hence, to a producer perspective, the PV producer can compensate a small part of the wind power uncertainty.

In a general way, the shape of a typical wind production curve does not have valleys as PV, as a consequence of the zero night PV production. Imbalances of wind production could be lower when PV production is available. Hence, depicted in Figure 4.6 is the combined curve of both productions. However, this example is not valid in all cases, since the wind and solar sources are dependent on a large number of factors, as it was presented before in Section 3.2.1.

In this strategy, the wind model is integrated with the PV model and both are dependent on each scenario w. Previously, in the other strategy, these scenarios were calculated separately. In the combined strategy, both technologies are submitted to the same production scenario, in order to get the same decision variables.

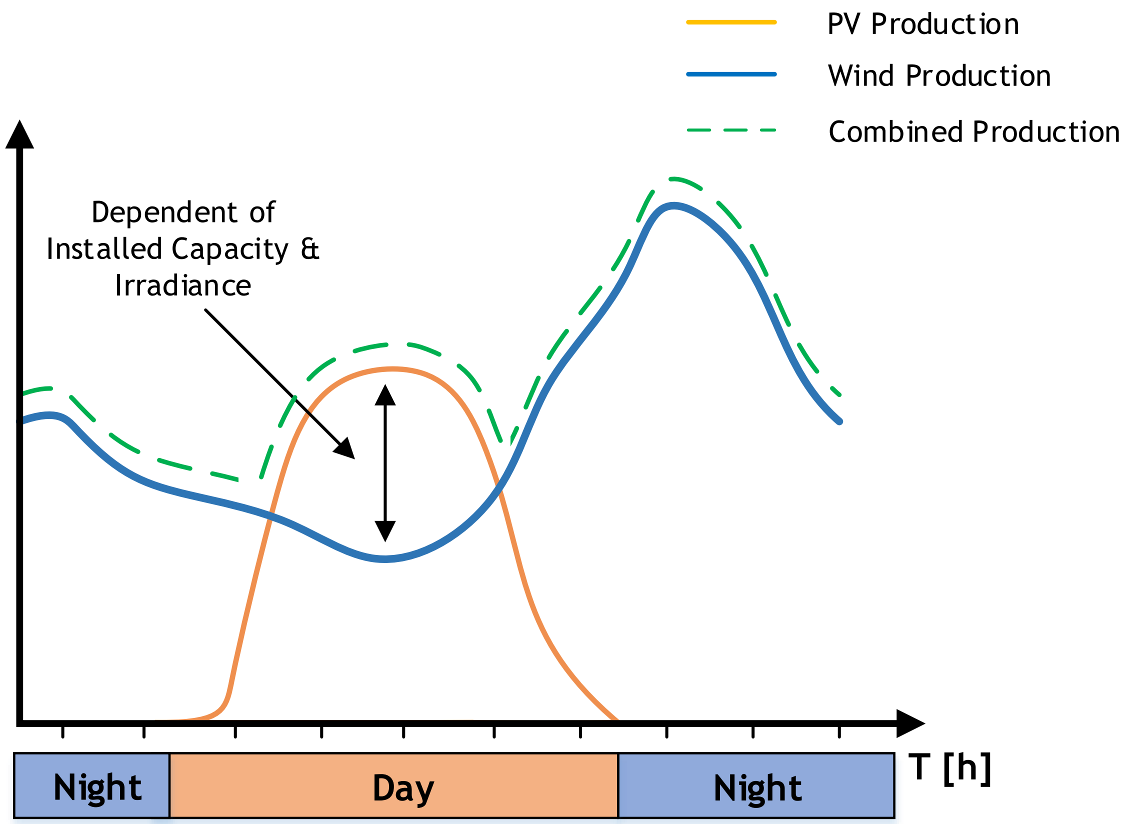


Figure 4.6 – Illustrative example of combining production (PV and Wind).

Hence, the profits are determined by the following equation (4.19):

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

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, the cost of both technologies has to be considered (c^W and c^{pv}). Imbalances are determined by $\Delta_{t,w}$ assuming a negative value if the scheduled amount in the DA market is lower than expected ($-\lambda^{-}_{t,w} \cdot \Delta^{-}_{t,w}$) or represented by a positive value if the amount exceeds the delivered production ($\lambda^{+}_{t,w} \cdot \Delta^{+}_{t,w}$).

Hence, the objective function is a summation of the offer $\lambda_{t,w} \cdot b_t$ plus imbalances minus costs of production wind power and costs of producing PV power $c^{W} \cdot g^{W}_{t,w} - c^{PV} \cdot g^{PV}_{t,w}$ for each scenario w.

4.5.1 Constraints

4.5.1.1 Offer Constraints

Both producers have to offer (b_t) their energy in the DA market at each hour. All productions are combined and offered to the market in range until the maximum power production (P_{max}). Evidently, when the production is zero no offer is made to the electricity market. This relationship can be observed in equation (4.20).

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

4.5.1.2 Imbalance Constraints

Since both technologies present sources of uncertainty, deviation has to be taken into account equation (4.22). These constraints are important in the balancing market to equilibrate the market from uncertain production of RES. The imbalance quantity ($\Delta_{t,w}$) is calculated by a difference between production ($g^{PV}_{t,w} + g^{W}_{t,w}$) and offer of both technologies (b_t).

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

However, there is only one possibility of production deviation for each period. These imbalances are due to lack of production ($\Delta^{-}_{t,w}$) or due to excess ($\Delta^{+}_{t,w}$) as it is noticed in equation (4.21).

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

The imbalances have an upper limit (P_{max}) determined by the summation of the installed capacity of both technologies. The equation (4.23) and equation (4.24) presents the deviation of the combined production.

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

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

Therefore, the proposed combined strategy can be summarized in the following equation (4.25):

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

4.6 Summary

The electricity prices in the day-ahead and adjustment markets are characterized by stochastic processes. The prices in the day-ahead market are considered to be independent from the producer. The optimization problem targets into maximizing the expected profits from offering energy in the day-ahead market. In the next chapter (Chapter 5) the results regarding the proposed strategy are presented.

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. In this chapter, the results regarding the proposed strategy are presented. It starts by stating the data input, leading to the results obtained.

5.2 Input Data

The case study comprises historical weather data (PV and wind) of several meteorological stations from Navarre [81], Northern Spain. The data was collected from 1^{st} of July to 30^{th} of September of 2014. Considering a total installed capacity of PV and wind technology of 50 MW each one, but with different marginal costs: $23,6$ €/MWh (PV park) and 17 €/MWh (wind farm). These costs were obtained from [82].

Solar irradiation is a source of uncertainty, it has to be forecasted before being considered for a market offer. To determine the power output of the solar park, a set of solar irradiation historical data spaced in 10 minutes intervals was required. The power output was determined using equation (4.1) with $\eta_n^{PV} = 0,143$, $A_n^{PV} = 1.6 \times 12$, G is the solar irradiation from previous data and $N = 18200$ is the total number of arrays present in the solar park. Each parameter considers a typical commercial PV array. The irradiation data is fitted using a normal distribution.

Additionally, to determine the power output of the wind farm, a set of historical data spaced in 10 minutes intervals was used. The conversion to WP is given by equation (4.5), where the area of turbine rotor is $80m^2$; the remaining values such as ρ^W is $1,2kg/m^3$, $c_p(v)$ is $0,59$, and the number of turbines considered are 25 of 2MW each, being a total wind power of 50 MW. The wind power production is approximated by a weibul distribution. After fitting each distribution per hour, the 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 uncertainty is introduced by the wind power, PV production and the market prices. Hence, the market prices considered were obtained from Iberian day-ahead market which are available in [83]. Moreover, the imbalance prices were taken from [84].

A two-stage scenario tree is presented, which describes the stochastic variables. The first stage (node) concerns the market prices while the second stage (node) about the announced production. For the first strategy (separate offering), two scenario trees are presented, one for the PV model and the other for the wind model as it is observed in Figure 5.1.

The third tree is considered for the combined model. This scenario tree has the market prices as the first node, the PV production as second node and the wind production as the third node. For each tree, 6 scenarios are considered for each node: the market prices, the PV and wind production. In total, for a separate offer strategy has a total number of scenarios equal to 36 ($w = 6 \times 6 = 36$). For both scenario trees, PV and wind model, the probability per scenario is:

$$\begin{gathered} w = P1 \times PV1 \\ w = 0,027 \times 0,027. \\ w = P1 \times W1 \\ w = 0,027 \times 0,027. \end{gathered}$$

All scenarios have the same probability of occurrence, being the summation of all probabilities equal to one. Hence, the probability of each scenario is $0,027$ $(1/36)$.

In the combined strategy, the number of scenarios for each source remains the same. However, the dependence between the tree sources in the same tree makes a total of 216 scenarios. This results from the connection of market prices, PV and wind production scenarios. Therefore, the total number of scenarios is given by $6 \times 6 \times 6 = 216$. The probability of occurrence of each scenario is smaller than the previous one, being equal to $0,0046$ $(1/216)$. The probability per scenario is: $w = P1 \times PV1 \times W1$ $w = 0,0046 \times 0,0046 \times 0,0046$.

