ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MASTER IN THE ELECTRIC POWER INDUSTRY

ECONOMIC ANALYSIS OF THE WIND POWER INTEGRATION IN AN A-FRR CONTROL AREA

Author: Carlos Gomes Álvarez
Supervisor: Carlos Pascual López

Madrid
July 2017

Master's Thesis Presentation Authorization

THE STUDENT:

CARLOS GOMES ÁLVAREZ

……………………………………………

THE SUPERVISOR

CARLOS PASCUAL LÓPEZ

Signed: …………………… Date: 04/ 07/ 2017

Authorization of the Master's Thesis Coordinator

Dr. Luis Olmos Camacho

Signed: …………………… Date: 04/ 07/ 2017

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MASTER IN THE ELECTRIC POWER INDUSTRY

ECONOMIC ANALYSIS OF THE WIND POWER INTEGRATION IN AN A-FRR CONTROL AREA

Author: Carlos Gomes Álvarez
Supervisor: Carlos Pascual López

Madrid
July 2017

ABSTRACT

This Master's Thesis is devoted to carry out an analysis of the economic consequences from the wind power integration within an specific aFRR control area ("Zona de Regulación"). This integration should be understood as a facilitator for the internal balancing of the wind power deviations. By means of this measurement, the AGC (Automatic Generation Control) will receive an additional setpoint from the wind power imbalances and it will adjust the output of the other technologies included in the aFRR control area in order to net its overall imbalance, without affecting the secondary reserves provisions.

The main assets considered in this work as the flexible units able to compensate the wind power imbalances have been the hydro units. Due to this fact, one of the main issues that is addressed along the thesis lies in the water resources valuation.

Basically, the analysis focuses on carrying out a comparison between the scenario where the wind power integration is implemented and the opposite one, in which wind power units settle their own imbalances in an individual way. Depending on different conditions, there will be hours in which the first scenario would be the optimal one and others in which it happens the contrary situation. Therefore, a decision making problem is also part of the scope of this work.

According to this, the economic analysis is developed through the implementation of an ex-post optimization model, which is embedded within an Excel tool. This tool incorporates all the required data queries to collect the needed information for the economic assessment such as market prices, imbalances prices, power units' schedules and final outputs, etc.

The main conclusions from the analysis are aimed to lay a set of strategic criteria in order to improve the decision making of the incumbent company's generation control center, which is the responsible for the real time imbalances internal regulation.

Table of contents

1. Introduction

1.1 Background and motivation

The problem to tackle in this Master's Thesis stems from the following situation: a generation company which operates in the Spanish electricity market has taken the decision of introducing its wind power units within the same Balance Responsible Party (BRP) in which the other company's units are included.

The main objective behind this decision lies in the ability of carrying out an internal balancing of the wind power deviations. For this purpose, other flexible units must be used to adjust their output tracking the real time wind power imbalances in such a way the BRP overall imbalance is netted. As a facilitator for this tracking procedure , the wind power portfolio has been introduced within the company's aFRR control area. In this way, the Automatic Generation Control (AGC) which controls the control area output is able, by the introduction of a new setpoint, to increase or decrease other technologies' output in order to compensate the possible wind power imbalances.

This decision has been taken based on some internal estimations performed within the incumbent company, since there not too many background studies about this particular issue regarding the Spanish framework and the profitability from this. Therefore, this Master's Thesis arises from the need of assessing the real net savings that are earned thanks to this new measurement.

It should be noted that up to the moment of this decision implementation, wind power used to face individually their own imbalances, within the imbalance settlement scheme applied in Spain (commonly known as "dual pricing frame"). According to this scheme, all the units that have a deviation from the hourly schedule is paid or charged the resulting imbalance price, which is different depending on the relative direction of the units' imbalance with respect to the system needs. As a consequence of this, there will be hours in which no overrun takes place for the particular agent and others in which that overrun does occur. The latter is the case intended to be removed by the new decision.

Focusing on what is expected from this work, the main task to address is to develop an assessment of the economic impact that the integration decision has had. To do so, it is especially relevant to take into account the expenses and recoveries of hydro resources, which are the main flexible assets to be used regarding the wind power imbalances compensation.

Therefore, as it is explained along the following sections, the tasks to be performed will consist in collecting all the data corresponding to the period in which the new methodology has begun to be applied and to do a calculation to quantify hourly the savings and expenses in comparison with the no wind power integration scenario.

This economic analysis was decided to be developed through an ex-post optimization model, which at the same time is integrated within an Excel tool. This tool allows to select a specific date range in which the needed data queries are executed and a set of calculations are displayed in a defined spreadsheet as a result of the optimization model execution.

The main issue behind the model is how the hydraulic resources are valuated, which brings up the concept of water value and its implications. In this particular work it must be understood linked to the analysis of the operation of hydro plants in a competitive generation power market, as it is addressed in some of the reviewed papers.

As it has been mentioned before, the decision of compensate the wind power imbalances is not always the optimal one. Therefore, some of the conclusions from this work are aimed to lay a set of strategic criteria in order to improve the decision making of the company's Generation Control Center .

1.2 Main objectives

- Development of an hourly tracking Excel application of the wind power imbalances regulated by means of the available assets included in the aFRR control area and giving as a result the net savings obtained with regards to the previous scenario of non-integration of wind power units, encompassing the following particular points:
  - Calculation of imbalances and settled costs for the different wind power programming units considering the case of non-integration of wind power units in the aFRR control area.
  - Calculation of imbalances and settled costs for the different wind power programming units considering the current implemented case of integration and valuation of the water resources that have been spent or recovered to that purpose within the new framework.
  - Comparison of old and new scenario case providing as results the net savings that are achieved due to the wind power integration in the company's FRR control area.
- Economic assessment of the decision performance carried out by the corresponding generation control center up to now, identifying prospective gaps to improve.
- Collection of the main conclusions about how to improve the joint exploitation of the wind power and hydro units, specifying particular strategies to consider according to the different characterized scenarios that have are identified.
- Setting the baselines to develop an real time optimization model with uncertainty inclusion.

1.3 Structure of the report

After this first approach carried in this Introduction section, below it is briefly described the structure followed in the document:

- State of the art. Here a revision of the different research works that have been consulted is included. It is mainly devoted to address two main issues : wind power imbalances management in a joint way with other flexible technologies such as hydro and the different approaches that can be used for the valuation of hydraulic resources.
- Description of the problem. At first, it is described an overview of the problem to be addressed, identifying the key difficulties to overcome. In order to lay the foundations to understand the problem, some different subsections are included to describe aspects such as the Spanish sequence of markets in which this work is framed, the Automatic Generation Control and aFRR control area typical characteristics along with the specific assumptions considered for the incumbent company and lastly, the basic explanation of the two mains aspects within the economic analysis: imbalance settlement and the hydraulic resources management.

- Proposed method. Here the main parts of the Excel tool are presented in detail. Besides that, the ex-post optimization model is described paying special attention to the procedure used for the hydraulic resources valuation.

- Results. Here the final results from the economic assessment model are presented. For the explanation, it is carried out a breakdown of different cases according to the imbalances characteristics (sign, relative direction with respect to the system needs, optimal decision).

- Conclusion. Finally, some conclusions drawn from the previous sections are collected and discussed here, as well as different further steps to take in order to improve the developed model.

2. State of the art

It should be noted that there is not too much previous literature regarding the specific target of the thesis, although some related papers have been examined and some main points from them are collected in the following paragraphs. It has been broken down into two broad fields:

- ✓ Strategy of wind power introduction in the aFRR control area
- ✓ Valuation of water within the hydro resources management

2.1 Strategy of wind power introduction in an aFRR control area.

The increase of wind power has been huge during recent years, both in Europe and the USA. As a result, the integration of wind power generation in electric power systems should be considered as a key issue and requires new frameworks in operation, control and management.

This integration is mainly linked to the corresponding uncertainties in system operation. For the sake of the optimal management of the system, it is necessary to include the information on uncertainty of wind power predictions, as well as the use of optimizations tools.

This high level of penetration of wind generation makes much more relevant the fact of having an accurate prediction system, due to the significant economic and technical impact from the forecast errors.

The general wind farms operation is focused on the injection of all the available wind power usable from the wind. Any imbalance in the expected wind power production would have an effect on the market operation, calling for additional power reserves in the system operation.

For this reason, it has arisen the need of new tools to manage and compensate the probable imbalances in wind power generation, apart from the pursuance of forecast error minimization.

Supply and demand must match all the time in an electric power system, being the Balance Responsible Parties (BRPs) the market participants or its chosen representative responsible for its imbalances. Regarding wind power producers, they are encouraged to take part actively in the balancing arrangements, by sending accurate schedules to the Transmission System Operator(TSO) and by participating in the provision of balancing services.

According to Van de Veen et al. [3], these balancing arrangements can be broken down into three main issues: balance responsibility, balancing service provision and imbalance settlement. In the section of Description of the problem these issues are discussed.

Here, it is important to mention that the integration of wind power generators in a single aFRR control area along with other technologies gives rise to the passive participation of wind power in the provision of balancing services. Taking into account this issues, the publication of system imbalance and imbalances prices close to real time turn out to be a relevant element for attenuating the system imbalances.

Van de Veen et al. [3] points out that imbalance prices encourages the Balance Responsible Parties BRPs to submit accurate energy programs to the TSO, avoiding any deviations in their final production. An incentive mechanism, in which the imbalance price changes on a program period basis depending on the size of the system imbalance, is a key characteristic of the balancing market. In the end, what happens is that BRPs market behaviour determines balancing market results, and that those results influence BRPs again. This incentive mechanism leads the market towards a system balance.

With regards to the imbalance settlement and pricing scheme to use, the mechanism differs among countries. Although this point is further described in section 3, it should be noticed that countries like Germany,the Netherlands and Belgium apply single pricing, while others such as the Nordic countries, France, UK and Spain apply dual pricing. Some researchers [4] have posed that when dual pricing schemed includes additional penalties, it usually affects more negative imbalance, leading to over-contract in the day-ahead or intraday markets.

Going back to issues covered in [3], it is important to highlight the following drivers defined there as the main influences in the BRPs imbalance volume: accuracy of forecasting tool, over- or under-contracting in day-ahead markets and internal balancing in real-time.

The issue related to over-/under-contracting in day-ahead markets is brought up in some of the reviewed papers. In [5] J.P Chaves-Ávila et al. it is shown for four European countries (Belgium, Denmark, Germany and the Netherlands) the impact of balancing rules on the profits of wind power producers and their bidding strategies. According to their results, the bids on these markets are not exclusively bound by the expected energy.

However, this is not the case it is addressed in this thesis, since the optimization model that is developed for the decision making only aims to manage the incumbent flexible resources operations on top of the final hourly schedules (P48), but no modification of the existing bidding strategies neither for wind power nor for the technologies used to compensate the imbalances is intended to pursue here.

Therefore, as it has already been mentioned and as it will be explained in the forward sections, the internal balancing in real-time is the driver to be considered in this work (by integration in aFRR control area).

Just to clarify the latter, it should be noticed that the present work aims to calculate the best operation of hydro resources plant, following two objectives in sequential way:

- Conventional management of the hydro resources within the different market sequence described in in section 3.5, having as results a final program (P48) for each of the hour within a day. These energy schedules are going to be dealt as known and computed inputs for the present work.

-Offer a reserve to wind power portfolio for managing the power imbalances. This required reserve will depend on the accuracy of the wind power forecasts.

Therefore, this work focuses on the best decision making with regard to the operation and management of a hydro portfolio, in which different type of resources are included as it is also explained in section 3.5 , in order to reduce until zero the imbalances in the whole aFRR control area. For that purpose, the AGC (automatic generation control) was modified by the introduction of a new setpoint corresponding to the signal from wind power imbalances. In section 3.3 a general overview of the AGC model and its functioning is described.

Regarding the joint management of a hydraulic and a wind power portfolio, the following paragraphs summarize the main ideas drawn from different researches and their implications for this thesis.

- Holttinen et al. [6] developed an analysis of errors in wind power production which showed dependence not only on the prediction horizon, but also on the predicted power level.

- Castronuovo et al. [7] proposed as an alternative the compensation of wind power imbalances by means of storage. They analysed the coordinated optimal daily operation of a wind farm and pump-storage unit in such a way the economic losses from operational restrictions are reduced. In the end, this joint management aims to smooth the output variation due to the intermittence of wind power resource.

- In [8] Castronuovo et altackle once again this issue of joint operation of hydro storage and wind power. In this case, they approach the topic dealing with the search of which is the size of wind farm and pump-storage unit that allows the optimization of the management. A optimisation model is developed in order to determine the strategy to be followed for the hours ahead by the pumping facility. The proposed methodology reveals the yield of significant yearly profits for the wind generator production.

- Matevosyan et al. takes a further step in [9]. Here, a multi-reservoir hydropower system is considered to be managed jointly with a wind farm. The target is a little bit different, without focusing on a pure market framework. In this case, this research aims for the minimization of congestion of transmission lines due to some specific problem that arise throughout the year.

- Angarita et al. defines in [10] two methodologies for the minimization of penalties corresponding to imbalances of a wind farm power output. The first one outlines an approach in which the wind farm bids alone in the day-ahead market, based on a statistical analysis of the expected output in order. The second one considers the joint management of a hydro power plant with the wind farm, aiming to minimize the imbalance costs from the wind resource.

Unlike the previous researches, it should be clarified that this theses does not deal with uncertainty in any case. The optimization model to define is thought to be an ex-post model. The inclusion of uncertainty is one of the key further steps to take in future works, especially regarding the system needs forecast.

2.2 Valuation of water and management of hydro reservoirs

2.2.1 Water value

This section is intended to carry out a review of the water value concept and how to consider it for this specific work, as well as the main guidelines for the hydro reservoirs management.

Generation companies with a hydro dominant portfolio are able to manage a large amount of stored energy in the form of water. For this purpose, reservoirs are used to manage that energy over time. Different reservoir sizes can be found within a portfolio and its capacity conditions the planning and operation of the resources. As a general classification they can be broken down into:

- Hyper-annual reservoirs
- Annual management reservoir
- Weekly modulation reservoirs
- Isolated pump-storage facilities.

Therefore, depending on this reservoir storage capacity mid-term and long-term planning are required for those annual and hyper-annual reservoirs, which should be joint coordinated with a short term operation. In order to achieve different mathematical models are used to provide the efficient signals and for guaranteeing that short term scheduling remain coherent with longer term objectives.

In section 3.5 the hierarchy in the incumbent company is depicted, specifying the relationship between the middle office and front office teams.

As it may be deduced, these issues entail an hierarchical organization both whether centralized or competitive environments are taken into account. Communication between both planning schemes is facilitated by the use of certain signals, which in the end come to be the well known water value concept.

Three types of guidelines are received by short term models from medium/long-term models:

- Primal (production oriented). These are the signals that most related papers tackle based on its easier use. They are focused on the available hydro energy to be exploited within a week or corresponding short-term period. In other words, the typical signal that it is provided for short term models here is the reservoir target level at the end of the specific period.

- Dual (price oriented). This one is completely linked to the hypothetical optimization model and its water balance constraint. Here it is where water value concept arises. It is understood as the variaton in the objective function of the corresponding optimization model when an additional hydro resource unit is available. Depending on the framework to be considered the objective function could be either a system cost minimization, individual agent's cost minimization or individual agent's profit minimization. Cost of hydro generation, which is almost zero, must be distinguished from the valuation of the hydraulic resources that in the end it is related to the substitution cost of stored water. A positive aspect of this approach lies in the flexibility that provides in order to react to changes in the short term that were not foreseen in the mid-term planning. On the other hand, it gives rise to a "binary" management since the production decisions relies on whether energy costs are above or below the specific water value.

- Future resource value curves (price and production mixed oriented). This approach allows to combine both primal and dual guidelines. A water value is established for each output scenario.

