ESCUELA TÉCNICA SUPERIOR DE INGENIERIA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

STUDY OF THE BIDDING STRATEGY OF A WIND POWER PRODUCER IN ELECTRICITY MARKETS

Autor: Eduardo Ramos Rodríguez
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Madrid
Junio 2015

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y ayuda durante todo el proyecto.

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A mi padre, por su experiencia
compartida y los consejos.

A mi familia, por enseñarme los
valores esenciales de la vida.

Estudio de la estrategia de oferta de un generador eólico en el mercado eléctrico

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Entidad colaboradora: ICAI-Universidad Pontificia Comillas.

Resumen del Proyecto

Hoy en día, la generación basada en fuentes de energías renovable (EERR) en España ha tenido que hacer frente a numerosos cambios en la regulación de su retribución, la última en Junio de 2014 (BOE 413/2014), en la que se eliminó las ayudas que sustentaban estas tecnologías. A pesar de estos cambios esta generación sigue pudiendo negociar su energía en los diferentes mercados que componen el mercado eléctrico liberalizado, un sistema que permite la competencia entre los agentes y una mayor eficiencia económica. Por lo tanto, tener que establecer nuevas estrategias para aumentar sus beneficios es necesario para la supervivencia de la generación eólica.

Los mercados eléctricos desde el punto de vista matemático pueden ser modelados como un juego en el que cada jugador oferta una cantidad de energía a fin de lograr la máxima rentabilidad, en otras palabras para maximizar su función de utilidad. Los mercados eléctricos de corto plazo en España comprenden: el mercado diario, los intradiarios y los mecanismos de ajuste de demanda y producción. Los mecanismos de ajuste comprenden los mercados de reserva secundaria, reserva terciaria, gestión de desvíos y de reserva a subir adicional. El objetivo del mercado es suministrar a los consumidores su demanda requerida; para ello se hace necesario un balance en tiempo real entre la oferta y la demanda.

La estrategia típica seguida por un generador eólico es ofertar su producción prevista sólo en el mercado diario y a su coste marginal. Ésta es una estrategia conservadora y no óptima, ya que no se beneficia de la posibilidad de reestructurar la oferta del mercado diario en otros mercados intradiarios así como en la gestión de desvíos.

En esta línea, el objetivo de un generador eólico sería maximizar sus beneficios logrando la mejor estrategia de oferta. Con el fin de reproducir las posibilidades estratégicas del generador eólico en un horizonte a corto plazo (un día), en el proyecto se han formulado matemáticamente dos modelos. En primer lugar un modelo determinista, o de información perfecta, que comprende aquella formulación en la que todos los parámetros son conocidos a priori. En segundo lugar se ha formulado un modelo estocástico, o probabilístico, que modelo los parámetros con un grado de incertidumbre. Para hacer una representación realista de la estrategia de oferta seguida en el modelo estocástico, se

han considerado distintos escenarios ponderados con probabilidad, basándose en datos históricos.

Ambos modelos ofrecen la posibilidad al generador eólico de lograr una mayor rentabilidad mediante las ofertas en el mercado diario, intradiarios y de gestión de desvíos, teniendo en cuentas las sus restricciones de operación.

El generador eólico no puede ofertar una potencia mayor que la instalada. Además, la compra de energía está penalizada en las funciones objetivo, debido a ser un coste. Sin embargo, no existe limitación para beneficiarse del arbitraje entre las subastas, beneficiándose así de la diferencia de precios y de los distintos tiempos de cierre de las subastas. Debido a la volatilidad de los mercados diarios y de gestión de desvíos, se hace necesario incluir una restricción de liquidez para no cambiar las estrategias seguidas por los competidores. Consecuentemente, se limita la oferta en estos mercados, en los que el volumen de energía negociada es considerablemente menor que la gestionada en el diario, al 10% de la potencia instalada.

Además, el modelado incluye una medida del riesgo tomado en la estrategia o actitud conservadora seguida por el generador eólico en sus operaciones, es decir una limitación para garantizar el suministro de energía y la no equivocación. Para ello, se modela la oferta por hora mediante una distribución triangular acumulada parametrizada en la que la probabilidad limita la banda de oferta posible. Ofertar más energía, que la limitada por la predicción de viento, implica asumir un riesgo, debido a que no se puede garantizar su suministro. La compra de energía se considera libre de riesgo.

Las restricciones de no *anticipatividad* incluidas en la formulación estocástica, conducen al generador eólico a seguir el horizonte de tiempo del mercado eléctrico. El fin último de estas restricciones es establecer el orden de tiempos de las distintas subastas.

El análisis de resultados sobre la estrategia de oferta seguida por el generador eólico consiste en varias simulaciones con el fin de ver la influencia del precio, la influencia de la producción, la sensibilidad del riesgo tomado en la operación del parque y la influencia de los desvíos en la toma de decisiones. Aparte de eso, una comparación entre el modelo determinista, el estocástico y la estrategia seguida por los agentes de la vida real se hará con el fin de ver la validez del enfoque hecho en el caso de estudio.

Una primera conclusión de las simulaciones realizadas, es que la principal diferencia entre el modelo información perfecta, el modelo estocástico y los agentes de la vida real, agentes que ofertan su producción en el mercado diario, es la rentabilidad que obtienen en sus operaciones. Ambas formulaciones matemáticas alcanzan una mayor rentabilidad que los agentes de la vida real, ya que se benefician de la posibilidad de reestructurar la oferta de energía del mercado diarios con los mercados intradiarios y de gestión de desvíos.

El modelo de información perfecta o modelo determinista comercia energía en los mercados en los que el precio es más alto, beneficiándose de arbitraje entre las subastas. Sin embargo, la estrategia seguida por el modelo con incertidumbre en la información, modelo estocástico, consiste en ofertar en los mercados en los que el precio esperado es mayor. El modelo estocástico comprende una decisión determinista en el mercado diario y decisiones estocásticas para los mercados intradiarios, de esta forma se negocia la mayor parte de la energía en el mercado diario. Esta formulación más conservadora y menos rentable no limita al generador eólico para reestructurar su oferta en los mercados de gestión de desvíos y los intradiarios, adquiriendo así una mayor rentabilidad en sus operaciones.

La energía comercializada en los mercados de gestión de desvíos se corresponde con la diferencia entre lo que se ha ofertado y lo que se ha despachado en cada hora, y representan una oportunidad para el generador eólico de obtener más beneficios. Desvíos a bajar incrementan la posibilidad de oferta del generador eólico en otros mercados, aumentando potencia disponible en éstos. Por otro lado, los desvíos a subir sólo son rentables cuando el precio del desvío es mayor que en los otros mercados.

El riesgo asumido en las operaciones se distribuye a lo largo de todas las horas del día de operación, adquiriendo un mayor grado de riesgo en las horas que hay una producción esperada mayor y un precio esperado de mercado más alto. Además, la región de factibilidad del problema representa un límite para los beneficios, incluso cuando se le deja espacio al generador eólico para ofertar con un menor grado de aversión al riesgo. Consecuentemente, la función de utilidad del riesgo tomado en la estrategia logra un máximo cuando las soluciones óptimas no cambian con éste.

Por último se ha modelado la instalación de un sistema de almacenamiento de energía en el propio parque eólico. La operación del parque con este sistema permitiría obtener una mayor rentabilidad así como mejorar la calidad del suministro. Con el coste actual del sistema de almacenamiento y los precios de los distintos mercados, se requiere de 40 años para rentabilizar la inversión en el sistema de baterías. Consecuentemente, instalar un sistema de almacenamiento, basado en baterías de níquel, no proporciona una solución rentable.

Study of the bidding strategy of a Wind Power Producer in electricity markets

Abstract

Nowadays, Renewable Energy Sources-Electricity, RES-E, in Spain have had to deal with a change in regulation, in June 2014 (BOE 413/2014), in which support schemes were removed. However, trading energy in the different markets that comprise the liberalized electricity market, a system that enables competition between agents and a greater economic efficiency, is allowed. Thus, having to establish new strategies to increase their profits is necessary for the wind generation survival.

Electricity markets can be modelled, from a mathematical point of view, as a game in which the player bids a quantity of energy in order to achieve the maximum profitability, in other words to maximize their utility function. Short-term markets in Spain comprises day-ahead market (DA), intraday markets (ID) and the balancing mechanism. The balancing mechanism consists on secondary reserve, tertiary reserve, deviation management and additional upward reserve markets. The aim of the market is to supply the consumers with the required demand; a real time balancing of supply and demand is required.

In the case of a real-life wind power producer (WPP) agent, the typical strategy is to bid the production in DA market at marginal cost, a conservative and less profitable strategy that not take advantage of the IDs and imbalance markets in order to restructure the bid in the DA.

The aim of the WPP is to maximize its profits achieving the best bidding strategy. In order to reproduce the strategic possibilities of a WPP in a short-term horizon of an operation day, two models are mathematically formulated. The deterministic model or perfect information model correspond to the mathematical formulation in which the parameters are known in advance. The stochastic model or probabilistic model corresponds to the formulation in which the parameters are modelled with uncertainty. In the case of the stochastic modelling different scenarios, pondered with a certain probability, are considered in order to make a realistic representation of the strategy followed by a WPP, based on historic data.

Both models gives the opportunity to the WPP to achieve the most profitable strategies in the DA, IDs and deviation market, taking into account the operability constraints.

The WPP is not able to bid more power than the rated capacity. Purchasing energy is penalized in the objective functions, due to being a cost for the WPP. However, arbitrage between auctions could be done, in order to benefit from the difference in prices and closure times. IDs and imbalance markets are volatile and liquid markets, in which the volume of energy traded is considerably lower than in DA. Consequently, ID and

imbalance bids are constrained to the 10% of the installed capacity, in order not to change the clearing price sufficiently to change the strategy followed by competitors.

The models includes constraints to measure the risk or level of operative conservation taken in the strategy followed by the WPP, by distributing the power bid with a triangular cumulative distribution. Bidding more energy than the boundaries established by the expected prediction is considered a risk for the WPP, since it cannot guarantee that this energy is going to be delivered due to having a lack of production. Buying energy is a risk free action.

Non-*anticipativity* constraints in the stochastic formulations are introduced to drive the WPP to follow the time horizon of the Spanish electricity market, in order to attain an order for the different auction closure times.

The bidding strategy result analysis consists on several simulations in order to see the influence of the price, production, risk taken and deviations on the decision making of the WPP. Apart from that, a model comparison between deterministic, real-life strategy follow by WPP agents and stochastic will be done in order to see the validity of the approach done in the case of study.

The first conclusion obtained from the simulations done is that the main difference between the perfect information model, the stochastic model and real-life agents, agents that bid the production in DA market, is the profitability they get in the operations. Both model formulations attains a better economic efficiency than real-life agents, since they benefit from the possibility to restructure the power bid in DA with the ID and imbalance markets.

Perfect information model or deterministic model trades energy in the markets where the price is higher, making more profits by benefiting from the arbitrage between auctions. However, the strategy followed with uncertainty on the information, stochastic model, is to bid in the markets where the expected price is higher. Having a deterministic decision in the DA and stochastic decisions for the IDs in the stochastic modelling means that the vast majority of the energy is traded in DA, a conservative action less profitable than the one taken by the perfect information model. The ID markets are used to restructure the strategy and to achieve a better strategy than bidding all the energy in DA, as happens in the perfect information modelling.

Deviations, power traded in the imbalance markets, are the difference between what is dispatched and what is bided hourly and represent an opportunity to the WPP to report more monetary benefits. Downward deviations are used by the WPP to increment the capacity to bid in other markets, whereas having upward deviations is only achieved when remuneration on the imbalance market are higher than in DA and IDs.

The risk taken in the operations is distributed among the hours of the day of operation, achieving more risk in the case of higher expected production and higher expected prices and less in the other hours. Apart from that, the feasibility region of the problem represents a limit for the profits, even though the risk aversion taken on the operations is higher. Consequently, the utility function for the risk achieved a maximum when the optimal solutions does not change with the risk.

Finally, it has been modelled an energy storage system installation on the WPP. The operation of the WPP including the energy storage system implies acquiring a better economic efficiency and quality on the service supplied. Having the current cost of the storage system and the current prices of energy in the different markets, 40 years are required to recover the investment. Consequently, installing a storage system, based on nickel, does not provide a cost effective solution.

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Chapter 1. INTRODUCTION

Wind generation is a renewable intermittent source of generation, exposed to sudden changes on the wind speed or shut downs due to high wind speeds, that makes difficult a real-time adjustment between demand and supply. The uncertainty of not adjusting the demand is overcome by introducing more thermal and hydro units in the energy portfolio.

Wind generation represents a challenge for the operation of the electric system; since it is strictly related to reactive energy consumption, due to the use of inductive turbines, and low frequency regulation, due to having low capacity of regulation for quasi-islanded systems (as Spain). However, wind turbines could work as an ancillary service for voltage control regulation, in order to help the system and to be remunerated for the service provided.

In the last decade, wind penetration has increased in the European countries in which both energies have positioned well enough in the electricity generation mix. At first, Renewable Energy Sources-Electricity (RES-E) were not competitive and needed support. In Spain, principally market push strategies through support schemes have been adopted in order to increase the penetration, a 2020 target of the European Commission. Additionally, technology pull strategies have been taken, investment in Research and Development that have triggered the initial investment for the construction of new wind farms.

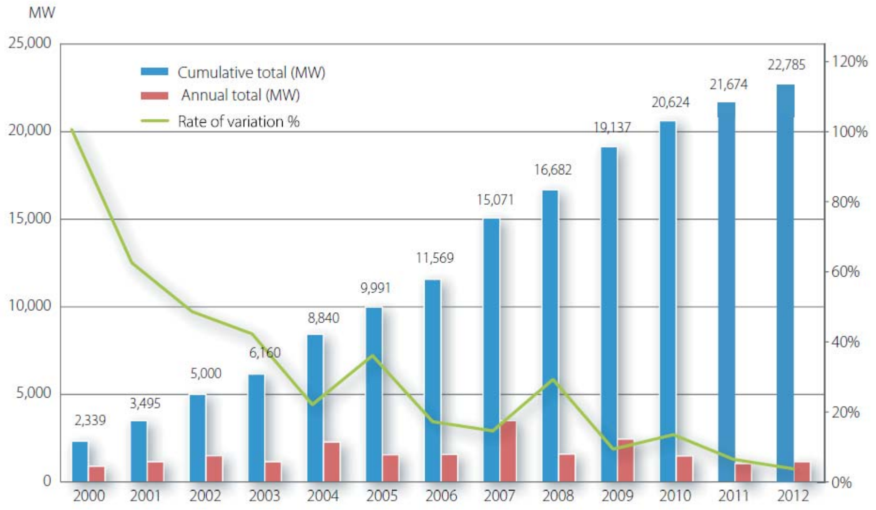

Fig 1.1. New and cumulative annual wind capacity and variation rate in Spain 2000-2012 [1].

Nowadays, RES-E in Spain have had to deal with a change in regulation, in June 2014 [2], in which support schemes were removed. However, trading energy in the different markets that comprise the liberalized electricity market, a system that enables competition between agents and a greater economic efficiency, is allowed. Thus, having to establish new strategies to increase their profits is necessary for the wind generation survival.

The aim of this project is to analyze the most profitable bidding strategy of a wind power producer (WPP) in the electricity markets. The analysis will first review the current electricity market structure and the typical bidding strategy of a wind generator. Then, a qualitative description of the WPP strategy will be presented with a deterministic and a stochastic optimization model. Finally, different case studies based on historical data will be used to assess the validity of the model. Apart from that, it will be dimensioned an energy battery in order to attain a greater economic efficiency.

The structure of the present document consist on five chapters and an appendix, distributed in the subsequent form:

The first chapter, current one, frames the scene of the wind generation and the objectives of the project.

The second chapter consist on the modelling of energy markets, highlighting the structure of the Spanish electricity market and Cournot conjecture to establish a new market equilibrium. In addition, the concept of residual demand and strategies adopted by market agents within the liberalized system are explained.

In the third chapter, the deterministic model and the stochastic model mathematical formulation will be presented, having into account the different input data considered depending on the model. Apart from that, the stochastic decision tree will be characterized in order to summarize the hierarchy of the stochastic strategy.

The results and sensitivity analysis in order to assess the validity of the models will be presented in the fourth chapter.

Finally, the fifth and last chapter summarizes the main contributions and conclusions and a new development path is proposed.

In order to complete the project, it has been included an appendix that evaluates the possibility of acquiring an energy battery to achieve a greater economic efficiency for the WPP, profitability.

Electricity is an asset with immediate delivery and traded in different markets. Consequently, the operation of the system is complex and done in real time, balancing supply and demand.

Electricity markets can be modelled as a game in which all the players or agents try to achieve their best strategy in order to maximize their profits. The rules of the game are constrained by the type auction and the system itself, operability. The market structure comprises Day-Ahead, Intra-Days and balancing mechanism markets, where the agents trade the energy and the operators balance supply and demand curves, guarantee the continuity and security of the system.

A sole agent establish its bids according to its residual demand curve, in which a new market equilibrium is achieved depending on its bid made and its competitors' bids. The residual curve of an agent depends on the capacity of the producer to change the market price, in other words it can be distinguish different types of agents depending on the slope of its residual demand curve. Price takers are agents that cannot change the market price, since the volume of energy traded is not comparable to the total demand, and therefore their residual demand curve is constant. However, price maker has a bigger market share and a decreasing residual demand slope.

The scope of the chapter is to define the structure of the electricity markets and how the market price is determined. Apart from that, it will be also analyzed how the competiveness in the Spanish electricity market is and what are the different strategies followed by the agents. Moreover, it will be characterized the wind farm used for the case of study.

2.1.Market Structure

The electricity short-term market in Spain comprises the Day-Ahead (DA), the Intra-Days (IDs) and the balancing mechanism. The balancing mechanism consists on secondary reserve, tertiary reserve, deviation management, and additional upward reserve markets and the congestion management consists on technical and security of supply constraints management. The additional upward reserve market, as it will be explained later, was recently established by the Spanish System Operator (SO) to handle situations when the reserves are at low margins [3]. Spanish agents can also trade energy through bilateral contracts, in order to reduce their uncertainty of being cleared in an auction [4]. The SO must be informed about the bilateral contracts before the DA is held. Nowadays, companies, like the generation company Iberdrola, are selling wind power trough bilateral contracts, even though it is an intermittent source of generation. This action can be explained since the energy delivered it is only the 10% of its installed capacity, a small quantity of energy that can be guaranteed as the wind energy capacity factor is around the 25%.

There are three kind of regulation reserves in Spain: primary, secondary and tertiary. In primary regulation, a non-remunerated and mandatory service, power is delivered. However, secondary and tertiary regulation is not mandatory and it is remunerated, energy and power is delivered.

The ID market occurs once the DA is cleared. ID market is divided in six centralized auction at day D-1, day before operation, and one auction at day D. The ID offers the opportunity to the agents to reschedule the power delivered in DA; in order to compensate equipment failures, forecast errors or to apply a more profitable strategy of operation. The ID market lead-times, difference between gate closure and delivery hour, vary between 3.25 and 6.25 h. Depending on the auction of the ID, there are different time horizons.

Moreover, a time horizon of sequence followed by OMIE is presented in the next figure.

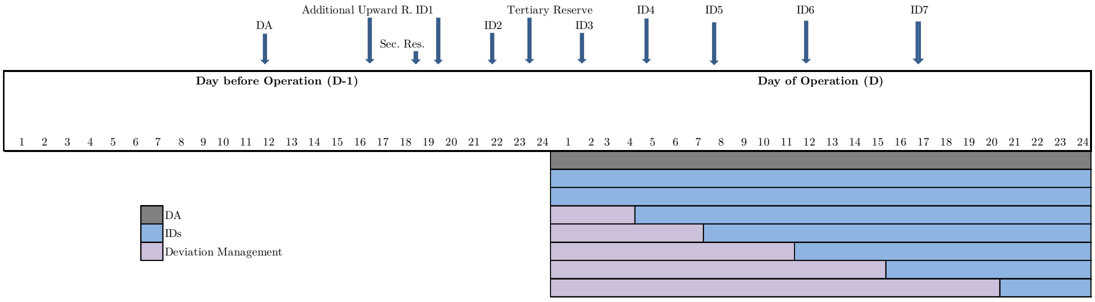

Fig 2.1. Short-term horizon of electricity market.

OMIE, the Iberian market operator (MO), is in charge of the operation of the DA and ID markets, without considering technical restrictions. The market clearing is made by aggregating all the supply coming bids and demand coming offers, processing them with a European algorithm called Euphemia [5]. Then the equilibrium price is achieved by intersecting both demand and supply curve. The equilibrium is the price at which supply is remunerated and the price that demand is willing to pay. The offers presented by demand and supply can be simple or complex, depending on its content [6]. Simple offers are economic bids that comprises both the period and the energy quantity offered. However, complex offers have additional technical restrictions, even though the observance of the requisites for simple offers is fulfilled. These restraints are:

- Indivisibility
- Load gradient
- Minimum income
- Scheduled shut down

To sum up, the separation of functions between the MO and the SO are illustrated.

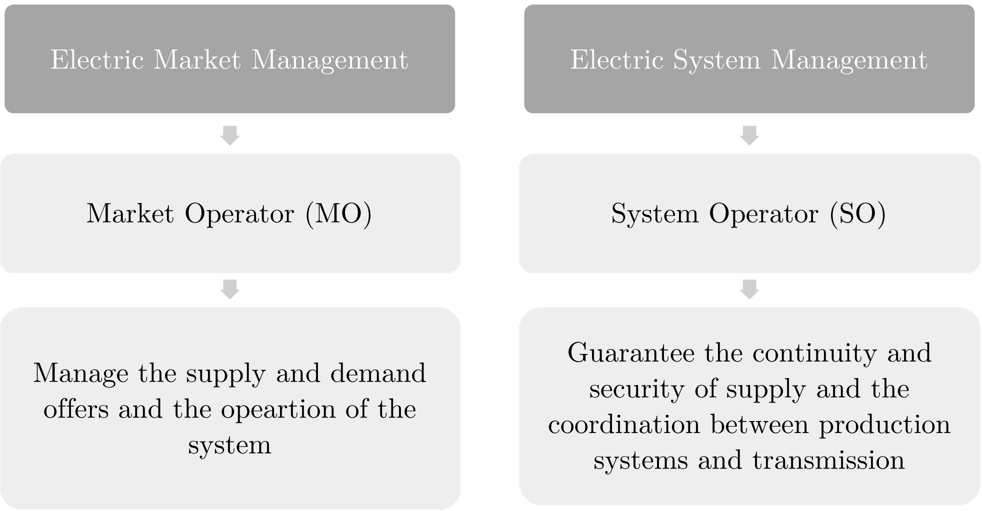

Fig 2.2. Functions differentiation of SO and MO.

The demand curve of the system is predictable and known in advance. An example of the demand curve is presented in the next figure.

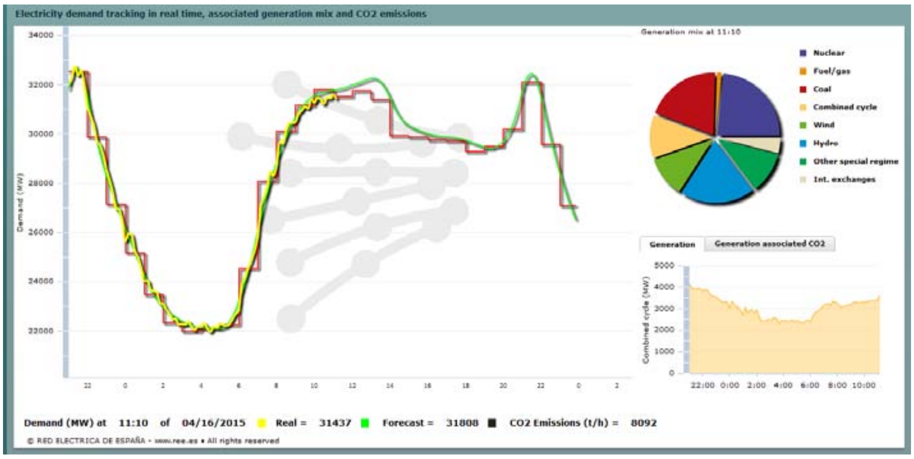

Fig 2.3. Demand for 16th of April 2015.