All the input data and the scenario generation were simulated with the use of MATLAB [85]. After the generation of the scenarios, a SMILP model is applied to determine the best profitable offer into the electricity market. The optimization problem is solved with the use of MATLAB to generate and show the data input and outputs, while GAMS [86] is used to solve the mathematical problem through CPLEX solver. For each technology, the maximum limit of production is given by the total installed capacity of each park.

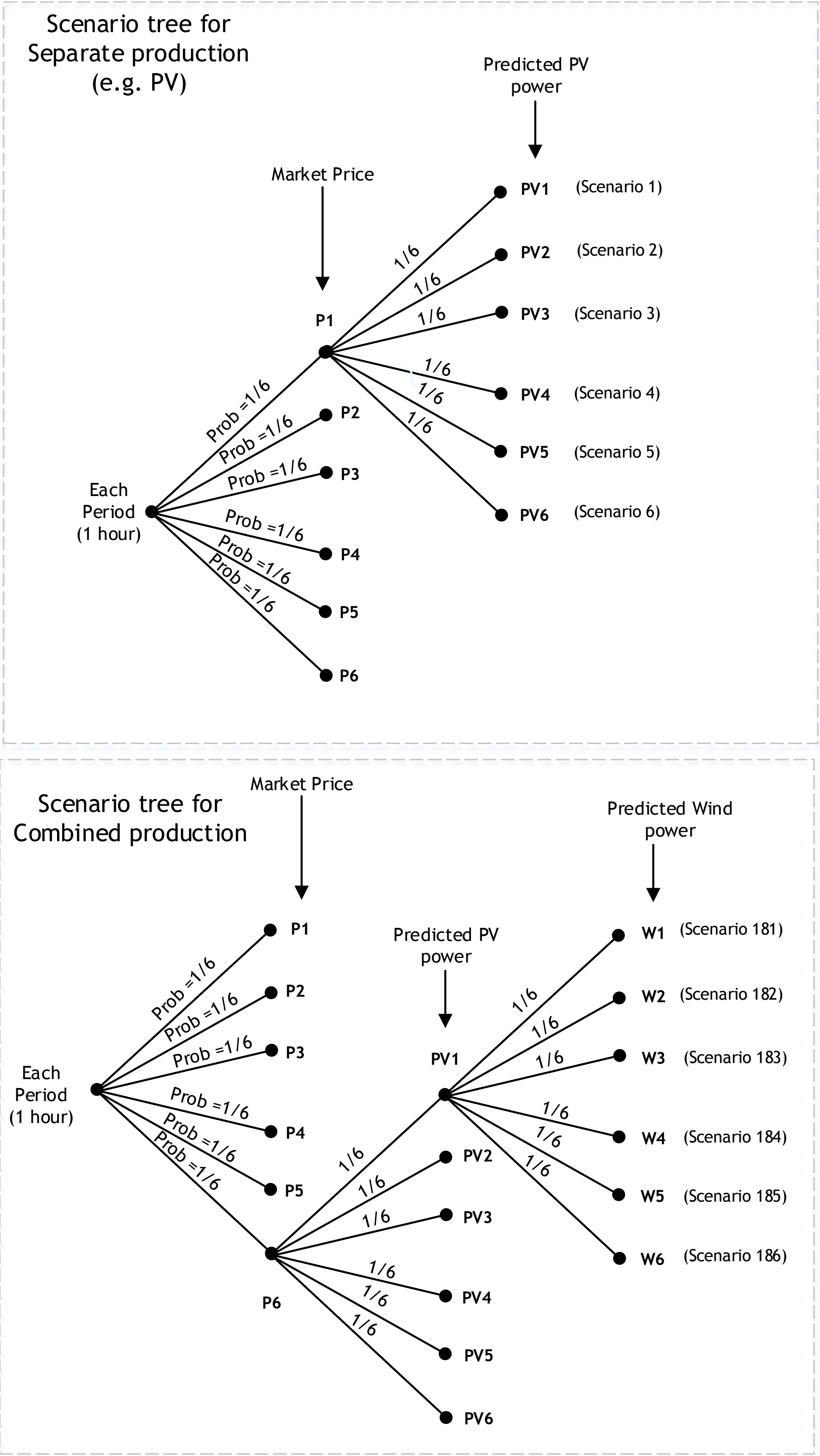


Figure 5.1 – Scenario schematic of the two different strategies.

5.3 Example: Analyzing One Scenario

Before presenting the results regarding the full spectrum of a week, a simpler example is presented, in order to demonstrate the working principles of the strategies. In this example only one scenario of a total of six scenarios was considered.

In Figure 5.2 a separate offer is presented. In this figure, the production of both technologies are presented as well as the deviation of each production ($g_{1,t}$) regarding the first scenario. The production ($g_{1,t}$) and deviation ($\Delta_{1,t}$) are variables dependent on the period and the scenario in question. The bid offer (b_t) is not variable in each scenario since it only depends on the period (t). The bid offer can be found by considering the most profitable case considering all the scenarios for each period. The deviation is given by the difference between the production and the bid offer (red marks in Figure 5.2).

For instance, observing Figure 5.2, the first hour has a production near 18 MW and an offer of 50 MW. The deviation assumes a negative value since it is a case where lack of production exists. In short, the production of first scenario is deviated by 32 MW from the optimal offer.

Another case is when the offer is zero, which offer is also depicted in the same (Figure 5.2). For instance, the fourth period ($t = 4$) of the first scenario has a red asterisk in zero, being the difference between the production and the offer 25 ($25(production) - 0(offer) = 25$).

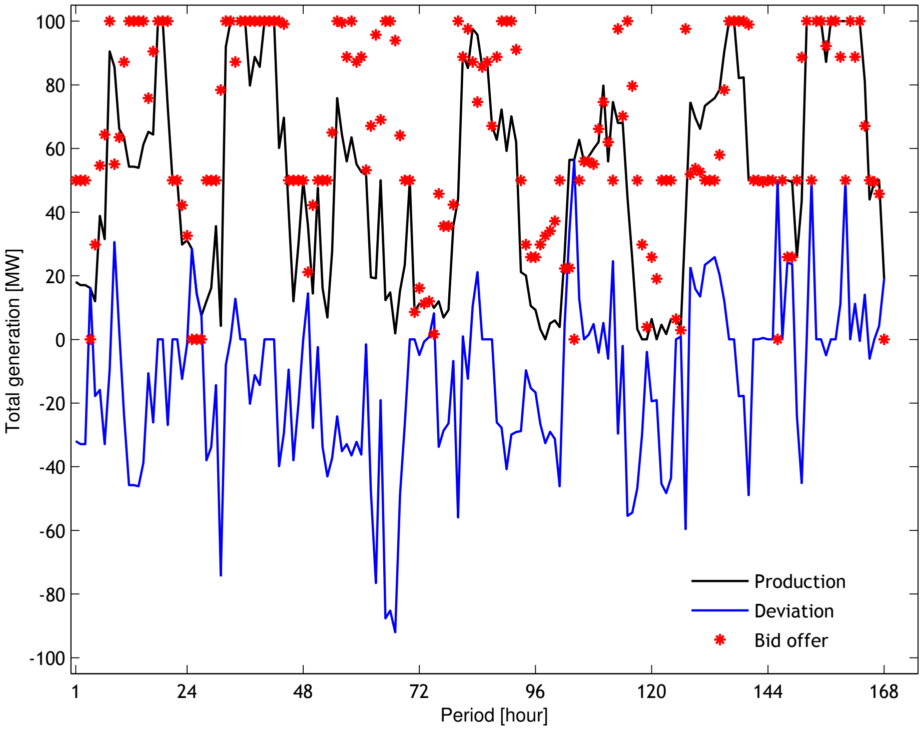


Figure 5.2 - Total production and deviation from first scenario separate offer.