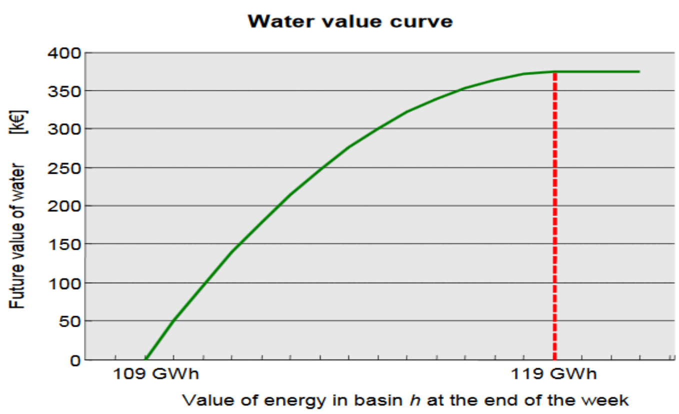


Figure 1 Water value curve

It will be seen in sections 3 and 4 that according to the actual hydro resources management of the incumbent company, primal approach is the one that fits better in order to define the exploitation.

Some aspects such as thermal units' ramps or detailed time representation are neglected in the medium term planning and along with the avoidable existing uncertainty (demand, inflows, fuel costs) makes that the forecasted conditions in the mid-term and the actual conditions that finally take place does not coincide. This is key in order to assess if primal or dual are better to use.

In [12] primal and dual approaches are compared within a centralized environment for annual resources, while in [14] the comparative analysis is extended to electricity markets.

If the differences are small, acceptable results with the primal approach. In any case, better results in the short-term programming are usually obtained by using an explicit valuation of the available resources (dual approach).

As it has been explained, water value entails the hydrothermal coordination for the medium-term horizon, in which the uncertainty plays a key role. Uncertainty it is typically tackled through scenario trees. Stochastic dual dynamic programming stands out among other techniques for a centralized environmental.

However, this work will not deal directly with uncertainty. As it will be better explained in the section 3 and 4 valuation of water is taken as computed inputs that already internalized the uncertainty modelling.

Most of the reviewed works address the valuation water under centralized environments, something that helps to understand the concept but not to implement in most of the power systems, like the one this thesis is about (Spanish system).

With regard to the latter, it is quite relevant the content of [13] This paper is one of the first works that goes deep into the water valuation under market framework, where generation companies cope with the hydrothermal coordination within a competitive environment. Two water values definitions are outlined: profit-based value and cost-based value. The second one turn out to provide a better long-term signal.

2.2.2 Hydro units modelling

The optimal operation of hydroelectric reservoirs is a very complex task due to the multiple and conflicting uses that can be given to the stored water and to the complex particularities of hydro systems: river-basin topology, non-linear input–output curves, water rights, guidelines imposed by the Hydrological Confederations Authorities, environmental flows, and so on. In particular, the dependence of the turbine efficiency with the net head is one of the major difficulties for solving the resulting optimization problems.

For all these reasons, in the reviewed literature it is very common to model the hydro generators by simplified energy representations that consider them as limited energy units. This way, the detailed and physical model is substituted by a composite representation, in which a group of cascaded reservoirs is modelled by using a single equivalent reservoir that stores, receives, and releases energy instead of water.

In this section, it is described the reservoirs management tackling the most significant considerations collected from the existing literature. For the specific explanation of the set of particularities considered in this work, the section 3 and 4 should be consulted.

- Head dependence

Hydro unit output depends mainly on the water flow (q), the net height (h) resulting from the difference between the stored water level and the elevation of the turbine drain, and the losses in the pipes (. Considering it, the power produced by a unit can be formulated as:

$$p = \rho \cdot g \cdot \eta \cdot q \cdot h$$

Where ρ represents water density , g gravitational acceleration and η the efficiency.

Besides that, plant output depends on the turbine operating point and therefore $\eta = \eta(h, q)$

A non-linear relationship is present between output, water flow and the net head.

This dependence is normally introduced as a characteristic surface. On top of that , it should be noted that net head in turn depends on the volume of water stored, the basin geometry and the water volume that can be stored immediately downstream in the event of consecutive overlapping reservoirs.

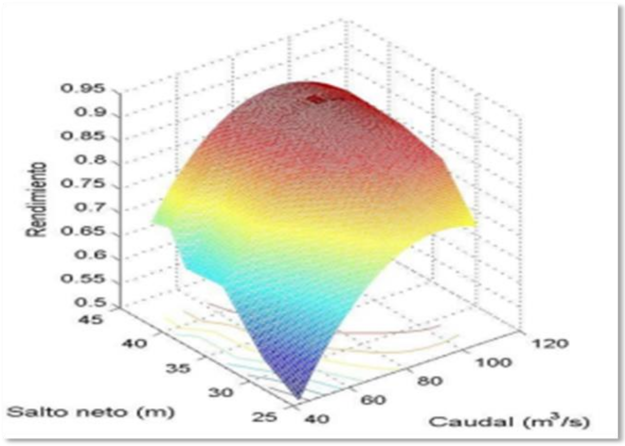


Figure 2 Head dependance

The correct modelling of such non- linear dependence relationships that interconnect decision variables to consider in the management optimization needs the use of specific mathematical models to guarantee that the feasibility of the solution.

- Catchment basin topology

Both temporal and spatial correlations should be considered in regard to the basins topologies. Any flow discharge from an upstream reservoir reaches the downstream plants after a certain lag time. Basin models also include those nodes on the river system where natural inflow enters the network.

Those nodes where withdrawals take place are usually modelled as negative inflow to represent water removal for different uses not related with electric generation, such as human consumption or irrigation.

Physical overlapping of each reservoir, plant and intake points bind the upstream and downstream water management.

All these spatial and time interconnections can be addressed under specific simplifications as it is explained in section 3.

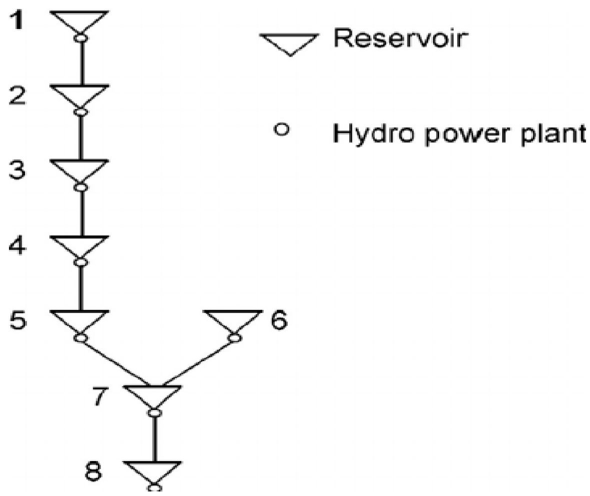


Figure 3 Basins topology

- Flow rights of way

Besides the physical consideration to be introduced in any hydraulic model, in order to obtain feasible management plans it is required to cope with other constraints unrelated to the electricity industry. These results from imposition of river basin authorities, irrigation associations or municipal governments.

These boundaries are usually referred as flow rights of way which, in the end, impose that flow rates must be kept within a specific range that will be different throughout the year dependent on the current conditions. For example, in the Spanish case a lot of these limitations stem from recreational uses.

Since these flow rates requisites arise at certain periods of the day , reservoir management must be flexible enough to adapt production to such requirements.

- Guarantee curves

River basin authorities mandates another kind of limitations, the so-called guarantee curves. These constraints binds water level in reservoirs to be kept within certain minimum and maximum limits.

They are aimed to is to ensure that , one hand hand there is enough water in reserve after wet seasons to guarantee supply during the dry season and on the other hand , that before the rainy season begins, there is available capacity to store water from rain, avoiding any undue spills . This is an important issue both from the energy and safety points of view, since it involves a loss of energy and it also jeopardize downstream safety conditions.

Two tyes of guarantee curves are taken into account in the company's portfolio management:

-Cushion curve. This aims for the non spill targets and floods attenuation.

- Minimum guarantee curve. This is considered to ensure the minimum use needs.

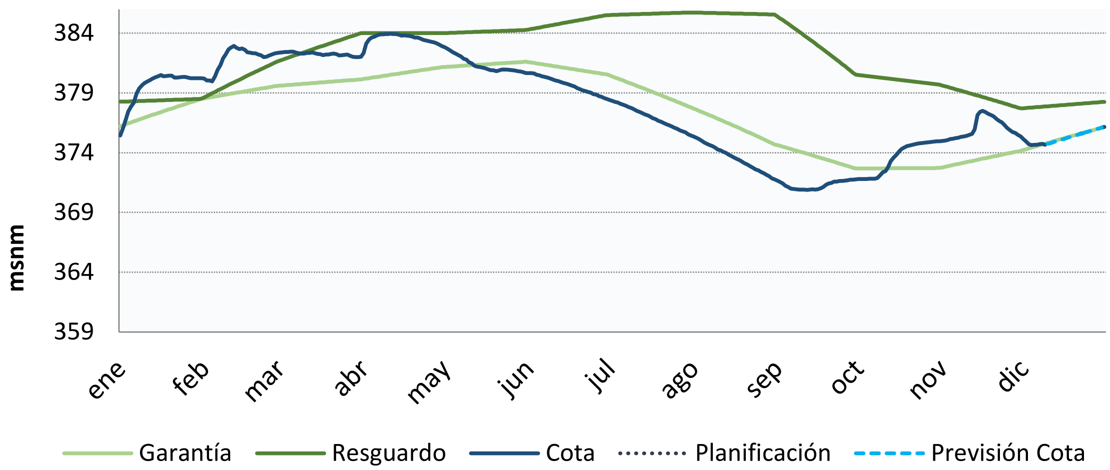


Figure 4 Guarantee curves

3. Description of the problem

3.1 Wind power imbalances management within the incumbent company

The problem to tackle in this thesis stems from the incumbent company's decision of introducing the wind power units within its aFRR control area, which is the single entity that aggregates the provision of the aFRR ancillary services. This decision was taken as a facilitator for the wind power imbalances compensation by the use of available operational reserves from other flexible units.

Before the implementation of this new measurement, wind power programming units used to settle their own deviations in an individual way and now are considered to be part of the same Balance Responsible Party (BRP) as the flexible units used for the imbalance compensation.

This decision was taken based on some previous estimations and now It has arisen the need of assessing the real net savings that are earned thanks to this action.

In the Spanish regulation the imbalances settlement is based on a dual pricing scheme. A description of this issue is carried out in section 3.5.1. Basically, through this frame all the units that incur in a deviation from the hourly program which do not coincide with the system needs have to pay or be charged the resulting price of the system imbalances management. As it was said before, up to the moment of this decision implementation wind power faced individually their own imbalances, within the dual pricing frame. The main goal of this work is to assess the economic impact of the integration decision, internalizing the expenses and recoveries of hydro resources, which are the main assets to be used regarding the wind power imbalances compensation. The valuation of the hydro resources used for the regulation plays a key role in order to perform the different parts of the thesis. As it is explained both in the state of the art section and in the following parts of this section, that valuation is brought on by the water value, which internalizes the hydrothermal coordination during the medium-term horizon.

Therefore, as it is explained in the following sections, the tasks to be carried out will consist in collecting all the data corresponding to this period in which the new measurement has begun to be applied and do a calculation to quantify hourly the savings and expenses comparing the new wind power integration scenario and the old wind power non-integration scenario. An application in Excel is intended to be developed in order to automatize this calculation having as inputs the different information about the markets programs and prices.

From the results of this work, the criterion considered by the company's Generation Control Center to manage the imbalances regulation can be also assessed and upgraded. For that purpose, the economic analysis is carried out through the development of an optimization model based on past data, which is built embedded in the aforementioned Excel application. As said before, the final goal is to help the assessment and identification of the improvement gaps related to the generation control center decision making. Some different cases are set out within the results sections depending on the hydro impoundment facilities and isolated pumped-storage plants management, as well as the imbalances pricing, system needs and day ahead market prices.

For the comparison of the aforementioned scenarios, it should be taken into account that the possible incomes earned in the non-integration scenario from the ancillary services market have been neglected. The referred incomes would come from the participation in those markets of the hydraulic reserves, which in the integration scenario are spent for the internal imbalances netting.

The reason behind not including this consideration in the model lies in the complexity of estimating those incomes. It should be noted that the ancillary services market results would not be the same when taking into account the integration and non-integration scenario. The volume (system needs) and price would not be the same. To address this point, a sensitivity analysis of the ancillary services market should be carried out. Due to complexity of the latter, it has been considered as a further step to take in a future improvement of the model described here.

3.2 Market framework

The current work is framed within the Iberian Electricity Market, which is formed by a sequence of different markets where generation and demand agents interact. In the following figure the different processes are specified such as the forward markets, day-ahead market, intraday markets , ancillary services and other real time management markets.

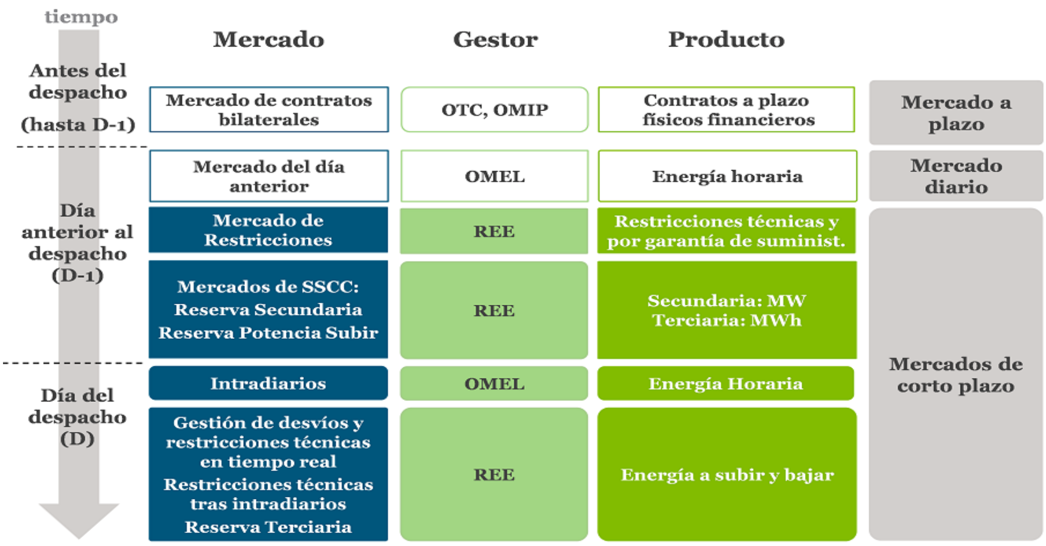


Figure 5 Market sequences

In the long term, agents close trades through different alternatives:

- Forward bilateral contracts (Physical or financial)
- Forward energy auctions (Physical or financial)
- Organized forward market (Physical delivery or settle by financial differences)

They are always price hedging mechanisms with respect to the Day-Ahead Spot auction market price, due to the fact that Day-Ahead spot market is a liquid physical market.

Day-ahead market is a physical market in which most energy volumes are traded. The product is hourly energy market with a time horizon of 24 hours, where the closing time is 12:00 h from the D-1. The clearing process is based on the EUPHEMIA algorithm with a marginal pricing. Sellers have different options to proceed for their production units:

- Declaration of unavailabilty with the TSO verification and Regulator inspections.
- Nominate a physical bilateral contract prior to 11 am.
- Send a bid to the Day-Ahead market.

As it is shown in the below figure, the PDBC (clearing resulting base D+1 program) is obtained from the coupling price clearing process in the Day-Ahead. Once the bilateral contracts are added on top of it , TSO publishes PDBF (functioning base D+1 program) .