In the Spanish spot market, the volume of energy traded in the ID is the 10-20 % of the energy traded in DA market, making the ID markets a volatile market.

The next figure represents the clearing of the DA of 16th of April 2015 [6].

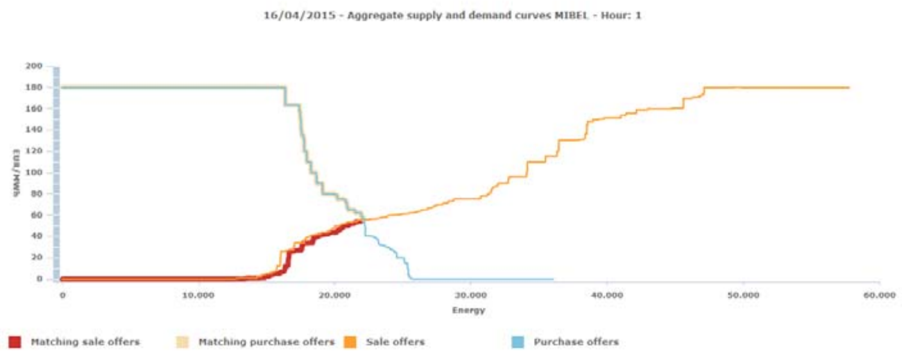

Fig 2.4. Clearing of DA hour 1 for 16th of April 2015.

The SO is responsible for the congestion management and system balancing, which are handled with additional markets. In Spain, if the market schedule does not comply with network constraints and/or reserve requirements, Kirchhoff laws, the SO re-dispatches generation through the procedure of management of technical constraints. These imbalances are due to the increasing of solar and wind generation, conventional generation imbalances or demand imbalances. A need to achieve feasibility to the market schedule is principally due to the displacement of thermal units and the growing penetration of RES-E; an unpredictable, variable and uncontrollable source of generation. The procedure to achieve the goal of guaranteeing the compliment of the technical constraints is by increasing the online reserve margins. An example of the intermittency of wind production is represented in the next figure.

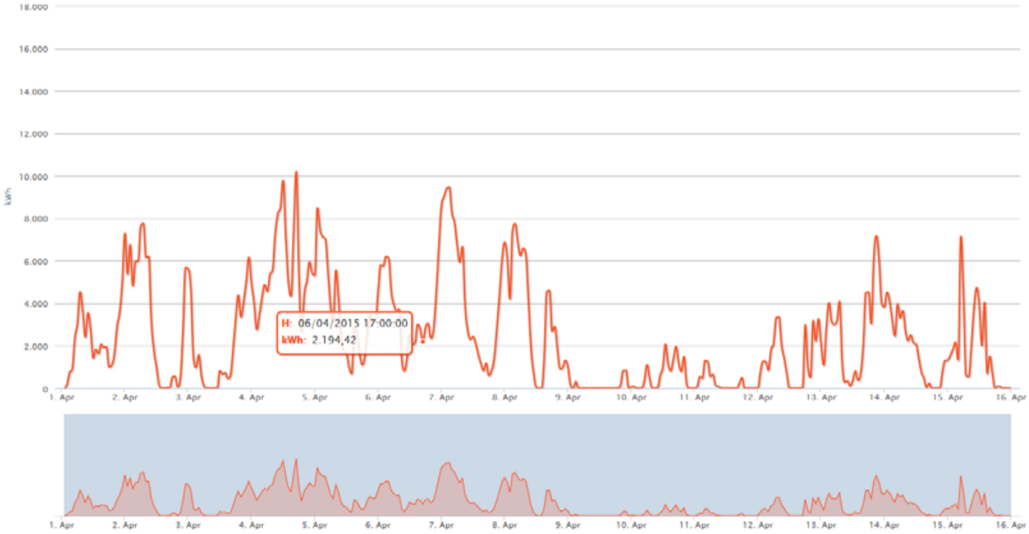

Fig 2.5. Energy produced by Sotavento Wind Farm for 15 days of April 2015 [7].

In May 2012, the Spanish SO started procuring additional reserves when there are low reserve margins, through the additional upward reserve market [8]. Once the additional upward reserve is delivered, the SO starts procuring reserves. The secondary reserve, upward and downward, are scheduled as power for the 24 hours of the day of operation and remunerated in [€/MW]. If the power is needed, the generator receives a remuneration of the energy activated in [€/MWh]. The secondary reserve, used due to the real time tracking of reserve requirements, is paid with the price of the tertiary energy that was needed to program in order to substitute that energy [9].

The tertiary reserve is mainly used to restitute the online secondary reserve used. Tertiary reserve is defined as the maximum variation of power which can perform a generating or consuming unit on a time not exceeding 15 minutes and that have to be hold for at least 2 hours. It is actuated manually. Tertiary reserve is remunerated in [€/MWh], since is an electricity energy delivery. The units that provide tertiary reserves receive an energy payment, corresponding to the marginal price of tertiary reserves.

Finally, if the SO predicts that generation and demand imbalance during a specific hour is greater than 300 MW and energy can no longer be traded in the ID market (i.e. deviation occurs after the gate closure of a ID market session and before the first hour of the next session's scheduling horizon), the deviation management market is called [3]. Deviations are principally used to solve the difference between demand and supply that occur after the gate closure of ID session and before the next session. Deviations act as a nexus between tertiary reserve and the ID markets, giving the SO a flexible mechanism to deal with the imbalance. Available units may present energy offers and accepted bids receive the marginal market price in [€/MWh].

Deviations can be settled by two different methods: single pricing and dual pricing.

Single pricing is a zero-sum game for the SO, there is no remuneration since the price of the imbalance is the price of the activated reserve [10] [11], being upward or downward the activated energy. In a single pricing system, the same imbalance price is applied for short and long positions for the different generation units. Short positioning correspond to the situation when the total scheduled generation is higher than the total demand, whereas long positioning correspond to the opposite situation. It has to be noticed that when there are negative balancing prices, the direction of the remuneration and penalizations also changes.

However, dual pricing strategies means a gain for the SO, usually used to reduce the transmission tariff. Dual pricing takes into account the direction or sign of the market. If a bidding strategy helps the system, it has a positive sign and negative if it is contrary to the direction. The reason behind this action is to penalize the negative sign strategies to the market due to the fact that they mean an increase on the reserves. Dual pricing systems use different imbalance prices for short and long positioning. The generation units that aggravate the system imbalance by deviating from negatively to the direction of the system are settled at an imbalance price of the activated reserve needed to correct the situation, whereas the units that benefit the system receive typically the DA market price.

System imbalance

Single Pricing

	Positive (Long)	Negative (Short)
Positive (Long)	$+\lambda_n^{DoDev}$	$+\lambda_n^{UpDev}$
Negative (Short)	$-\lambda_n^{DoDev}$	$-\lambda_n^{UpDev}$

Dual Pricing

	Positive (Long)	Negative (Short)
Positive (Long)	$\theta_n^+ \cdot \lambda_n^{DoDev}$	$\theta_n^+ \cdot \lambda_n^{DA}$
Negative (Short)	$\theta_n^- \cdot \lambda_n^{DA}$	$\theta_n^- \cdot \lambda_n^{UpDev}$

Table 2.1. Single and dual pricing, where λ_n^{UpDev} represents the price of upward imbalances and θ_n^+ the positive sign of the direction to the market for n hours.

2.2.COURNOT MARKET EQUILIBRIUM

In liberalized systems, such as Spanish one; there is an interdependency between the actions or decisions that take the different agents. As a result, the market can be considered a game, in which players try to maximize their utility function. The market is subject to constraints, such as the kind of bid or to the clearing model.

The Cournot equilibrium, introduced by Antoine Agustin Cournot for non-cooperative players in his work *"Recherches sur les principes mathématiques de la théorie des Richesses"* in 1838, is the equilibrium achieved when maximizing the profit of the players. They decide the quantity of a good to produce without knowing the decisions taken by competitors.

As it is said in [12], the problem that Cournot equilibrium has to deal with the inelasticity of the demand for real markets. In other words, the price depends on the bids of the generators, a fact that is not measured by Cournot conjecture in which the strategic variable is the quantity produced.

For the calculation of the equilibrium, it is needed to maximize the profit for all the agents. In our case of study, only two agents are going to be considered:

- The Wind Farm

- Competitors, without specifying the type of technology or the owner.

The profit for every firm, f=1 or 2, is:

$$Profit_f = \lambda \cdot P_f - C_f(P_f)$$

Eq 2.1.

Where λ is the marginal price, P_f the quantity of energy produced for all the firms and $C_f(P_f)$ is the cost function.

The maximum is achieved, where the derivative on the later equations equals to cero.

$$\lambda + \frac{\partial(\lambda)}{\partial\left(P_f\right)} \cdot P_f - \frac{\partial\left(C_f\left(P_f\right)\right)}{\partial\left(P_f\right)} = 0 \qquad \forall f$$

Eq 2.2.

Apart from that, generation must balance demand.

$$D = \sum_f P_f$$

Eq 2.3.

The Cournot conjecture says that variations in price with respect to production are the same for every firm and equal to the demand slope. This means that if there is any variation on the quantity offered, only the demand is going to react and not the other agents. The demand slope is negative.

$$\frac{\partial(\lambda)}{\partial\left(P_f\right)} = \delta$$

Eq 2.4.

The new equilibrium will be achieved when:

$$\lambda + \delta \cdot P_f - \frac{\partial\left(C_f\left(P_f\right)\right)}{\partial\left(P_f\right)} = 0 \qquad \forall f$$

Eq 2.5.

For every wind producer, the operational cost or variable cost $\partial\left(C_f(P_f)\right) / \partial\left(P_f\right)$ are null.

2.3.RESIDUAL DEMAND CURVE

As it was explained previously, the agents build their aggregate supply curve for every auction of the operation day and send them to the SO. The SO constructs the aggregate supply and demand curve for every hour, considering all the bid of all the agents, and establishes the market equilibrium price, where both curves intersect.

The supply of the competitors $P_{competitors}$, considering them as a sole agent, is the demand minus the bid of our WPP for every hour Q_{WPP}. The demand is a function of the price.

$$P_{competitors}(\lambda) = D(\lambda) - P_{WPP}(\lambda)$$

Eq 2.6.

And in terms of the bid of the wind power producer,

$$P_{WPP}(\lambda) = D(\lambda) - P_{Competitors}(\lambda)$$

Eq 2.7.

The residual demand curve is the inverse of the last equation; it is the relationship between the price and the quantity bid by the WPP.

$$R_{WPP}(\lambda) = D(\lambda)^{-1} - P_{Competitors}(\lambda)^{-1}$$

Eq 2.8.

This residual demand is what the WPP see for establishing the new equilibrium price, which depends on the bid made. Each firm takes the quantity to produce from its competitors and evaluates its residual demand, behaving as a monopoly.

The WPP's new price λ' will be calculated taking into account Cournot equilibrium and residual demand concept. λ' is going to appear in the objective function of the model as the price for the bidding energy.

$$\lambda' = \left[\delta\left(P_{WPP} - 0.5P_{WPP}^{Installed}\right)\right] + \lambda$$

Eq 2.9.

It is important to highlight that λ was attained when the WPP bids the 50% of the capacity installed, a typical bid used to model the new clearing price.

2.4.COMPETITION IN ELECTRICITY MARKETS AND STRATEGY

A spot market is a financial market in which assets are traded for imminent delivery, such as electricity market [13]. The manner that an individual agent represents its position in the electric market, spot market, can be categorized in two main groups [14].

1. **Price taker**: the company is unable to affect prices and adopts the clearing price. The residual demand curve of this model is constant and its value is the equilibrium price.

2. **Price maker**: the company influences the market price with its bids. For the model, the behavior of the rest of agents does not change due to the insignificancy of the increment/decrement on the price. In this case, the residual demand is represented as a decreasing linear function.

The strategy usually used by generation agents is to bid at its marginal cost, even though they are price makers or takers. Retailers try to maximize their income making bids to buy in a decreasing aggregate demand curve, ordering their offer from the one that is more satisfactory and needed to the one unsatisfactory. A price taker does not affect the market price by definition; but in fact, its bid shifts the aggregated demand/supply curve [15]. Consequently, a new price will be achieved, especially in volatile markets such as the ID markets. For electricity markets the strategic variable in order to achieve the maximum profit is the energy delivered. The strategy fulfilled by a real-life WPP agent is to bid the expected production in the DA market, a conservative and less profitable strategy that not take advantage of the IDs and imbalance markets in order to restructure the bid in the DA.

Price makers or takers are exposed to uncertainty or risk in their operations, different scenarios that will be analyzed with the model formulation.

2.5.Wind Farm

The WPP analyzed in the project is Sotavento Galicia, S.A [16]. The society was established in 1997, promoted by the "Xunta of Galicia", and created the Experimental Wind Farm of Sotavento.

The shareholders of Sotavento Galicia SA are:

- Public entities
    - Energy Institute of Galicia (INEGA)
    - Institute for Energy Diversification and Saving of Energy (IDEA)
- Private entities
    - Enel Green Power Spain, S.L.
    - Iberdrola Renewables Galicia, S.A.
    - Energy of Galicia, S.A. (ENGASA)

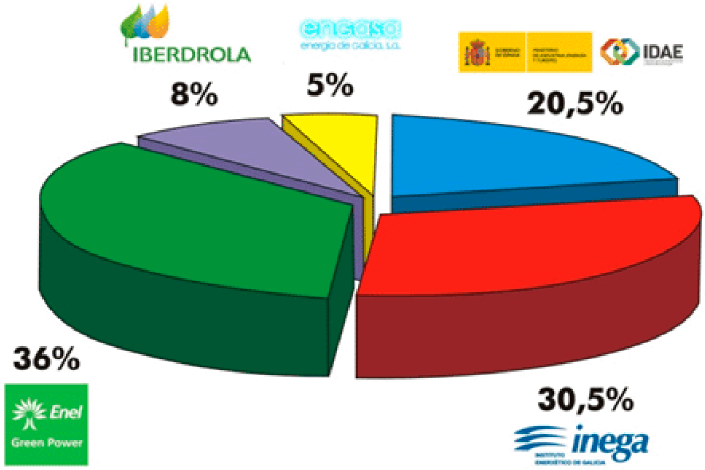

Fig 2.6. Shareholders of Sotavento and their position on the wind farm.

The main technical data are summed up in the next bullet points:

- Number of Wind Turbines: 24
- Different technologies: 5
- Different models: 9
- Power rating of the WPP: 17.56 MW
- Average annual generation: 33364 MWh
- 9 km high-volt energy feed line to the substation at A Mourela in As Pontes (A Coruña)
- Prevailing winds: on the east-west axis
- Average wind speed at the site: 6.41 m/s

The main characteristics of wind turbines installed in the WPP are explained in the next table.

Type of Turbine	Unitary Power [kW]	Number of units Installed	Rotor Diameter [m]	Tower height [m]	Blade Pitch	Turbine Velocity	Generation
Neg Micon NM-48 750	750	4	48	45	Fixed	Fixed	Asynchronous
Gamesa G-47	660	4	47	45	Variable	Variable	Asynchronous
Made AE-46	660	4	46	45	Fixed	Fixed	Asynchronous
Izar-Bonus MK-IV	600	4	44	40	Fixed	Fixed	Asynchronous

Ecotecnia 44/640	640	4	44	46	Fixed	Fixed	Asynchronous
Neg Micon NM-52 900	900	1	48	45	Fixed	Fixed	Asynchronous
Made AE-52	800	1	52	50	Variable	Variable	Synchronous
Made AE-61	1320	1	61	60	Fixed	Fixed	Asynchronous
Izar-Bonus 1,3 MW	1300	1	62	49	Variable	Fixed	Asynchronous

Table 2.2. Main characteristics of the Wind farm

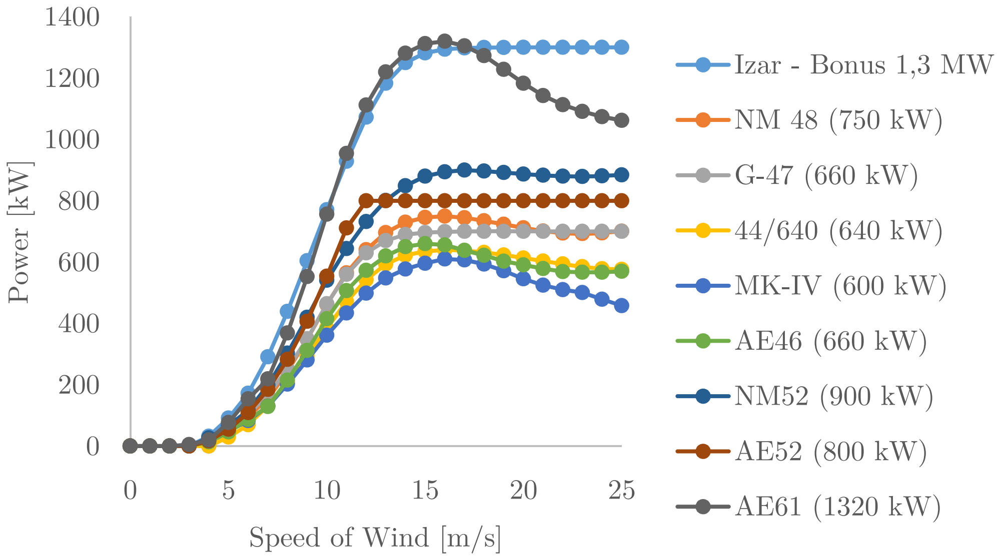

Fig 2.7. Power of the types of turbines versus speed of wind.

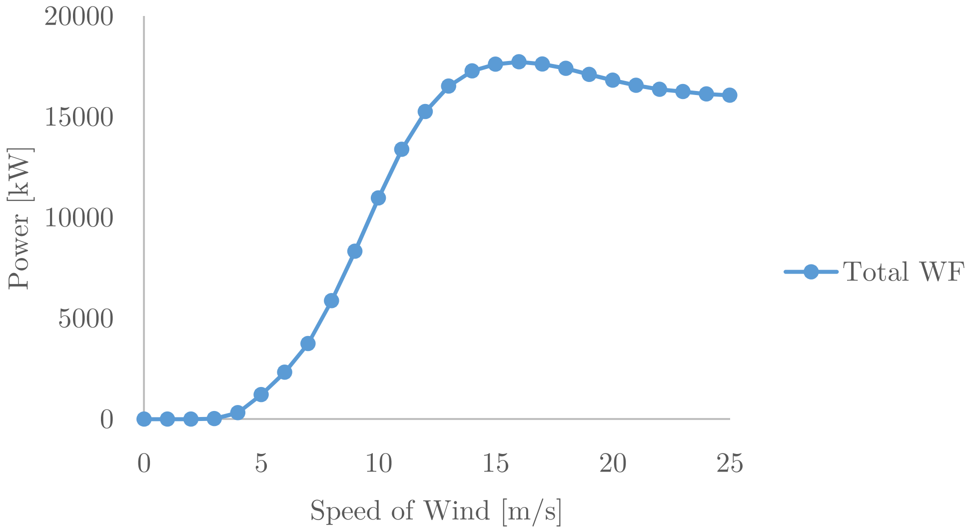

Table 2.3. Power of the whole WPP versus speed of wind.

2.6. CONCLUSIONS

Electricity markets, a spot market in which electricity is delivered immediately, represents the game in which the agents can attain economic efficiency. Short-term markets in Spain comprises DA, IDs and the balancing mechanism. The balancing mechanism consists on secondary reserve, tertiary reserve, deviation management, and additional upward reserve markets and the congestion management consists on technical and security of supply constraints management. The aim of the game is to supply the consumers with the required demand, real time balancing.

According to Cournot conjecture, the market equilibrium is attained when the agents or players of the game maximize their utility function. However, not all the agents have the same market share and power. Consequently, two different approaches could be done at this point:

- Price taker, an agent that cannot affect market prices and adopts the equilibrium price. Even though a price taker adopts the clearing price, it shifts the aggregate supply curve.

- Price maker, an agent with market power to influence the price. Its bids are able to attain a new equilibrium.

The bidding curve see by a sole agent is denominated residual demand and it is dependent on the market-clearing price. The residual demand curve is a negative decreasing linear curve; except for price takers that is a constant and corresponds to the equilibrium price, since agents have no power to affect the market price.

The WPP of the case of study, Sotavento, is considered a price taker that can shifts the aggregate supply curve. The WPP's new price, λ', will be calculated taking into account Cournot equilibrium and residual demand concept.

Chapter 3. Mathematical Formulation

The mathematical formulation consists on a deterministic model and a stochastic model for the maximization of the profits of the wind farm [19]. Modeling is understood as a complex mathematical representation of reality. Optimization, selection of the best alternative in a set of available alternatives complying with the constraints, for our case of study is the strategy that a wind producer must follow for having the best economic performance.

- Deterministic: Model in which the parameters are known in advance with certainty, no probability of scenarios occurs.

- Stochastic: Model in which parameters are not known, are modelled as random variables with known distributions. In the case of study, the probabilities are estimated with historic data and also discretized. Other way of estimating the distribution probabilities could be through simulation.

The data extraction is made through a Matlab code that access to the URL of the Spanish electricity market historic data and process it in order to have a realistic and dynamic view of what is happening.

3.1.Deterministic Input Data

The model receives as input data, also known as parameters in mathematical formulation:

- Price of the energy in the different markets
- Slope of the residual demand
- Production of the Wind Farm
- Power installed in the WPP
- Prediction error curve
- Risk curve
- Deviations
    - Sign of the deviation to the market
    - Price of Upward/Downward deviations
    - Power dispatched along the day

Price of the energy in the different markets

The price of the energy is expressed in [€/MWh] and it refers to price where the aggregate demand curve offers and aggregate supply curve offers intersect. The SO receives the biddings from the suppliers and the consumers and create the aggregate curves ordering them by price. The price of the intersection is the price that will be paid to offers that are leftwards, the other offers will be excluded from the market auction.

Slope of the residual demand curve

As a way to make the model more realistic, the residual demand curve will be calculated and used as input.

The assumption to make the calculation is that the slope demand curve in our bidding day is similar to historic data from other days. As a result, a linear decreasing estimation of different days and the bidding day will be accurate enough to make the calculation. Furthermore, the IDs residual demand slope will be the same that in the DA auction, in order to deal with the volatility of the IDs and small quantity of energy bid.

For analyzing the historic data:

- The Monday's demand curve is similar to other Mondays.
- Tuesday, Wednesdays and Thursday are similar between them.
- Friday's demand curve seems similar to other Fridays.
- Saturday is similar to other Saturdays.
- Sunday is similar to other Sundays.

In other to have a significant sample, 9 days of different consecutive weeks are studied according to the criteria defined above.

Production of the Wind Farm

The production of the wind farm is known in advance; since all the agents trading with wind energy have meteorological masts. The production of the different wind turbines installed in the wind farm is carried by using data from the temperature and wind velocity measures.