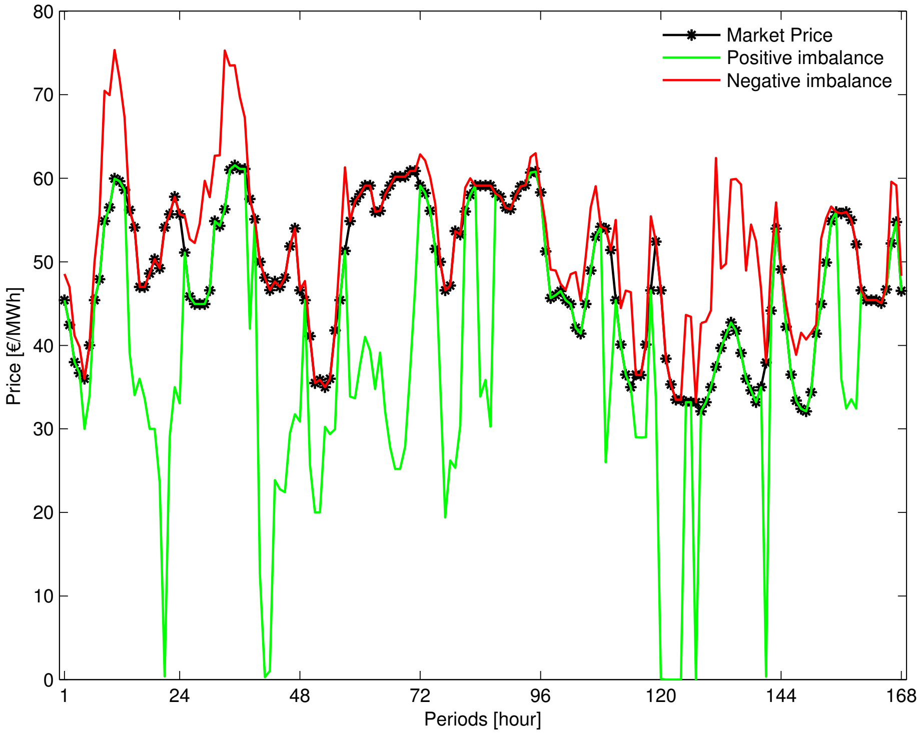


Figure 5.3 – Market prices and imbalances from the scenario 1.

In Figure 5.3 the market prices and the imbalance market prices are presented. Negative imbalances are equal or higher to the market price. For instance, if a participant produces less energy than what announced, the participant has a cost higher than the market price. On the other hand, participants will have less benefits compared to the market price when they produce more energy.

In the first scenario, most of the market prices remain the same in case of overproduction due to the equal value of the positive imbalance price and the market price. However, this is not a rule in price behavior. Not always is possible to achieve the same extra profit amount as the market price.

In the hours 24, 44, 124, 144, it is not profitable to produce more energy than schedule, since the extra amount received from the generation of more energy into the market is almost zero. For the participant there will be no extra profit. At the same time, the market price and the negative imbalance price is the same, which means a penalty is applied for delivering less energy.

5.4 Test Case: Market Price and Imbalances

The marginal price scenarios of the DA market are presented in Figure 5.4. The volatility is represented by different scenarios of the market price. This volatility is caused by several factors (e.g. mix of types of generation, difference between demand and supply).

The most profitable period to sell energy is in the hour where the highest price occurs, the participant can have more benefits from selling energy in that hours. On the other hand, some careful attention has to be done in the hours where the lowest price is present. Prices are higher during peak hours and lower in other periods. A high volatility in peak hour is expected, since it is the period when most energy is required. Looking at the first four days ($t = 96$), the prices follow the same pattern with similar prices being a cyclic behavior. However, in last three days of the evaluated range it is noticeable a price drop. However, with the increase of the time horizon, the precision of the forecasts are lower than for a less time horizon.

The market prices are achieved by the intersection of demand and the supply. If one of these two factors (demand or supply) lowers, leads to a direct influence on the market price. Typically, if the demand which relates the human habits remains the same, the supply can only affect directly to the electricity price.

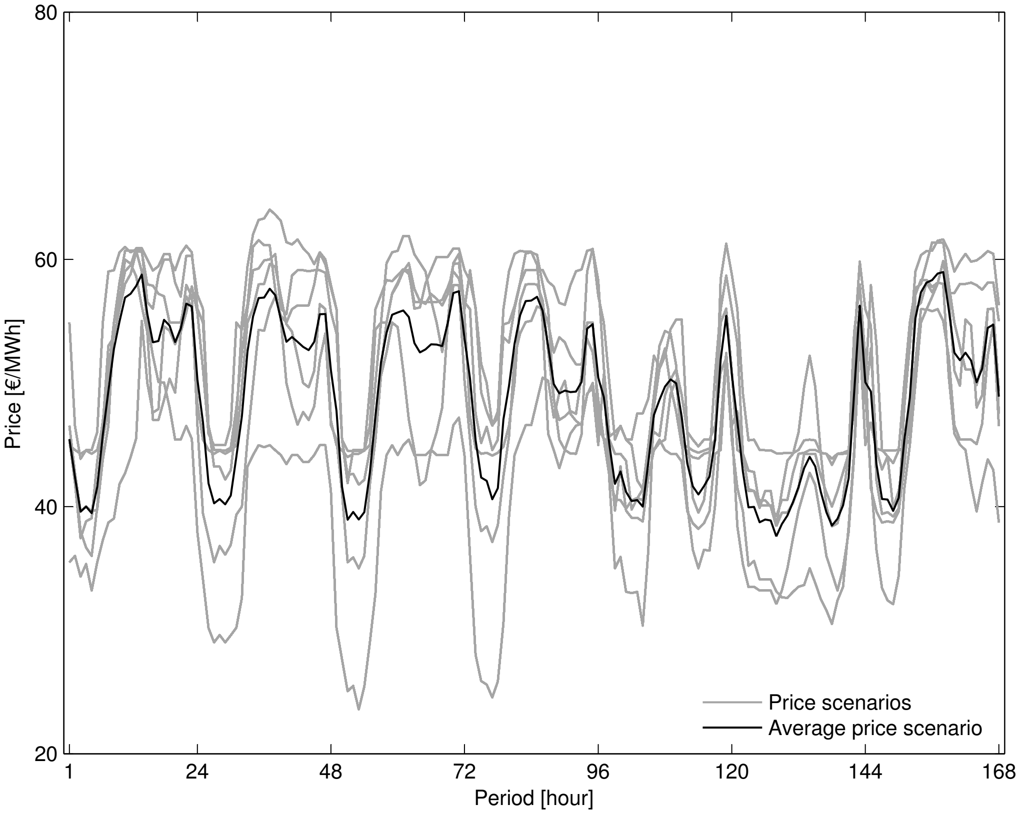


Figure 5.4 – Price scenarios [€/MWh] and average price scenarios from July to September 2014.

Table 5.1: Maximum and minimum values of market prices and imbalances scenarios [€/MWh].

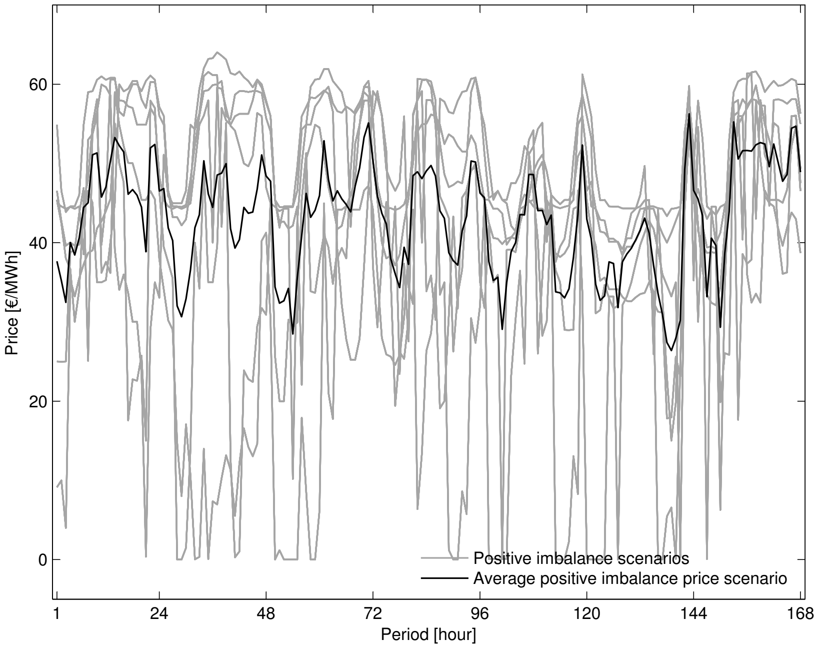
	Min	Max
Market price [€/MWh]	23,58	60,02
Positive Imbalance [€/MWh]	0	60,02
Negative Imbalance [€/MWh]	23,58	75,35

In the Iberian market, the prices are lower at night periods, since a reduction of energy demand is given. On the other hand, during the day (morning and afternoon), an increase in prices is expected. Hence, during night periods the price value drops to $23,58$ €/MW, while during the day it can achieve 60 €/MW according to Table 5.1 (results from the price graphs).