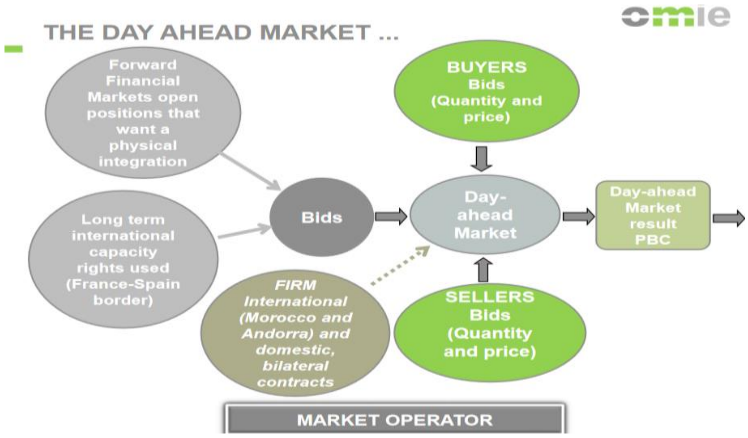


Figure 6 Day-ahead market PBC

Since the day-ahead market does not include any network considerations, except from the cross-border interconnections feasibilty compliance, TSO carries out the corresponding checking procedure for the network constraints. This analysis includes the run of different power flows calculations as well as contingency tests related to different assets' trips (lines, transformers, generation units). TSO solves the congestion by asking agents for bids in a two phases process, keeping the system balance . Technical constrainst market is based on a pay-as-bid clearing.

In addition, there is a procedure for the allocation of upwards reserve power which aims for thermal geneation availabilty in order to guarantee the security of supply.

PDBF plus the results from technical constraints and upwards reserve allocation gives rise to the PDVP program (feasible D+1 program).

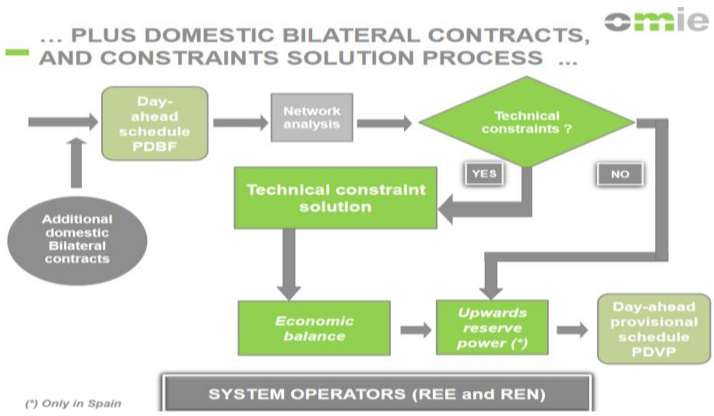


Figure 7 Bilateral contracts and constraints solution process - PDVP

As an option for the agents to adjust their bids according to updated conditions closer to real time, there are six intraday markets, as it is shown in the following figure. These auctions are managed by the TSO in this case.

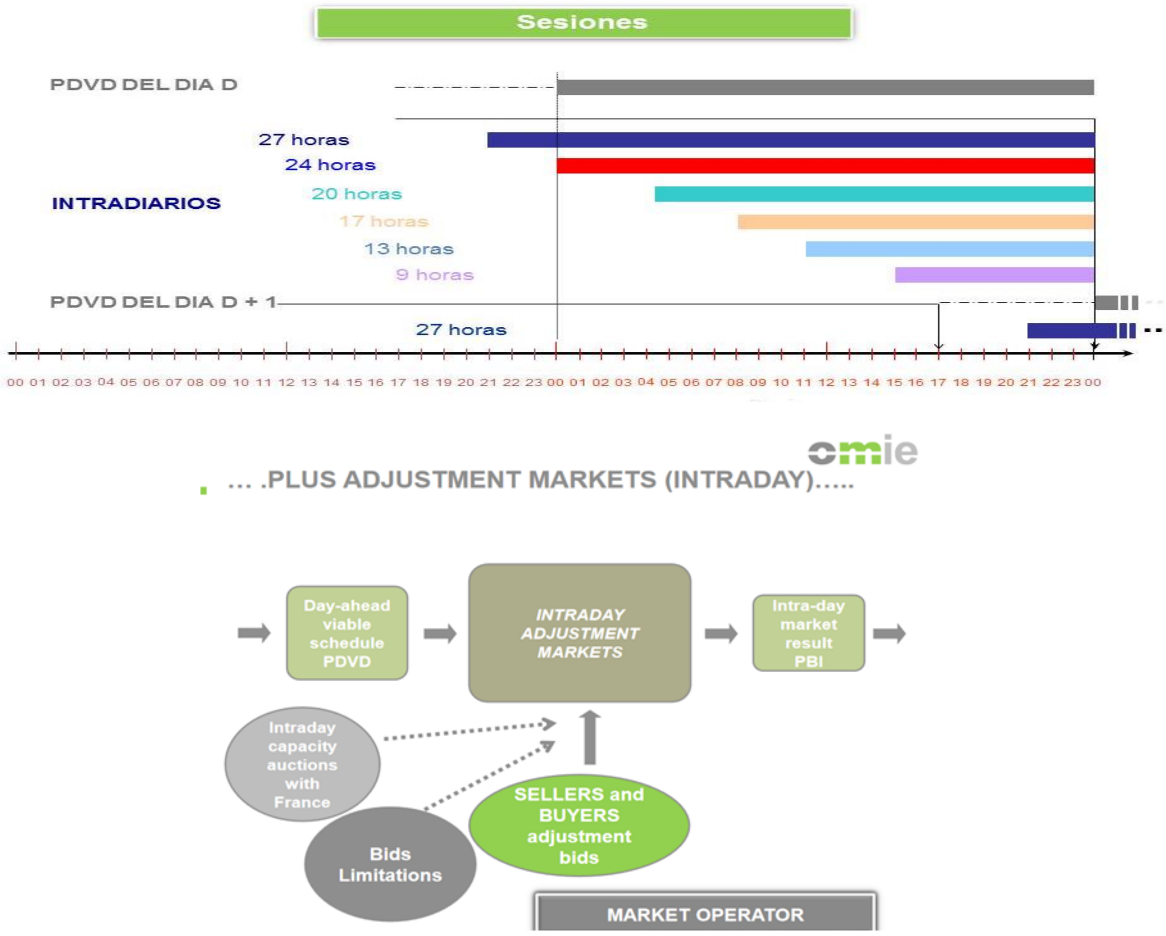


Figure 8 Intraday markets

After every intraday auctions TSO publishes the so-called PHF (hourly final program). Once a intraday auction ends , the agents are not able to modify their program for the horizon that falls within the current time until the initial horizon of the following intraday auction.

INTRADAY SESSIONS
Timetable

	SESSION 1st	SESSION 2th	SESSION 3rd	SESSION 4th	SESSION 5th	SESSION 6th
OPENING OF THE SESSION	17:00	21:00	01:00	04:00	08:00	12:00
CLOSING OF THE SESSION	18:45	21:45	01:45	04:45	08:45	12:45
MATCHING	19:30	22:30	02:30	05:30	09:30	13:30
BREAKDOWN RECEPTION	20 minutes after finished the matching process					
CONSTRAINT ANALYSIS	20:10	23:10	03:10	06:10	10:10	14:10
PHF PUBLICATION	20:20	23:20	03:20	06:20	10:20	14:20
SESSION HORIZON (Hourly period)	27 hours (22-24)	24 hours (1-24)	20 hours (5-24)	17 hours (8-24)	13 hours (12-24)	9 hours (16-24)

Figure 9 Intraday sessions-Timetable

For example, in the case of the second intraday session the bidding horizon is 1-24 hour and the gate- closure is at 21:45 h. The horizon for the following intraday session covers 5-24 hours. Therefore, there is "dead" period between 21:45 h of D-1 and the hour 5 of D+1 in which it is not possible to alter the final bid for the hours 1 to 4. This becomes specially relevant in the case of wind power management. Considering the worst case,hour 4, the last possible bid to submit is ,at best, able to account for a 5 hours ahead forecast. The best case, hour 1, allows to use the 2 hours ahead prediction. The closer to real time the better for wind power management in order to minimize the final imbalances between real production and final programs.

In relation to this issue, it is important to point out the upcoming implementation of the new continuous intraday market (XBID) accross EU bidding areas.

Horario					Subasta MIBEL		Mercado Continuo
Día	Ronda * del continuo	Periodo	Hora inicio de periodo	Hora fin de periodo	Nº subasta	Periodos de negociación incluidos en horizonte de la subasta	Periodos de negociación abiertos en el mercado continuo
D	20	18	17:00	18:00	1		20,21 (D↓)
D	21	19	18:00	19:00	1	22-24 día D, 1-24 día D+1	21
D	22	20	19:00	20:00	-		22,23,24
D	23	21	20:00	21:00	-		23,24
D	24	22	21:00	22:00	2	1-24 día D+1	24
D	1	23	22:00	23:00	-		1,2,3,4 (D+1↓)
D	2	24	23:00	0:00	-		2,3,4
D+1	3	1	0:00	1:00	-		3,4
D+1	4	2	1:00	2:00	3	5-24 día D	4
D+1	5	3	2:00	3:00	-		5,6,7
D+1	6	4	3:00	4:00	-		6,7
D+1	7	5	4:00	5:00	4	8-24 día D	7
D+1	8	6	5:00	6:00	-		8,9,10,11
D+1	9	7	6:00	7:00	-		9,10,11
D+1	10	8	7:00	8:00	-		10,11
D+1	11	9	8:00	9:00	5	12-24 día D	11
D+1	12	10	9:00	10:00	-		12,13,14,15
D+1	13	11	10:00	11:00	-		13,14,15
D+1	14	12	11:00	12:00	-		14,15
D+1	15	13	12:00	13:00	6	16-24 día D	15
D+1	16	14	13:00	14:00	-		16,17,18,19,20,21
D+1	17	15	14:00	15:00	-		17,18,19,20,21
D+1	18	16	15:00	16:00	-		18,19,20,21
D+1	19	17	16:00	17:00	-		19,20,21
D+1	20	18	17:00	18:00	1		20,21
D+1	21	19	18:00	19:00	1	22-24 día D, 1-24 día D+1	21
...	...	...	...	...	...	...	...

*Ronda del continuo: Periodo que se negocia por última vez en el mercado continuo

Figure 10 Continuous intraday market XBID

In the case of Spain there will be a hybrid model with the current six auctions mixed with the continuous trading. At the beginning of the following hour after an auction finishes, the continuous trading will be opened for those hours not included in the next auction horizon. In this way, the gate-closure for all the periods within a day will be one hour.

Under this new framework ,the wind power portfolios are expected to reduce their imbalances, since it is going to be possible to bid according the one hour ahead forecasts.

TSO is also responsible for running the ancillary services markets which consist of:

- Secondary regulation band.
- Real time management.
    - Tertiary reserves market.
    - Imbalance management market.

For the present work, these markets are the most relevant, so a deeper explanation of the procedures is covered in the following paragraphs.

Fastest balancing service corresponds to the primary regulation or frequency Containment Reserve, as Network Codes on Balancing Mechanisms refers to it. However, in the case of Spain this is a compulsary and not remmunerated service, which is automatically provided by each of the enabled generation units. It aims for keeping the balance between supply and demand, and requires a response time below 30 seconds.

For longer activation times the system uses the Frequency Restoration Reserves (FRR), among which the secondary and tertiary reserves are included in the case of Spain.

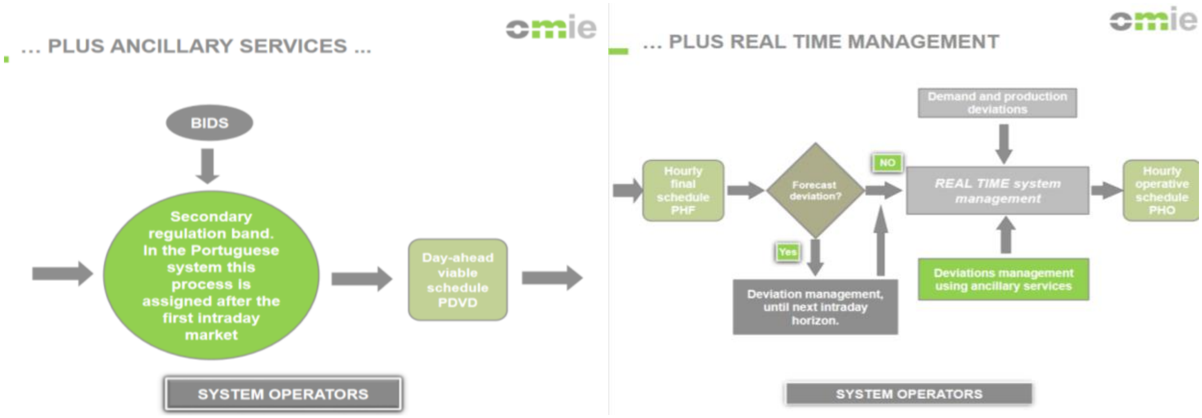


Figure 11 Real time markets

- **Secondary regulation band**

It corresponds to the operating reserve used to restore frequency to the nominal value and interconnection flows to the scheduled value after sudden imbalance occurrence. Spain TSO defines it as an optional service and subject to market mechanisms.

This service is provided by the aFRR control areas (called as "Zonas de Regulación" in Spain) according to the TSO requirements which are submitted by a master regulator, RCP (Regulación Compartida Peninsular). In the section 3.3 a wider description of both the concepts of control areas and RCP are included.

The overall secondary operating reserves comprise the aggregated reserves provided by every agent in the system. The maximum response time to the TSO requirement is established at 30 seconds and the service should be provided for at least 15 minutes.

The allocation process of the secondary regulation band is managed by TSO following a merit order clearing procedure. Agents responsible for aFRR control areas submit bids for each programming units individually for every hour. This bids must be firm in an aggregated way for the control areas. The clearing process is based on marginal pricing, so that all the involved agents are paid the same price.

If the allocated band to an agent is not feasible according to the PVP program , the agent must bid the required energy in the intraday auctions.

When secondary reserves are used , providers are paid at the tertiary reserves marginal price.

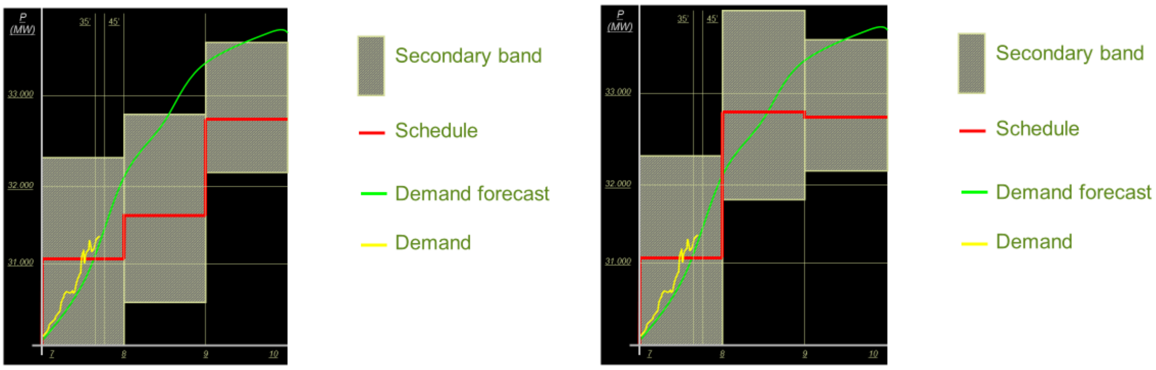


Figure 12 Secondary regulation band

- ***Tertiary reserves***

It is usually referred as the mFRR (manual frequency restoration reserves). Unlike the secondary reserves, this service is subject to compulsory bidding by the agents. The ramp requirement is fixed at 15 minutes with a minimum duration of 2 hours.