An example of data from the Wind Farm of Sotavento:

Data [Hour of day 9/2/2015]	Speed [m/s]	Direction (º)	Energy [kWh]	Production [pu]
1	12.68	55.00	12799.63	0.73
2	15.31	59.00	13526.29	0.77
3	16.66	50.00	13486.20	0.77
4	18.49	56.00	15578.39	0.89
5	23.13	58.00	8568.04	0.49

6	21.47	60.00	10109.40	0.58
7	21.41	50.00	13758.58	0.78
8	17.53	47.00	15346.15	0.87
9	14.95	53.00	14981.47	0.85
10	13.85	57.00	15051.47	0.86
11	13.15	67.00	15235.16	0.87
12	15.27	75.00	14495.23	0.83
13	14.07	72.00	14161.68	0.81
14	13.05	70.00	12899.97	0.73
15	12.30	71.00	11476.55	0.65
16	12.42	68.00	12232.68	0.70
17	13.88	70.00	12274.90	0.70
18	12.92	75.00	13022.76	0.74
19	8.88	92.00	3217.53	0.18
20	7.28	62.00	6932.71	0.39
21	6.65	57.00	5978.73	0.34
22	7.95	70.00	4115.12	0.23
23	9.54	86.00	5749.65	0.33
24	9.52	85.00	5643.79	0.32

Table 3.1. Wind farm of Sotavento for the day 9/2/2015 [17]

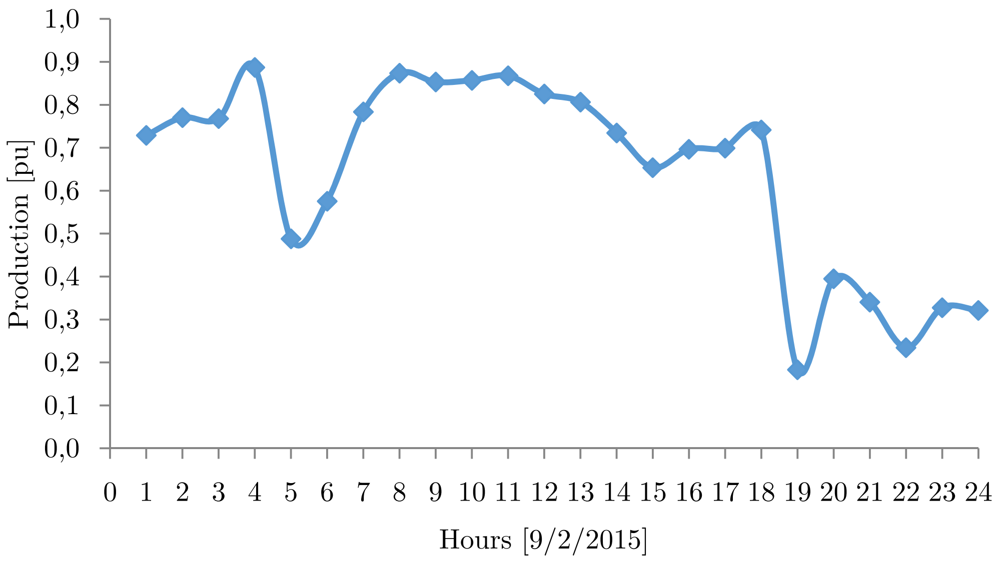

Fig 3.1. Production of the WPP for the 9th of February 2015.

Power installed in the Wind Power Farm

The power installed of the wind farm is also introduced as data. The only limitation that it has is that it must be lower than the 5% of the demand, since in other case the strategy of the competitors will change as the volume of energy available would not be negligible for the demand.

For example, the 3rd of March of 2015 the minimum demand was 17539.7 MWh at 8th hour in the valley of the curve. As a result, the maximum installed capacity of the Wind Farm that is bidding that day is 877 MW.

Prediction error curve

The prediction error curve takes into account the error in the forecast of wind, both in production and in metering the amount of wind. The curve measures the error in % as a function of the time in which the prediction is made.

The curve used for the model, comes from Sipreólico [18].

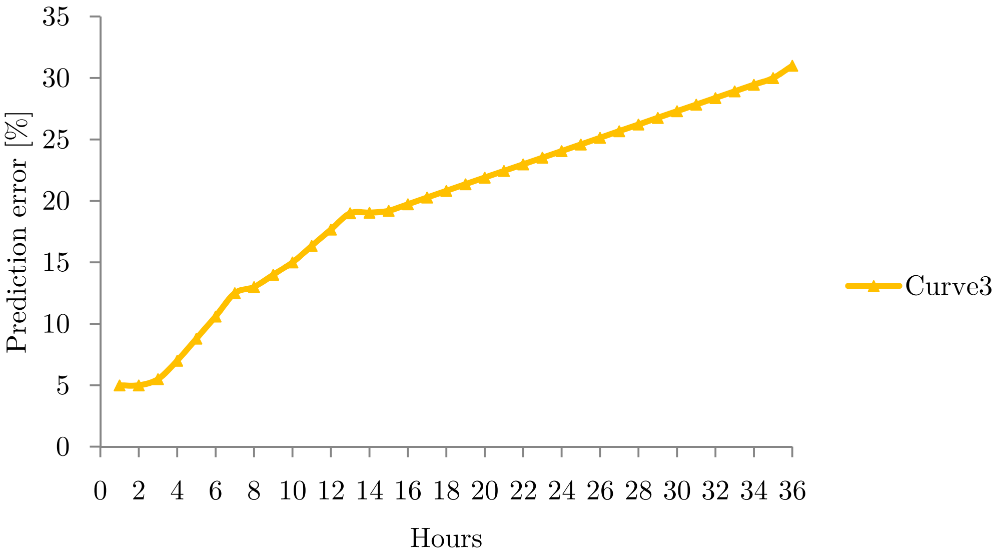

Fig 3.2. Prediction error curve.

The curve presented is the one that enters as a parameter in the deterministic model.

Deviations

Imbalances are mainly used to solve the difference between demand and supply that occurs after the gate closure of ID session and before the next session. The imbalance prices are expressed in [€/MWh]. It is a volatile market in which small quantities of energy are traded. For a WPP is an opportunity to make more profits.

Imbalance can be approached for two different methods: single pricing and dual pricing. SO in single pricing deviations receive no remuneration, it is only the price of the activated reserve. However, dual pricing strategies means a gain for the SO, usually used to reduce the transmission tariff. As it was explained before, dual pricing takes into account the direction or sign of the market. If a measure helps the system, it has a positive sign and negative if it contrary to the direction. The reason behind this action is to penalize the negative sign strategies to the market due to the fact that they mean an increase on the reserves. The case of study is Spain, in which dual pricing imbalances strategies are used.

The next table shows how generation units are remunerated in Spain.

Dual Pricing

	Upward Deviations	Downward Deviations
Positive	$\theta_n^+ \cdot \lambda_n^{UpDev}$	$\theta_n^+ \cdot \lambda_n^{DoDev}$
Negative	$\theta_n^- \cdot \lambda_n^{UpDev}$	$\theta_n^- \cdot \lambda_n^{DoDev}$

Table 3.2. Dual pricing, where λ_n^{UpDev} represents the price of upward imbalances and θ_n^+ the positive sign of the direction to the market for n hours.

Deviations, as definition, are the upward/downward energy derived from the difference between the final power dispatched and bidding of the generation unit. The power dispatched in the case of study is known in advance for the deterministic model and is estimated with probabilities in the stochastic model.

3.2.Deterministic Formulation

The deterministic model formulation, parameters known in advance with no probabilistic distribution, is subdivided into indices, parameters, variables, objective function and constraints. The aim of the model is to maximize the expected revenue according to the constraints of the market. The wind farm is able to bid in the DA market and restructure its bid through the IDs and deviation markets, in order to achieve the best strategy or to deal with the forecasting error of wind.

The power bid for every hour and every market and the revenue is the output of the model, only solved in a short-term electricity market of one day.

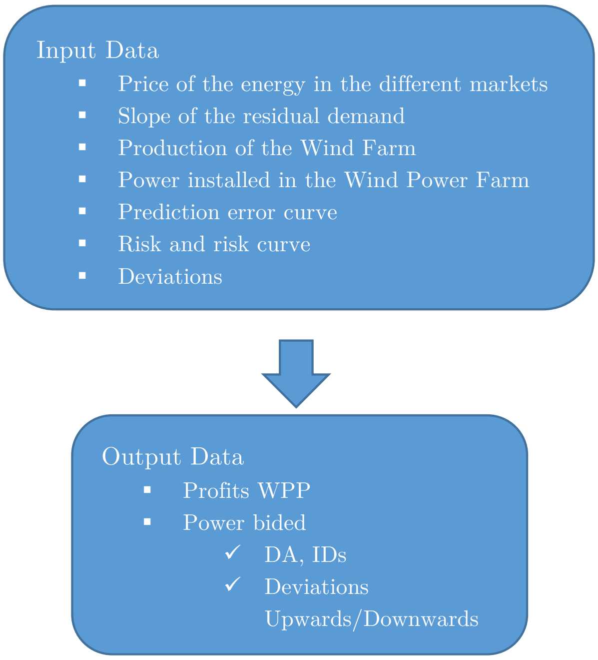

Fig 3.3. Summary of Deterministic model.

The case study problem is a MIQP (mixed integer quadratic programming), since there are both integer and binary variables, with a quadratic objective function. The problem has 7263 equations and a resolution time of 16 sec.

3.2.2. INDEXES

The indexes of the deterministic model represent dimensions of the problem and are structured in the next table.

Indexes Nomenclature

Name	Definition	
n	Hour of the day	h01, …, h24
nn	Hours for the wind forecast error curve, axis of the curve	hour1, …, hour36
mar	Bidding markets	DA, ID1, …, ID7
$intra$	Subset of markets that only comprises the IDs	ID, …, ID7
$marr$	Alias of *mar*	
$markethours_{n,mar}$	Hour of the day in which is possible to bid, depends on the market in consideration	
s	Discretization of the risk operation curve or level of operative conservation, by using a triangular cumulative distribution	s00, …, s11

Table 3.3. Indexes of the deterministic model.

$markethours_{n,mar}$ is defined as the hours in which can be traded depending on the market taken into consideration. For example, in ID7 is not possible to bid in hour 1, since the auction is made earlier than the bid hour.

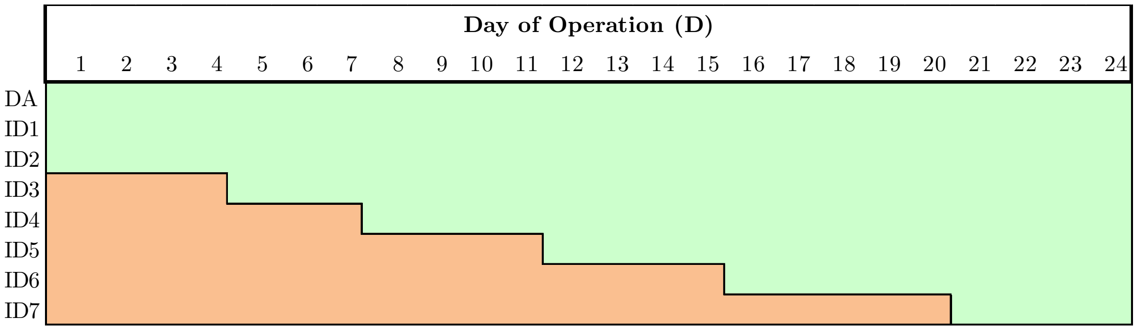

Fig 3.4. Summary of $markethours_{n,mar}$.

3.2.3. PARAMETERS

The parameters that entered in the model represent the data known in advance. Most of the data are extracted from OMIE and ESIOS webpage, the market and system operators of the electricity market.

Parameter Nomenclature

Name	Definition	Units
$\lambda_{n,mar}^{DA,IDs}$	Price of the energy in hour n and market mar, in other words is the DA and ID market price	[€/MWh]
$\delta_{n,mar}$	Slope of the residual demand curve	[€/MW²h]
λ_{n}^{UpDev}	Hourly price of the upward deviations	[€/MW]
λ_{n}^{DoDev}	Hourly price of the downward deviations	[€/MW]
$\theta_{n}^{\pm}$	Hourly sign of the deviation to the market. If the strategy helps the electricity system, the sign is positive and on the contrary is negative when the power produced by the WPP represents a problem for the system	[1/-1]
P^{Inst}	Power installed in the WPP	[MW]
P_{n}^{Prod}	Production hourly production of the WPP	[pu]
$P_{n}^{Dispatch}$	Power dispatched when the liquidation of the hour is made	[MW]
$\overline{P}_{n,mar}$	Upper bound of the power bided	[MW]
$\underline{P}_{n,mar}$	Lower bound of the power bided	[MW]
$risk$	Risk taken on the biddings or level of operative conservation	[pu]

$dif_{n,mar}$	Lead times between the gate closure of the market and the bid hour, computed for the error in the wind forecast	[h]
$error_{nn}$	Error in prediction of wind, takes into account the error of metering and forecasting of wind.	[%]
$step_s$	Discretization steps of power bided	[%]
$prob_s$	Probability of success in the bidding	[pu]
$\beta^{+}_{n,mar,s}$	Steps for the positive discretization of the curve	[MW]
$\beta^{-}_{n,mar,s}$	Steps for the negative discretization of the curve	[MW]

Table 3.4. Parameters of the deterministic model

$\overline{P}_{n,mar}$and $\underline{P}_{n,mar}$ are the upper and lower bound of the power for every hour and market, represents a band width for the power bided. Both takes into account the error on wind prediction for the WPP. The error depends on the lead times between the bid hour and the gate closure of the auction.

$$\overline{P}_{n,mar} = P_n^{Prod} \cdot P^{Inst} \cdot \frac{1 + error_{nn \in dif_{n,mar}}}{100} \qquad \forall n, mar \in markethours_{n,mar} \qquad \text{Eq 3.1.}$$

$$\underline{P}_{n,mar} = P_n^{Prod} \cdot P^{Inst} \cdot \frac{1 - error_{nn \in dif_{n,mar}}}{100} \qquad \forall n, mar \in markethours_{n,mar} \qquad \text{Eq 3.2.}$$

$\beta^{+}_{n,mar,s}$ and $\beta^{-}_{n,mar,s}$ represent the points of the interval in which it is possible to bid due to the risk operation measurement or level of operative conservation, both for selling and for buying energy in the markets. The level of operative conservation is explained as the bandwidth limitation for every bid in every market and hour, implies a boundary for the operation of the WPP.

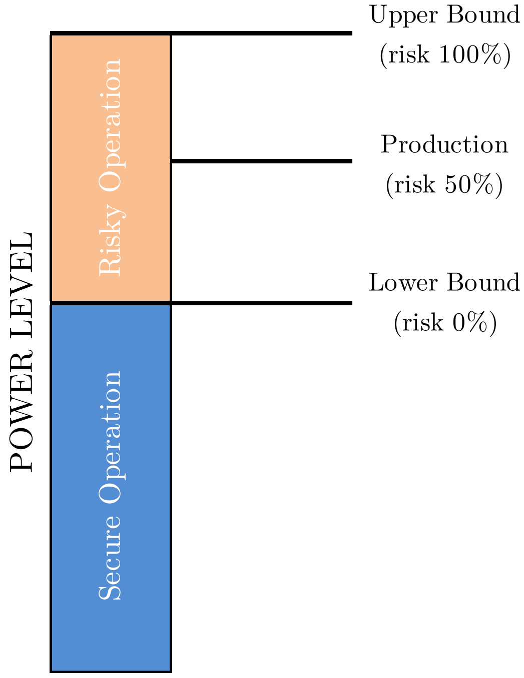

Fig 3.5. Power level bidding strategy considering risk.

As a result, every power bided strategy of WPP is comprised between two intervals or steps.

$$\beta^{+}_{n,mar,s} = \underline{P}_{n,mar} + step_s \cdot \frac{\overline{P}_{n,mar} - \underline{P}_{n,mar}}{100} \qquad \text{Eq 3.3.}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

$$\beta^{+}_{n,mar,'s00'} = 0 \qquad \text{Eq 3.4.}$$
$$\forall n, mar \in markethours_{n,mar}$$

$$\beta^{-}_{n,mar,s} = P^{Inst} \qquad \text{Eq 3.5.}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

$$\beta^{-}_{n,mar,'s00'} = 0 \qquad \text{Eq 3.6.}$$
$$\forall n, mar \in markethours_{n,mar}$$

3.2.4. VARIABLES

The variables are the decisions that affect the objective function. Variables can be classified in independent, main or control variables and in dependent, auxiliary or state variables, but mathematically all are the same.

Variables Nomenclature

Name	Definition	Units
$P_{n,mar}^{DA,IDs}$	Power bided of the WPP	[MW]
$P_{n,mar}^{+}$	Positive power bided of the WPP	[MW]
$P_{n,mar}^{-}$	Negative power bided of the WPP	[MW]
$Pk_{n,mar,s}^{+}$	Power for positive risk curve parametrization	[MW]
$Pk_{n,mar,s}^{-}$	Power for negative risk curve parametrization	[MW]
Δ_n^{Up}	Upward deviation	[MW]
Δ_n^{Do}	Downward deviation	[MW]
$Xk_{n,mar,s}^{+}$	Binary variable for the positive parametrization of the risk curve (Decision)	{0/1}
$Xk_{n,mar,s}^{-}$	Binary variable for the negative parametrization of the risk curve (Decision)	{0/1}
ξ^1	Value of the Objective Function 1 (Profits)	[€]
ξ^2	Value of the Objective Function 2 (Profits)	[€]

Table 3.5. Variables of the deterministic model.

The variable definition is as follow:

- Positive variables

$$P_{n,mar}^{+}, P_{n,mar}^{-}, Pk_{n,mar,s}^{+}, Pk_{n,mar,s}^{-}, \Delta_n^{Up}, \Delta_n^{Do} \geq 0$$
$$\forall n, mar, s \qquad \text{Eq 3.7.}$$

- Binary variables

$$Xk_{n,mar,s}^{+}, Xk_{n,mar,s}^{-} \in \{0,1\}$$
$$\forall n, mar, s \qquad \text{Eq 3.8.}$$

- Free variables

$$P_{n,mar}^{DA,IDs}, \xi^1, \xi^2 \; free \qquad \text{Eq 3.9.}$$

3.2.5.Objective Function

The objective function is explained as the quantifiable measure of the performance of a system to be maximized or minimized.

ξ^1, objective function, represent the profits expected by the WPP when no deviations are taken into account. The justification of making this approach is to see how risky to the market the strategies fulfilled by the WPP are. These kind of strategies can jeopardize the system operability or can mean an increase on the reserves needed (CCGT and other thermal units), in order to maintain the service.

$$\xi^1 = \max \sum_{markethours_{n,mar}} \left[\left(\delta_{n,mar}\left(P_{n,mar}^{DA,IDs} - 0.5P^{Inst}\right)\right) + \lambda_{n,mar}^{DA,IDs}\right] \cdot P_{n,mar}^{DA,IDs} \cdot 1hour \qquad \text{Eq 3.10.}$$

However, ξ^2, objective function, represents the profits for the DA, IDs and gives the option to the model to take advantage of the deviation, a measure to correct wind forecast errors or to achieve a better strategy. In this case, the system is not jeopardized, since penalizations in the objective function to the biddings that are negative to the market signals are introduced.

$$\begin{aligned}\xi^2 = \max \sum_{markethours_{n,mar}} & \left[\left(\delta_{n,mar}\left(P_{n,mar}^{DA,IDs} - 0.5P^{Inst}\right)\right) + \lambda_{n,mar}^{DA,IDs}\right] \\ & \cdot P_{n,mar}^{DA,IDs} \cdot 1hour \\ & + \sum_{n} \Delta_n^{Up} \cdot \lambda_n^{UpDev} \cdot \theta_n^{\pm} \cdot 1hour \\ & + \sum_{n} \Delta_n^{Do} \cdot \lambda_n^{DoDev} \cdot \theta_n^{\pm} \cdot 1hour\end{aligned} \qquad \text{Eq 3.11.}$$

3.2.6.Constraints

The constraints represent the set of relationships that variables are obliged to satisfy, can be expressed as equations and inequalities.

The power bided in DA and IDs is a free variable defined with two positive ones, one for selling and other for buying energy.

$$\begin{gathered}P_{n,mar}^{DA,IDs} = P_{n,mar}^{+} - P_{n,mar}^{-} \\ \forall n, mar \in markethours_{n,mar}\end{gathered} \qquad \text{Eq 3.12.}$$

For every hour of the operation day the power offered, taking into account DA and IDs, by the WPP could not exceed the installed capacity of the wind farm. Bidding more energy will mean buying it in the electricity market, a non-desirable strategy due to the cost of electricity. An action of buying energy is not limited, since it is a strategy for making money in the next auction. Arbitrage, taking advantage of the difference in prices between two markets, is not constrained since in electricity markets simply is a better decision.

$$\sum_{mar\leq marr \,\in\, markethours_{n,mar}} P_{n,mar}^{DA,IDs} \leq P^{Inst}$$
$$\forall n$$

Eq 3.13.

For ID markets, liquidity constraints are introduced into the deterministic model, since IDs volume of energy traded on these markets is considerably lower than in the DA market. If the WPP is permitted to bid with the installed capacity in the IDs, the change in prices of the ID markets, very volatile to big changes in the energy bided will mean a counterstrategy from the competitors. The counterstrategy prediction is out of the approach, strategies of the competitors are not changed in the case of study due to the little power or position of the WPP in the spot markets. The power bided in IDs boundary is the 10% of the installed capacity, both for selling and for buying.

$$P_{n,mar}^{+} \leq 0.1 P^{Inst}$$
$$\forall n, mar \in intra$$

Eq 3.14.

$$P_{n,mar}^{-} \leq 0.1 P^{Inst}$$
$$\forall n, mar \in intra$$

Eq 3.15.

Deviations, as definition, are the power difference between what is dispatched and what is bided for an hour of the operation day. Deviations can be both upwards or downwards and, depending on the direction of the system, can be penalized or remunerated, in the objective function. For a deterministic model, the optimality maximization of profits will be attained when positive sign strategies for the market are accomplished, while there are possibilities to make money with deviations.

$$P_{n}^{Dispatch} - \sum_{mar \in markethours_{n,mar}} P_{n,mar}^{DA,IDs} = \mathit{\Delta}_{n}^{Up} - \mathit{\Delta}_{n}^{Do}$$
$$\forall n$$

Eq 3.16.

For the deviation market, liquidity constraints are introduced into the deterministic model, since the volume of energy traded in the deviation market is considerably lower than other market. Deviation market is a volatile market. The power bided in deviation market boundary is the 10% of the installed capacity, both for upward and downward deviations.

$$\mathit{\Delta}_{n}^{Up} \leq 0.1 P^{Inst}$$
$$\forall n$$

Eq 3.17.

$$\Delta_n^{Do} \leq 0.1 P^{Inst}$$
$$\forall n$$

Eq 3.18.

As a way to measure the success of the biddings, the power offered is distributed as a triangular cumulative distribution. Each of the probabilities measures the range of success of the strategies made for every hour and every market or level of operative conservation, DA and IDs. Since having a continuous cumulative distribution is quite challenging for the GAMS, a parametrization of the curve is made. The next equations represent this idea for selling and buying energy.

$$Pk_{n,mar,s}^{+} \geq Xk_{n,mar,s}^{+} \cdot \beta_{n,mar,s}^{+}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

Eq 3.19.

$$Pk_{n,mar,s}^{+} \leq Xk_{n,mar,s}^{+} \cdot \beta_{n,mar,s+1}^{+}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

Eq 3.20.

$$P_{n,mar}^{+} = \sum_{s} Pk_{n,mar,s}^{+}$$
$$\forall n, mar \in markethours_{n,mar}$$

Eq 3.21.

$$Pk_{n,mar,s}^{-} \geq Xk_{n,mar,s}^{-} \cdot \beta_{n,mar,s}^{-}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

Eq 3.22.

$$Pk_{n,mar,s}^{-} \leq Xk_{n,mar,s}^{-} \cdot \beta_{n,mar,s+1}^{-}$$
$$\forall n, mar \in markethours_{n,mar}, s$$

Eq 3.23.

$$P_{n,mar}^{-} = \sum_{s} Pk_{n,mar,s}^{-}$$
$$\forall n, mar \in markethours_{n,mar}$$

Eq 3.24.

Only one interval can be chosen for an offer, is not possible to bid at the same time two quantities of energy. The intervals of power are 10%.

$$\sum_{s} Xk_{n,mar,s}^{+} = 1$$
$$\forall n, mar \in markethours_{n,mar}$$

Eq 3.25.

$$\sum_{s} Xk_{n,mar,s}^{-} = 1$$
$$\forall n, mar \in markethours_{n,mar}$$

Eq 3.26.