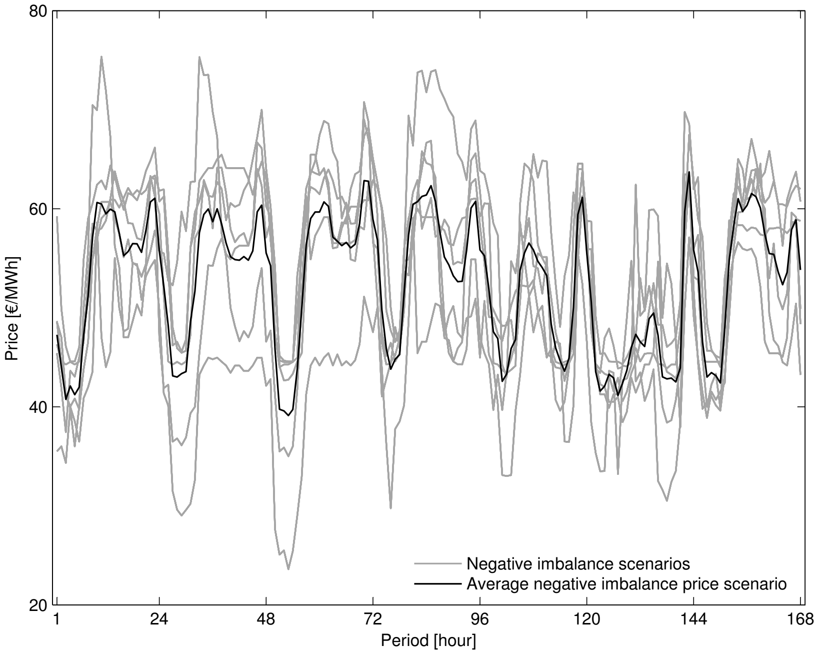
In Figure 5.5, the imbalance prices for 168 hours are presented. It is observable that the positive imbalance prices (Figure 5.5a) are lower than negative imbalance prices (Figure 5.5b). Therefore, a deviation of production does not have the same amounts, regarding the penalties and benefits for the producer. According to the Figure 5.5, if a producer has a negative deviation will have to pay higher amounts when compared to the received amount due to possible benefits.

Hence, in general is more risky to have a negative imbalance when compared to the positive one. As presented in the previous Table 5.1, the minimum and maximum values of negative imbalance ($23,58$ € and $75,35$ € , respectively) are higher than positive imbalances with minimum value zero and maximum $60,02$ €. For instance, there are periods where producer may not receive extra payments for supplying more energy to the market.

Comparing both imbalances, it is easily identified that both imbalances depend on market price volatility. When positive imbalances are higher, the negatives are also higher. On the other hand, when the positive imbalance is lower, the negative imbalances follow the same behavior. Therefore, attending the previous data, the imbalance prices are lower in the last three days due to a direct influence of market price drop.



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



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

Figure 5.5 – Prices scenarios, in [€/MWh], from July to September, 2014.

5.4.1 Production

In Figure 5.6a the PV production scenarios are presented. There are always some instances with zero value in approximately 24 hours interval. This period is characterized by night period where solar irradiation is not available for PV production. The other non-zero period, the average value of PV production is 50 MWh. This is related to the summer season where sun has more irradiation. It is depicted in figure 6 PV scenarios (grey colored line) and they are very close to the mean value. However, on third day between 48 and 72 hour period, is observed the most variable period achieving in one scenario, a production of 10 MWh.

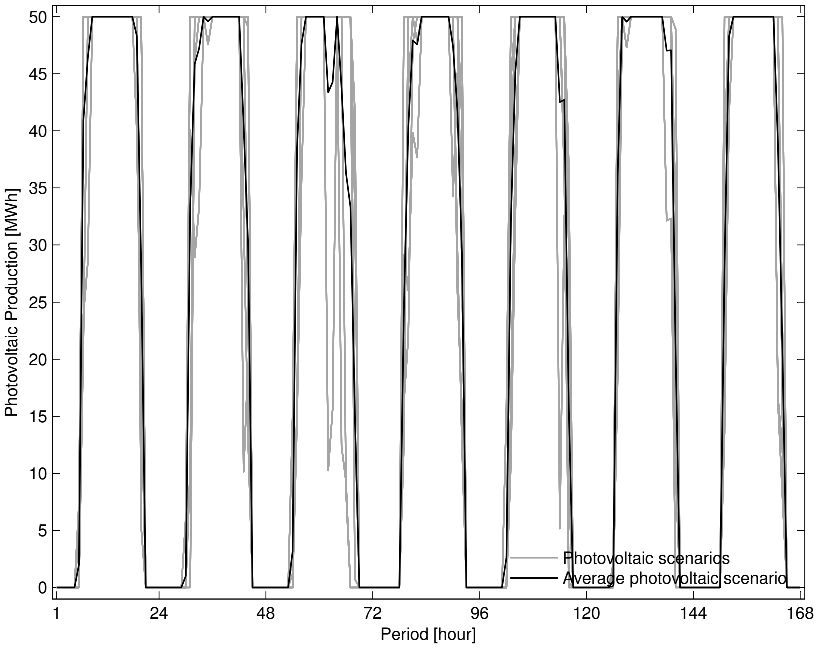
In Figure 5.6b the wind production scenarios are presented. Comparing to PV, wind production scenario are more volatile due to the high volatility of the wind speed in this period. This production is oscillatory, being more profitable at some periods and non-profitable at others. However, wind power is available most of the time when comparing to PV, contributing for more offer opportunities into the electricity market. In the week in question, the wind production varies between an average of 17 MWh and 50 MWh.

However, the easiest way to understand the behavior of the production scenarios is by taking into account different possible outcomes. In a decision-making process, the decision-maker needs to make the best possible decision regarding the current information given at the time. Regarding industry decision processes, it is widely common to address every situation in three possible outcomes: the best possible outcome (max. production), the worst possible outcome (min. production) and the typical outcome (average production). Evidently, all these outcomes are represented as scenarios. However, to facilitate the decision-making process in industry, these three outcomes get the more attention with respect to the other scenarios, since they limit the region of possible decisions. For instance, in many cases if the decision-maker can bare the consequences of the worst possible scenario, most probably a favor decision is made.

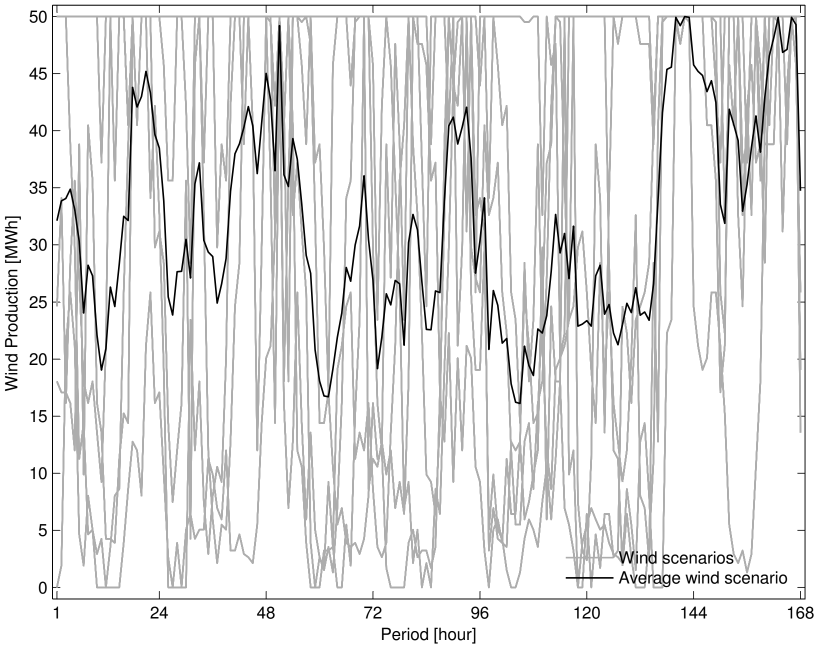
Regarding the volatility associated with the production of RES, the following figures will address this concern for the decision-maker. In Figure 5.7, the three different PV productions are presented. The best possible outcomes are demonstrated with 50 MW of production every day. Depending on the decision-maker decisions, the gap presented between maximum and minimum production may presents a more careful attention due to the uncertainty of production.

Nonetheless, this deviation is significant in times of sunrise or sunset. The first moment is given by the period $t = 7$, reaching the a difference in more than 50% between maximum (50 MWh) and minimum (21,64 MWh). In period $t = 9$ there is also a difference (maximum 50 and minimum 28). Moreover, the pattern is the same in sunset periods ($t = 19$ and $t = 20$) with significant changes.

For instance, in this period it is not secure to bid in an average spot, since the gap between the average and minimum production is considerable. In period $t = 8$, the decision needs to be made taking into account the difference between the average and the minimum, in order to prevent the risks of possible negative imbalances associated with a mismatch between the announced production and actual production. Evidently, the decision needs to be made considering all information.



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



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

Figure 5.6 – RES production scenarios [MWh] from July to September, 2014.