Every unit enabled to provide this service must submit bids for its available upward/downward tertiary reserves at every period of the day D+1.

Agents shall update their bids within the day as long as the available reserves undergo any change from the initial bids of D-1 such as: use of the capacity for either intraday markets, imbalance management, use of secondary reserves, unavailability

The gate-closure for the tertiary reserves updating takes place one hour before the beginning of the programming period.

The allocation of this service is based on a marginal price market following a merit order procedure without any complex condition. Final setpoint provided by SO is confirmed 15 minutes before the corresponding hour.

It is important to take into account that part of the wind power portfolio considered here is enabled to provide tertiary reserves. For the economic assessment it is going to be considered the possible penalties that results for the non-compliance of tertiary reserves allocation only in the case of non-integration of wind power in the control area. Below it is explained which is the procedure to calculate these penalties along with some examples . The information about this is further detailed in the operational procedure 14.4 from REE [17].

- Penalties due to not-compliance of tertiary reserves and imbalances management allocation

For the calculation these are the terms to account for:

STGS. Upward reserves for tertiary regulation and imbalance management.

STGB. Downward reserves for tertiary regulation and imbalance management.

MBC. Power Unit Bus measurements (Medida en “Barras de Central”) of all the wind power units enabled for tertiary regulation.

EMERS. Upward real time constraints.

EMERB. Downward real time constraints.

ERS. Reference energy --> Upward : PHF + STGS + EMERS / Downward : PHF + STGB + EMERB

Examples:

- *Case of upward tertiary reserves:*

$$Non - complied\ energy\ =\ max\ [-STGS, min\ (0, MBC - ERS)]$$

$$Penalty\ payment\ =\ EINC \cdot\ PBAL \cdot\ 0{,}2$$

$$PBAL = average\ price\ for\ upward\ tertiary\ reserves\ and\ imbalance\ management$$

Table 1 Upward tertiary reserves

	ERS	MBC	A = min(0, MBC-ERS)	EINC=max(-STGS,A)
PHF	**2.621,90**			
EMERS	**0,00**			
STGS	**432,60**			
	3.054,5	**2.922,49**	**-132,01**	**-132,01**

$$Penalty\ payment\ =\ EINC \cdot\ PBAL \cdot\ 0{,}2\ =\ -132{,}01 \cdot 68{,}78 \cdot\ 0{,}2\ =\ \mathbf{-1186}\ €$$

- *Case of downward tertiary reserves:*

$$Non - complied\ energy\ ==\ min\ [-STGB, max\ (0, MBC - ERB)]$$

$$Penalty\ payment\ =\ EINC \cdot\ PMD$$

$$PMD = day - ahead\ market\ price\ for\ an\ specific\ hour$$

Table 2 Downward tertiary reserve

	ERS	MBC	A =max (0, MBC-ERB)	EINC=-min (-STGB,A)
PHF	**3.265,10**			
EMERB	**0,00**			
STGB	**-508,30**			
REG	**-115,10**			
	2.756,8	**3.288,9**	**532,1**	**-508,30**

$$Penalty\ payment\ =\ EINC \cdot PMD =\ -508.3 \cdot\ 6\ =\ -3049.8\ €$$

➢ ***Hourly schedules definition***

In order to allow a better understanding of different points to deal with in this work, below the sequence of hourly energy programs are summarized:

- PBC. Day-ahead clearing base program ("Programa base de casación"): scheduled energy for every program period (hourly) broken down into the different bidding units and resulting from the day ahead clearing process. NEMO (market operator) is the one responsible for publishing it.

- PDBF. Day-ahead base program ("Programa diario base de funcionamiento"): scheduled energy for every program period (hourly) broken down into the different programming units (UP) and resulting from the day ahead market clearing proccess and the bilateral contracts nomination. SO is the one responsible for publishing it, as well as the rest of the following programs.

- PVP. Day-ahead provisional feasible program ("Programa diario viable provisional"): it incorparates the changes in the scheduled energy that stem from the technical constraints allocation procedure.

- PVD. Day-ahead firm feasible program ("Programa diario viable definitivo"): it incorporates the aFRR (secondary regulation band) allocations.

- PHF. Final hourly program ("Programa horario final"): scheduled energy after each one of the corresponding intraday market auctions, internalizing the aggregation of all the previous programs. There is one PHF for each of the intraday auctions.

- PHO. Operating hourly program ("Programa horario operativo"). Scheduled energy established and published by the SO 15 minutes before the beginning of the corresponding program period. It includes tertiary reserves and imbalance management allocations.

3.3 AGC and aFRR Control Areas

3.3.1 General overview

For an adequate introduction and understanding of the issues covered in the sections of methodology and results I consider especially relevant to give an general overview of the AGC and control areas foundations. As it is well known, power-frequency regulation in a power system aims for keeping the frequency within the rated range when facing unexpected power variations in the system. For that purpose, it makes use of the spinning reserves that are available at the corresponding moment. This regulation is organized in three different segments with different time scales: Frequency Containment Process, automatic Frequency Restoration Process and manual Frequency Restoration Process. For the Spanish case, the different timewise requirements have already been specified when the balancing markets were explained in section 3.2.

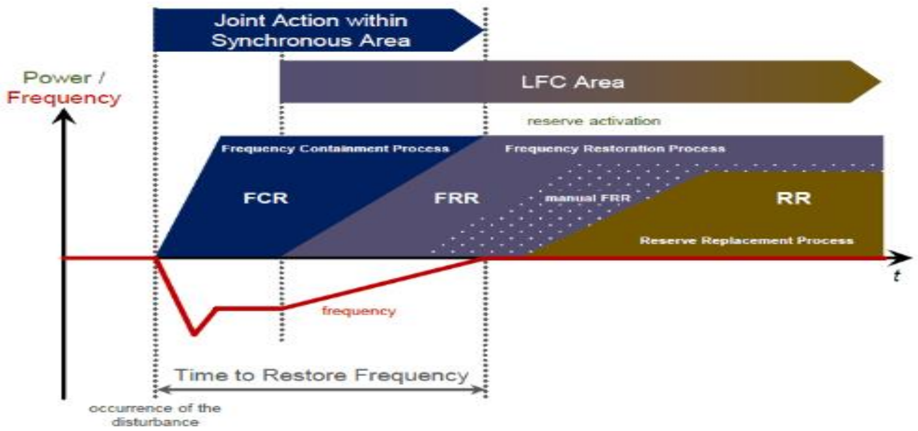


Figure 13 Ancillary services

In the particular case of Automatic Generation Control (AGC) , the focus should be placed on the automatic frequency restoration reserves (aFRR). Both AGC and aFRR control areas ("zonas de regulación") concepts can be explained from a common and unique approach.

Automatic Frequency Restoration Process is carried out in a hierarchical way for Spanish power system. A centralized mechanism called as RCP ("Regulación Compartida Peninsular") is the facilitator for the calculation of regulation commanded values that the TSO (Red Eléctrica de España REE) is in charge of submitting.

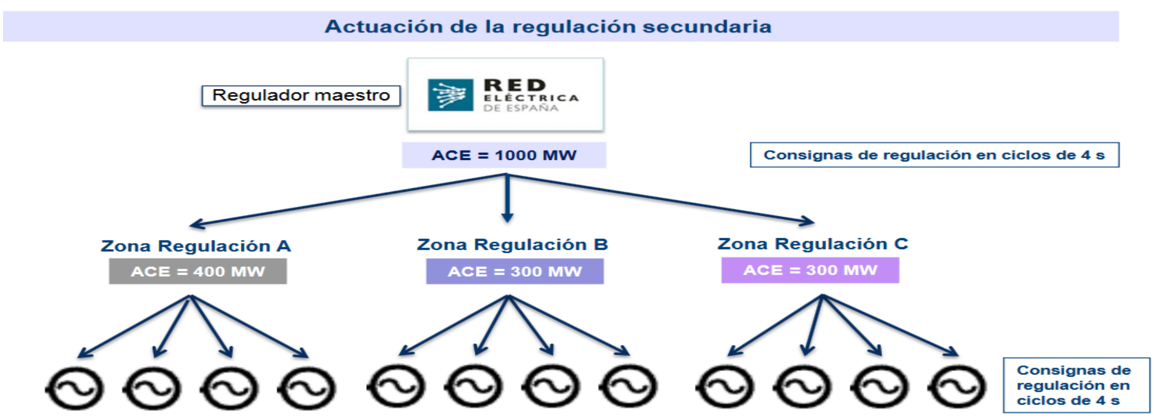


Figure 14 "Regulación compartida peninsular"

Therefore, through that procedure the TSO calculates the CRR (Company Regulation Requirement), which is sent as the commanded value to the aFRR control areas. AGCs act as the controllers of the control areas, allowing them to calculate its area control error, ACE, which is the amount of generation that must be altered in order to fulfil the interconnection programs and to maintain the system frequency at its nominal value.

AGC computes the control area error ACE as follows:

$$ACE = CRR + \frac{1}{G} \cdot NID - 10 \cdot B_{ZONA} \cdot \Delta f$$

Where:

CRR. Company Regulation Requirement, computed by the master regulator of the RCP proportional to the allocated band to the corresponding aFRR control area

NID. aFRR control area imbalance

G. Attenuation factor of the aFRR control area imbalance.

B_{ZONA}. Part of the Bias of the Spanish system proportional to the allocated band to the corresponding aFRR control area

Δf. Frequency deviation = real frequency – rated frequency

Once the total required output variations are computed for an specific control area, its controller (AGC) should distribute those variations among the different units that are activated for regulation. The distribution is carried out according to both economic and time response criteria.

In short, AGC is responsible for taking the following actions:

- ✓ ACE calculation for its particular aFRR control area.
- ✓ Output variation in the control area in order to face the aforementioned ACE.
- ✓ Distribute that variation among the aFRR activated units, obtaining the setpoint for each of them.

Besides that, some other objectives regarding cost and control dynamic issues should be achieved by the AGC:

- ✓ Keep the response dynamic within adequate limits and minimize the non-compliance of response criteria. Those criteria are defined by the TSO.
- ✓ Minimize the energy cost linked to regulation mode activation. The normal approach for the units distribution is an economic dispatch.
- ✓ Minimize the regulation efforts of the units. It should be noted that the functioning under regulation mode, what implies additional strength for the units. These entails a greater wear and tear, which increases operational and maintenance costs. It also gives rise to efficiency decreases. Therefore, AGC are usually designed to attenuate this over exertion as much as possible. It can be done by minimizing the units setpoints variations, what allows to reduce the output changes.

In the following figure it can be observed the diffrenent control segments in which an AGC it is broken down:

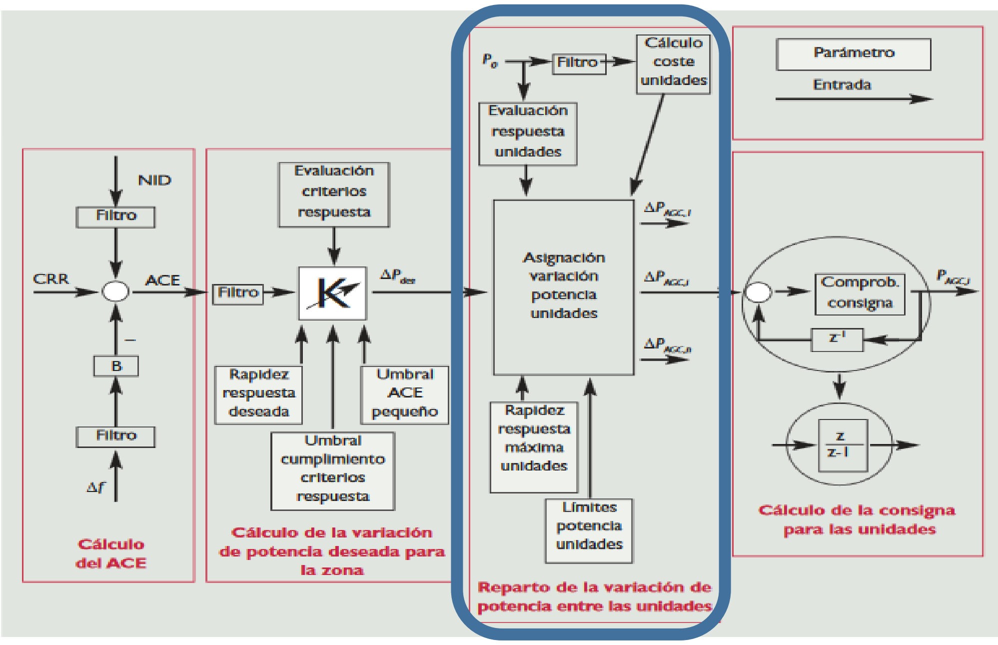


Figure 15 AGC control loops

Among these blocks that can be distinguished, the one that takes more relevance in regard to this work is the third block. It corresponds to the output changes distribution among the units in regulation mode. Before running the distribution, the AGC verifies the response time of each unit. These values are taking into account along with the costs and operational limits for carrying out the final distribution in the most adequate way.

However, it should be noted that there exist a priorization among the three aforementioned goals. At first, it is aimed to comply with the speed requirements and if there is available margin, afterwards the economic optimization (economic dispatch) is run.

In the following subsection, the particular assumptions considered for the incumbent AGC and control area are described. As it will be seen, for the analysis included in this work the response time details are not internalized. It must be reminded that the scope of the work does not cover a deep AGC analysis.

The first and fourth blocks shown in the above figure are responsible for the setpoints calculation. For that purpose, on top of the computed setpoint of the previous cycle it is added the sum of the output variation resulting from third block. In this way, it is achieved the necessary integral action for eliminating the control area error ACE in the steady state.

Below the mathematical calculations for the aFRR control area response is computed as follows.

$$PGCD_t = PGC_{t-1} + ACE_{t-1}$$

Where:

PGC_{t-1}. Output power under control in the t-1 cycle which is equal to the sum of the output power of every unit that is activated within the aFRR control area)

ACE_{t-1}. aFRR control area error for the t-1 cycle

3.3.2 AGC specific functioning and decision making under wind power integration scenario

In order to facilitate the wind power imbalance netting as a Balance Responsible Party (BRP) , it has been introduced this imbalance as an additional setpoint into the AGC . In the previous subsection it was described that ACE computes the control area error as follows:

$$ACE = CRR + \frac{1}{G} \cdot NID - 10 \cdot B_{ZONA} \cdot \Delta f$$

Now, if we refer to the wind power imbalance as IMB_{wind}, the control area error would be computed as:

$$ACE = IMB_{wind} + CRR + \frac{1}{G} \cdot NID - 10 \cdot B_{ZONA} \cdot \Delta f$$

This change is implemented within the first block of the AGC.

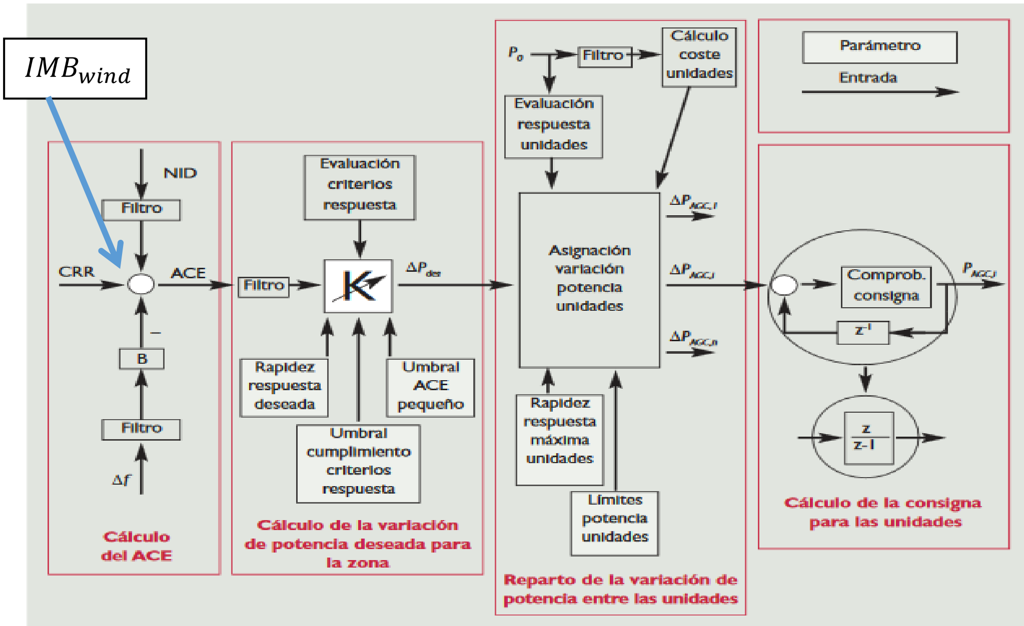


Figure 16 AGC control loops- Setpoints

Some specific features and assumptions for the AGC functioning with regard to the imbalances regulation are specified below:

- One important hypothesis to take into account is that wind power imbalances regulation does not have any effect on committed secondary band regulation from aFRR control area.