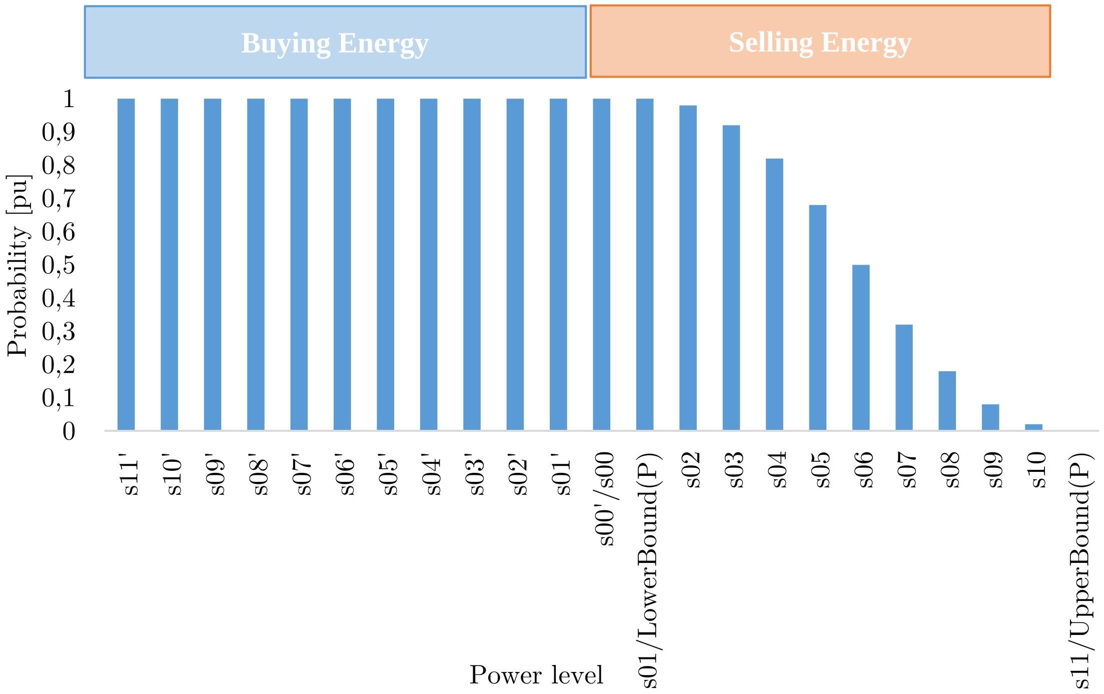

Fig 3.6. Summary of risk parametrization.

The risk of all operations or strategies made by WPP for the whole day must be lower than the parameter that limited the risk of the day, *risk* [20]. The WPP best strategy is to take more risk when it can achieve higher profits and compensate this risk assumed when the price of energy is lower. The risk can only be taken in selling energy, since buying is a secure strategy that not produce uncertainty in the operation.

$$\sum_{markethours_{n,mar,s}} Pk^{+}_{n,mar} \cdot prob_s \leq \sum_{markethours_{n,mar}} P^{+}_{n,mar} \cdot risk \qquad \text{Eq 3.27.}$$

3.3. STOCHASTIC INPUT DATA

The stochastic model receive as input data the same that in the deterministic model but with the difference of having a probabilistic distribution, parameters in the mathematical formulation:

- Price of the energy in the different markets
- Slope of the residual demand
- Production of the WPP
- Power installed in the WPP

- Prediction error curve
- Risk curve
- Deviations
    - Sign of the deviation to the market
    - Price of Upward/Downward deviations
    - Power dispatched along the day

Price of the energy in the different markets

The price of the energy in DA and ID markets is expressed in [€/MWh] and it refers to price where the aggregate demand curve offers and aggregate supply curve offers intersect. The SO receives the biddings from the suppliers and the consumers and create the aggregate curves ordering them by price. The equilibrium price is the price that generators dispatched receive from the energy delivered, in the other hand it is the price that retailers must paid for the energy consumed.

For the stochastic formulation, the DA price is known in advance by using the demand prediction made by ESIOS. Demand leaves room for this approach due to being very predictable.

In the case of the IDs, three scenarios are used for the mathematical formulation; high, medium or low price. Each of the ID markets is correlated with DA prices, the supposition is made through an analysis of historic data that enters into the model. The next figure represents the ID1 price of hour 1 in term of DA price, 16 days are used to make a statistically coherent sample. The medium price is the output of the analysis.

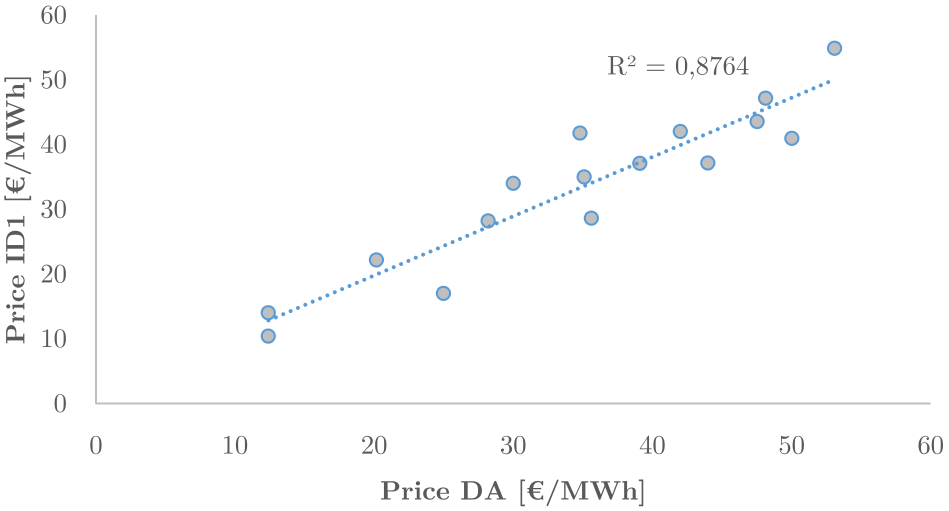

Fig 3.7. ID1 price in hour 1 correlation with DA price.

The other IDs have a similar linear regression with DA prices.

In order to see what a low and high price in ID markets is, a study of historic data is done. The study changes dynamically with the sample. However, it is averagely consider high price a 10% more than in the medium price and low price is 12% less than the medium one.

The probability of having high, medium and low prices is also a parameter of the model.

Probability of Prices	
High	0.20
Medium	0.60
Low	0.20

Table 3.6. Probability of the different price scenarios expressed unitarily.

Slope of the residual demand curve

As in the deterministic model, the residual demand slope of the WPP is calculated and used as input into the stochastic model.

The residual demand slope is estimated using historic data for 10 previous days to the operation day. The need of the residual demand curve is explained as necessity of having a more realistic approach for the price of the energy, change with the quantity bided. Since the ID markets are volatile and the energy traded is significant to the power installed in the WPP, the residual demand of these markets is supposed to be the same as in DA market.

Production of the WPP

The use of meteorological masts made the production a parameter known in advance. The production of the different wind turbines installed in the wind farm is carried by using data from the temperature and wind speed measures. The production parameter in the stochastic model is the same as in the deterministic model.

Power installed in the WPP

The capacity of the WPP is a parameter; it will be around 50 MW or the installed capacity of Sotavento. The boundary that the installed capacity has is that it cannot exceed the 5% of the valley demand of the operation day, a volume of energy traded negligible. Because of this assumption, the strategy of the WPP is not changing the counterstrategy of the rivals.

Prediction error curve

The prediction error curve takes into account the error in the forecast of wind, both in production and metering the amount of wind. The curve measures the error in % as a function of the time in which the prediction is held.

The curves used for the model, comes from Sipreólico [18].

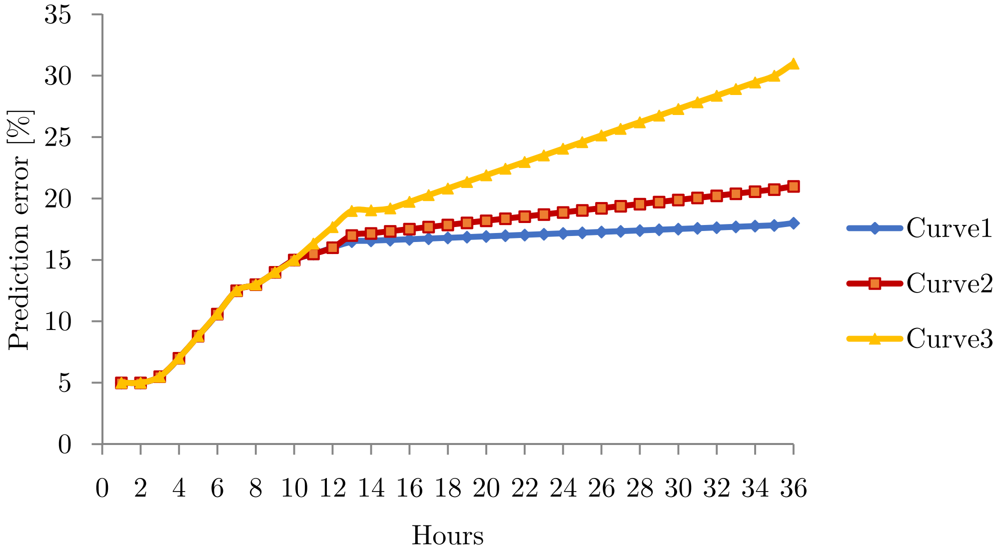

Fig 3.8. Prediction error curves.

For the stochastic model, the three curves are analyzed for the decision-making on the power bided. Each one is weighted with a probability.

Probability of wind forecasting	
Curve 1	0.33
Curve 2	0.33
Curve 3	0.33

Table 3.7. Probability of wind forecasting

Deviations

Deviation market, a volatile market in which small quantities of energy are traded, is used to balance demand and supply at the gate closure clearing. The deviations are remunerated in [€/MWh].

As it was explained in the deterministic formulation, there are two system of pricing deviations. Single pricing gives no remuneration to the SO; it is the price of the activated reserve. However, dual pricing means a gain for SO, used for the reduction in the transmission tariff. Dual pricing involves a penalty for deviations that are contrary to the market direction and remuneration for those that help the system. The goal behind this type of deviations is to charge the generator that has a negative sign to the system with the reserves additionally activated to deal with the imbalance occurred.

The case of study is Spain, in which dual pricing imbalance strategies are used.

The next table shows how generation units are remunerated in Spain.

Dual Pricing

	Upward Deviations	Downward Deviations
Positive	$\theta_n^+ \cdot \lambda_n^{UpDev}$	$\theta_n^+ \cdot \lambda_n^{DoDev}$
Negative	$\theta_n^- \cdot \lambda_n^{UpDev}$	$\theta_n^- \cdot \lambda_n^{DoDev}$

Table 3.8. Single and dual pricing, where λ_n^{UpDev} represents the price of upward imbalances and θ_n^+ the positive sign of the direction to the market for n hours

Deviations are the upward/downward energy derived from the difference between the final power dispatched and bidding of the generation unit. The power dispatched in the stochastic model has three different values: high, medium or low. High power dispatched is a 10% more of the medium one and low power dispatched is a 10% less than the medium one. The probabilities of having them are represented in the next table.

Probability of Power Dispatched	
High	0.30
Medium	0.50
Low	0.20

Table 3.9. Probabilities of power dispatched

The sign or direction to the market is not known in the stochastic approach. For this reason, three typical scenarios for different signs are considered. The main difference with the deterministic formulation is the uncertainty of when the sign is going to occur along the operation day.

Probability of Deviation Sign	
Sign $50\%^{+}/50\%^{-}$	0.33
Sign $60\%^{+}/40\%^{-}$	0.33
Sign $40\%^{+}/60\%^{-}$	0.33

Table 3.10. Probabilities of deviation sign

Finally, it has been noticed that the deviation price depends on the wind prediction of the day of operation. Two different scenarios can be spot for each upward or downward deviations. One is to have a null price in the deviation and the other is to have a price different from zero, estimated with a linear regression that depends on the wind.

The next figure represents the fact that the price in the deviations could be estimated with the wind, several days and hours that have different null deviation price in terms of the wind in that hour and that day.

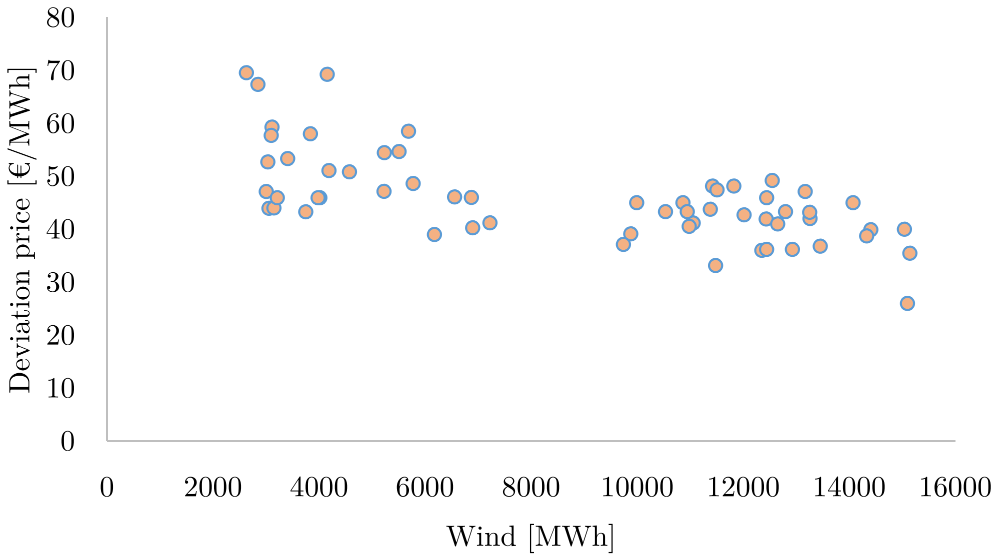

Fig 3.9. Upward deviations price in term of the wind of that day and hour.

Since prices are not always null, a probabilistic distribution for the occurrence of null and positive prices is need. In order to make it, a dynamic analysis, consisting on evaluating the number of positive and null prices within an interval of wind, is made. The analysis depends on the day of operation.

Probability of Wind

Hours	Wind Up1	Wind Up2	Wind Do1	Wind Do2
h06	0.13	0.38	0.05	0.45
h07	0.00	0.50	0.00	0.50
h08	0.13	0.38	0.05	0.45
h09	0.13	0.38	0.05	0.45
h10	0.00	0.50	0.00	0.50

Table 3.11. Probability of wind among the hours 6 to 10, 11th of March of 2015

The later table represents the probability of having a null or positive sign in the downward and upward deviations of the 11th of March of 2015. Wind Up1 and Wind Do1 are the probabilities of a price different from null, whereas the others are the null price probabilities.

3.4. STOCHASTIC FORMULATION

The stochastic model formulation, parameters known in advance with a probabilistic distribution, is subdivided into indices, parameters, variables, objective function and constraints. As in the deterministic model, the goal is to maximize the expected revenue according to the constraints of the market. The wind farm is able to bid in the DA market and restructure its bid through the IDs and deviation markets, in order to achieve the best strategy, to deal with the forecasting error of wind or an abrupt change in the production.

The power bid, for every hour and every market, and the revenue is the output of the model, only solved in a short-term electricity market of one day. The biding strategy will first take a decision on the DA market, deterministic decision, and later on evaluate the scenarios and decide about the power bided in IDs and deviation markets, stochastic decisions. Depending on the scenario, the stochastic decision will be different.

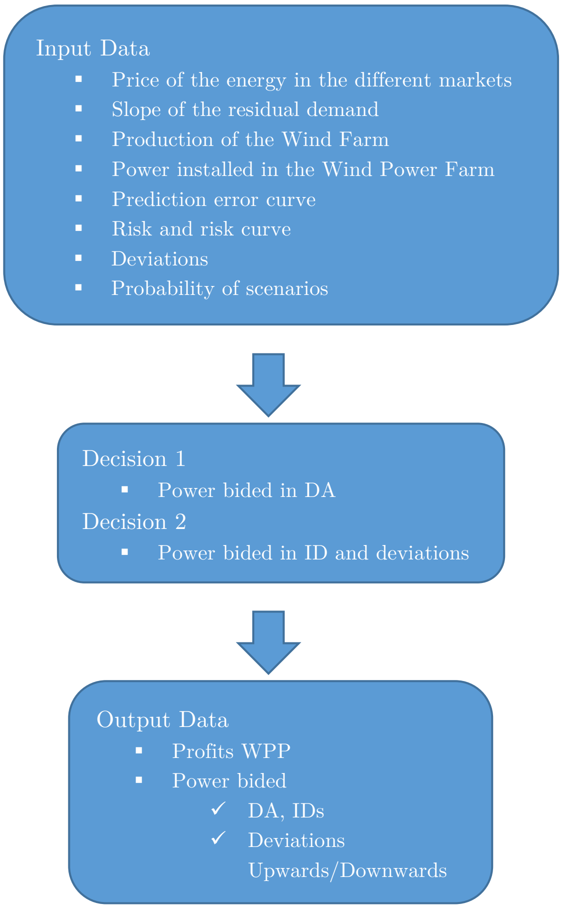

Fig 3.10. Summary of stochastic model.

The case study problem is a MIQP (mixed integer quadratic programming), since there are both integer and binary variables, with a quadratic objective function. The problem has 2453384 equations and a resolution time of 20 min with 324 scenarios for each hour.

3.5.STOCHASTIC DECISION TREE

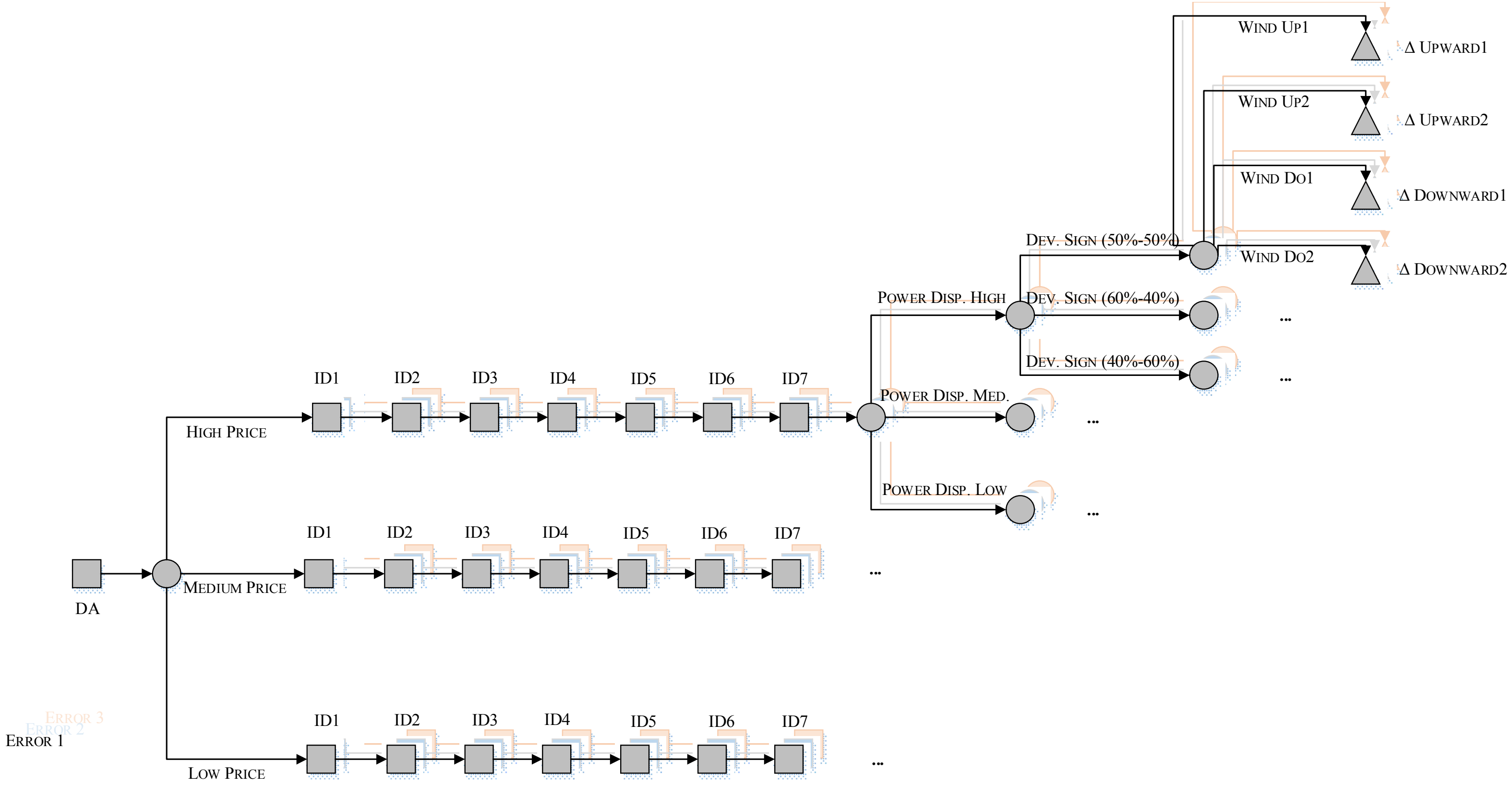

Fig 3.11. Decision tree for an hour in which the seven IDs are, depending on the hour a reduction on the number of IDs is done.

3.5.2. INDEXES

The indexes of the stochastic model represent dimensions of the problem and are structured in the next table.

Indexes Nomenclature

Name	Definition	
n	Hour of the day	h01, …, h24
nn	Hours for the wind forecast error curve, axis of the curve	hour1, …, hour36
mar	Bidding markets	DA, ID1, …, ID7
da	Subset of markets that only comprises the DA	DA
$intra$	Subset of markets that only comprises the IDs	ID, …, ID7
$marr$	Alias of mar	
$markethours_{n,mar,sc^{price}}$	Hour of the day in which is possible to bid, depends on the market in consideration	
s	Discretization of the risk operation curve or level of operative conservation, by using a triangular cumulative distribution	s00, …, s11
sc^{error}	Scenarios of the different prediction error curves	
sc^{price}	Scenarios of the different prices (high, medium or low)	
sc^{wind}	Scenarios of the different deviations, depending on the wind	
sc^{windUp}	Subset of scenarios of wind, upward deviations	
sc^{windDo}	Subset of scenarios of wind, downward deviations	
sc^{Pdisp}	Scenarios od the power dispatched	
sc^{dev}	Scenarios of the sign of the deviations	
$type^{dev}$	Type of deviation	Positive/ Negative

Table 3.12. Indexes of the stochastic model

$markethours_{n,mar,sc^{price}}$ is defined as the hours in which can be traded depending on the market and scenarios of price taken into consideration. For example, in ID7 is not possible to bid in hour 1, although the price is high, medium or low. This is due to the auction is made earlier than the bid hour.

3.5.3. PARAMETERS

The input or parameter that entered in the model represent the data known in advance. Most of the data are extracted from OMIE and ESIOS webpage, the market and system operators of the electricity market.

Parameters Nomenclature

Name	Definition	Units
$\lambda^{DA,IDs}_{n,mar,sc^{price}}$	Price of the energy in hour *n* and market *mar*, in other words is the DA and ID market price	[€/MWh]
$\delta_{n,mar}$	Slope of the residual demand curve	[€/MW²h]
$\lambda^{Up/DoDev}_{n,sc^{wind}}$	Hourly price of the upward and downward deviations	[€/MW]
$\theta^{\pm}_{n,type^{dev}}$	Hourly sign of the deviation to the market. If the strategy helps the electricity system, the sign is positive and on the contrary is negative when the measure adopted by the WPP represents a problem for the system	[1/-1]
P^{Inst}	Power installed in the WPP	[MW]
P^{Prod}_{n}	Production hourly production of the WPP	[pu]
$P^{Dispatch}_{n,sc^{Pdisp}}$	Power dispatched when the liquidation of the hour is made	[MW]
$\overline{P}_{n,mar,sc^{price},sc^{error}}$	Upper bound of the power bided	[MW]
$\underline{P}_{n,mar,sc^{price},sc^{error}}$	Lower bound of the power bided	[MW]
$risk$	Risk taken on the biddings or level of operative conservation	[pu]
$dif_{n,mar}$	Lead times between the gate closure of the market and the bid hour, computed for the error in the wind forecast	[h]
$error_{nn,sc^{error}}$	Error in prediction of wind, takes into account the error of metering and forecasting of wind.	[%]
$step_{s}$	Discretization steps of power bided	[%]
$prob_{s}$	Probability of success in the bidding	[pu]
$prob^{error}_{sc^{error}}$	Probability of prediction error in different scenarios	[pu]
$prob^{price}_{sc^{price}}$	Probability of price in different scenarios	[pu]
$prob^{wind}_{n,sc^{wind}}$	Probability of wind in different scenarios	[pu]
$prob^{Pdisp}_{sc^{Pdisp}}$	Probability of power dispatched in different scenarios	[pu]
$prob^{dev}_{sc^{dev},type^{dev}}$	Probability of deviation sign in different scenarios	[pu]
$\beta^{+}_{n,mar,sc^{price},sc^{error},s}$	Steps for the positive discretization of the curve	[MW]
$\beta^{-}_{n,mar,sc^{price},sc^{error},s}$	Steps for the negative discretization of the curve	[MW]

Table 3.13. Parameters of the stochastic model

$\overline{P}_{n,mar,sc^{price},sc^{error}}$ and $\underline{P}_{n,mar,sc^{price},sc^{error}}$ are the upper and lower bound of the power, for every hour, market and for every scenario of forecasting error, and represents a band width for the power bided. Both take into account the error on wind prediction for the

WPP, considering the three curves. The error depends on the lead times between the bid hour and the gate closure of the auction.

$$\overline{P}_{n,mar,sc^{price},sc^{error}} = P_n^{Prod} \cdot P^{Inst} \cdot \frac{1 + error_{nn,sc^{error} \in dif_{n,mar}}}{100}$$
$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}$$ Eq 3.28.

$$\underline{P}_{n,mar,sc^{price},sc^{error}} = P_n^{Prod} \cdot P^{Inst} \cdot \frac{1 + error_{nn,sc^{error} \in dif_{n,mar}}}{100}$$
$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}$$ Eq 3.29.