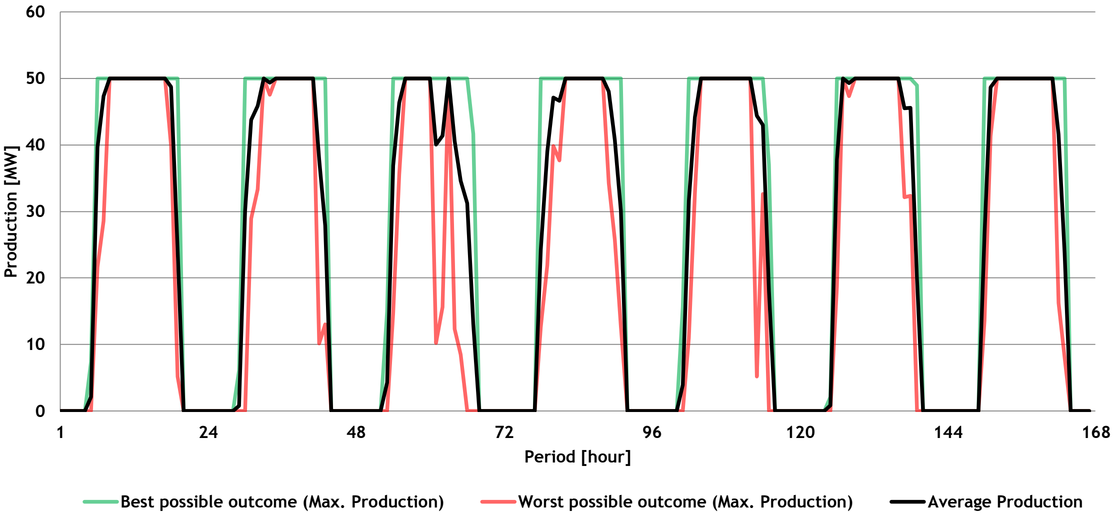


Figure 5.7 – The PV production [MWh]: best possible outcome; worst possible outcome and average of scenario production.

However, the decision-making process is more complicated with respect to the time horizon increases especially in the second, third and fourth day. For instance, the third day presents more volatility in sunny hours. A peak happens during periods $t = 62$ and $t = 63$, representing differences of 30 MW between maximum and minimum. In the same day, another peak is presented 2 hours later. Due to the behavior of PV production during this week, this is an untypical day. Moreover, by the fact of long time horizon in these simulations, more tests can be done closer to the third day, confirming if the initial predictions match. The nature of uncertainty of production is highly volatile to make a decision in a long horizon, since the error of prediction increases.

On other hand, the wind production is also studied for the possible outcome. In Figure 5.8, the wind production is presented. The best outcome generated is almost 50 MW in every period of 168 hours. However, the minimum production is significantly low (less than 10 MW) in several periods, even zero in some periods (e.g. $10 - 15$ hours).

For a decision-maker point of view, these scenarios represent a lot of instability in the wind power offering. In spite of having an average offering value relatively high, a careful examination is required in order to assess the best possible decision. The volatility can cost a lot of money to the participant. Most of the periods a more conservative decision is advised, in order to reduce the risks of possible deviations due to non-compliance of the announced supply.

In this week, only the last two days present a better case to bring more energy into the market. Nonetheless, the average value is considerable taking into account the minimum value. Only four periods can be considered the average value of production due to the closer distance from the maximum value. These periods are: 51, 138 to 144, 163, 166 and 167.

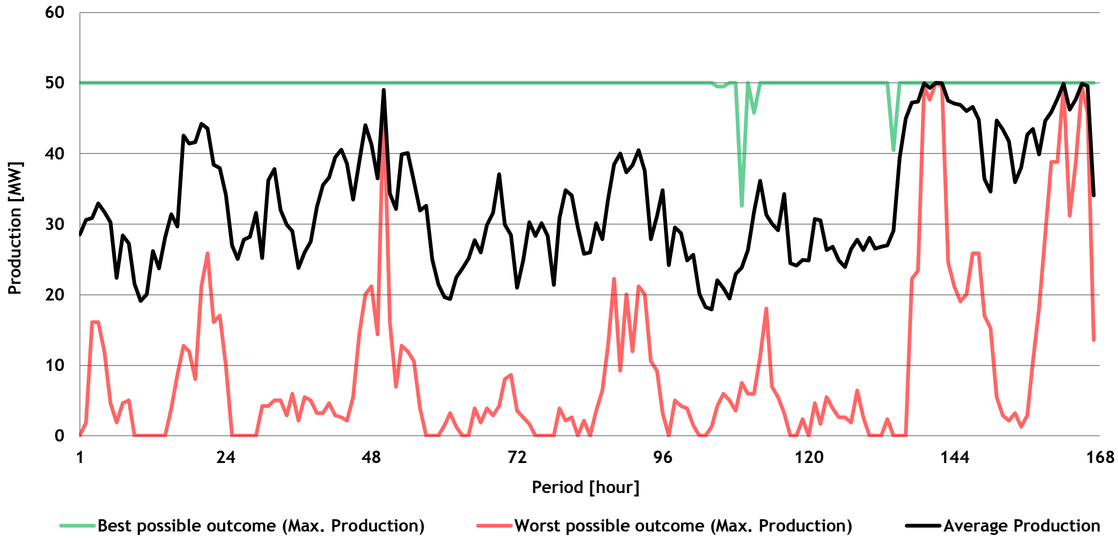


Figure 5.8 – The wind production [MWh]: best possible outcome; worst possible outcome and average of scenario production.

The combination between wind and PV production is depicted in Figure 5.9. First of all, the production is higher when combining both productions together, due to the maximum installed capacity of technologies.

Second, it is visible the difference from the previous two cases (Figure 5.7 and Figure 5.8). Combining both technologies will increase the possibility of offering more energy into electricity market. At night periods, the production is supplied by wind technology.

The current case comparing to the previous case (Figure 5.8) is similar in night periods where wind is supplying all the offer. Nonetheless, the situation is different during daylight periods, where PV production is available increasing the dome of production comparing to the same (Figure 5.8). Moreover, it is evident the contribution of combining technologies due to the increase of minimum production value (of a combined offer) than the previous wind curve. It may represent an advantage of combining PV with wind production for a more profitable offer, since it increases the possibility of having more energy to be delivered in the DA market.

Another important point to analyze, is the market price (Figure 5.10). The price behavior is essential in the decision-making process of this nature. In some periods, probably it is not profitable to take more risk in the bidding, selling more energy in the market, keeping a conservative position. Especially at times of lower production and where the profits can be higher with higher deviations.

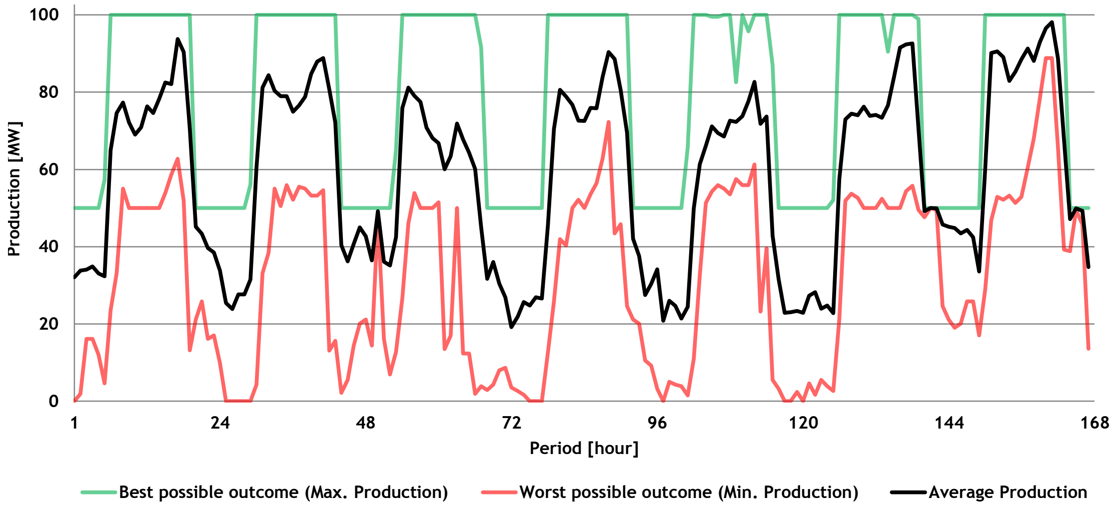


Figure 5.9 – The combined production [MWh]: best possible outcome; worst possible outcome and average of scenario production.