- As it has already been mentioned many times, the decision on whether regulate the wind power imbalance or not is manually taken and it will have a binary characteristic. The latter means that the imbalance is decided to be noticed to TSO as a whole (all or nothing) . The real procedure within the AGC consists of enabling or disabling the wind power imbalances tracking mode through the activation of the additional setpoint (iIMB_{wind}) in the first control block.

- Hydro resources real time management within the aFRR control area and therefore, within the AGC, is as follows:

  - Hydro generation units (turbines) are manually enabled to be actively following the AGC third block setpoints. By means of this control block the distribution of the ACE is carried out in an automatic way between the enabled units at the corresponding moment.

  - Pumping units are actuated manually (decision on startups), with no integration in the automatic tracking mode of AGC third block. It should be noted that these units are not included within the aFRR control area. The reason behind this fact lies in their discrete characteristic.

- ✓ As a consequence of the previous point, the decision making strategies analysis focuses only on the manual decisions to be taken by the generation control center: activation of the hydro generation units within the AGC and pumping units startup management.

- As it will be explained later, the economic assessment model based on ex-post optimization is defined under a set of assumptions and therefore, it does not reflect faithfully the real AGC functioning. For example, spatial-temporal correlations fixed by the topologies or the ramp limits in the increase/decrease of generation are not embedded in the model. In the end, the model is aimed to be an effective approximation of the AGC functioning.

The following figure shows a real functioning evolution of AGC regarding imbalances regulation and RCP tracking, explicitly displaying hydraulic portfolio real time variations from P48:

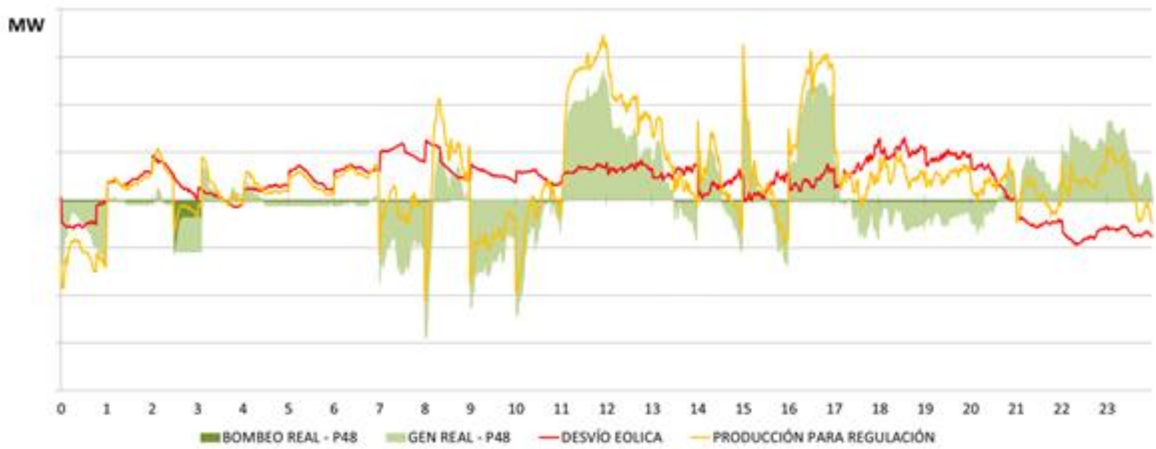


Figure 17 Wind power imbalances regulation tracking

3.4 Excel application for economic assessment

Here are explained the main features that are aimed to be included in the final excel application that is intended to collect the economic assessment of the different scenarios regarding wind power imbalances management.

In an overall approach, the excel tool will be divided into the following parts:

- User's interface excel sheet where it will be possible to introduce a specific range of dates and to run the programme that execute the database queries and the final economic valuation resulting from the optimization model.

- Different spreadsheets where the information from the database queries will be collected. This information will include:

  - Market prices.
  - System imbalances
  - Wind power market scheduled output
  - Wind power final production
  - Hydro basins market scheduled output

- Final spreadsheet where the overall economic assessment will be summarized in an hourly basis. It will contain different data deemed to be relevant for the final results and picked from the other sheets. The critical information to be provided by the tool will appear here, specifying the optimal decision that should have taken and the resulting savings/losses from the actual decision taken by the generation control centre of the incumbent company.

In the proposed method section 4 it can be found a much more detailed information of how the different data queries have been built and run, as well as a description of the different commands used for the calculation procedures and obtainment of the final results.

3.5 Economic analysis of the imbalances management

Once the main aspects to include in the excel tool has been developed, it is possible to describe the key issues regarding the economic analysis development.

For that purpose, it is important to describe the way of analysing both the management of wind power and hydro units. Taking into account some of the ideas that have been discussed in the section 2, below it is explained which are the main approaches that are implemented in this work. For a deeper explanation of how the analysis is developed and how the final results are obtained, the section 4 cover all those issues.

3.5.1 Imbalances settlement

As it was mentioned in the section 2 there are three main issues within the balancing arrangements: balance responsibility, balancing service provision and imbalance settlement.

The balance responsibility entails the obligation for market agents to submit schedules. However, the limited predictability of meteorological factors has significant consequences for wind production forecasts and therefore, the ability to submit accurate schedules.

With regards to the balancing services, as it was explained before in this work, the TSOs usually buy the balancing services in the balancing markets. However, passive participation from wind power generators in the provision of balancing services take place when they incur in imbalances in the final production and other units, included in a single control area, modify their output to regulate this energy in order to compensate the deviations.

The last aspect of balancing mechanisms corresponds to how the balancing costs are allocated to BRPs, that is, how the imbalance prices are determined.

To do so, two main schemes are applied around the world: single vs dual pricing. The difference between them lies in the application of either the same or different imbalance prices depending on their relative direction compared with the system needs.

To clarify this, now it is shown an example using the below figure and considering the following conditions:

- The overall imbalance of the system is negative, that is, the system needs upward energy.
- BRP A (generator) is incurring in an upward imbalance ("A SUBIR": metered energy > scheduled energy) and therefore, its behaviour goes in the same direction of system needs ("FAVORABLE").
- BRP B (generator) is incurring in a downward imbalance ("A BAJAR": metered energy < scheduled energy) and therefore, its behaviour goes in the opposite direction of system needs. ("CONTRARIO").

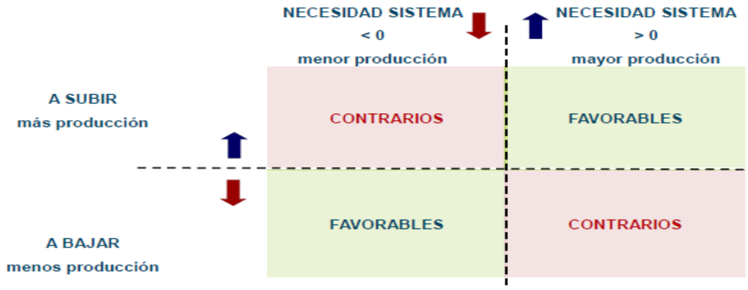


Figure 18 Imbalance settlement scheme

If it is applied the single pricing scheme to that example, only one imbalance price would exist. It is calculated as the weighted average price of the activated ancillary services. This price would be applied to both BRPs as follows:

- BRP A upward imbalance would be paid at the single imbalance price.
- BRP B downward imbalance would be charged at the single imbalance price.

However, if a dual pricing scheme is applied, two different prices would exist for the upward imbalances and for the downward imbalance. If the system needs upward energy, the price for the upward imbalance price would be the day-ahead market price, while the price for the downward imbalance price would be the same as in the single price scheme (weighted average price of the activated ancillary services) which in this case would be higher than the day-ahead market price. As a consequence, the settlement for the BRPs would be:

- BRP A upward imbalance would be paid at the day-ahead market price.
- BRP B downward imbalance would be charged at the downward imbalance price, which is higher than the day-ahead market price.

BRP B would see the same settlement, but BRP A has a lower income with the dual pricing scheme. Within the section of conclusion, there is a brief analysis of this implications into the economic analysis results of the thesis.

For the specific Spanish case and therefore, for this work, the dual pricing scheme is the one applied. Below some particular points of the Spanish settlement are shown, but for a deeper explanation of its details it should be consulted the corresponding operational procedure from the TSO ("Procedimiento de operación 14.4").[19]

The imbalance settlement for the Spanish case is computed taking into account the metered production in power unit bus and the Settlement Hourly Programo or PHL ("Programa Horario de Liquidación").For a certain unit, the PHL is obtained from the sum of :

- Energy of PHF (Final hourly program)

- Energy of PHO (Operating hourly program, without including the noticed imbalances).

The metered production results from the sum of the measurements at every frontier point of all the physical units integrated in a programming unit. That frontier points corresponds with the so called "power unit bus".

The computation of the imbalance prices is carried out following the already explained dual pricing scheme:

-Upward imbalances prices

$$PDESVS = \min(PMD, PMPRTSB)$$

PMPRTSB : weighted average price of the allocated downward energy through the imbalance management procedure, tertiary regulation (mFRR) and secondary regulation (aFRR).

Figure 19 Upward imbalances

-Downward imbalances prices

$$PDESVB = \max(PMD, PMPRTSS)$$

PMPRTSS : weighted average price of the allocated upward energy through the imbalance management procedure, tertiary regulation (mFRR) and secondary regulation (aFRR).

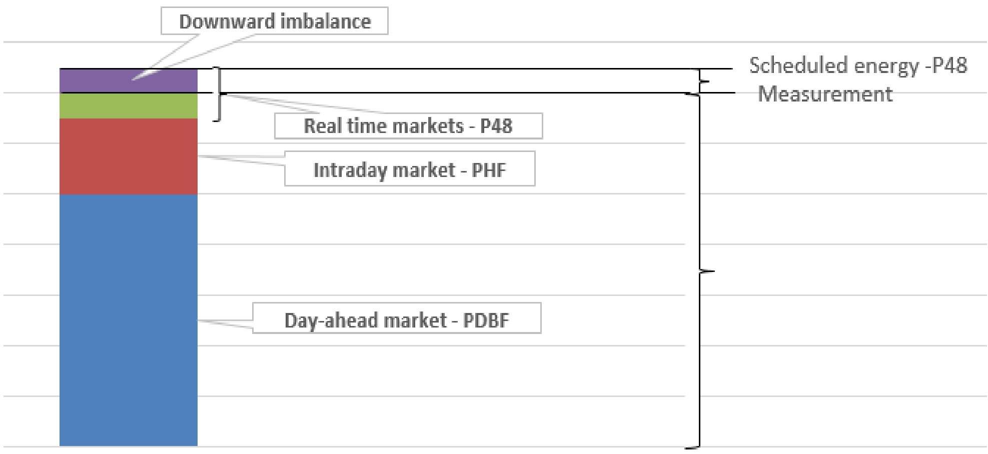


Figure 20 Downward imbalances

3.5.2 Hydraulic resources management

Within the incumbent company, it can be done the following breakdown of hydroelectric systems:

- Run-of-the-river. These hydroelectric systems harvest the energy from flowing water to generate electricity in the absence of a large dam and reservoir This type of hydroelectric generation uses the flow rate of water to generate power instead of the power from water falling a large distance, although water may still experience some vertical drop in a run-of-the-river system. It is typical from areas where there is little to no water storage, such as in a river. These generation units are deemed to be non-dispatchable, since it is not possible to perform a controlled management of its production. According to this fact, the opportunistic cost and therefore, the value of water, is considered to be zero. As a consequence of this, it will be seen how the output from these systems are excluded of the scope of this work since they cannot provide any flexibility to regulate imbalances.

- Daily modulation reservoir. In this case, a daily optimization is carried out in order to generate energy during the best periods within the day. For this reservoirs, the value of water loses its meaning as long term signal, since only the daily energy dispatch is taken into account.

- Regulation reservoir. Within this type, there can be distinguished different reservoirs according to the temporal horizon: weekly, monthly, annual or even hyper-annual management.
  Here, a medium and long-term planning is required, which should be joint coordinated with a short term operation. In order to achieve it, different mathematical models can be used to provide the efficient signals and for guaranteeing that short term scheduling remains coherent with longer term objectives.
  The specific hierarchy for the incumbent company is as follows:

  - Medium and long term. It is developed a planning that tackles the uncertainty by means of a stochastic mathematical model. As a brief overview, this consists of building a scenario tree. The idea behind this optimization is to take into account that the distribution of future natural inflows will be the same as it has been in the past.
    The scenario tree represents how the stochasticity is revealed over time: the different states of the random parameters and simultaneously the non-anticipative decisions over time. Correlation among parameters is also taken into account.

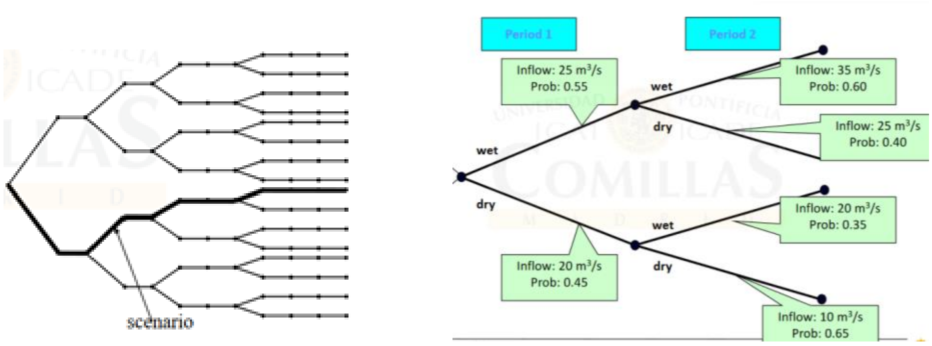


Figure 21 Long term planning – Scenario trees

This model is run periodically. At every execution only the results for the first period is considered, which at the same time it is the link with the short term exploitation.

- Short term. Here a deterministic model is used. With the results from the long term stochastic model, which will be the evolution of the reserves or the target output at the given period , a deterministic optimization is carried out. The latter provides an optimum water value, which in these cases do include a long term signal. If it is reviewed what it had been explained along the section 2 with regard to the different water value approaches, it can be clearly identified that the primal guideline is the oneused here.

  With the expected reserves evolution as an input, below a thermal gap estimation is computed with a two weeks horizon and taking into account the demand and non-dispatchable generation forecast.