$\beta^{+}_{n,mar,sc^{price},sc^{error},s}$ and $\beta^{-}_{n,mar,sc^{price},sc^{error},s}$ represents the points of the interval in which is possible to bid due to the risk operation measurement or level of operative conservation, both for selling and for buying energy in the markets. The level of operative conservation is explained as the bandwidth limitation for every bid in every market and hour, implies a boundary for the operation of the WPP.

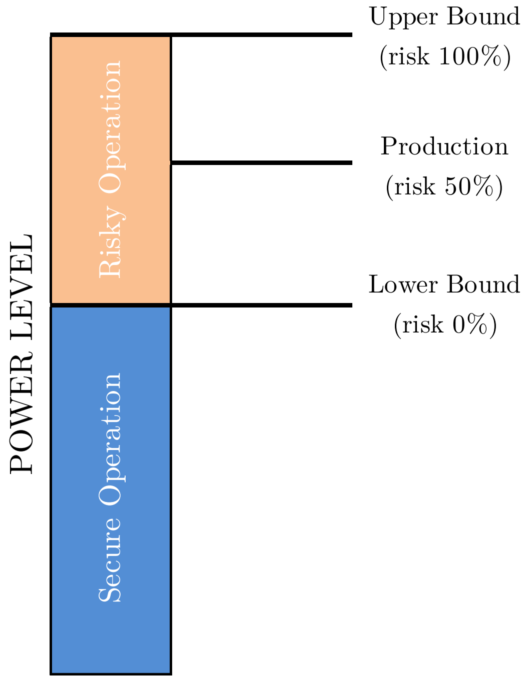

Fig 3.12. Power level bidding strategy considering risk.

As a result, the power bided, strategy of WPP, is comprised between two intervals or steps. The width of the intervals is the 10%, resulting in power strategies of ±5%.

$$\beta^{+}_{n,mar,sc^{price},sc^{error},s} = \underline{P}_{n,mar,sc^{price},sc^{error}} + step_s \cdot \frac{\overline{P}_{n,mar,sc^{price},sc^{error}} - \underline{P}_{n,mar,sc^{price},sc^{error}}}{100}$$ Eq 3.30.

$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}, s$$

$$\beta^{+}_{n,mar,sc^{price},sc^{error},'s00'} = 0$$
$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}, s \qquad \text{Eq 3.31.}$$

$$\beta^{-}_{n,mar,sc^{price},sc^{error},s} = P^{Inst}$$
$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}, s \qquad \text{Eq 3.32.}$$

$$\beta^{-}_{n,mar,sc^{price},sc^{error},'s00'} = 0$$
$$\forall n, mar, sc^{price} \in markethours_{n,mar,sc^{price}}, sc^{error}, s \qquad \text{Eq 3.33.}$$

3.5.4. VARIABLES

For simplicity on the mathematical formulation of the stochastic model, from now a variable that depends on $sc^{price}, sc^{error}, sc^{wind}, sc^{dev}$ and sc^{Pdisp} will depend on a set called sc, that comprised the later ones.

Variables Nomenclature

Name	Definition	Units
$P^{DA,IDs}_{n,mar,sc}$	Power bided of the WPP	[MW]
$P^{+}_{n,mar,sc}$	Positive power bided of the WPP	[MW]
$P^{-}_{n,mar,sc}$	Negative power bided of the WPP	[MW]
$Pk^{+}_{n,mar,sc,s}$	Power for positive risk curve parametrization	[MW]
$Pk^{-}_{n,mar,sc,s}$	Power for negative risk curve parametrization	[MW]
$\Delta^{Up}_{n,sc}$	Upward deviation	[MW]
$\Delta^{Do}_{n,sc}$	Downward deviation	[MW]
$Xk^{+}_{n,mar,sc,s}$	Binary variable for the positive parametrization of the risk curve (Decision)	[0/1]
$Xk^{-}_{n,mar,sc,s}$	Binary variable for the negative parametrization of the risk curve (Decision)	[0/1]
ξ^{1}	Value of the Objective Function 1 (Revenues)	[€]
ξ^{2}	Value of the Objective Function 2 (Revenues)	[€]

Fig 3.13. Variables of the stochastic model.

The variable definition is as follow:

- Positive variables

$$P^{+}_{n,mar,sc},\ P^{-}_{n,mar,sc},\ Pk^{+}_{n,mar,sc,s}, Pk^{-}_{n,mar,sc,s}, \Delta^{Up}_{n,sc}, \Delta^{Do}_{n,sc} \geq 0 \quad \forall n, mar, sc, s \tag{Eq 3.34.}$$

- Binary variables

$$Xk^{+}_{n,mar,sc,s}, Xk^{-}_{n,mar,sc,s} \in \{0,1\} \quad \forall n, mar, sc, s \tag{Eq 3.35.}$$

- Free variables

$$P^{DA,IDs}_{n,mar,sc}, \xi^1, \xi^2\ free \tag{Eq 3.36.}$$

3.5.5. OBJECTIVE FUNCTION

ξ^1, The first objective function, represent the profits expected by the WPP when no deviations are taken into account. As it was explained in the determinist formulation, the justification of making this approach is to see how risky to the market the strategies fulfilled by the WPP are. These kind of strategies can jeopardize the system operation or can mean an increase on the online reserve needs (CCGT and other thermal units) in order maintain the service, in order to hedge the risk introduced by an intermittent technology. However, since the volume of energy traded by the studied WPP studied is smaller, no bigger correction actions will be need.

$$\begin{aligned} \xi^1 = \max \sum_{markethours_{n,mar,sc^{price},sc}} & [(\delta_{n,mar}(P^{DA,IDs}_{n,mar,sc} - 0.5P^{Inst})) \\ & + \lambda^{DA,IDs}_{n,mar,sc^{price}}] \cdot P^{DA,IDs}_{n,mar,sc} \cdot prob^{error}_{sc^{error}} \cdot prob^{price}_{sc^{price}} \\ & \cdot prob^{wind}_{n,sc^{wind}} \cdot \sum_{type^{dev}} prob^{dev}_{sc^{dev},type^{dev}} \cdot prob^{Pdisp}_{sc^{Pdisp}} \\ & \cdot 1hour \end{aligned} \tag{Eq 3.37.}$$

However, ξ^2, the second objective function, represents the profits for the DA, IDs and gives the option to the model to take advantage of the deviation, a measure to correct wind forecast errors or to achieve a better strategy. In this case, the system is not jeopardized, since penalizations in the objective function to the biddings that are negative to the market signals are introduced. In fact, deviations are another market for the WPP to make more profits.

$$
\begin{aligned}
\xi^2 = \max \sum_{markethours_{n,mar,sc^{price}},sc} & [(\delta_{n,mar}(P^{DA,IDs}_{n,mar,sc} - 0.5P^{Inst})) \\
& + \lambda^{DA,IDs}_{n,mar,sc^{price}}] \cdot P^{DA,IDs}_{n,mar,sc} \cdot prob^{error}_{sc^{error}} \cdot prob^{price}_{sc^{price}} \\
& \cdot prob^{wind}_{n,sc^{wind}} \cdot \sum_{type^{dev}} prob^{dev}_{sc^{dev},type^{dev}} \cdot prob^{Pdisp}_{sc^{Pdisp}} \\
& \cdot 1hour \\
& + \sum_{n,type^{dev},sc \cap sc^{windUp}} \left\{ \Delta^{Up}_{n,sc} \cdot \lambda^{\frac{Up}{DoDev}}_{n,sc^{wind}} \cdot \theta^{\pm}_{n,type^{dev}} \right. \\
& \cdot prob^{error}_{sc^{error}} \cdot prob^{price}_{sc^{price}} \cdot prob^{wind}_{n,sc^{wind}} \\
& \left. \cdot prob^{dev}_{sc^{dev},type^{dev}} \cdot prob^{Pdisp}_{sc^{Pdisp}} \cdot 1hour \right\} \\
& + \sum_{n,type^{dev},sc \cap sc^{windDo}} \left\{ \Delta^{Do}_{n,sc} \cdot \lambda^{\frac{Up}{DoDev}}_{n,sc^{wind}} \cdot \theta^{\pm}_{n,type^{dev}} \right. \\
& \cdot prob^{error}_{sc^{error}} \cdot prob^{price}_{sc^{price}} \cdot prob^{wind}_{n,sc^{wind}} \\
& \left. \cdot prob^{dev}_{sc^{dev},type^{dev}} \cdot prob^{Pdisp}_{sc^{Pdisp}} \cdot 1hour \right\}
\end{aligned}
\qquad \text{Eq 3.38.}
$$

3.5.6. CONSTRAINTS

The constraints represents the set of relationships that variables are obliged to satisfy, can be expressed as equations and inequalities.

The power bided in DA and IDs is a free variable defined with two variables, one for selling and other for buying energy. This formulation is needed since buying energy has no risk for the WPP; it is a secure strategy for making more profits in other markets.

$$
\begin{gathered}
P^{DA,IDs}_{n,mar,sc} = P^{+}_{n,mar,sc} - P^{-}_{n,mar,sc} \\
\forall n, mar, sc \in markethours_{n,mar,sc^{price}}
\end{gathered}
\qquad \text{Eq 3.39.}
$$

The power bided for every hour of the operation day cannot exceed the power installed. If the capacity installed is overpassed, the WPP should buy that energy. The objective function penalize the energy bought, resulting in a cost for the WPP. However, the WPP is able to benefit from arbitrage between markets, taking advantage of the difference in prices and auction closure times. To sum up, buying energy is a non-constrained source of profit, if it is sold in a more profitable market.

$$
\begin{gathered}
\sum_{mar \leq marr \in markethours_{n,mar,sc^{price}}} P^{DA,IDs}_{n,mar,sc} \leq P^{Inst} \\
\forall n, mar, sc \in markethours_{n,mar,sc^{price}}
\end{gathered}
\qquad \text{Eq 3.40.}
$$

Liquidity constraints are introduced into the stochastic model, again the volume of energy bid in IDs, volatile markets, cannot suppose a change on the ID market equilibrium price. Since, the total energy traded in these markets is considerably similar to the installed capacity of the WPP of study. However, in DA market the WPP is able to bid at its maximum capacity, constrained by its bandwidth between the upper and lower bound. The reason to make this approach is not to change the strategy used by the competitors in the game, due to an alteration in the price. The counterstrategy prediction is out of this approach, strategies of the competitors are not changed in the case of study due to the little power or position of the WPP in the spot markets. The maximum energy possible to bid in the IDs, both for buying and selling, is the 10% of the installed capacity.

$$P^{+}_{n,mar,sc} \leq 0.1P^{Inst}$$
$$\forall n, mar, sc \in intra$$
Eq 3.41.

$$P^{-}_{n,mar,sc} \leq 0.1P^{Inst}$$
$$\forall n, mar, sc \in intra$$
Eq 3.42.

As it was explained before, deviations are the power difference between what is dispatched and what is bided for an hour of the operation day. Deviations can be both upwards or downwards and depending on the direction of the system can be penalized or remunerated in the objective function. For a stochastic model, sign of the deviation will be introduce with a probability, there is no knowledge of when the deviation is going to occur. Therefore, the optimality maximization of profits will be attained with fewer deviations than in the deterministic, due to the uncertainty of occurrence.

$$P^{Dispatch}_{n,sc^{Pdisp}} - \sum_{mar \in markethours_{n,mar,sc^{price}}} P^{DA,IDs}_{n,mar,sc} = \Delta^{Up}_{n,sc} - \Delta^{Do}_{n,sc}$$
$$\forall n, sc$$
Eq 3.43.

Deviations also need to be constrained with a boundary of the 10% of the installed capacity, since are a volatile market in which the volume of energy traded is considerably similar to the power installed. The liquidity of the market must be assured with these constraints.

$$\Delta^{Up}_{n,sc} \leq 0.1P^{Inst}$$
$$\forall n, sc$$
Eq 3.44.

$$\Delta^{Do}_{n,sc} \leq 0.1P^{Inst}$$
$$\forall n, sc$$
Eq 3.45.

As a way to measure the success of the biddings, the power offered is distributed as a triangular cumulative distribution. Each of the probabilities measure the range of success of the strategies made for every hour and every market or level of operative conservation, DA and IDs. Offering more energy will mean a more risky action for the system and for not covering what the WPP offered, buying energy will be needed to cover the production dispatched. Only selling energy represents risk in the operations, buying is a risk-free action. As it was explained before, a continuous cumulative distribution is quite challenging for the GAMS, so a parametrization of the curve is made. The next equations represent this idea for selling and buying energy.

$$Pk^{+}_{n,mar,sc,s} \geq Xk^{+}_{n,mar,sc,s} \cdot \beta^{+}_{n,mar,sc^{price},sc^{error},s} \qquad \forall n, mar, sc, s \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.46.}$$

$$Pk^{+}_{n,mar,sc,s} \leq Xk^{+}_{n,mar,sc,s} \cdot \beta^{+}_{n,mar,sc^{price},sc^{error},s+1} \qquad \forall n, mar, sc, s \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.47.}$$

$$P^{+}_{n,mar,sc} = \sum_{s} Pk^{+}_{n,mar,sc,s} \qquad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.48.}$$

$$Pk^{-}_{n,mar,sc,s} \geq Xk^{-}_{n,mar,sc,s} \cdot \beta^{-}_{n,mar,sc^{price},sc^{error},s} \qquad \forall n, mar, sc, s \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.49.}$$

$$Pk^{-}_{n,mar,sc,s} \leq Xk^{-}_{n,mar,sc,s} \cdot \beta^{-}_{n,mar,sc^{price},sc^{error},s+1} \qquad \forall n, mar, sc, s \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.50.}$$

$$P^{-}_{n,mar,sc} = \sum_{s} Pk^{-}_{n,mar,sc,s} \qquad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.51.}$$

Only one interval can be chosen for an offer, is not possible to bid at the same time two quantities of energy. The intervals of power are separated by a 10% of the total energy bided in that hour of the operation day.

$$\sum_{s} Xk^{+}_{n,mar,sc,s} = 1 \qquad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.52.}$$

$$\sum_{s} Xk^{-}_{n,mar,sc,s} = 1 \qquad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \qquad \text{Eq 3.53.}$$

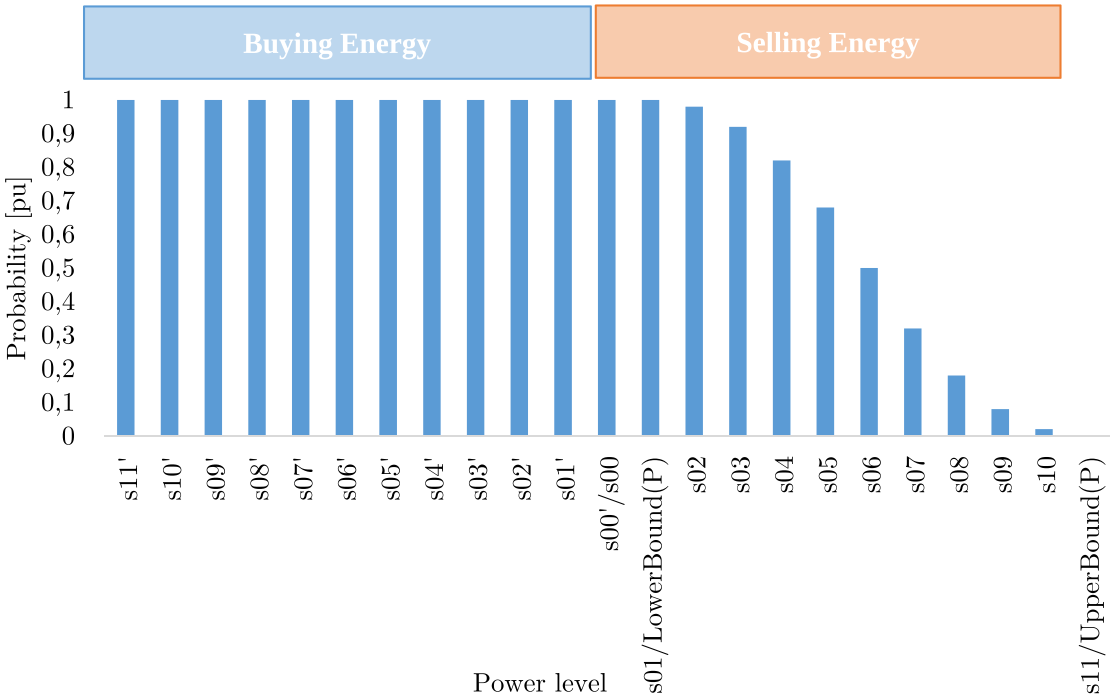

Fig 3.14. Summary of risk parametrization.

The limit of the success of the operations of bidding is constrained with the next inequality, in which the parameter $risk$ [20] is the boundary. The WPP is able to compensate the risk among the whole day of operation; as a result, it can make more profits when the expected price of the market is higher.

$$\sum_{markethours_{n,mar,sc^{price}},s} Pk^{+}_{n,mar,sc,s} \cdot prob_s \leq \sum_{markethours_{n,mar,sc^{price}}} P^{+}_{n,mar,sc} \cdot risk \qquad \text{Eq 3.54.}$$

Non-anticipativity constraints are need to be introduced, since a limitations for when the decisions are taken are necessary. The WPP bidding in the DA cannot be affected by the scenarios of price of the IDs nor for the deviations scenarios. There is a sequence of time in the decision-making. Consequently, the next equalities are used to restraint the concept just explained.

$$P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}} = P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}+1} \qquad \text{Eq 3.55.}$$

$$\forall n, mar, sc \in markethours_{n,mar,sc^{price}}$$

$$P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}} = P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev}+1,sc^{Pdisp}} \quad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \tag{Eq 3.56.}$$

$$P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}} = P^{DA,IDs}_{n,mar,sc^{price},sc^{error},sc^{wind}+1,sc^{dev},sc^{Pdisp}} \quad \forall n, mar, sc \in markethours_{n,mar,sc^{price}} \tag{Eq 3.57.}$$

$$P^{DA}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}} = P^{DA}_{n,mar,sc^{price}+1,sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}+1} \quad \forall n, DA, sc \in markethours_{n,mar,sc^{price}} \tag{Eq 3.58.}$$

$$P^{DA}_{n,mar,sc^{price},sc^{error},sc^{wind},sc^{dev},sc^{Pdisp}} = P^{DA}_{n,mar,sc^{price},sc^{error}+1,sc^{wind},sc^{dev},sc^{Pdisp}+1} \quad \forall n, DA, sc \in markethours_{n,mar,sc^{price}} \tag{Eq 3.59.}$$

3.6. CONCLUSIONS

The main objective of deterministic and stochastic models is to maximize the short-term profit of the WPP. A deterministic model or perfect information model is a model in which the parameters are known in advance and a stochastic model or probabilistic model is a model in which the parameters are modelled with uncertainty. In the case of the stochastic modelling different scenarios are considered in order to make a realistic representation of the strategy followed by a WPP. The scenarios will be probabilistically distributed since there is uncertainty on what is going to happen in the operation day.

Both models give the opportunity to the WPP to achieve the best strategy in the DA, IDS and imbalance market, taking into account the constraints of the mathematical formulation.

The WPP is not able to bid more power than the installed capacity. A penalization to the WPP for buying energy is made in the objective functions, since it is a cost for the WPP. However, arbitrage between auctions could be done, in order to benefit from the difference in prices and closure times. Due to the volatility or liquidity of the ID and imbalance markets, the WPP is constrained to bid in these markets below the 10% of the installed power, a boundary that cannot be exceed. The reason behind the constraint is not to affect its market equilibrium prices, in other words, the strategy followed by competitors.

Deviations, power traded in the imbalance markets, are the difference between what is dispatched and what is bided for an hour of the operation day. Deviations can be both upwards or downwards and depending on the direction of the system can be penalized or remunerated.

Apart from that, the models include a way to measure the risk taken in the strategy of the WPP or level of operative conservation, by distributing the power bid with a triangular cumulative distribution. Bidding more energy than the limits established by the prediction is considered a risk for the WPP, since it cannot guarantee that this energy is going to be delivered due to having a lack of production. Consequently, this differential energy should be bought in the operation markets considered. Buying energy is a risk free action.

Non-anticipativity constraints are used to drive the WPP to follow the time horizon of the Spanish electricity market. A consideration that only is applied for the probabilistic modelling, stochastic.

Chapter 4. Result analysis

The bidding strategy result analysis consists on several simulations in order to see the influence of the price, production, risk taken and deviations on the decision making of the WPP. Apart from that, a model comparison between deterministic, real-life strategy follow by WPP agents and stochastic will be done in order to see the validity of the approach done in the case of study. When referring to real-life strategies followed by agents, it means bidding all the production in the DA market, in order to not deal with the uncertainty of the subsequent markets.

The order followed in the result analysis is:

1. Hourly analysis for deterministic and stochastic models; windy hour, normal hour and not wind hour.
2. Daily analysis for deterministic, real-life strategy and stochastic models, for profits of the WPP and the strategy followed.
3. Price decision making for the stochastic model; high, medium and low ID prices.
4. Risk analysis and profits boundaries.
5. Deviation influence analysis.

4.1. Hourly analysis

For the hourly analysis, the day chosen is the 18th of March of 2015. The WPP, Sotavento, has a power rating of 17.56 MW and the risk taken for all the analysis is the 50% that can be distributed among all the strategies during the whole day. The hours analyzed are hour 10, 19 and 24; a not so windy hour, a windy hour and a normal hour.

The next figure summarized the power bided for the deterministic and stochastic model according to the production of the WPP of the day of operation. Both models strategy is to offer more power than the produced since the prediction error is not taken into account. For the maximization of profits, the WPP tries to offer at the upper bound of the bandwidth derived from the prediction error curve.

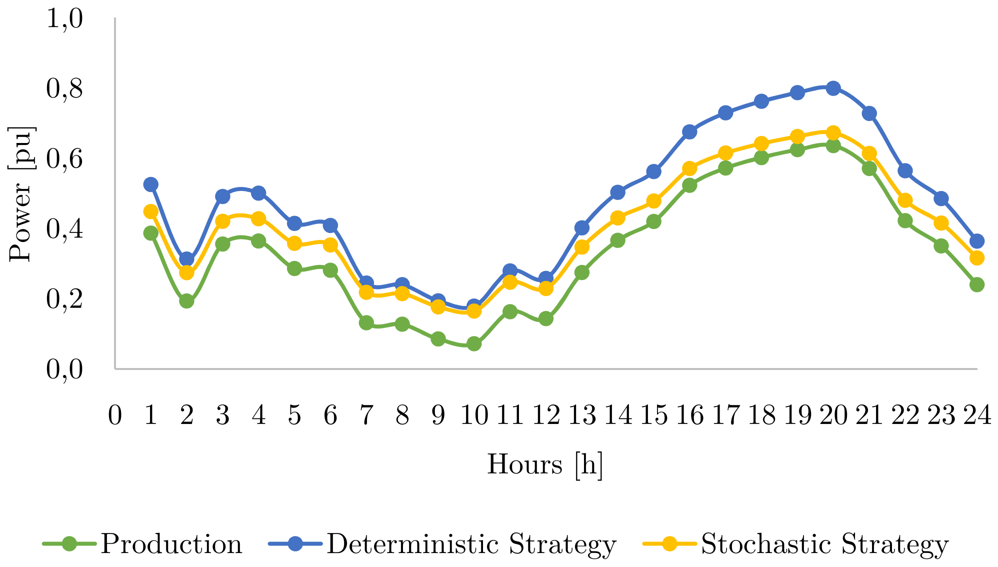

Fig 4.1. Deterministic, stochastic strategy and production of the WPP the 18th of March of 2015.