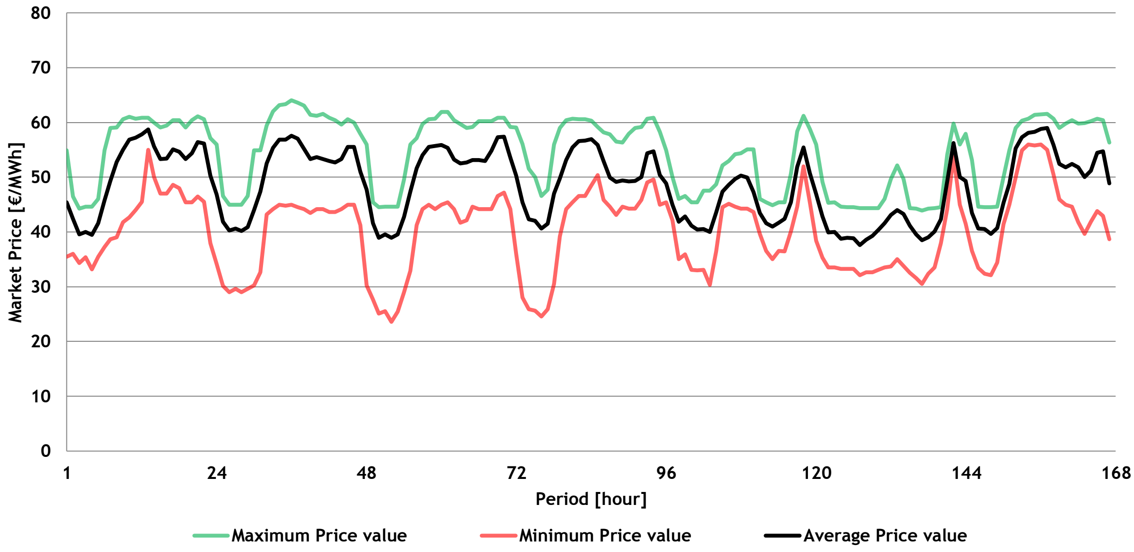


Figure 5.10 – The market prices [€/MWh]: Maximum price value; minimum price value and average price value.

5.4.2 Comparing both Strategies

A separate and combined offer are simulated in order to verify the possible outcomes of both strategies. In Table 5.2 the profit and deviations are presented. Evaluating the results, the first conclusion that can be drawn regards the profit. The market participant receives the same amount of profit if using a combined offer or a separate offer. However, analyzing the standard deviation, is evident the differences. For this week, almost 7066 € are saved from the combined offer when compared to the separate offer. This strategy represents a better option when compared to the separate offer, since it can achieve the same profits but with lower deviation. Evidently, the deviation is not a bad point on a market offer, but rather presents the possible outcomes of a bad prediction.

Additionally, analyzing the imbalances it is noticeable that a separate offer has less negative imbalances comparing to combined offer and more positive imbalances. Besides having a lower deviation, combined offer achieved the same profit with lower risk (lower standard deviation of the profit) compared to the separate offer.

Regarding the production, wind power was more profitable in this week than PV since PV is a limited technology and it does not produce energy at night periods. Basically, half of the day is wasted by technology limitation, showing a disadvantage to the investor in choosing PV technology. However, the introduction of PV in a combined offer significantly reduce the imbalances associated with the offer during day periods. This is an important point since it reduces the possible penalties associated with the lack of production that can be balanced by the PV production. In this specific situation, the profits of selling PV energy were 44344 € lower than the profits come from wind power.

Regarding the power output, wind power has a total deviation of 2320 MW while PV power has approximately 380 MW. This is explained by the fact that the period in question represents a summer season, which typically the irradiation is higher. During the night, there is not deviation associated with the PV production, since it is unable to produce during these periods.

The production deviation caused by the PV power represents a $8210,57$ € (16%) out of a total of $49804,20$ €, being the other 84% caused by the wind production. However, the differences of profit in both strategies are not significant, having a difference of 500 € in favor of the combined offer. Moreover, the combined offer has lower deviation. Observing the profit and deviation, the combined offer has more profit with lower deviation in the order of 7066 € which represents 0,463 MW delivered.

Table 5.2: Total profits, standard deviation of the total profits, average positive imbalances and average negative imbalances for both strategies.

	Wind Power	PV Power	Separate Offer	Combined Offer
Profit [€]	163 205,54	118 861,55	282 067,08	282 519,11
Standard deviation [€]	41 593,63	8 210,57	49 804,2	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]	1 422,9	303,2	1 726,1	1 473,85

In Figure 5.11, a short vision of the offer of PV and wind production in the DA market is presented. Comparing both offers, it is possible identify periods with the same amount of energy production. Equal offers occur in the first peak. These hours are part of the night period, where PV power is not able to produce energy. Hence, it is safe to assume that this production only derives from the wind production, showing not variance in the offer. At that period, the wind power is only offered as a combined or separate offer (depending on strategy).

Most of the time, separate offer is more capable to deliver more energy that combined strategy. For example, between 60 to 72 hours, a big different amount is delivered by each strategy, being higher with an increment of 30 MWh of difference. The same differences can be detected in the hour 130 and in 144 to 168 period.

However, a combined offer has a higher profit with lower energy offered as it is presented in Table 5.2. Hence, selling much energy in the market is not equivalent of making much money due to the price volatility. Moreover, it is possible to find same periods with zero MWh of bidding. In this cases, the energy produced will not give enough profit from selling the energy. Insufficient energy delivered will have an nonviable return, since it is not enough to cover the costs of production. However, a participant is obligated to offer in every period in the DA market even if it is non-profitable. Therefore, these decisions require careful evaluation regarding the possible outcomes with the available information.

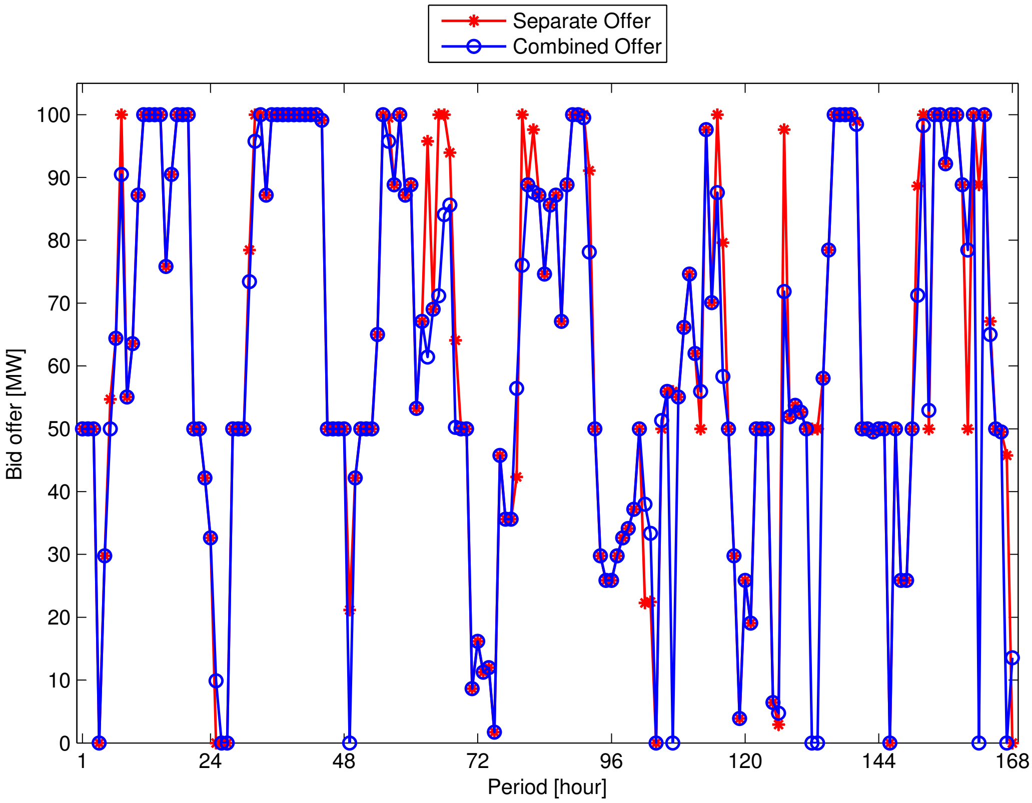


Figure 5.11 - Comparison between Separate offer and Combined Offer of PV and Wind power production [MWh].

Chapter 6

Final Considerations

The increased pressures due to climate change paradigm, led to the rethink the production sources of electrical energy. The appointed solution is the use of RES due to the benefits that it brings. It is expected the increased use of RES technologies such as wind and solar. However, these technologies are considered non-dispatchable since they are significantly affected by weather conditions. This variable production significantly affects its market integration, leading to price volatility.

In this work a strategy was proposed to aid the decision-making under the uncertainty of variable production from RES. It was studied the effect of bidding PV and wind as a separate offer in electricity market as well as combine both technologies together into a single offer. In an investor point of view, it is desirable to have the higher return of investment possible, since RES have high initial investments and long payback periods. However, the use of prediction techniques can aid on reducing the uncertainty of production, leading to the reduction of these effects.

Prediction techniques are required when offering in electricity markets. Typically these markets have balancing mechanisms, that in case of lack of production reserves needs to be operational in order meet the demand. Regarding a producer, if it fails to provide the energy that it announced (offered) into the market, a penalty is applied. However, the producer can also receive incentives for providing more energy then what was initially reported. Still, these benefits are low and are less then the penalties. Due to the nature of the resource, producers that rely on RES to offer in electricity markets could be compromised if the offers are not done properly.