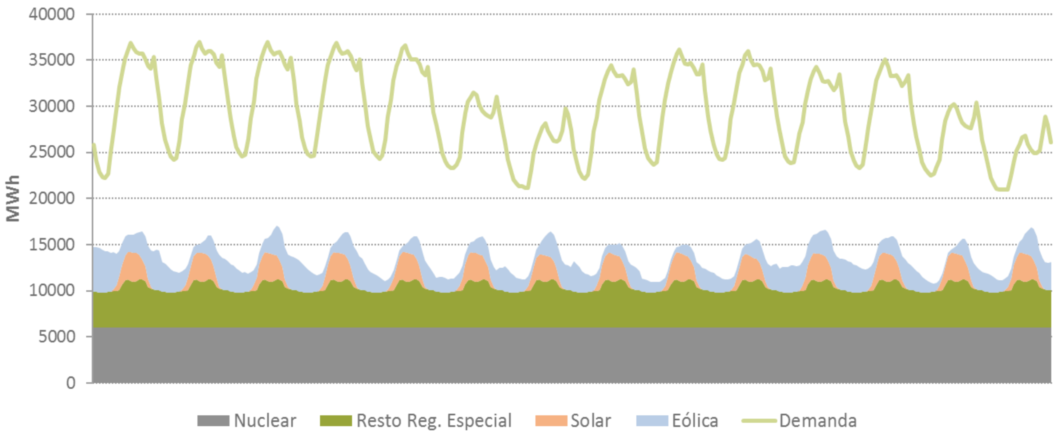


Figure 22 Thermal gap

As a result of that estimation, a forecast of the day-ahead market prices is carried out and a monotone curve is obtained.

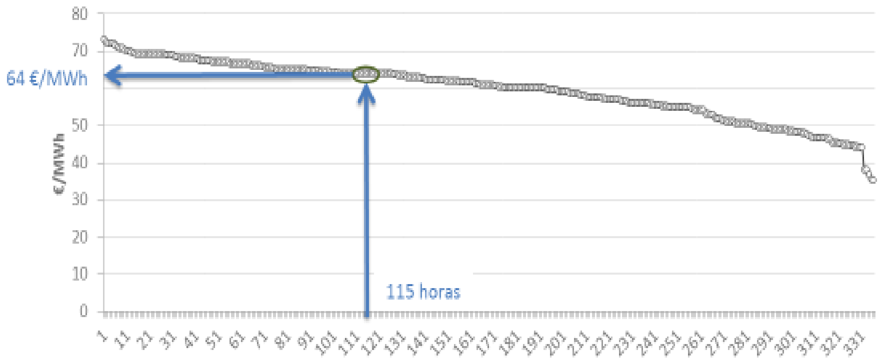


Figure 23 Prices monotone curve

By means of this curve and the primal guideline for the corresponding reservoir exploitation, its respective water value is established.

As it was already explained in section 2, the primal approach considered for the water value does not internalize the reaction to changes in the short term that were not foreseen in the mid-term planning. Due to this fact, when final conditions are different a reassessment of short term exploitation needs to be done. But this depends on the type of modifications. If the changes are due to a temporary situation such as a unit unavailability, the exploitation should not vary. However, if it corresponds to a structural situation, which would be noted looking at the forward markets, a new run of the long term model should be executed.

- Pump-storage units . Here the optimization is focused on the spread between the purchase and sale prices. For this purpose, it should be taken into account the technical efficiency between the actions of pumping and generating with the turbine. For this work, this kind of assets are very relevant for the regulation issue since it provides an additional flexibility for compensating the upward imbalance. Particularly, the main asset to consider here is an isolated pumping facility whose temporal horizon for the optimization is one week. The exploitation starts from the estimation of the monotone curve of the weekly prices, with a typical functioning based on pumping during the valley hours and generating during the peak periods, as long as the minimum spread bound by the efficiency is fulfilled.
  In the methodology section it is described how these facilities are included within the economic model, paying a special attention to their discrete functioning.

Once all the different types of hydroelectric systems have been reviewed, below it is depicted a breakdown of the hydraulic output considered:

- Regulation output. This is the production that should be considered for the imbalance compensation, since it is the one that can be adjust in a non-constrained way.

- Conditioned output. This is the production that results from the externalities already explained in the section 2 : flow rights of way and guarantee curves.

- Daily modulation output. This is the other production values that are considered for this work, since it can be also modified for purpose like the imbalances issue.

- Non-dispatchable output. Here the production from the run-of-river facilities are included and therefore, it is not possible to alter the final output.

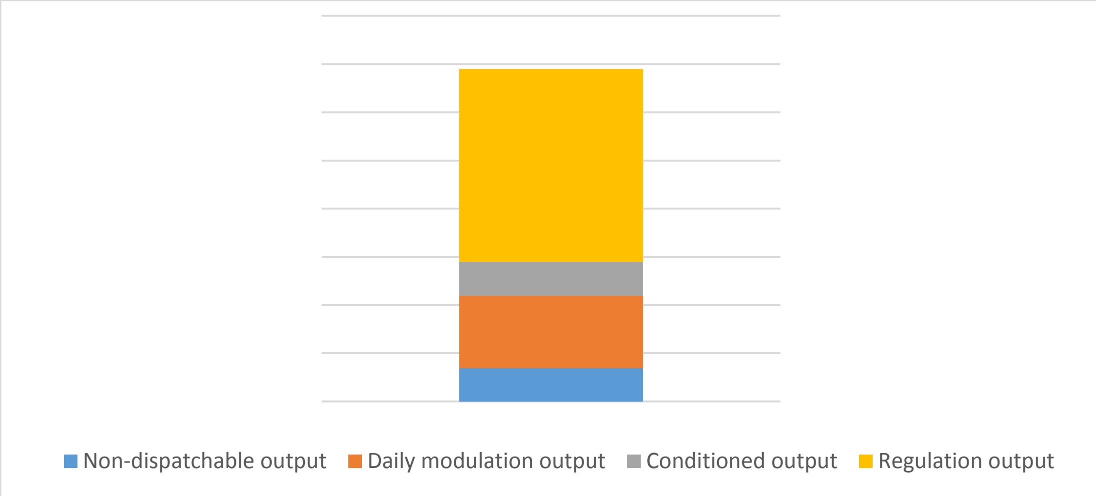


Figure 24 Hydraulic output

In the methodology section it is detailed how the available hydraulic resources for the imbalance regulation are computed, specifying the particular market schedules that are taking into account. The different constraints to introduce are also described there and in the subsection corresponding to the ex-post optimization model.

4. Proposed method

In this section it is firstly presented the Excel tool developed that integrates the whole model used to carry out the economic analysis. The corresponding methodology for the elaboration of the ex-post optimization model and the details about the procedure used for the water valuation are explained afterward in 4.2 and 4.3.

4.1 Excel tool modules for the economic analysis

- Interface main sheet

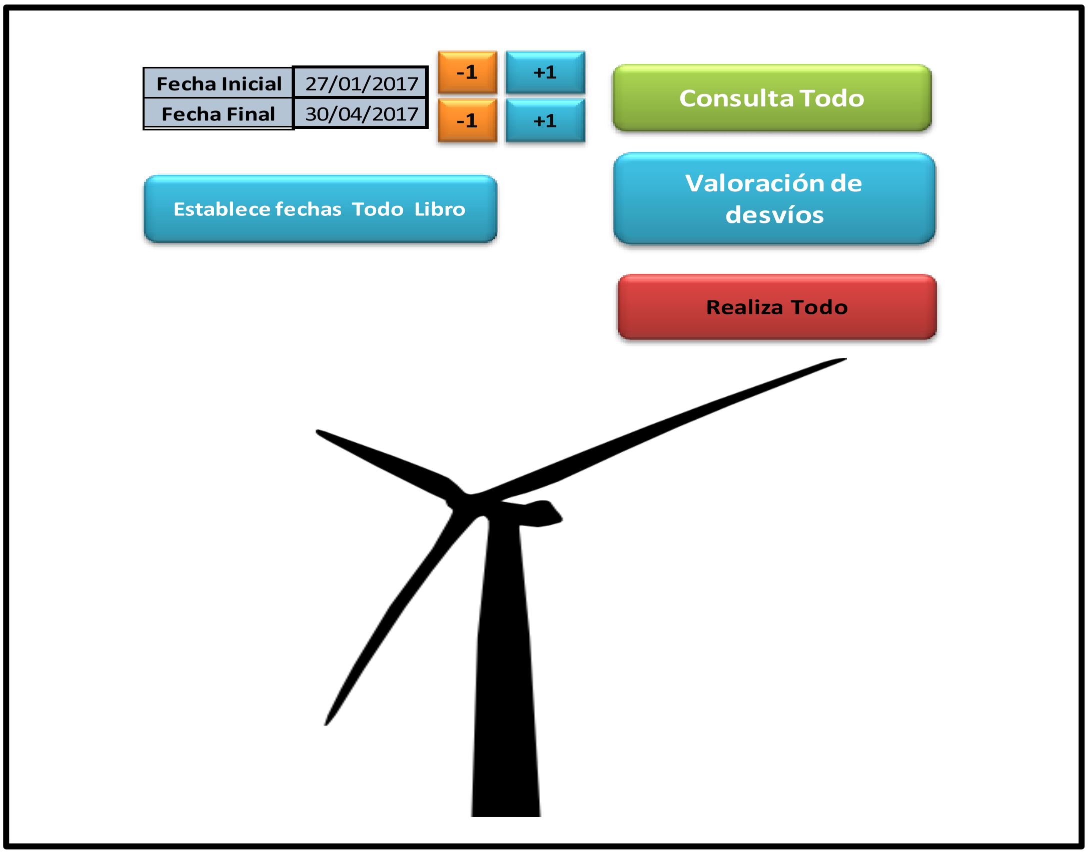


Figure 25 User's interface sheet

- Dates range input . Here the user will specify the initial and the final dates between it is aimed to do the corresponding queries and calculations

- Command button "Establece fechas Todo Libro". It allows to equalise the date ranges that are considered in each of the spreadsheets.

- Command button "Consulta todo". It runs the whole Excel queries that are implemented in each of the spreadsheets.

- Command button "Valoración de desvíos". Once the data queries are executed, with this command the calculations of the "Valoración de desvíos" spreadsheet is run.

- Command button "Realiza todo". Its activation gives rise to the execution both actions of "Consulta todo" and "Valoración de desvíos".

➢ Market prices spreadsheet

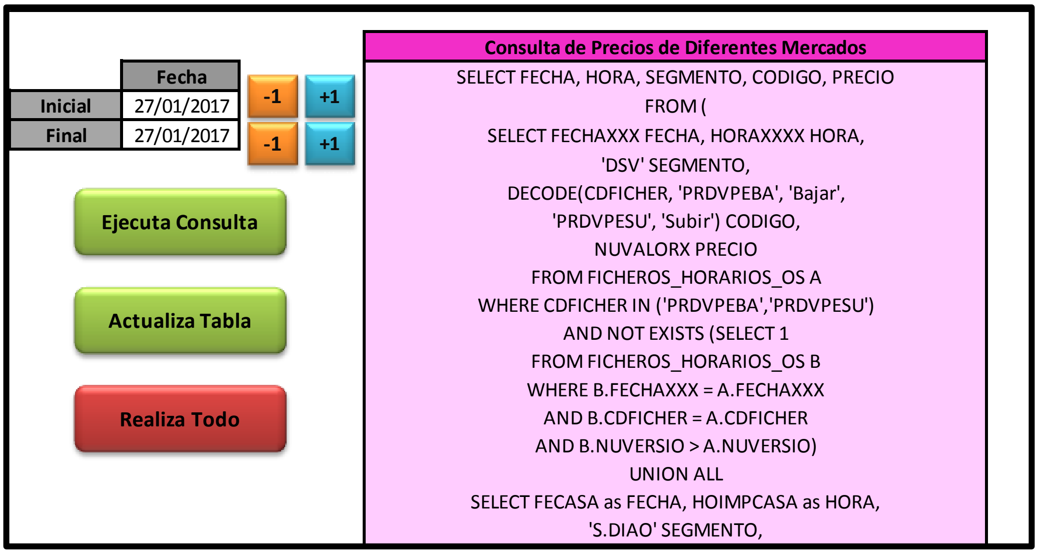


Figure 26 Market prices queries

- Command button "Ejecuta Consulta". It executes the SQL query in order to obtain from the market database the prices of the different sequential markets: day-ahead, seven intradays auctions, upward and downward, secondary regulation , upward and downward tertiary reserves energy, upward and downward imbalance management.

- Command button "Actualiza tabla". Once all the previous market prices are collected through the SQL query, this command builds and updates the dynamic table (an example for one day can be seen below) where the resulting prices are sorted out according to the different dates and hours in the vertical axis and to the chronological markets in the horizontal axis.

- Command button "Realiza todo". It executes the action from both previous commands.

Promedio de PRECIO		Etiquetas de columna																
		S.DIAO	S.INTRD							SEC			TER		DSV		GDV	
Etiquetas de fila	HORA	Diario	Int. 1	Int. 2	Int. 3	Int. 4	Int. 5	Int. 6	Int. n+1	Banda	Bajar	Subir	Bajar	Subir	Bajar	Subir	Bajar	Subir
27/01/2017	1	69,49	76,10	75,49						22,60		92,00	64,31		69,49	69,49		
27/01/2017	2	64,95	66,17	66,78						27,68	64,95	85,00	65,10	73,39	80,32	64,95		
27/01/2017	3	63,20	68,20	70,25						16,64	63,10	71,42	63,20		71,42	63,20		
27/01/2017	4	60,71	65,71	67,90						28,51	84,88	61,00			61,00	60,71		
27/01/2017	5	60,49	64,49	66,33	68,10					17,83	83,17	71,91		60,49	67,73	60,49		
27/01/2017	6	62,95	63,75	63,95	63,35					17,70	47,00			71,92	71,92	62,95		
27/01/2017	7	64,50	65,30	65,00	65,00					28,51	45,16			72,89	72,89	64,50		
27/01/2017	8	79,11	80,66	79,11	79,11	78,11				24,42	60,07	92,00	65,96	91,80	79,11	63,88		
27/01/2017	9	87,00	86,00	87,00	86,50	85,26				24,90	75,00		81,82		87,00	78,55		
27/01/2017	10	91,25	90,25	91,25	90,08	88,75				19,30	82,21	88,00	86,07		91,25	91,06		
27/01/2017	11	90,00	89,00	90,00	89,48	91,02				13,92	90,00	90,50		90,00	90,03	90,00		
27/01/2017	12	89,40	89,40	89,77	89,40	90,13	89,40			13,28	86,40	90,90		90,40	90,46	89,40		
27/01/2017	13	82,87	82,90	85,58	83,50	84,11	84,86			21,85		92,80		87,75	88,74	82,87		
27/01/2017	14	79,56	79,60	80,70	80,46	80,56	80,00			16,30	81,24	86,45		81,50	82,58	79,56		
27/01/2017	15	77,28	78,68	80,00	79,28	80,33	80,00			22,77	81,37	81,00		80,50	80,69	77,28		
27/01/2017	16	75,51	76,15	78,00	78,10	78,10	76,67	79,10		18,70		81,50		80,50	80,79	75,51		80,50
27/01/2017	17	76,08	76,78	78,02	78,56	79,07	79,03	79,73		16,70	81,57	81,50		81,00	80,62	76,08		80,00
27/01/2017	18	78,55	79,69	79,44	80,10	80,55	80,38	80,05		16,00	76,50	83,70		82,50	81,60	78,55		80,00
27/01/2017	19	84,44	84,44	86,44	85,88	86,36	84,44	85,44		23,50	76,44			86,94	84,44	76,44		86,94
27/01/2017	20	84,49	84,49	86,49	86,73	85,75	86,00	88,00		23,71	83,00				86,94	84,49		86,94
27/01/2017	21	79,56	80,00	81,56	84,55	81,06	81,50	82,08		20,00	79,56	81,00		80,50	80,52	79,56		
27/01/2017	22	76,77	80,25	79,66	81,77	81,76	80,00	78,02	79,77	31,58	81,34	95,56		95,00	95,04	76,77		
27/01/2017	23	73,78	77,33	76,28	78,78	78,78	78,77	76,28	73,10	31,58	78,00	87,00		87,00	73,78	63,41		
27/01/2017	24	70,30	73,71	72,80	75,30	73,29	75,00	74,19	73,48	27,11	66,30	86,73		86,00	86,02	70,30		