The strategy followed with perfect information, deterministic, is to bid in the markets where the price is higher. In the case of study, the IDs have a higher market price than the DA. Therefore, the WPP power strategy is to maximize the bid in the IDs, but satisfying with the constraint that the capacity bided in these markets is equal to or less than 10% of the installed capacity.

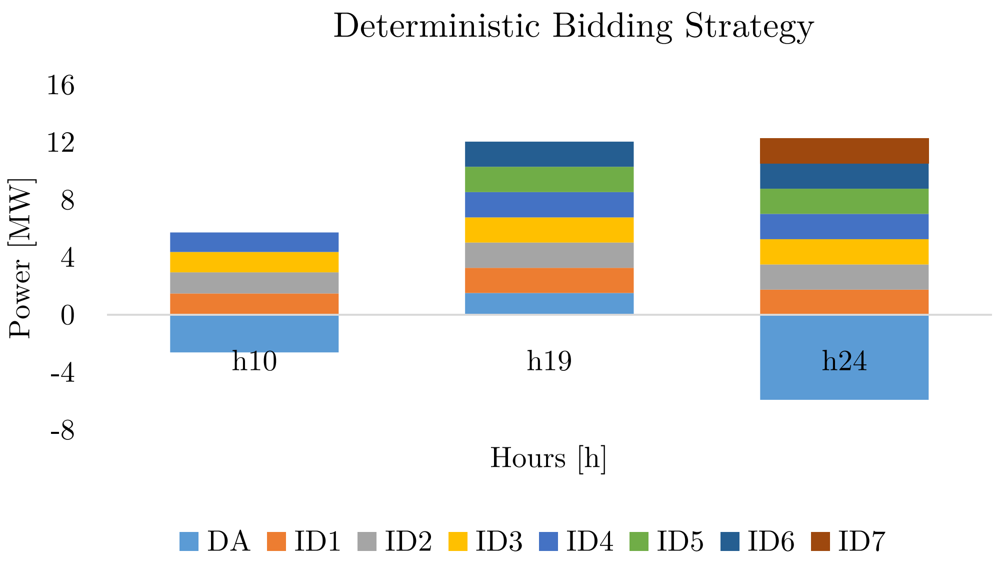

Fig 4.2. Deterministic bidding strategy for DA and IDs in the hours 10, 19 and 24 of the 18th of March of 2015.

As it is shown in the later figure, in hour 10 and 24 the WPP is buying energy in the DA and selling at a higher price in the IDs, in making advantage of the arbitrage between markets due to the different closure times of the auctions. Apart from that, in hour 10, a not so windy hour in which the production is 0.07 pu, the WPP takes more risk in the biddings. That risk in exceed is counterbalance with the windy hours, such as the hour 19 of the day of operation, in which the probability of success in the strategy followed and the volume of energy traded are higher. In fact, the probability of success of the hour 19 is 100%.

The deviations for the hours of operations analyzed are represented in the next figure. Moreover, since there is no penalty or remuneration of having downward deviations its value is 1.76 MW, the maximum deviation that can be achieved due to the limiting 10% constraint. The WPP takes advantage of having downward deviations since can trade more energy in other markets where the price is different from null. In hour 19, the upward deviations takes the value of 1.76 MW, due to of having a highly profitable imbalance price on that hour.

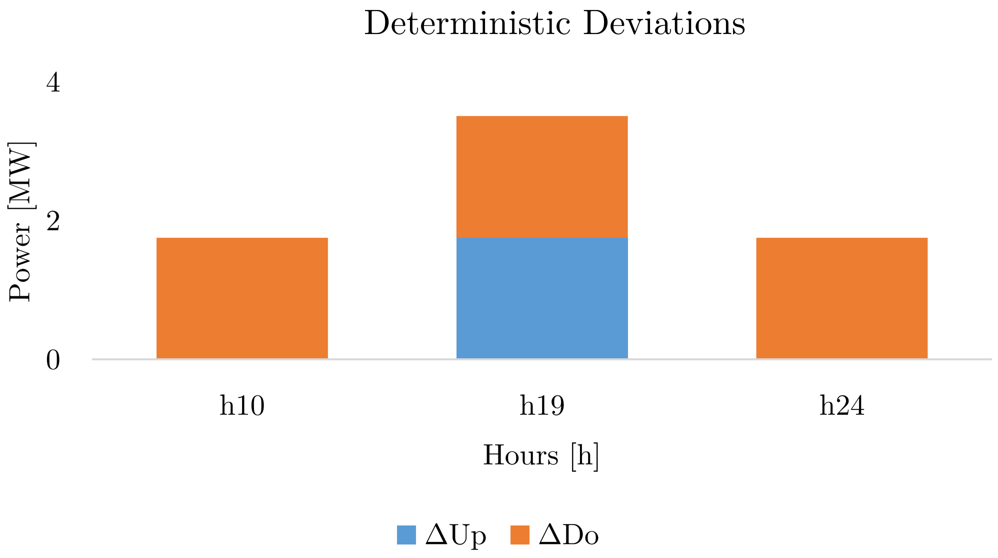

Fig 4.3. Deterministic bidding strategy for Δ^{Up} and Δ^{Do} in the hours 10, 19 and 24 of the 18th of March of 2015.

The strategy followed with uncertainty on the information, stochastic parameters, is to bid in the markets where the prediction price is higher. However, since the DA power bid is a deterministic decision with no uncertainty, due to how it is modelled the stochastic model, the vast majority of the energy traded will be in the DA market. The ID markets will be used to restructure the strategy and to achieve a better strategy than bidding all the energy in DA. In the case of study, the IDs price is higher than in the DA, high price scenario. The bids in the IDs are constrained by a boundary of the 10% of the installed capacity.

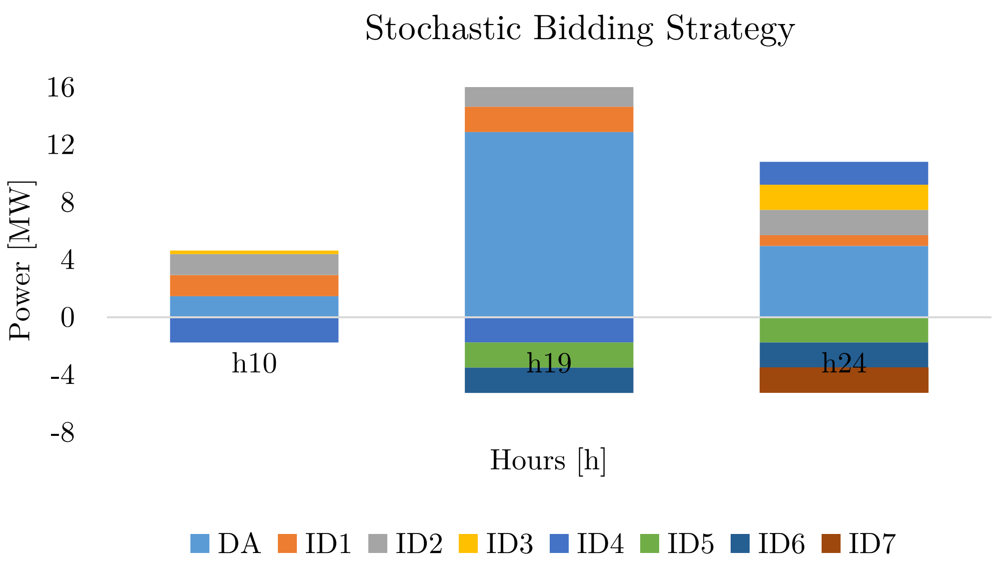

Fig 4.4. Stochastic bidding strategy for DA and IDs in the hours 10, 19 and 24 of the 18th of March of 2015.

In the previous figure, the WPP for all the hours improves its strategy by buying energy in some IDs, such as ID 4, ID 5 and ID 6, and selling in DA and the other IDs. By making this strategy, the WPP has more volume of energy available for making profits when the price is predicted to be higher, such as in DA, ID 1 and ID 2. As it happens in the deterministic strategy, the not so windy hour is more prompt to not success in the biddings, a risk that is assumed by the windy hour in which the volume of energy traded is higher. In fact, the probability of success of the windy hour, hour 19, is 100 %.

The deviations for the operation hours analyzed are represented in the next figure. The deviations for the stochastic model are a weight of all the possible scenarios for the imbalances, in order to achieve a strategy that deals with all of them. In the case of the stochastic strategy, deviations are not at its maximum value since there are scenarios in which the deviations are penalized. In hour 19 the upward deviation takes positive value, meaning profits for the WPP, since it is a highly remunerated hour for the upward deviations. The WPP takes advantage of having downward deviations since can trade more energy in other markets where the price is different from null, predicted by the model using historic data.

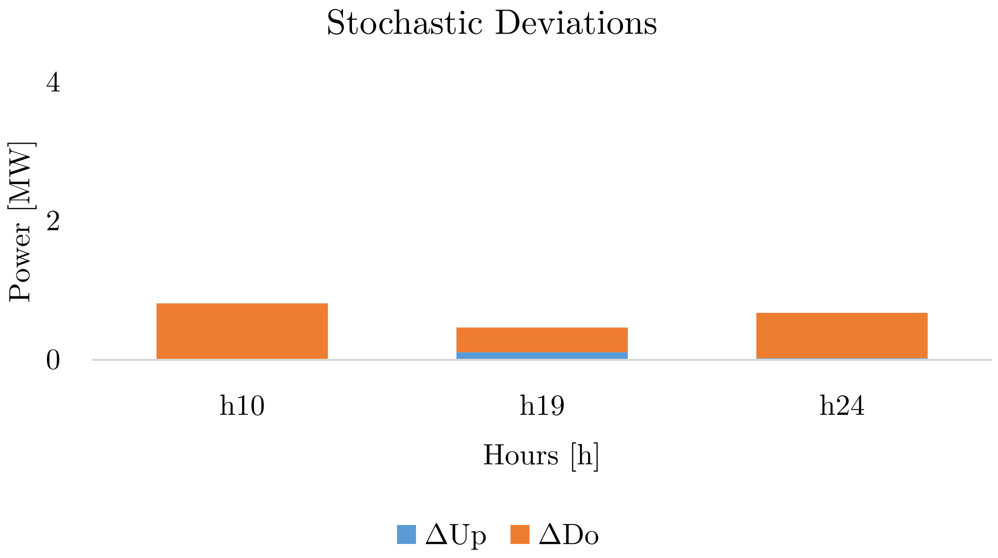

Fig 4.5. Stochastic bidding strategy for $\varDelta^{Up}$ and $\varDelta^{Do}$ in the hours 10, 19 and 24 of the 18th of March of 2015.

The next table sum up both strategies for the WPP and exemplified what was explained previously, having perfect information gives to the WPP the opportunity to have more profits due to bidding in markets with higher prices. The stochastic strategy is more conservative and sells the bulk of energy in DA market.

	Deterministic Strategy [MW]			**Stochastic Strategy [MW]**		
	h10	h19	h24	h10	h19	h24
DA	-2.60	1.52	-5.91	1.46	12.89	4.96
ID1	1.49	1.76	1.76	1.47	1.76	0.74
ID2	1.47	1.76	1.76	1.46	1.76	1.76
ID3	1.41	1.76	1.76	0.24	0.49	1.76
ID4	1.36	1.76	1.76	-1.76	-1.76	1.59
ID5	0.00	1.76	1.76	0.00	-1.76	-1.76
ID6	0.00	1.76	1.76	0.00	-1.76	-1.76
ID7	0.00	0.00	1.76	0.00	0.00	-1.76
$\varDelta^{Up}$	0.00	1.76	0.00	0.00	0.10	0.02
$\varDelta^{Do}$	1.76	1.76	1.76	0.81	0.36	0.65

Table 4.1. Summary of the strategies followed by the WPP.

The profits of both strategies are similar, although they are higher for the deterministic one, as it was expected. The most profitable hour is the windy hour, in which more energy can be traded due to a bigger production.

Profits [€]			
	h10	h19	h24
Deterministic	196.75	754.05	329.84
Stochastic	157.03	540.87	225.65

Table 4.2. Hourly profits of the WPP in hours 10, 19 and 24 of the 18th of March of 2015.

4.2. DAILY ANALYSIS

For the daily analysis, the day chosen is the 2nd of February of 2015. The WPP, an EDPR (EDP Renewables) wind farm in Spain, has a power rating of 41.65 MW and the risk taken for all the analysis is the 50% that can be distributed among all the strategies during the whole day. Due to confidentiality, the name of the wind farm cannot be declared. The day of operation is a windy day of February, in which the expected production is high.

A real-life agent bidding strategy, such as EDPR trading department, is to sell the whole production in the DA. The strategy followed is a conservative one, in which the deviation market and ID markets are not used to restructure or to make more profit of the WPP. Consequently, the expected profits will be lower than the results with both models. The risk taken in the operation is the 50%, since the wind prediction error can be upward or downward.

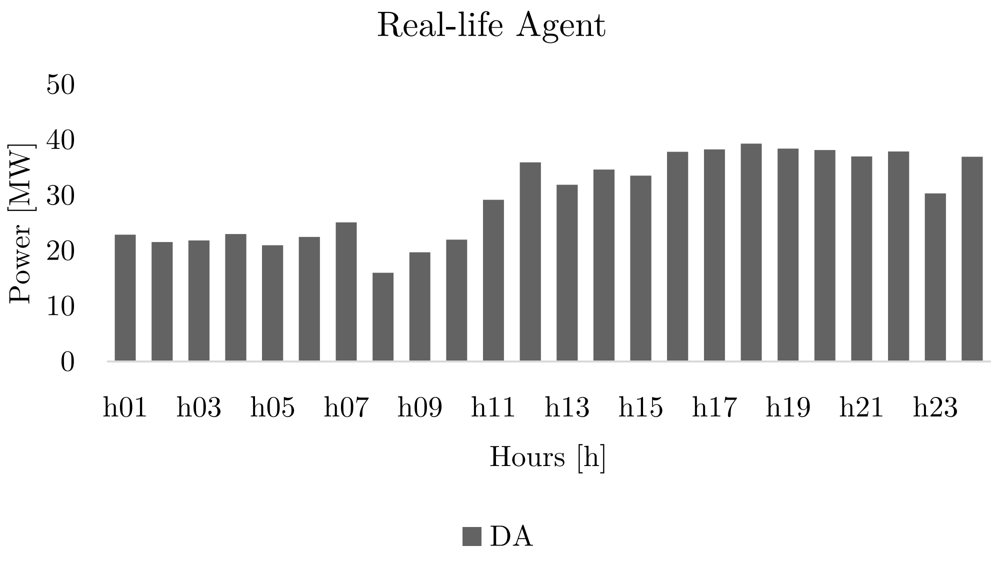

Fig 4.6. Real-life agent bidding strategy (EDPR trading) for the 2nd of February of 2015.

As happens in the previous analysis, the strategy followed with perfect information, deterministic, is to bid in the markets where the price is higher. In the case of study, the IDs has a higher market price than the DA in general. As a result, the WPP strategy followed is to bid less energy in the DA and try to bid as much as it could, satisfaction of the constraint that limit to the 10% the energy bid in the IDs, in the IDs. Apart from that, since not all the IDs has prices bigger than the DA or the other IDs, the WPP buys energy in that markets in order to make profits in the next auction, arbitrage.

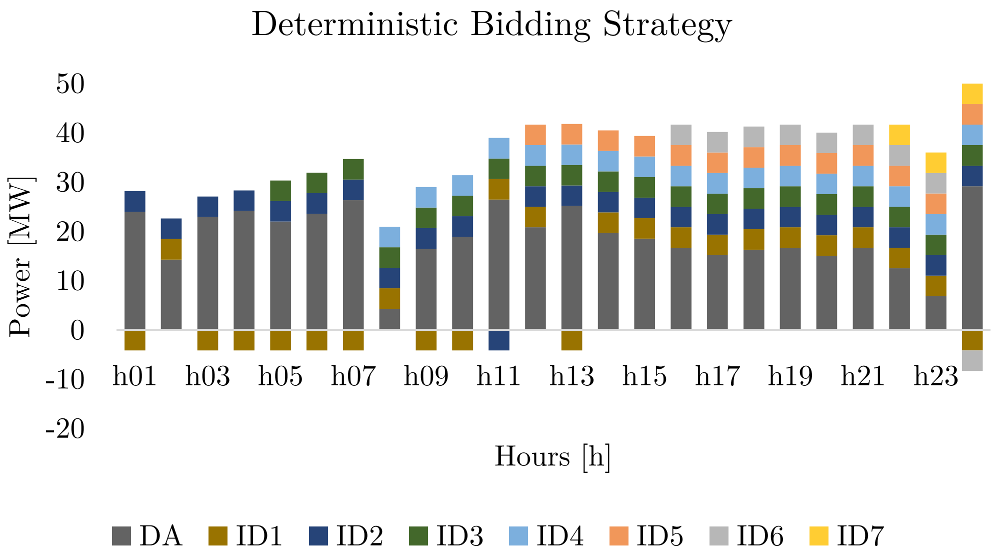

Fig 4.7. Deterministic bidding strategy for DA and IDs for the 2nd of February of 2015.

The deviations are represented in the next figure. In this case, the WPP benefits from a null price of downward deviations, since an increment on the power bided on other markets can be made with no penalization. Apart from that, since the price of the upward deviations in some specific hours are higher than in the DA or the IDs, the WPP sells energy in that hours in order to be more profitable. That is the case of hours 1, 2, 3, 4, 17, 18 and 20 of the day of operation, in which is achieved a null net deviation.

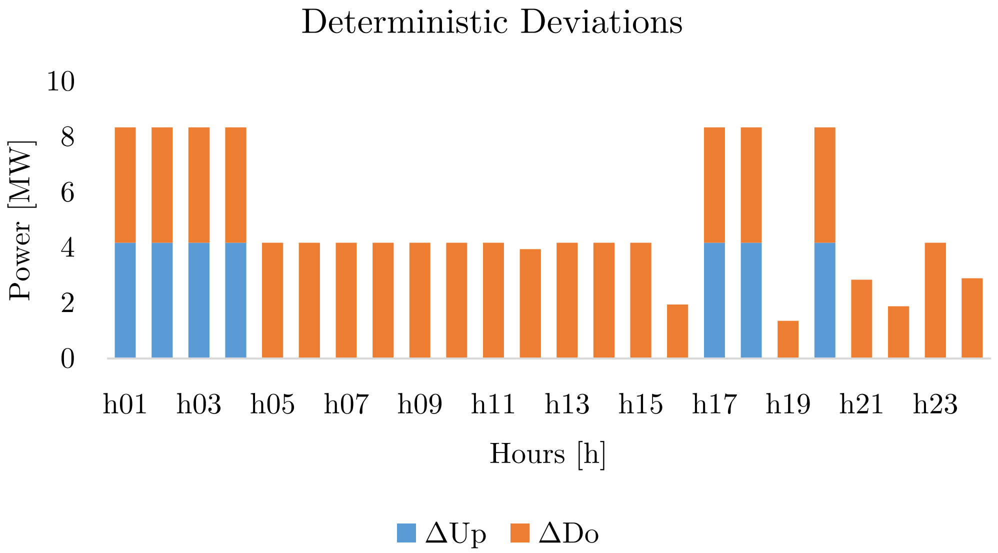

Fig 4.8. Deterministic bidding strategy for Δ^{Up} and Δ^{Do} for the 2nd of February of 2015.

The strategy followed with uncertainty on the information, stochastic parameters, is to bid in the markets where the prediction price is higher. However, the modelling of the stochastic model consists on a deterministic decision in the DA and stochastic decisions for the consecutive markets, consequently the bulk of energy is traded in the DA market. The ID markets will be used to restructure the strategy and to achieve a better strategy than bidding all the energy in DA. The scenario of price is this case is to have higher prices in the IDs than in the DA, high price scenario. Depending on the hour, the WPP buys energy in some IDs in order to sell it in other ones.

The risk taken in the operations is achieved by distributing it among the hours, more risk in the case of higher expected production and higher expected prices and less in the other hours. Finally, the WPP achieved the 50% of success in its bidding, taking into consideration that selling energy is not risk penalized.

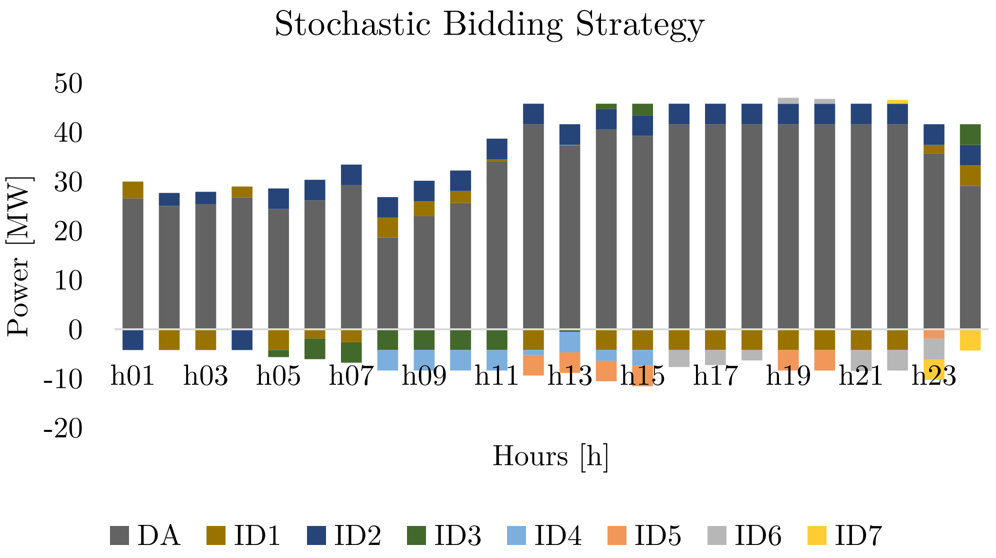

Fig 4.9. Stochastic bidding strategy for DA and IDs for the 2nd of February of 2015.

The deviations are represented in the next figure. In this case of study of the stochastic model, the WPP deviations are weighted among the scenarios of imbalances. As result, it is not as good as the deterministic strategy but it benefits from a null price of downward deviations, having more energy available to trade in DA and in IDs. Apart from that, since there is prediction of having a price different from null in some hours of the upward deviation market, the WPP trades part of its energy in those hours predicted. It has to be mention that the prediction is made erroneously and consequently in some hours the action made is not the correct one. However, due to deviations volatility and non-predictable price the strategy is consequently valid.

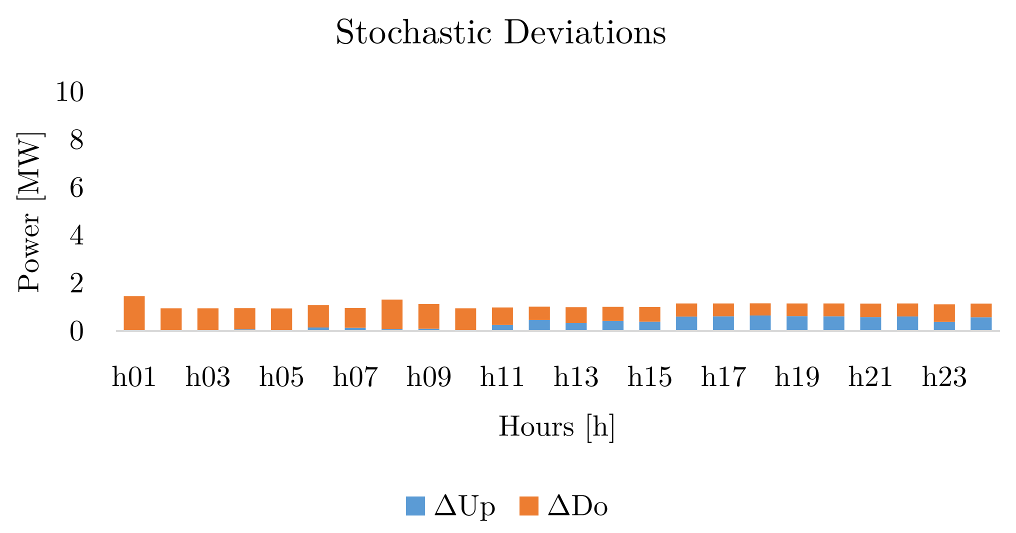

Fig 4.10. Stochastic bidding strategy for Δ^{Up} and Δ^{Do} for the 2nd of February of 2015.