In this work, the uncertain production was considered in the offers. The production profiles were modulated with the use of historical data. Additionally, real market prices were considered as well for the imbalance prices. All this information combined led to the creation of several scenarios that envisions to predict possible outcomes. These scenarios were designed for both offering strategies analyzed in this work (single-offer and combined offer). Additionally, the best possible outcomes were determined taking into account all possible scenarios generated.

Evaluating the results, it was noted that the use of a combined offer strategy brings practically similar profits when compared to single offer. However, the use of the combined offering strategy can significantly reduce the standard deviation of selling in Iberian day-ahead market. Results have shown that a combined strategy can save 7066 € in a week, due to the reduction of penalty imbalances.

It was observable in the results that wind is more profitable when compared to the PV production, mainly due to the availability of resource. The PV limitation of only producing energy during day periods presents lesser incomes to the RES holder.

However, it was demonstrated that using PV combined with wind production can reduce the production imbalances during the day of the wind production. During the day periods, the combined offer achieved less imbalances due to PV compensation of production, leading to a safer bidding offer.

The results presented several instances where the best possible decision that a decision-maker could take is not to offer energy into the electricity market. However, this is against Iberian market rules since the market participants are obligated to participate in all offers. Therefore, when facing this situation the decision-maker needs to bid the lowest possible amount in order to prevent possible consequences from negative imbalances.

6.1 Future Work

It is evident the gap existent in the PV research field. A possible work is the further extend the studies of combining PV technologies with other renewable technologies (e.g. storage, hydro). Moreover, the technique presented in this work considers the offers to be risk-neutral. Other future work possibility is the addition of risk in the prediction model in order to improve the offers. Additionally, a cost-benefit analysis could be perform in order to assess the optimal PV installed capacity for a given installed capacity of wind.

Other possible work is the improvement of scenario generation. In this work the scenarios were considered to have the same probability of occurrence. In order to approximate more the prediction model to reality additional data can be used to further shape these scenarios (e.g weather forecasts). The use of additional data can reduce possible repeated scenarios, leading to a improvement of the prediction.

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).

Bibliography

[1] European Environment Agency. (2014) Trends and Projections in Europe 2014. [Online]. Available: http://www.eea.europa.eu/

[2] DIRECTIVE 2009/28/CE. (2009) EUROPEAN PARLIAMENT AND OF THE COUNCIL. [Online]. Available: http://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32009L0028&from=PT

[3] Renewable Energy progress report. (2013) European commission. [Online]. Available: http://ec.europa.eu/energy/renewables/reports/reports_en.htm

[4] R. Castro, "Uma introdução às energias renováveis: Eólica, fotovoltaica e mini-hídrica," *Instituto Superior Técnico da Universidade Técnica de Lisboa, 1ª Edição*, 2011.

[5] BP. (2014) Statistical Review of World Energy 2014. [Online]. Available: http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy.html

[6] Rede Elétrica Nacional. O SETOR ELÉTRICO. [Online]. Available: http://www.ren.pt/pt-PT/o_que_fazemos/eletricidade/o_setor_eletrico/

[7] European Comission. (2014) EU Energy Markets in 2014. [Online]. Available: http://ec.europa.eu/energy/sites/ener/files/documents/2014_energy_market_en_0.pdf

[8] Bloomberg New Energy Finace. (2014) EUROPEAN RENEWABLE ENERGY INVESTMENT SET TO SURGE BY 2030 ON BACK OF NEARLY 1 TRILLION OF INVESTMENT. [Online]. Available: http://about.bnef.com/press-releases/european-renewable-energy-investment-set-surge-2030-back-nearly-1-trillion-investment/content/uploads/sites/7/2014/06/gremo-pr-europe.pdf

[9] X.-P. Zhang, *Restructured electric power systems: analysis of electricity markets with equilibrium models*. John Wiley & Sons, 2010, vol. 71.

[10] S. Hunt, *Making competition work in electricity*. John Wiley & Sons, 2002, vol. 146.

[11] F. P. Sioshansi and W. Pfaffenberger, *Electricity market reform: an international perspective*. Elsevier, 2006.

[12] J. P. T. Saraiva, J. T. Saraiva, J. L. P. da Silva, M. T. P. de Leão, J. L. P. P. da Silva, M. T. C. P. da Silva, and P. de Leão, *Mercados de Electricidade-Regulação e Tarifação de Uso das Redes*. FEUP Edições, 2002.

[13] J. Chow, R. de Mello, and K. Cheung, "Electricity market design: An integrated approach to reliability assurance," *Proceedings of the IEEE*, vol. 93, no. 11, Nov 2005.

[14] L. Meeus, K. Purchala, and R. Belmans, "Development of the internal electricity market in europe," *The Electricity Journal*, vol. 18, no. 6, pp. 25 - 35, 2005.

[15] DIRECTIVE 96/92/CE. (1996) EUROPEAN PARLIAMENT AND OF THE COUNCIL. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31996L0092&from=PT

[16] J. S. Paiva, "Redes de energia eléctrica: uma análise sistémica, 2a edição," 2007.

[17] DIRECTIVE 2003/54/CE. (2003) EUROPEAN PARLIAMENT AND OF THE COUNCIL. [Online]. Available: https://www.energy-community.org/pls/portal/docs/36275.PDF

[18] DIRECTIVE 2009/72/CE. (2009) EUROPEAN PARLIAMENT AND OF THE COUNCIL. [Online]. Available: http://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:32009L0072&from=EN

[19] K. Imran and I. Kockar, "A technical comparison of wholesale electricity markets in north america and europe," *Electric Power Systems Research*, vol. 108, no. 0, pp. 59 - 67, 2014.

[20] ASSEMBLEIA DA REPÚBLICA. (2004) Resolução da Assembleia da República n.o 33-A/2004. [Online]. Available: http://www.erse.pt/pt/mibel/construcaoedesenvolvimento/Documents/RAR33A.pdf

[21] Decreto-Lei n 44/1997. (1997) Diário da Républica. [Online]. Available: http//dre.tretas.org/dre/79557/

[22] Galp energia. (2011) O negócio da eletricidade em Portugal. [Online]. Available: http://www.galpenergia.com

[23] U. Stridbaek *et al.*, "Lessons from liberalised electricity markets," *IEA publication*, 2006.

[24] Entidade Reguladora dos Sistemas Energéticos. (2015) Eletricidade: Mais de 3,9 milhões de clientes aderiram ao mercado livre até março. [Online]. Available: http://www.erse.pt/pt/mibel/construcaoedesenvolvimento/Documents/RAR33A.pdf

[25] Nordpool. Day-ahead Market. [Online]. Available: http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/

[26] D. W. Bunn, *Modelling prices in competitive electricity markets*, 2004.

[27] J. Cochran, M. Miller, M. Milligan, E. Ela, D. Arent, A. Bloom, M. Futch, J. Kiviluoma, H. Holtinnen, A. Orths *et al.*, "Market evolution: Wholesale electricity market design for 21 st century power systems," *Contract*, 2013.

[28] J. Morales, A. Conejo, H. Madsen, P. Pinson, and M. Zugno, *Integrating Renewables in Electricity Markets: Operational Problems*, ser. International Series in Operations Research & Management Science. Springer US, 2013.

[29] V. Kaminski, *Energy markets*. Risk Books, 2012.

[30] M. Kopsakangas-Savolainen and R. Svento, *Modern Energy Markets: Real-Time Pricing, Renewable Resources and Efficient Distribution*, ser. Green Energy and Technology. Springer, 2012.

[31] C. Klessmann, C. Nabe, and K. Burges, "Pros and cons of exposing renewables to electricity market risks—a comparison of the market integration approaches in germany, spain, and the uk," *Energy Policy*, vol. 36, no. 10, pp. 3646--3661, 2008.

[32] S. G. Henderson and B. L. Nelson, "Chapter 1 stochastic computer simulation," in *Simulation*, ser. Handbooks in Operations Research and Management Science, S. G. Henderson and B. L. Nelson, Eds. Elsevier, 2006, vol. 13, pp. 1 - 18.

[33] S. W. Wallace and S.-E. Fleten, "Stochastic programming models in energy," in *Stochastic Programming*, A. Ruszczynski and A. Shapiro, Eds. Elsevier, 2003, vol. 10, pp. 637 - 677.

[34] R. Kovacevic, G. Pflug, and M. Vespucci, *Handbook of Risk Management in Energy Production and Trading*, ser. International Series in Operations Research & Management Science. Springer, 2013.

[35] R. J.-B. Wets, "Chapter {VIII} stochastic programming," in *Optimization*, ser. Handbooks in Operations Research and Management Science, A. R. K. G.L. Nemhauser and M. Todd, Eds. Elsevier, 1989, vol. 1, pp. 573 - 629.

[36] A. Conejo, E. Castillo, R. Minguez, and R. Garcia-Bertrand, *Decomposition Techniques in Mathematical Programming: Engineering and Science Applications*. Springer Berlin Heidelberg, 2006.

[37] S. T. Rachev, S. V. Stoyanov, and F. J. Fabozzi, *Advanced stochastic models, risk assessment, and portfolio optimization: The ideal risk, uncertainty, and performance measures*. John Wiley & Sons, 2008, vol. 149.