Figure 27 Market prices

- Wind power units' market programs spreadsheet

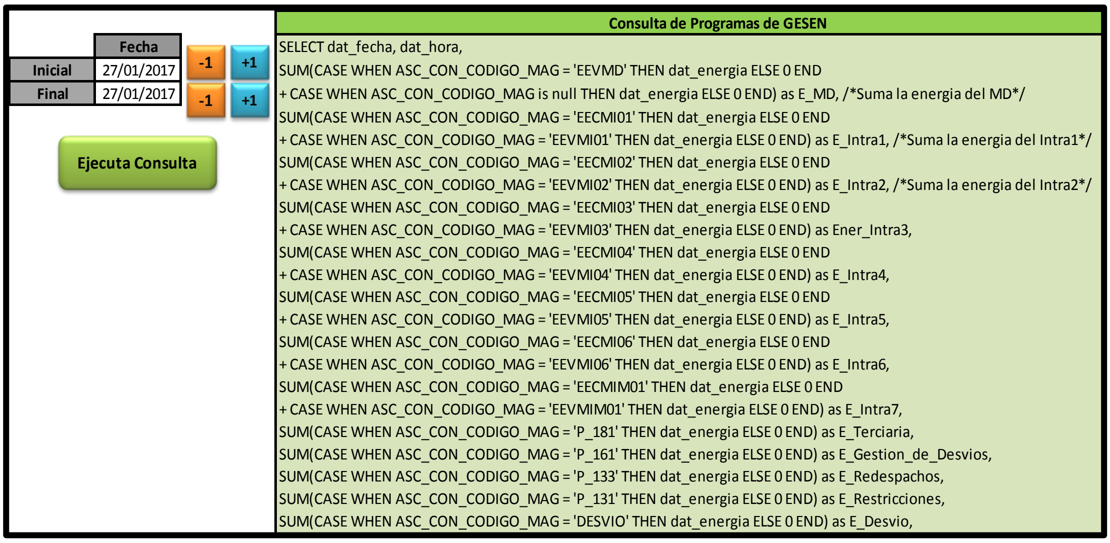


Figure 28 Wind power programmes queries

- Command button "Ejecuta Consulta". It executes the SQL query that extracts from the settlement database the corresponding programmes for the wind power portfolio. It includes the following scheduled blocks: day-ahead market allocation, seven intraday auctions, tertiary reserves energy, imbalance management energy, real time redispatches and technical constraints allocation. From these data the different energy programmes can be computed in order to be used in the "Valoración de desvíos" spreadsheet. Besides the query execution, it displays and sorts out the data in a table as the one shown below.

  Two separated spreadsheets are devoted for the wind power portfolios considered: not-enabled and the enabled for the provision of tertiary reserves.

DAT_FECHA	DAT_HORA	E_MD	E_INTRA1	E_INTRA2	ENER_INTRA3	E_INTRA4	E_INTRA5	E_INTRA6	E_INTRA7	E_TERCIARIA	E_GESTION_DE_DESVIOS	E_REDESPACHOS	E_RESTRICCIONES
27/01/2017	1	1192,4	-17,4	37,6	0	0	0	0	0	0	0	0	0
27/01/2017	2	1210,5	-18,5	31,3	0	0	0	0	0	0	0	0	0
27/01/2017	3	1239	-49,9	40,8	0	0	0	0	0	0	0	0	0
27/01/2017	4	1240,1	-42,9	21	0	0	0	0	0	0	0	0	0
27/01/2017	5	1196,5	-37,3	2	39,8	0	0	0	0	0	0	0	0
27/01/2017	6	1126,9	-30,4	-13,7	31	0	0	0	0	0	0	0	0
27/01/2017	7	1039,4	-28,1	6,3	11,1	0	0	0	0	0	0	0	0
27/01/2017	8	964,1	9,7	-47,4	9,9	6,1	0	0	0	0	0	0	0
27/01/2017	9	898	19,9	-74,9	0,5	11	0	0	0	0	0	0	0
27/01/2017	10	834,6	7,8	-47,3	-5,6	9,1	0	0	0	0	0	0	0
27/01/2017	11	786,3	14,1	-9,5	-13,2	4,5	0	0	0	0	0	0	0
27/01/2017	12	753,7	20,6	12,3	-10,6	-9,2	114,2	0	0	0	0	0	0
27/01/2017	13	753,8	24,3	13,1	-21,7	2,4	-20,6	0	0	0	0	0	0
27/01/2017	14	722,1	44,7	-15,2	0	3,4	-13	0	0	0	0	0	0
27/01/2017	15	728,4	28,1	-43,1	-1,1	-8,2	16,1	0	0	0	0	0	0
27/01/2017	16	711,4	28,9	-56,4	0,8	36,7	-30,5	-23,5	0	0	0	0	0
27/01/2017	17	762,1	20,7	8,3	-5,1	-11	-52,7	-20,4	0	0	0	0	0
27/01/2017	18	823,8	28,1	26,8	-2,2	-4,4	-96,4	-14,8	0	0	0	0	0
27/01/2017	19	928,5	-2,1	31,8	-0,6	-9,7	-106,8	-12,8	0	0	0	0	0
27/01/2017	20	1013,8	-8,6	22	-0,2	29,9	-73,8	-40,3	0	0	0	0	0
27/01/2017	21	1092	4	8,8	-2,6	12,3	-25	-72	0	0	0	0	0
27/01/2017	22	1178,6	-3,7	-17	-4,6	11,7	10	-65,2	20	0	0	0	0
27/01/2017	23	1253,6	-6,6	-32,4	-2,1	9,2	16,9	-50,2	28,6	0	0	0	0
27/01/2017	24	1315,5	-12	-37,6	9,4	6,2	19,4	-41	35	0	0	0	0

Figure 29 Wind power market programmes results

- Hydro basins market programs spreadsheets

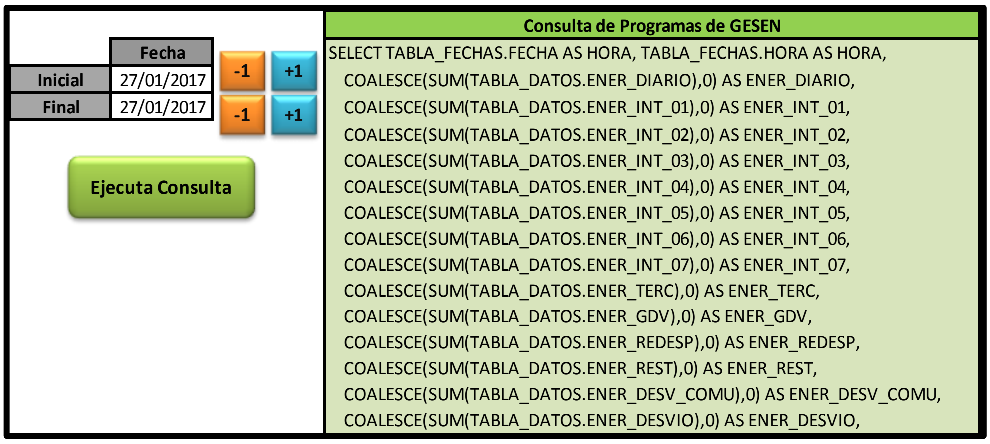


Figure 30 Hydro market programmes queries

- Command button "Ejecuta Consulta". It executes the SQL query that extracts from the settlement database the corresponding programmes for the hydro basins portfolio. It includes the same scheduled blocks as in the wind power case. From these data different energy programmes can be computed in order to be used for the building of the upward and downward staircase, which is detailed in 4.3. Besides the query execution, it displays and sorts out the data in a table as the one shown below.

  An independent spreadsheet is devoted for each one of the basins that are considered in this work, distinguishing the pumping facilities within the corresponding basins. For more details about this, the subsection should be consulted.

HORA	HORA	ENER_DIARIO	ENER_INT_01	ENER_INT_02	ENER_INT_03	ENER_INT_04	ENER_INT_05	ENER_INT_06	ENER_INT_07	ENER_TERC	ENER_GDV	ENER_REDESP	ENER_REST
27/01/2017	1	895,3	0	0	0	0	0	0	0	-70,8	0	0	-34,5
27/01/2017	2	717,9	0	0	0	0	0	0	0	0	0	0	-252,9
27/01/2017	3	717,9	0	0	0	0	0	0	0	0	0	0	-200,9
27/01/2017	4	34,9	57	0	0	0	0	0	0	0	0	0	-34,9
27/01/2017	5	0	32	0	0	0	0	0	0	0	0	0	0
27/01/2017	6	540,5	0	0	0	0	0	0	0	0	0	0	-213,6
27/01/2017	7	717,9	0	0	0	0	0	0	0	0	0	0	-318,5
27/01/2017	8	1330,4	0	0	0	-104,2	0	0	0	-99,2	0	0	-55,6
27/01/2017	9	1449	-84,2	0	0	-150	0	0	0	-170	0	0	-41,4
27/01/2017	10	1449	0	0	0	0	0	0	0	-85	0	0	-13,5
27/01/2017	11	1449	0	0	0	0	0	0	0	0	0	0	-13,4
27/01/2017	12	1449	0	0	0	0	0	0	0	0	0	0	-28,6
27/01/2017	13	1449	0	0	0	0	0	0	0	0	0	0	-81,1
27/01/2017	14	1401,3	0	0	0	0	0	0	0	0	0	0	-97,1
27/01/2017	15	1148,3	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	16	929	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	17	1021,8	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	18	1148,3	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	19	1449	0	0	0	0	0	0	0	0	0	0	-117,7
27/01/2017	20	1449	0	0	0	0	0	0	0	0	0	0	-119,4
27/01/2017	21	1401,3	0	0	0	0	0	0	0	0	0	0	-27,5
27/01/2017	22	1148,3	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	23	895,3	0	0	0	0	0	0	0	0	0	0	0
27/01/2017	24	895,3	0	0	0	0	0	0	0	0	0	0	0

Figure 31 Hydro market programmes results

- Measurement spreadsheet

  - Command "Actualizar consulta". It allows to execute the SQL query in order to obtain the real production of both the wind power portfolio and the hydro basins. This information is used for the computation of the imbalances from wind power, which represents one of the critical values to generate in the tool, and also the imbalances of hydro portfolio. The latter is not explicitly employed in the tool, but it has been useful for the correlation analysis carried out for other purposes out of the scope of this work.

  - Command "Update tabla". This command updates the table in which the different measurements are shown.

INI MES	FIN MES		ACTUALIZAR CONSULTA		UPDATE TABLA
27.ene.17	27.ene.17				

FECHA	MEDIDA	UOF	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23	H24
27/01/2017 0:00	MWh BC	X	0	-	-	-222,3	-288,0	-31,7	-	-0,0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-156,0
27/01/2017 0:00	MWh BC	X	921	460,4	331,5	148,2	198,0	198,9	225,0	848,6	971,3	1.373,6	1.442,6	1.417,5	1.417,3	1.203,2	1.127,6	1.074,8	978,2	1.238,3	1.250,4	1.539,0	1.804,0	1.410,8	967,3	763,2
27/01/2017 0:00	MWh BC	X	20	20,0	19,6	19,6	19,4	19,2	17,5	17,1	30,8	31,5	29,9	30,1	29,3	29,4	29,6	29,9	29,5	29,1	26,3	68,3	68,5	67,5	59,8	59,6
27/01/2017 0:00	MWh BC	X	25	24,7	24,7	24,7	24,7	24,7	24,4	24,7	24,7	23,3	19,3	9,3	10,4	22,3	24,7	24,1	22,5	20,7	24,0	18,5	20,6	24,1	23,9	24,2
27/01/2017 0:00	MWh BC	X	1.257	1.270,7	1.365,3	1.277,8	1.322,5	1.276,6	1.198,1	1.061,8	947,3	817,5	746,4	717,3	697,0	687,1	756,8	725,6	802,2	833,1	869,2	903,6	984,2	1.084,7	1.148,4	1.207,1
27/01/2017 0:00	MWh BC	X	1.035	942,5	977,8	893,8	765,4	767,8	719,1	707,2	764,6	760,4	746,9	836,6	868,1	965,5	1.104,2	1.031,2	1.075,4	1.105,4	1.062,4	1.014,0	1.077,8	1.095,7	1.140,9	1.241,4
27/01/2017 0:00	MWh BC	X	45	46,1	51,3	49,9	40,9	43,6	61,6	58,9	60,9	53,3	55,1	44,5	35,6	41,7	37,2	17,2	7,6	7,5	12,6	7,2	5,8	5,0	15,7	27,4
27/01/2017 0:00	MWh BC	X	10	7,7	7,5	8,1	30,2	31,3	34,5	36,0	66,5	78,0	78,2	45,4	37,6	39,8	39,5	39,2	38,4	51,2	209,3	212,3	90,4	63,1	59,2	156,4
27/01/2017 0:00	MWh BC	X	-190	-708,9	-1.396,3	-1.409,6	-1.407,0	-1.293,4	-281,4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27/01/2017 0:00	MWh BC	X	-1	-1,2	-1,9	-1,9	-1,9	-1,8	-0,8	-0,4	-0,4	1,5	217,3	560,1	791,6	785,6	404,1	307,7	560,6	781,4	516,4	567,5	362,7	389,4	215,8	269,5
27/01/2017 0:00	MWh BC	X	314	280,9	232,9	196,1	205,3	204,6	206,0	288,3	471,0	501,6	408,9	383,2	286,7	279,6	280,9	272,3	285,7	293,5	424,4	476,2	516,0	442,9	348,5	294,8
27/01/2017 0:00	MWh BC	X	0	-0,2	-14,3	-222,4	-227,9	-88,8	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,1	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2	-0,2
27/01/2017 0:00	MWh BC	X	0	-0,5	-32,9	-37,6	-37,7	-37,7	-37,7	-10,8	-0,0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27/01/2017 0:00	MWh BC	X	115	2,8	1,0	0,9	0,8	0,7	1,2	346,7	493,4	767,4	975,6	1.054,3	1.047,9	928,7	204,5	121,1	118,1	346,4	543,1	582,5	543,6	452,5	279,7	304,8

Figure 32 Units' final output

- Economic assessment spreadsheet

  - "P48". Final scheduled energy (closest to real time) which is formed by the final hourly program (PHF) and the real time dispatches resulting from the ancillary services provision .established and published by the SO 15 minutes before the beginning of the corresponding program period. It includes tertiary reserves and imbalance management allocations. In this case, it only refers to aggregated wind power portfolio not enabled for the provision of tertiary reserves.

  - "P48 NO HAB". Same as the previous variable, but refered to wind power portfolio enabled for the provision of tertiary reserves.

  - "Asignación terciaria". Tertiary reserves provision that has been allocated to the wind power portfolio.

  - "Asignación Gestión desvíos". Imbalance management provision that has been allocated to the wind power portfolio.

  - "Medida eólica no habilitada". Final metered production of the not enabled wind power portfolio.

  - "Medida eólica habilitada". Final metered production of the enabled wind power portfolio.