The next table summarizes the profits achieved by the three different kinds of agents; all of them are price takers of the market since they cannot vary sufficiently the market equilibrium price in order to change other agent's strategies. As it is expected, the deterministic strategy makes more profits, due to having perfect information. In the case of the stochastic, it followed a better strategy than the real-life agents, although it has uncertainty in the information. The profit difference between the stochastic and the real-life agent is about the 3%, 1045.52 €.

Profits [€]		
Diary [2th of February of 2015]		%
Deterministic	42972.27	23.47
Stochastic	35850.47	3.00
Real Life Agent	34804.95	-

Table 4.3. Profits for the 2nd of February of 2015 depending on the strategy made.

4.3. PRICE DECISION MAKING ANALYSIS

For the price decision making analysis in the stochastic model; high, medium and low ID prices, the day chosen is the 16th of March of 2015. The WPP of the case of study is a typical wind farm of 50MW of installed capacity. The risk in the operations is the 50%, it will be distributed among the hours of the day. The WPP will follow a more risky strategy in the hours with higher prices.

The production expected for the day of operations is presented in the next figure.

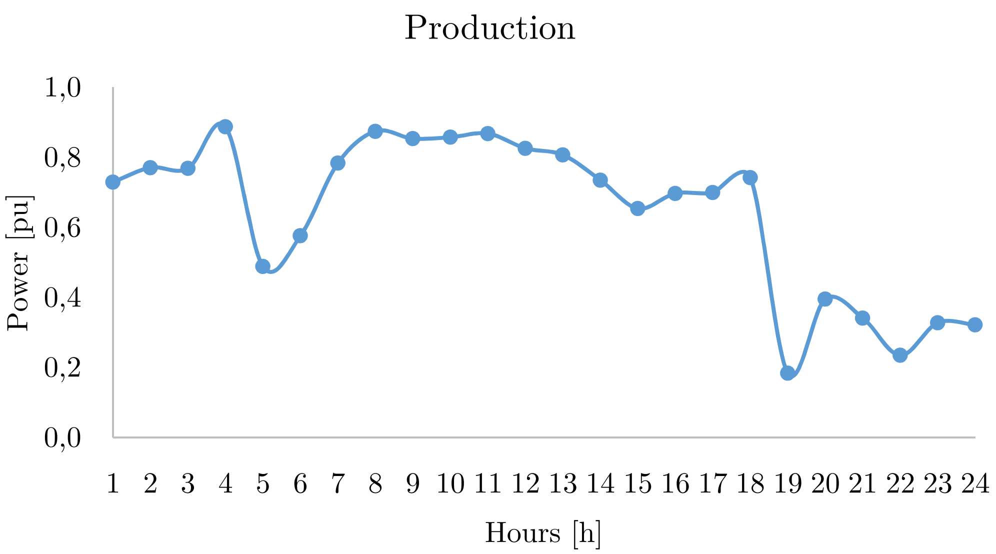

Fig 4.11. Production of the WPP the 16th of March of 2015.

As in the other analysis, the strategy followed by WPP is to bid in the markets with higher prices but taking into consideration that the first decision is a deterministic one, DA market. In addition, that the power available to bid in the IDs is constrained to the 10% of the installed capacity. As a result, the ID markets will be used to restructure the strategy and to achieve a more profitable strategy. The subsequent figures sum up the strategies followed by the WPP for the different scenarios of price.

The risk taken in the operations is achieved by distributing it among the hours, more risk in the case of higher expected production and higher expected prices and less in the other hours. Finally, the WPP achieved the 50% of success in its bidding, taking into consideration that selling energy is not risk penalized.

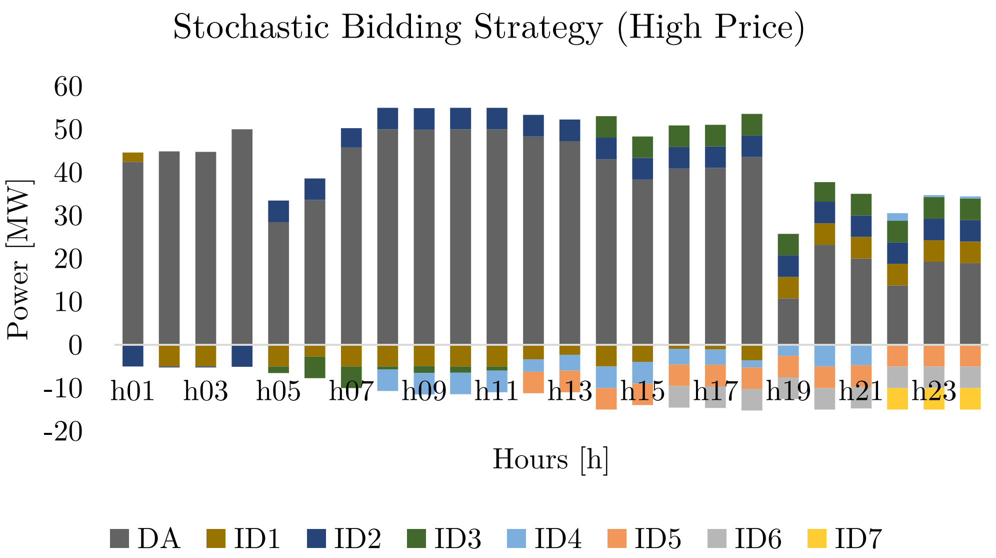

Fig 4.12. Stochastic bidding strategy for DA and IDs for the 16th of March of 2015 in a high price scenario.

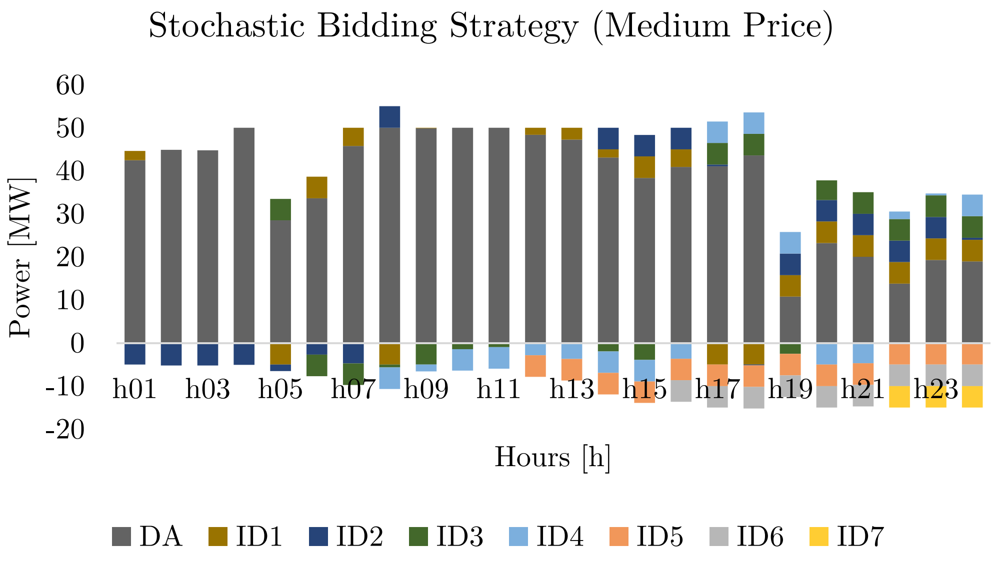

Fig 4.13. Stochastic bidding strategy for DA and IDs for the 16th of March of 2015 in a medium price scenario.

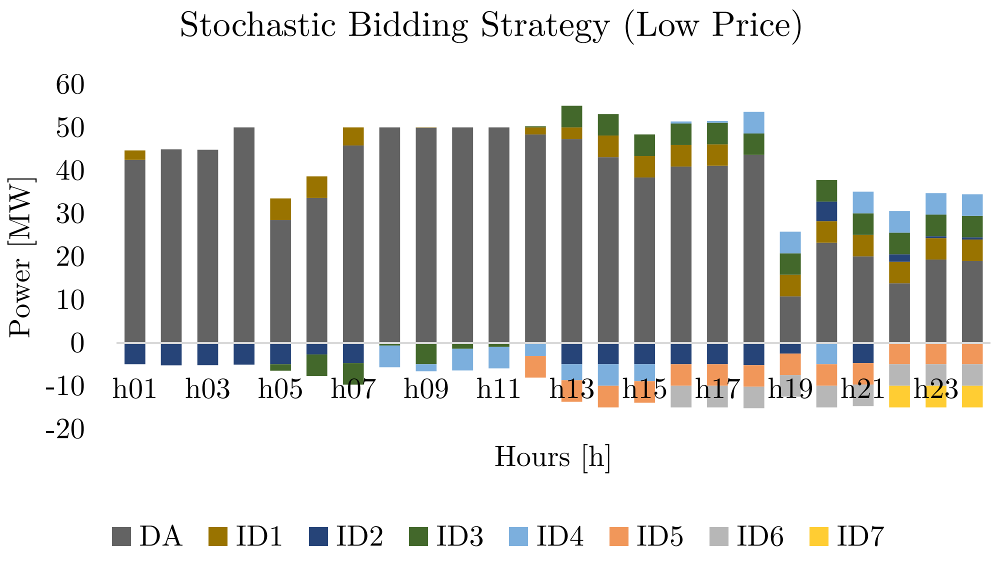

Fig 4.14. Stochastic bidding strategy for DA and IDs for the 16th of March of 2015 in a low price scenario.

The main difference between the strategies for the different price scenarios does not lie on the total volume of energy traded throughout the whole day or among each hour. It lies on the market in which the energy is sold or bought, such in hour 17. In hour 17 the DA power bid is the same due to being a previous decision not related with the IDs power bid.

Strategy h17 [MW]			
	High price	Medium Price	Low Price
DA	41.05	41.05	41.05
ID1	-1.05	-5.00	5.00
ID2	5.00	0.40	-5.00
ID3	5.00	5.00	5.00
ID4	-3.54	5.00	0.40
ID5	-5.00	-5.00	-5.00
ID6	-5.00	-5.00	-5.00
ID7	0.00	0.00	0.00

Table 4.4. Difference of power bid for hour 17.

Finally, the profits expected by the WPP for the different scenarios of prices are expressed in the next table. The fact that the day of operation was a day in which low prices scenario happened determines that the profit expected is higher than for the other scenarios, being the less profitable the high price in which strategy followed differ more from the reality.

Profits [€]		
Diary [16th of March of 2015]		%
High Price	43821.61	-
Medium Price	43828.75	0.02
Low Price	43850.47	0.07

Table 4.5. Profits for the 16th of March of 2015 depending on the price scenario decision making.

4.4. RISK ANALYSIS

For the risk analysis and profits boundary, the day chosen is the 18th of March of 2015. The WPP, Sotavento, has a power rating of 17.56 MW. The scope of this analysis is to determine if the risk suppose a boundary for the profits made by the WPP, the risk is distributed among all operations of the day. The day of operations is considered a high price day, in which the IDs are subjected to have higher prices than in DA.

The utility risk figure represents the efficient frontier between the risk and the profits of the WPP.

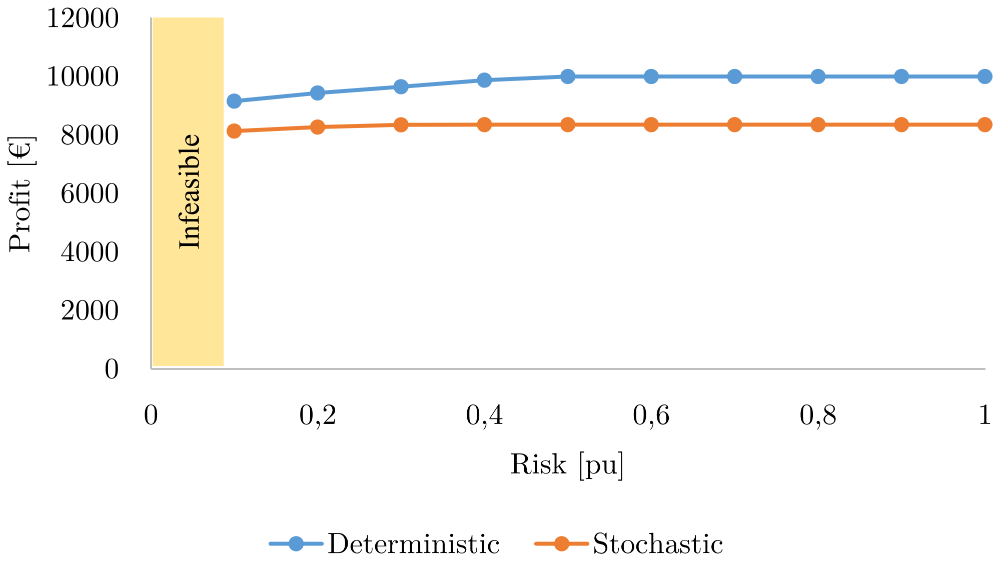

Fig 4.15. Utility risk curve of the WPP the 18th of March of 2015.

As a summary of the sensitivity analysis, the next table with the profits expected according to the risk assumed is presented.

		Profits [€]	
		Deterministic	Stochastic
Risk	*1*	9994.46	8342.41
	0.9	9994.46	8342.41
	0.8	9994.46	8342.41
	0.7	9994.46	8342.41
	0.6	9994.46	8342.41
	0.5	9994.46	8342.41
	0.4	9866.15	8342.41
	0.3	9643.46	8339.60
	0.2	9430.83	8261.66
	0.1	9151.16	8127.91
	0	Infeasible	Infeasible

Table 4.6. Profit dependency in the risk taken for the WPP the 18th of March of 2015.

Increasing the risk or level of operative conservation on the strategy followed by the WPP more than a certain value does not report monetary benefits. This is a consequence of the feasibility region of the problem, in which the risk constraint is binding, same solution is achieved even in the absence of the constraint, and are the other constraints of the mathematical formulation responsible of limiting the problem.

As a result, limiting the risk in perfect information model to a value higher than the 50% will mean that the best possible bidding strategy, still feasible, is the same as having a 50%. In the case of a risk lower than the 50%, the feasibility region of the problem is reduced by the risk constraint and the expected profits are lower.

The utility of having more risk on the strategy in the case of the probabilistic model is limited to the 40% of risk in the operations.

It is the stretch out or shrink of the bidding bandwidth what makes the WPP to achieve sooner the maximum utility with a higher or lower risk, in other words the parameter upper and lower bound is what limit this maximum.

However, different profits are expected between the two models, due to having perfect information in the deterministic and uncertainty on the parameter on the stochastic.

4.5. DEVIATION INFLUENCE ANALYSIS

For the deviations influence analysis, the day chosen is the 7th of April of 2015. The WPP, Sotavento, has a power rating of 17.56 MW and the risk taken for all the analysis is the 50% that can be distributed among all the strategies during the whole day.

The production of WPP on the day of operation is summarizes in the next figure.

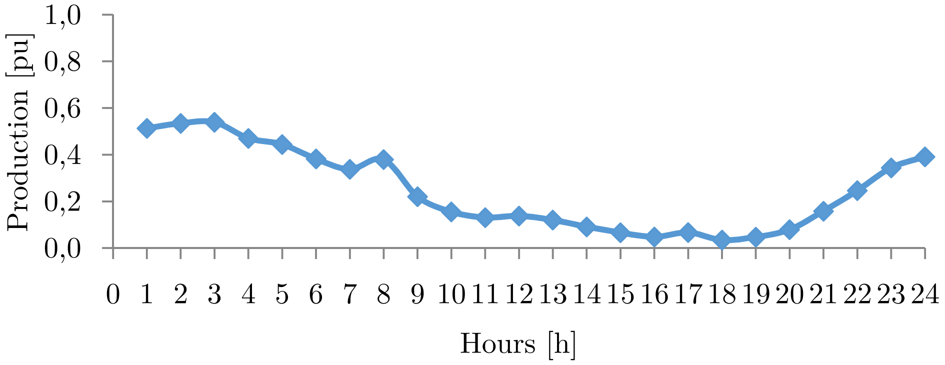

Fig 4.16. Production of the WPP the 7th of April of 2015.

The operation day is considered a low price scenario, in which generally speaking lower prices for the IDs than in DA market will be attained.

Profits [€]		
Diary [7th of April of 2015]		%
High Price	5602.81	-
Medium Price	5625.26	0.40
Low Price	5652.79	0.89

Table 4.7. Daily profits without taking into account deviations.

As happens in previous analysis, the strategy followed by the WPP in the probabilistic model is to bid more energy in DA and less in IDs, since they are constrained to the 10% of the rated power. Apart from that, since not all the IDs has prices bigger than the DA or the other IDs, the WPP buys energy in that markets in order to make profits in the next auction, taking advantage of the arbitrage due to having different closure times.

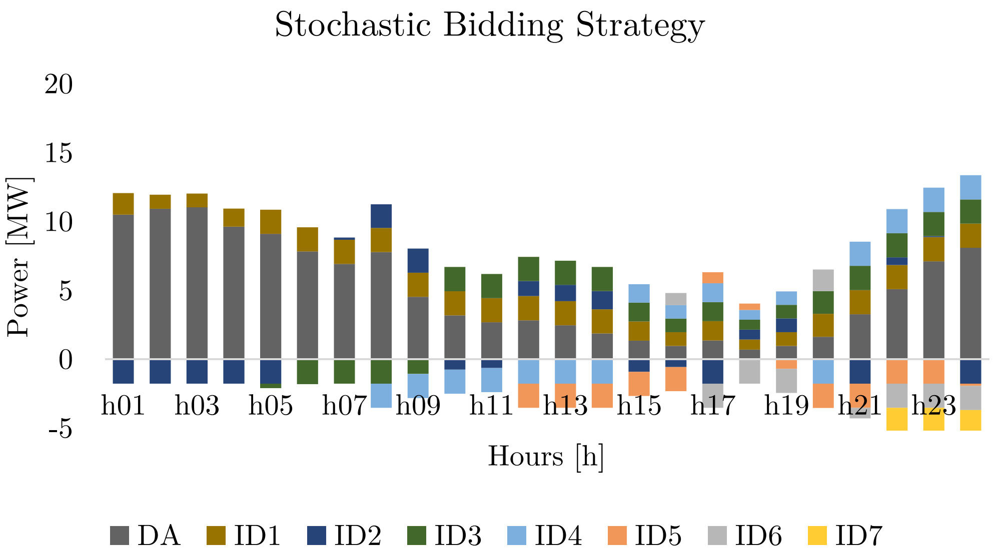

Fig 4.17. Stochastic bidding strategy for DA and IDs for the 7th of April of 2015.

For the operation day, downward deviations are remunerated in some hours of the day. However, upward deviations are not remunerated nor penalized. In this case of study, the WPP benefits from a positive price of downward deviations, not only due to the remuneration but also since an increment on the power bided on other markets can be made with no penalization. Consequently, more energy is available to bid in DA and IDs. Apart from that, since having a null price on the upward deviations for all the hours, the WPP best strategy is not to have upward deviations, since they limit the capacity to bid in other markets.

The best strategy attained by the WPP for the deviation is represented in the next figure, where there are only downward deviations.

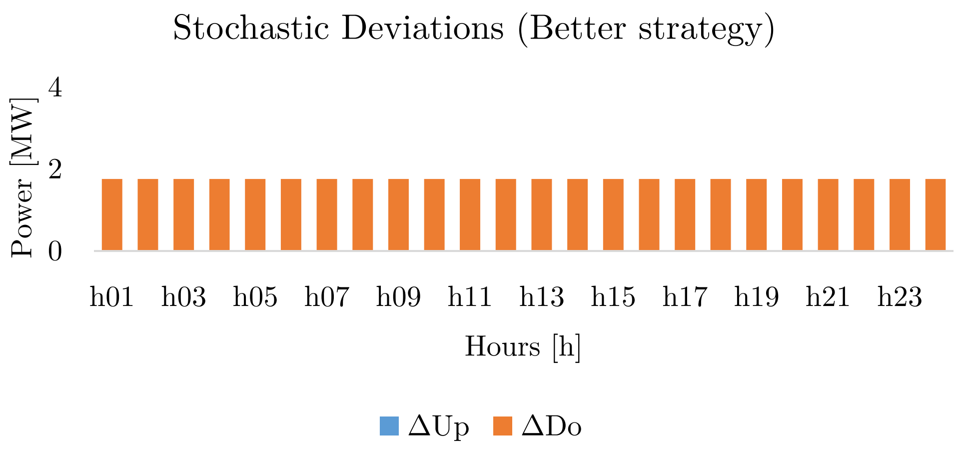

Fig 4.18. Stochastic bidding strategy for $\varDelta^{Up}$ and $\varDelta^{Do}$ for the 7th of April of 2015.

The worst strategy followed by the WPP in deviation markets is represented in the next figure, where the downward deviations are lower than the maximum capacity constrained by the model. Consequently, less profit will be achieved by this strategy.

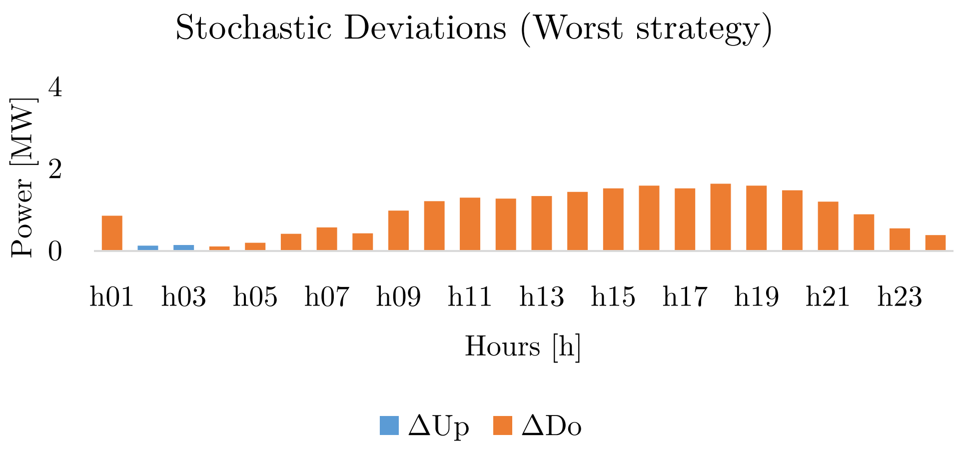

Fig 4.19. Stochastic bidding strategy for $\varDelta^{Up}$ and $\varDelta^{Do}$ for the 7th of April of 2015.

The profits expected for both strategies are presented in the next table, having higher economic efficiency in the first strategy explained.

Profits [€]		
Diary [7th of April of 2015]		%
Minimum Profit	5959.16	-
Maximum Profit	6194.03	3.94

Table 4.8. Profits for deviations for the 7th of April of 2015 depending on the strategy made

Finally, depending on the strategy followed by the WPP, the profits for the operation day varies between a certain limits. The box-and-whiskers plot represents the different profits according to the strategies fulfilled by the WPP.

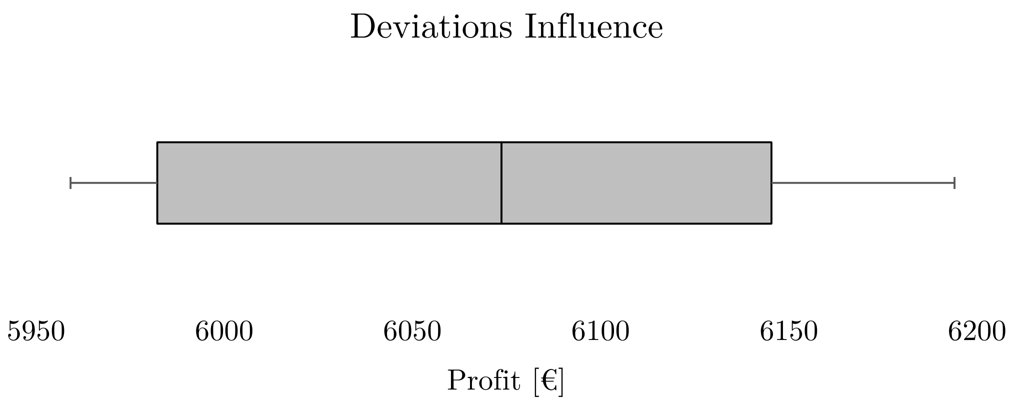

Fig 4.20. Box-and-whiskers plot of the profits depending on the deviation strategy for the 7th of April of 2015.