[38] L.-A. Barroso and A. Conejo, "Decision making under uncertainty in electricity markets," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, pp. 3 pp.-.

[39] A. Zahedi, "A review of drivers, benefits, and challenges in integrating renewable energy sources into electricity grid," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9, pp. 4775 - 4779, 2011.

[40] S. Singh and I. Erlich, "Strategies for wind power trading in competitive electricity markets," *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 249-256, March 2008.

[41] D. Biggar and M. Hesamzadeh, *The Economics of Electricity Markets*, ser. Wiley - IEEE. Wiley, 2014.

[42] A. Wood and B. Wollenberg, *Power generation, operation, and control*. Wiley, 1984.

[43] R. Weron, "Electricity price forecasting: A review of the state-of-the-art with a look into the future," *International Journal of Forecasting*, vol. 30, no. 4, pp. 1030 - 1081, 2014.

[44] L. E. Jones, *Renewable Energy Integration: Practical Management of Variability, Uncertainty, and Flexibility in Power Grids*. Academic Press, 2014.

[45] E. DeMeo, G. Jordan, C. Kalich, J. King, M. Milligan, C. Murley, B. Oakleaf, and M. Schuerger, "Accommodating wind's natural behavior," *IEEE Power and Energy Magazine*, vol. 5, no. 6, pp. 59-67, Nov 2007.

[46] N. Hatziargyriou and A. Zervos, "Wind power development in europe," *Proceedings of the IEEE*, vol. 89, no. 12, pp. 1765-1782, Dec 2001.

[47] M. Vilim and A. Botterud, "Wind power bidding in electricity markets with high wind penetration," *Applied Energy*, vol. 118, no. 0, pp. 141 - 155, 2014.

[48] J. Manwell, J. McGowan, and A. Rogers, *Wind Energy Explained: Theory, Design and Application*. Wiley, 2010.

[49] N. Jenkins and I. of Electrical Engineers, *Embedded Generation*, ser. IEE Power Series. Institution of Engineering and Technology, 2000.

[50] F. Vallee, J. Lobry, and O. Deblecker, "Impact of the wind geographical correlation level for reliability studies," *IEEE Transactions on Power Systems*, vol. 22, no. 4, pp. 2232-2239, Nov 2007.

[51] X. Liu and W. Xu, "Economic load dispatch constrained by wind power availability: A here-and-now approach," *IEEE Transactions on Sustainable Energy*, vol. 1, no. 1, pp. 2-9, April 2010.

[52] A. Sanchez de la Nieta, J. Contreras, and J. Munoz, "Optimal coordinated wind-hydro bidding strategies in day-ahead markets," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 798-809, May 2013.

[53] J. Morales, A. Conejo, and J. Perez-Ruiz, "Short-term trading for a wind power producer," *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 554-564, Feb 2010.

[54] B. Parida, S. Iniyan, and R. Goic, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1625 - 1636, 2011.

[55] A. Luque and S. Hegedus, *Handbook of Photovoltaic Science and Engineering*. Wiley, 2003.

[56] L. Shi, Y. Luo, and G. Tu, "Bidding strategy of microgrid with consideration of uncertainty for participating in power market," *International Journal of Electrical Power & Energy Systems*, vol. 59, no. 0, pp. 1 - 13, 2014.

[57] J. S. González, M. B. Payán, J. R. Santos, and Ángel Gaspar González Rodríguez, "Maximizing the overall production of wind farms by setting the individual operating point of wind turbines," *Renewable Energy*, vol. 80, no. 0, pp. 219 - 229, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960148115000993

[58] M. De-Prada-Gil, C. G. Alías, O. Gomis-Bellmunt, and A. Sumper, "Maximum wind power plant generation by reducing the wake effect," *Energy Conversion and Management*, vol. 101, no. 0, pp. 73 - 84, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0196890415004823

[59] R. Thresher, M. Robinson, and P. Veers, "To capture the wind," *Power and Energy Magazine, IEEE*, vol. 5, no. 6, pp. 34-46, Nov 2007.

[60] E. Bitar, R. Rajagopal, P. Khargonekar, K. Poolla, and P. Varaiya, "Bringing wind energy to market," *IEEE Transactions on Power Systems*, vol. 27, no. 3, pp. 1225-1235, Aug 2012.

[61] G. Singh, "Solar power generation by {PV} (photovoltaic) technology: A review," *Energy*, vol. 53, no. 0, pp. 1 - 13, 2013.

[62] M. Raugei and P. Frankl, "Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks," *Energy*, vol. 34, no. 3, pp. 392 - 399, 2009.

[63] L. Hirth, "Market value of solar power: Is photovoltaics cost-competitive?" *Renewable Power Generation, IET*, vol. 9, no. 1, pp. 37-45, 2015.

[64] A. Martinez-Rubio, F. Sanz-Adan, and J. Santamaria, "Optimal design of photovoltaic energy collectors with mutual shading for pre-existing building roofs," *Renewable Energy*, vol. 78, no. 0, pp. 666 - 678, 2015.

[65] S. Brunton, C. Rowley, S. Kulkarni, and C. Clarkson, "Maximum power point tracking for photovoltaic optimization using ripple-based extremum seeking control," *IEEE Transactions on Power Electronics*, vol. 25, no. 10, pp. 2531-2540, Oct 2010.

[66] A. Fabbri, T. Román, J. Abbad, and V. Quezada, "Assessment of the cost associated with wind generation prediction errors in a liberalized electricity market," *IEEE Transactions on Power Systems*, vol. 20, no. 3, pp. 1440-1446, Aug 2005.

[67] M. Khalid and A. Savkin, "A method for short-term wind power prediction with multiple observation points," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 579-586, May 2012.

[68] J. Garcia-Gonzalez, R. de la Muela, L. Santos, and A. Gonzalez, "Stochastic joint optimization of wind generation and pumped-storage units in an electricity market," *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 460-468, May 2008.

[69] J. Tastu, P. Pinson, P.-J. Trombe, and H. Madsen, "Probabilistic forecasts of wind power generation accounting for geographically dispersed information," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 480-489, Jan 2014.

[70] E. Lorenz, J. Hurka, D. Heinemann, and H. Beyer, "Irradiance forecasting for the power prediction of grid-connected photovoltaic systems," *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, vol. 2, no. 1, pp. 2-10, March 2009.

[71] J. Shi, W.-J. Lee, Y. Liu, Y. Yang, and P. Wang, "Forecasting power output of photovoltaic systems based on weather classification and support vector machines," *IEEE Transactions on Industry Applications*, vol. 48, no. 3, pp. 1064-1069, May 2012.

[72] A. Chaouachi, R. Kamel, R. Andoulsi, and K. Nagasaka, "Multiobjective intelligent energy management for a microgrid," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1688-1699, April 2013.

[73] G. Capizzi, C. Napoli, and F. Bonanno, "Innovative second-generation wavelets construction with recurrent neural networks for solar radiation forecasting," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 23, no. 11, pp. 1805-1815, Nov 2012.

[74] J. Matevosyan and L. Soder, "Minimization of imbalance cost trading wind power on the short-term power market," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1396-1404, Aug 2006.

[75] L. Baringo and A. Conejo, "Strategic offering for a wind power producer," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4645-4654, Nov 2013.

[76] A. Botterud, Z. Zhou, J. Wang, R. Bessa, H. Keko, J. Sumaili, and V. Miranda, "Wind power trading under uncertainty in lmp markets," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 894-903, May 2012.

[77] S. Martin, Y. Smeers, and J. Aguado, "A stochastic two settlement equilibrium model for electricity markets with wind generation," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 233-245, Jan 2015.

[78] A. Al-Awami and M. El-Sharkawi, "Coordinated trading of wind and thermal energy," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 3, pp. 277-287, July 2011.

[79] A. Schaffarczyk, *Understanding Wind Power Technology: Theory, Deployment and Optimisation*. John Wiley & Sons, 2014.

[80] Euroelectric, *Flexible gas markets for variable renewable generation*, 2014.

[81] Meteorología y climatología de Navarra. [Online]. Available: http://meteo.navarra.es/

[82] IDAE. Spanish Renewable Energy Plan for 2005--2010. [Online]. Available: http://www.idae.es/uploads/documentos_PER_2005-2010_8_de_gosto-2005_Completo.(modificacionpag_63)_Copia_2_301254a0.pdf

[83] OMIE. Operador del Mercado Ibérico de Energía-Polo Español, S. A. [Online]. Available: http://www.omie.es/files/flash/ResultadosMercado.swf

[84] REE. Red Eléctrica de España, e·sios. [Online]. Available: http://www.esios.ree.es/web-publica

[85] The Mathworks Inc., Matlab. [Online]. Available: http://www.mathworks.com

[86] GAMS. (2015) General Algebraic Modeling System. [Online]. Available: http://www.gams.com