4.6. CONCLUSIONS

Real-life strategies followed by real agents mean bidding all the production in the DA market, a conservative action made in order to not deal with the uncertainty of the subsequent markets. However, the maximum profitability of bidding is not achieved.

Perfect information model and probabilistic model attain better economic efficiency than real-life agents, since both formulations benefit from the possibility to trade in ID and imbalance markets.

Perfect information model or deterministic model bids in the markets where the price is higher, making more profits by benefiting from the arbitrage between auctions. Purchasing energy, a cost for the WPP, will be attained when the price is lower than in other auction.

The strategy followed with uncertainty on the information, stochastic model, is to bid in the markets where the expected price is higher. However, the modelling of the stochastic model consist on a deterministic decision in the DA and stochastics decision for the consecutive markets, consequently the bulk of energy is traded in the DA market. The ID markets will be used to restructure the strategy and to achieve a better strategy than bidding all the energy in DA.

Deviations represent an opportunity to the WPP to restructure the bids in the IDs and DA and to attain higher profits. Downward deviations are used by the WPP to increment the capacity to bid in other markets, an action made when downward deviation price is null or positive in which the WPP also attain higher economic efficiency. Usually, having upward deviations is only achieved when remuneration on the imbalance market are higher than in DA and IDs, since it constraints the power bided in those markets.

The risk taken in the operations is distributed among the hours of the day of operation, achieving more risk in the case of higher expected production and higher expected prices and less in the other hours. Apart from that, increasing the risk to a certain value does not report monetary benefits, since the feasibility region of the problem is not constrained in those cases by the risk taken on the operations. Consequently, the utility function for the risk achieved a maximum when the optimal solutions does not change with the risk, depending on the stretch out or shrink of the bidding bandwidth the maximum is achieved with a different value of the level of operative conservation.

Chapter 5. CONCLUSIONS AND FURTHER DEVELOPMENT

This last chapter sums up the results obtained among the whole project. Firstly, a section about the conclusions obtained summarizes the mains aspects developed in the case of study. Finally, some paths for further development are introduced, in order to continue with the work done.

5.1. CONCLUSIONS

Electricity is an asset with immediate delivery and traded in spot markets. Electricity markets can be thought as a game in which the player bids a quantity of energy in order to achieve the maximum economic efficiency, in other words to maximize their utility function. Short-term markets in Spain comprises DA, IDs and the balancing mechanism. The balancing mechanism consists on secondary reserve, tertiary reserve, deviation management, and additional upward reserve markets and the congestion management consist technical and security of supply constraints management. The aim of the game is to supply the consumers with the required demand; a real time balancing of supply and demand is required.

According to Cournot conjecture, the market equilibrium is attained when the agents or players of the game maximize their profits; it is the intersection of the aggregated supply and demand curve. Since not all the agents has the same market share and power to change the market equilibrium price, two different approaches could be done:

- Price taker, an agent that cannot affect market prices and adopt the equilibrium price. Even though, a price taker adopt the clearing price, it shifts the aggregate supply curve.

- Price maker, an agent with market power to vary the equilibrium price with its bid. A new market-clearing price will be attained.

The bidding curve seen by a sole agent is denominated residual demand; a negative descendant linear curve, except for price takers that correspond to constant equal to the clearing price.

The strategy followed by generators is to bid at its marginal cost, even though they are price makers or takers. In the case of a real-life WPP agent, the most popular strategy is to bid the production in DA market, a conservative and less profitable strategy that not take advantage of the IDs and imbalance markets in order to restructure the bid in the DA.

The aim of the WPP is to maximize its profits achieving the best bidding strategy. In order to reproduce the strategic possibilities of a WPP in a short-term horizon of an operation day, two models are mathematically formulated. The deterministic model or perfect information model correspond to the mathematical formulation in which the parameters are known in advance. The stochastic model or probabilistic model corresponds to the formulation in which the parameters are modelled with uncertainty. In the case of the stochastic modelling different scenarios are considered in order to make a realistic representation of the strategy followed by a WPP, based on historic data.

Both models gives the opportunity to the WPP to achieve the most profitable strategies in the DA, IDs and deviation market, taking into account the constraints of the mathematical formulation.

The WPP is not able to bid more power than the rated capacity. Purchasing energy is penalized in the objective functions, due to being a cost for the WPP. However, arbitrage between auctions could be done, in order to benefit from the difference in prices and closure times. IDs and imbalance markets are volatile and liquid markets, in which the volume of energy traded is considerably lower than in DA. Consequently, ID and imbalance bids are constrained to the 10% of the installed capacity, in order not to change the clearing price sufficiently to change the strategy followed by competitors.

The models includes constraints to measure the risk taken in the strategy followed by the WPP, by distributing the power bid with a triangular cumulative distribution. Bidding more energy than the boundaries established by the expected prediction is considered a risk for the WPP, since it cannot guarantee that this energy is going to be delivered due to having a lack of production. Buying energy is a risk free action.

Non-anticipativity constraints in the stochastic formulations are introduced to drive the WPP to follow the time horizon of the Spanish electricity market, in order to attain an order for the different auction closure times.

The main difference between the perfect information model, the stochastic model and real-life agents, agents that bid the production in DA market, is the profitability they get in the operations. Both model formulations attains a better economic efficiency than real-life agents, since they benefit from the possibility to restructure the power bid in DA with the ID and imbalance markets.

Perfect information model or deterministic model trades energy in the markets where the price is higher, making more profits by benefiting from the arbitrage between auctions. However, the strategy followed with uncertainty on the information, stochastic model, is to bid in the markets where the expected price is higher. Having a deterministic decision in the DA and stochastic decisions for the IDs in the stochastic modelling means that the vast majority of the energy is traded in DA, a conservative action less profitable than the one taken by the perfect information model. The ID markets are used to restructure the strategy and to achieve a better strategy than bidding all the energy in DA, as happens in the perfect information modelling.

Deviations, power traded in the imbalance markets, are the difference between what is dispatched and what is bided hourly and represent an opportunity to the WPP to report more monetary benefits. Downward deviations are used by the WPP to increment the capacity to bid in other markets, whereas having upward deviations is only achieved when remuneration on the imbalance market are higher than in DA and IDs.

The risk taken in the operations is distributed among the hours of the day of operation, achieving more risk in the case of higher expected production and higher expected prices and less in the other hours. Apart from that, the feasibility region of the problem represents a limit for the profits, even though the risk taken on the operations is higher. Consequently, the utility function for the risk achieved a maximum when the optimal solutions does not change with the risk, depending on the stretch out or shrink of the bidding bandwidth the maximum is achieved with a different value of the level of operative conservation.

5.2.Further development

During the consecution of this project, there has been identified several paths for a future development. The most relevant are listed below.

- Studying different markets, such as secondary reserve and tertiary reserve, will give the WPP another opportunity to trade with electricity and to attain a better economic efficiency. Furthermore, secondary and tertiary reserve markets lead the WPP to restructure its bid and to correct the wind prediction error. In terms of benefits, the WPP will acquire more profitability with perfect information model than with stochastic, since the energy traded must be bounded due to being volatile markets. As happens in the modelling done, the WPP will bid the vast majority of the energy in DA.

- The stochastic model is sensitive to the expected price of the energy. Consequently, a better prediction tool for clearing prices will be required to attain a better knowledge of the input parameters. The prediction tool done, based on historic data, leaves a gap of error that could be fill by using a prediction tool based on aggregated supply and demand curves intersection.

- The models formulated constrains the WPP rated power by an upper bound of the 5% of the valley demand, in order not to change competitors' strategy due to being a not negligible variation for the demand. Real-life agents trade energy of several wind farms; as a result, the possible energy to bid outnumbers the upper bound explained. Modelling price takers with a considerable market power can be approached with a better formulation of the residual demand curve and consequently with a better approach to achieve the new market equilibrium.

- Storage of energy suppose a profitable advance for the modelling of bidding strategy of a wind power producer. A unit commitment for pumping is the path to be followed in order to mathematically model the storage. Thus, the purchased energy for strategic reasons, in order to benefit from the arbitrage between auctions, could be done by a delivery from the hydro plant. Storage also gives the opportunity to the WPP to sell the energy in the electricity markets or to use it to pump water upstream.

Chapter 6. Appendix

The appendix includes an economic valuation of including an energy storage system in the WPP.

6.1. Economic valuation of including an Energy Storage System to the WPP

Being wind, an intermittent source of generation means that the WPP face contingents due to changes in wind speed, which are traduced in a loss of revenues that can happen in hours in which there are high market prices. Apart from that, intermittent supply can lead to energy curtailments, which are traduced in a reduction on the annual production. A curtailment happens when the operator does not dispatch the WPP, even though there is availability of wind.

Having energy storage implies security to the WPP, to be more confident about its bids and to meet future dispatch requirements.

The aim of the energy storage is to charge when there are valley prices and to discharge when there are peak prices, in order to take more advantage of the peak pricing opportunities. By smoothing the output curve, the WPP improves the quality of supply.

The selected battery for the economic valuation is Durathon, a General Electric solution for energy storage.

GE energy storage systems comprises:

- The DC battery, where energy is stored using a nickel technology.
- Converter form AC to DC
- Control system, manages the operation of the battery

GE's Durathon battery is a versatile, durable and effective solution to the WPP storage of energy. Moreover, the solution proposed by GE gives the opportunity to the WPP to create a scalable system with several batteries dispositions, designed to provide continuity of supply over extended periods.

In order to dimension the battery, it has been chosen a typical day of operation with a typical profile for production. The operational day is the 20th of March of 2015. The WPP, Sotavento, has a power rating of 17.56 MW and the risk taken for all the analysis is the 50% that can be distributed among all the strategies during the whole day.

The production profile is presented in the next figure.

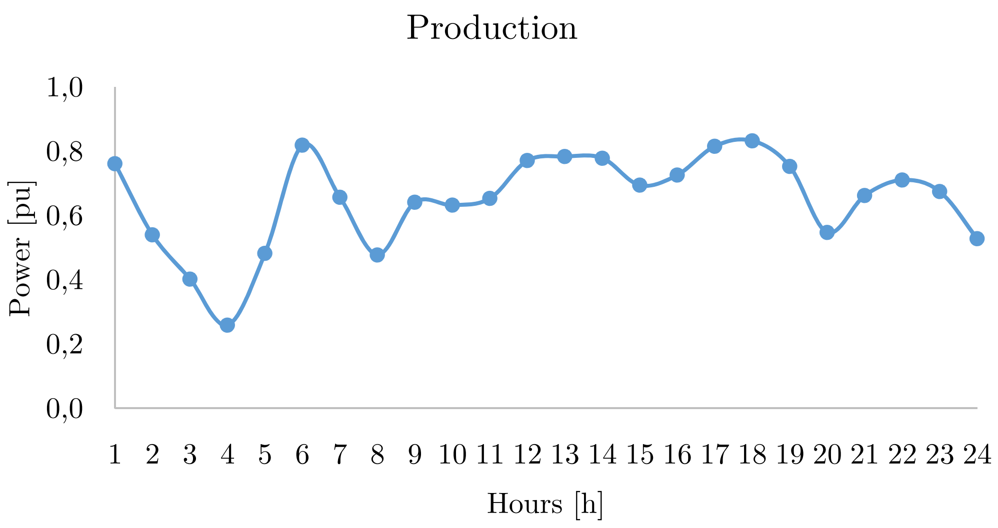

Fig 6.1. Production profile of the WPP the 20th of March of 2015.

The price distribution among the different auction on the 20th of March of 2015 is represented subsequently.

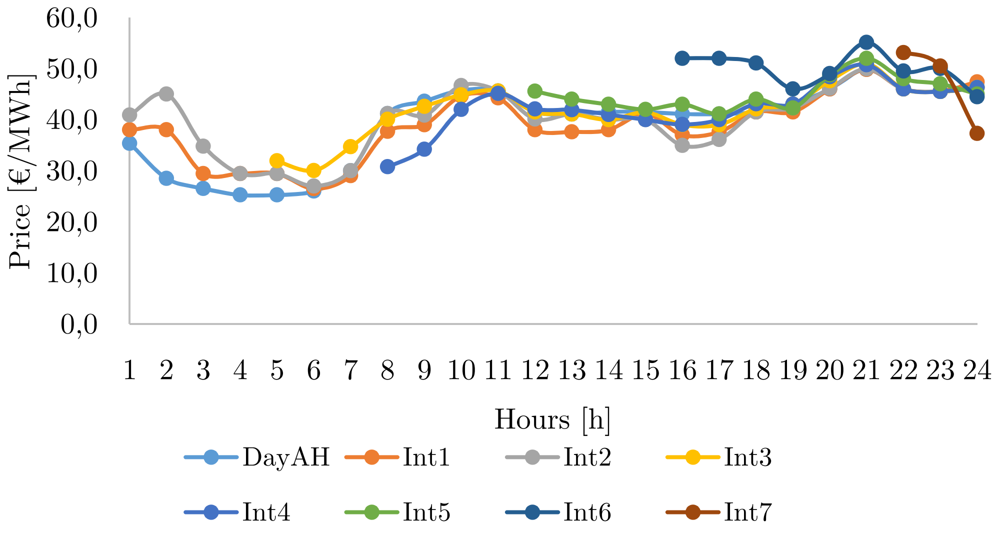

Fig 6.2. Price distribution among the different auctions on the 20th of March of 2015.

The strategy followed by the WPP, using the probabilistic model, is presented in the next figure. The WPP bids in the markets where the expected price is higher and buys energy in those that have a lower expected market price, making profits by taking advantage of the difference between the closure auction times. The WPP trades the bulk of energy in the DA market and use the IDs to restructure the bids and to achieve a more profitable strategy.

The scenario of price in the case of study is to have higher prices in the IDs than in the DA, high price scenario. Depending on the hour, the WPP buys energy in some IDs in order to sell it in other ones.

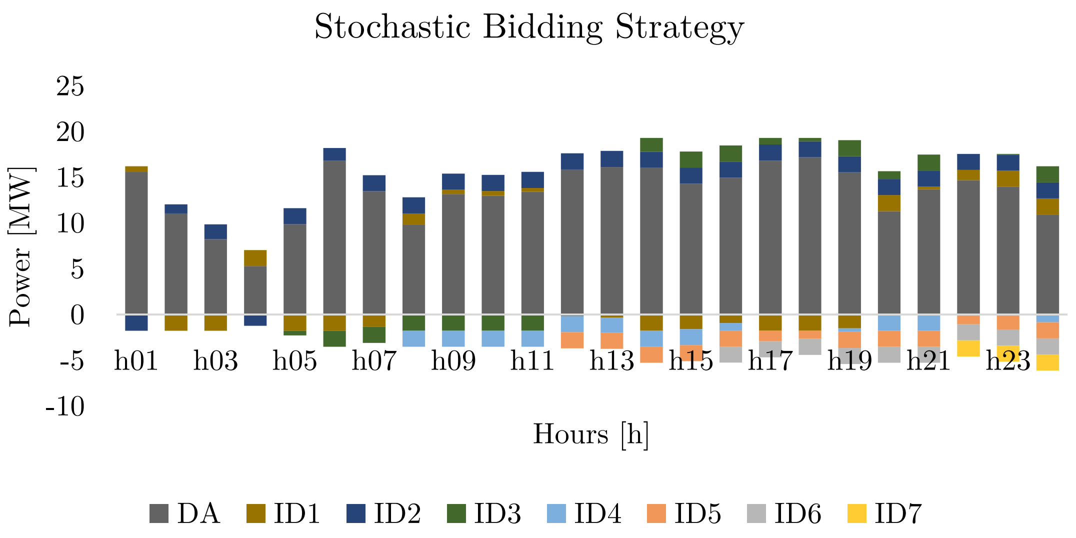

Fig 6.3. Stochastic bidding strategy for DA and IDs for the 20th of March of 2015.

In order to compliment the mathematical formulation of the modelling, energy storage has been included into the model. The aim of the energy storage is to maximize the economic efficiency acquired with a battery.

Indexes Nomenclature		
Name	Definition	
n	Hour of the day	h01, …, h24
mar	Bidding markets	DA, ID1, …, ID7
$markethours_{n,mar}$	Hour of the day in which is possible to bid, depends on the market in consideration	

Parameter Nomenclature		
Name	Definition	Units
$\lambda_{n,mar}^{DA,IDs}$	Price of the energy in hour *n* and market *mar*, in other words is the DA and ID market price	[€/MWh]
$P^{Battery}$	Rated power of the storage system	[MW]
η	Performance of the battery	[pu]

The performance or yield of the battery, η, is the ratio between the electrical energy received in the charging and energy delivered by the accumulator during discharge.

$$\eta = \eta^{Charge} \cdot \eta^{Discharge} = 0.81 \tag{Eq 6.1.}$$

The variables of the energy storage problem are decisions of when to charge or discharge the battery along the operation day.

Variables Nomenclature		
Name	Definition	Units
$X^{Charge}_{n,mar}$	Binary variable for charging the battery (Decision)	[0/1]
$X^{Discharge}_{n,mar}$	Binary variable for discharging the battery (Decision)	[0/1]
ξ	Value of the Objective Function (Revenues)	[€]

The aim of objective function of the optimization problem of the energy storage is to maximize the profits obtained with the battery. Charging the battery is penalize with the cost of the energy bought in the market auction.

$$\xi = \max \sum_{markethours_{n,mar}} \lambda^{DA,IDs}_{n,mar} \cdot P^{Battery} (X^{Discharge}_{n,mar} - X^{Charge}_{n,mar}) 1hour \tag{Eq 6.2.}$$

The constraints represents the set of relationships that variables are obliged to satisfy, can be expressed as equations and inequalities.

Energy storage system cannot charge nor discharge the battery in the same hour in different electricity markets.

$$\sum_{mar} X^{Charge}_{n,mar} \leq 1 \qquad \forall n \tag{Eq 6.3.}$$

$$\sum_{mar} X^{Discharge}_{n,mar} \leq 1 \qquad \forall n \tag{Eq 6.4.}$$

Charging or discharging in the same hour is not possible for the energy storage.

$$\sum_{mar} X^{Charge}_{n,mar} + X^{Discharge}_{n,mar} \leq 1 \qquad \forall n \tag{Eq 6.5.}$$

The performance of the charging and discharging cycle is constrained by the yield parameter. There is not perfect efficiency on the cycle.

$$\sum_{markethours_{n,mar}} X_{n,mar}^{Discharge} \leq \sum_{markethours_{n,mar}} X_{n,mar}^{Charge} \cdot \eta$$

Eq 6.6.

Sotavento WPP offers the possibility to install a battery of 1MW, since the power transformer of the substation of the WPP has a rated power of 20/24 MVA (ONAN/ONAF) [21]. Apart from that, installing a bigger energy storage system is not recommended due to the liquidity of the ID markets, since charging or discharging in ID is not constrained.

The bidding strategy of the storage system is to attain the maximum economic efficiency by buying energy with a market price lower than the market where energy is sold.

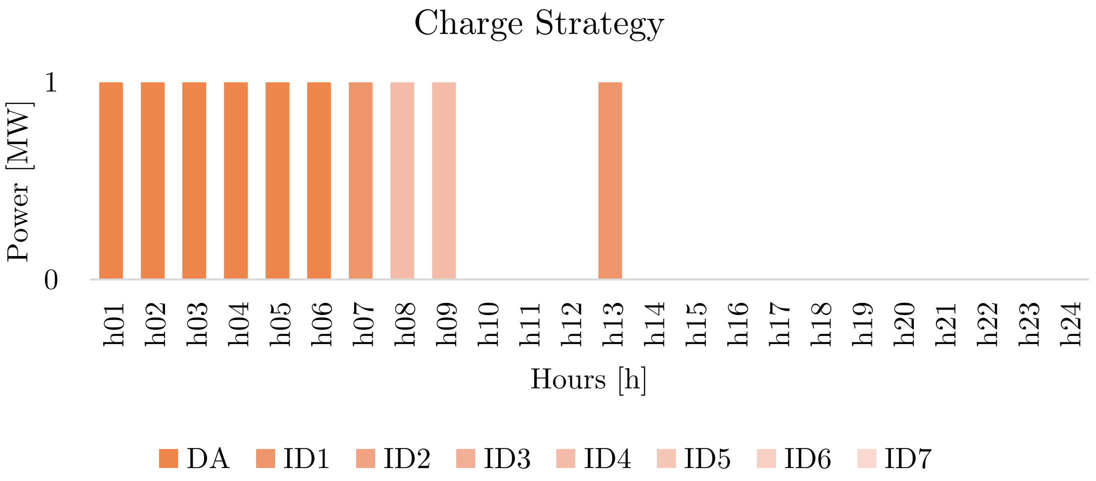

Fig 6.4. Charging strategy for the energy storage system on the 20th of March of 2015.

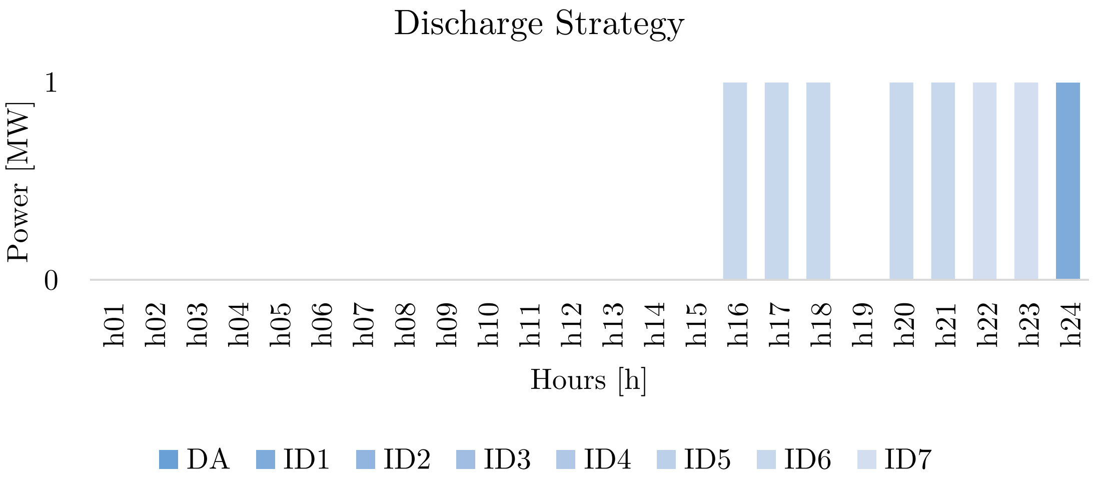

Fig 6.5. Discharging strategy for the energy storage system on the 20th of March of 2015.

Taking into account the results of charging and discharging obtained by the model, the energy storage system consist on two batteries of 1 MW, whose energy is 6 MWh and 4MWh. The models elected for the storage system are [22]:

- 1x DC6 MWh
- 1x DC4 MWh

The profits obtained by the WPP including the energy storage system are sum up in the next table.

Profits [€]		
Diary [20th of March of 2015]		%
Bidding Strategy	11370.38	99.03
Battery	111.78	0.97
Total	**11482.16**	**100.00**

Table 6.1. Economic efficiency of the energy storage system for the WPP the 20th of March of 2015

The profitability of the energy storage system made the WPP to recover the investment in 40.44 years. Consequently, the installation of a storage system does not provide a cost effective solution, even though the load is shifted in order to achieve a greater profitability.

Business Plan[€]		
Costs		Units
Investment	1500000.00	€
Maintenance (10%)	150000.00	€
Profits		Units
Operation Profits	111.78	€/day
Years to recover investment	**40.44**	**years**

Table 6.2. Business plan for the energy storage system.

The price of the storage system needed to recover the investment in 20 years, the lifetime of a wind farm, is 741.84 €/kW.

Business Plan[€]		
Costs		Units
Investment	**741.81**	**€/kW**
Profits		Units
Operation Profits	111.78	€/day
Years to recover investment	20.00	years

Table 6.3. Cost effective investment

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