- "Medida total". Final metered production of the whole wind power portfolio.
- "Desvío habilitada". Imbalance in which the enabled wind power portfolio incurs.
- "Desvío total". Imbalance in which the whole wind power portfolio incurs.
- "PMD". Hourly day-ahead market price.
- "PDESVB". Hourly price for the downward imbalances within the Spanish dual pricing scheme.
- "PDESVS". Hourly price for the upward imbalances within the Spanish dual pricing scheme.
- "PTERB". Hourly price for the downward tertiary reserves.
- "PTERS". Hourly price for the upward tertiary reserves.
- "PGDESVB". Hourly price for the downward imbalances management market.
- "PGDESVS". Hourly price for the upward imbalances management market
- "Necesidades del Sistema". System needs in terms of the overall needs.
- "Sentido desvío (Favor/contra)". Direction of the imbalance from wind power portfolio: same or opposite the system needs direction.
- "Valoración de desvíos". Economic valuation of the imbalances from wind power portfolio. It is calculated according to the settlement rules presented in section 3. It should be noted that the final values computed here account for an absolute valuation and not for a relative overrun in comparison with the day-ahead market price PMD.
- "Valoración de desvíos terciaria + gestión desvíos". Economic penalty resulting from the non-compliance with the tertiary reserves and imbalance management energy allocated by the TSO. Both scheduled energies are considered as a whole.
- "Valoración total". It integrates the sum of the economic valuation of the imbalances and the penalties from the non-compliance with tertiary reserves and imbalance management allocatons.
- "Valoración recurso hidráulico". It represents the total value that is allocated to hydraulic resources involved in the regulation of the corresponding hourly wind power imbalances.
- "Decisión óptima". Here it is specified whether the optimal decision is to regulate the whole imbalance by means of the available hydraulic resources or to incur in the total wind power imbalance by noticing it to the TSO.

DAT_FECHA	DAT_HORA	P48	P48 NO HAB	P48 HAB	Asignación terciaria	Asignación gestión desvíos	Medida eólica no habilitada	Medida eólica habilitada	Medida real total	Desvío habilitada	Desvío total
	1	1746,7	1050	696,7	-55,3	0	X	X	X	X	X
	2	1893,9	1105,3	788,6	0	0	X	X	X	X	X
	3	1922,1	1120,3	801,8	0	0	X	X	X	X	X
	4	1888,5	1100,8	787,7	-18,2	0	X	X	X	X	X
	5	1917,8	1125,7	792,1	-40,9	0	X	X	X	X	X
	6	1954,1	1131,8	822,3	-25,2	0	X	X	X	X	X
	7	1986	1141,2	844,8	-13,1	0	X	X	X	X	X
	8	2053,4	1160,7	892,7	0	0	X	X	X	X	X
	9	2076,1	1162,8	913,3	0	0	X	X	X	[illegible]	[illegible]
	10	2161,2	1195,5	965,7	0	0	X	X	X	[illegible]	[illegible]
	11	2338,1	1268,7	1069,4	-22,7	-13,6	X	X	X	[illegible]	[illegible]
	12	2524	1306	1218	3,4	-15	X	X	X	X	X
	13	2713,1	1389,5	1323,6	0	-25,6	X	X	X	X	X
	14	2908,4	1457,3	1451,1	0	0	X	X	X	X	X
	15	3025	1491,5	1533,5	0	0	X	X	X	X	X
	16	3150,5	1545,2	1605,3	0	0	X	X	X	X	X
	17	3259,2	1591,7	1667,5	0	0	X	X	X	X	X
	18	3328,2	1645	1683,2	0	0	X	X	X	X	X
	19	3346,9	1642	1704,9	0	0	X	X	X	X	X
	20	3379,5	1692,4	1687,1	0	0	X	X	X	X	X
	21	3358,1	1711	1647,1	0	0	X	X	X	X	X
	22	3337,5	1709,3	1628,2	0	0	X	X	X	X	X
	23	3545,1	1879,7	1665,4	0	0	X	X	X	X	X
	24	3565,1	1911,4	1653,7	0	0	X	X	X	X	X

PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS	Necesidades sistema	FAVOR / CONTRA	Valoración desvíos	Valoración desvíos terciaria	Valoración total	Valoración recurso hidráulico	Decisión óptima	Ahorro Regular vs Desvío comunicado
48,51	48,51	48,51	34,43				BAJAR	FAVOR	X	X	X	X	Regular	426,73534
42,1	46,1	42,1		45,63			SUBIR	CONTRA	X	X	X	X	Regular	681,86036
36,68	42,54	36,68		41,9			SUBIR	CONTRA	X	X	X	X	Regular	891,32528
34,4	34,4	6,82	10				BAJAR	FAVOR	X	X	X	X	Regular	35,72806
33,81	33,81	1,97	1,97				BAJAR	CONTRA	X	X	X	X	Regular	2215,6168
34,09	34,09	1,97	1,97				BAJAR	CONTRA	X	X	X	X	Regular	1941,49754
41,91	[illegible]	1,97	1,97				BAJAR	CONTRA	X	X	X	X	Regular	4071,7896
48	[illegible]	9,82	1,97				BAJAR	CONTRA	X	X	X	X	Regular	7415,25483
[illegible]	[illegible]	28,25	25,1				BAJAR	CONTRA	X	X	X	X	Regular	2046,81214
[illegible]	[illegible]	32,88	30,1		39,1		BAJAR	CONTRA	X	X	X	X	Regular	843,04216
[illegible]	[illegible]	47,08	38,1		37,1		SUBIR	FAVOR	X	X	X	X	Comunicar desvío	-848,24633
43,47	[illegible]	43,47		48	26		SUBIR	FAVOR	X	X	X	X	Comunicar desvío	-998,68202
41,02	53,32	41,02		53,19	26		SUBIR	CONTRA	X	X	X	X	Regular	405,01122
39,83	50,51	39,83		50,33	25		SUBIR	CONTRA	X	X	X	X	Regular	468,44468
39,1	47,86	39,1		47,23	20,1		SUBIR	CONTRA	X	X	X	X	Regular	62,47873
37,3	44,43	37,3		44			SUBIR	CONTRA	X	X	X	X	Comunicar desvío	-344,27107
36,21	48,89	36,21		48,66			SUBIR	CONTRA	X	X	X	X	Regular	180,33039
38,15	53,79	38,15		53,77			SUBIR	CONTRA	X	X	X	X	Regular	1387,75147
42,18	51,86	42,18		51,77			SUBIR	CONTRA	X	X	X	X	Regular	491,7012
44,95	50,29	44,95		50,22			SUBIR	FAVOR	X	X	X	X	Regular	11,6377
41,01	47,42	41,01		46,86			SUBIR	CONTRA	X	X	X	X	Comunicar desvío	-0,08484
39,1	49,34	39,1		49,33			SUBIR	CONTRA	X	X	X	X	Regular	120,51694
36,25	46,06	36,25		46			SUBIR	CONTRA	X	X	X	X	Comunicar desvío	-39,77044
34,56	42,76	34,56					SUBIR	FAVOR	X	X	X	X	Comunicar desvío	-0,00224

Figure 33 Results spreadsheet

- Hydro basins day-ahead market bids

  In this spreadsheet the queries and display of the day-ahead market bids that correspond to the hydro basins are carried out.

- Upward staircase & Downward staircase

  In these spreadsheets the corresponding price-energy staircases for the valuation of the water resources are built. In 4.3, it can be consulted a detailed explanation of the building of this staircase.

4.2 Economic analysis calculations

4.2.1 Ex-post optimization model

The economic model is aimed to be built under an ex-post optimization basis, that is, in this approach no uncertainty appears. This optimization tool based on past data is thought to be developed in order to help the assessment and identification of the improvement gaps related to the generation control center decision making of the incumbent company. Here is important to have in mind those comments included in section 3 regarding the AGC functioning and the final decisions the generation control centre act on manually.

This part will provide useful results to assess the strategy's performance followed by the generation control center of the incumbent company and to draw some conclusions about different strategic improvements to implement.

The rest of this subsection is devoted to describe the optimization problem distinguishing its typical structure of objective functions, decision variables, input data and constrainst. Alhtough this is described as the model were built to be solved with an optimization solver software, the implementaiton of the model is carried out by using an VBA programme that is embedded within the Excel tool previously described.

Instead of that optimization solving, in this case different loops and conditional instructions are defined in VBA in order to solve the model. The main issue behind the program is the part devoted to valuate the hydro resources, which is done by the energy reserves staircase procedure that is explained in 4.2.3. With these staircases , a loop is built to allocate the wind power imbalance among the available hydro units following a economic merit-order and subject to the constrains specified later in this subsection.

The scheme of the ex-post optimization model would be the following:

- Objective function

$$Min\ \boldsymbol{Y_{REGULA}} \cdot \left[\left(\sum_I \boldsymbol{Reg_{turb_i}} \cdot \boldsymbol{y_{turb_i}} \cdot \boldsymbol{Water\ value_{turb\ i}}\right) - \left(\sum_I \boldsymbol{Reg_{pump_i}} \cdot \boldsymbol{y_{pump_i}} \cdot \boldsymbol{Water\ value_{pump_i}}\right)\right] - \boldsymbol{Y_{DESVÍA}} \cdot [\boldsymbol{IMB_{wind}} \cdot \boldsymbol{Price_{imb}}]$$

- Decision variables

Decision variables correspond to the manual decisions to be taken by generation control center:

Y_{REGULA} : binary variable. It takes a value of 1 if the decision is to regulate the wind power imbalances

$Y_{DESVÍA}$: binary variable. It takes a value of 1 if the decision is to notice the wind power imbalances to the TSO and not regulate

y_{turb_i} : binary variable. It takes a value of 1 if the decision is to enable the turbine i within the AGC in order to follow the imbalances regulation tracking mode.

y_{pump_i} : binary variable. It takes a value of 1 if the decision is to enable the pump i within the AGC in order to follow the imbalances regulation tracking mode

Reg_{turb_i} :continuous variable. Its value corresponds with the regulation energy used from turbine i.

Reg_{pump_i} : continuous variable. Its value corresponds with the regulation energy used from turbine i.

- Input data

As it is an ex-post optimization, none of the data are subject to uncertainty. All the required values are taken as inputs. Below it is specified the different hourly information that is managed within the model:

- Wind power imbalance: IMB_{wind}
- Water values for the units i considered: $Water_{value_{turb\ i}}$, $Water_{value_{pump\ i}}$. As it is explained in following subsection about staircase building and according to the hydro resources management explanation, these are taken directly from the price-energy hourly bids.
- Market prices: day-ahead market prices, tertiary reserves market prices, imbalance management market prices, imbalances prices ($Price_{imb}$)
- Units' programmes :
    - Hydro units. Non-dispatchable energy, conditioned energy, $P48_{turbine\_i}$, $P48_{pump\_i}$, Tertiary reserves and imbalance management allocations.
    - Wind power : $P48_{enabled\ wind\ power}$, $P48_{not\ enabled\ wind\ power}$
- Units measurements
- Hydro units limitation: $P_{\max\_turbine\_i}$, $P_{\max\_pump\_i}$

- Constraints

As it was explained in section 3 , the real AGC functioning encompasses an automated distribution of the imbalance regulation needs among the enabled units within the AGC at a certain moment. This distribution is run by the AGC carrying out an economic dispatch along with other physical constraints. For this simplified model , the merit-order dispatch is addressed by the mentioned price-energy staircase construction. What is shown below corresponds to the physical constrains that are included in the model. Regulation ramps of the units, efficiency losses and spatial-temporal correlation within a basin topology are the main ones that are missing here and therefore, this fact makes the model differ from the actual AGC functioning.

- **Equality between wind power imbalance and hydraulic regulation**

$$\sum_{I} Reg_{turb\_i} - \sum_{I} Reg_{pump_i} = -IMB_{wind} \cdot Y_{REGULA}$$

- **Water values limitation**

Since the water values that are used stem from an primal approach, as it was explained back in the document, this valuation is not implicitly flexible to face short term conditions changes from the long and medium term planning. In connection with that and with the achievement of reserves targets levels, a limitation has been included to the water values in this model. Both the upper and lower limits will be fixed by the tertiary reserves and imbalance management market prices for the energy that is known to be included in the particular P48 of the corresponding. This is not applied for upward reserve energy not scheduled within the P48 of the hour.

$$\boldsymbol{Downward\ tert.reserves\ price\ (PTERB) < Water\ value_i < Upward\ tert.reserves\ price\ (PTERS)}$$

AND

$$\boldsymbol{Downward\ imb.managment\ price\ PGDSVB < Water\ value_i < Upward\ imb.management\ price\ PGDSVS}$$

- **Energy balance in an equivalent reservoir**

The energy balance in the equivalent reservoir is a constraint that is not modelled but it is assumed to be implicit embedded in the hydraulic management models from the current model take its inputs.

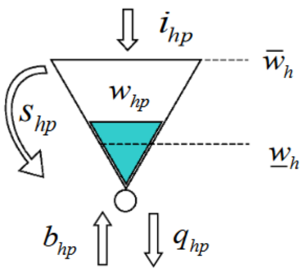


Figure 34 Energy balance in a single reservoir

The below equation shows that the energy stored (w_{hp}) in an equivalent reservoir in a catchment basin h at the end of period p is the amount existing at the end of the preceding period ($w_{h(p-1)}$)), less production (q)) and spills (s_{hp})) occurring during the period, plus the energy associated with pumping $\eta_h \cdot b_{hp}$ and the energy equivalent of natural inflows i_{hp}.

$$w_{hp} = w_{h(p-1)} - [q_{hp} + s_{hp} - \eta_h \cdot b_{hp}] + i_{hp}$$

- **Output limits**

Moreover, in the catchment basins the net output Is limited:

$$P48_{turbine\_i} + Reg_{turb\_i} \leq P_{\max\_turbine\_i} \cdot y_{turb\_i}$$

$$P48_{turbine\_i} + Reg_{turb\_i} \geq P_{\min\_turbine\_i} \cdot y_{turb\_i}$$

Pumping capacity is likewise limited to nominal capacity:

$$P48_{pump\_i} + Reg_{pump\_i} \leq P_{\max\_pump\_i} \cdot y_{pump\_i}$$

$$P48_{pump\_i} + Reg_{pump\_i} \geq P_{\min\_pump\_i} \cdot y_{pump\_i}$$

In the case of having considered each pumped storage unit to be modelled individually, it may not be always possible to disregard the fact that when the reversible machines operate as pumps, the power demand is a unit magnitude. In other words, there are usually only two pumping states, $\{0, P_{\max\_pump\_i}\}$. To model this discrete functioning, the following constrain should be used instead of the one shown above:

$$P48_{pump\_i} + Reg_{pump\_i} = P_{\max\_pump\_i} \cdot y_{pump\_i}$$

Although this effect is disregarded in the model discussed here, one example from the results sections is devoted to carry out a sensitivity analysis of both approaches (continuous vs discrete pumping). The staircase modelling would become a bit more complex for the discrete pumping.

- **Limits to equivalent reservoirs and long-term guidelines**

This is another constrain that is considered to be implicitly included within the long term hydraulic management from the current economic model arises. The idea The volume stored in reservoirs is subject to certain limits that may not be breached, as well, to other considerations. In the horizon considered, these are taken as inputs and remain constant throughout this horizon.

$$\underline{w_h} \leq w_{hp} \leq \overline{w_h}$$

A further improvement for the model would be the inclusion of equations to make reserve limits time-dependent.

4.2.2 Hydro resources valuation. Prices-energy staircase

Starting from what has been explained along the section 3 about the hydro resources management, here it is going to be further described how in the thesis' model it is actually valuated the water used for the wind power imbalances regulation.

As it was pointed out, the hydro management model encompasses two levels of optimization: stochastic model in the long term and deterministic model in the short term having as inputs the results from the long term model. This input was based on a primal approach, that is, a target level for the reserves are established as the setpoint to reach at the end of the corresponding period. Therefore, through this management model it is not obtained an explicit water value.

However, it was explained that a monotone curve of the forecasted prices for day-ahead market is used to decide the final bids. Taking into account that these final bids are computed in such a way the target level imposed by the long term model is reached, it is reasonable to consider those bids as the best proxy of the water value.

Having this in mind, it should be noted all the hydro basins management through the different markets are out of scope of this economic assessment and the final programmes (P48) are taken as inputs. Likewise, the bids for the day-ahead market are also obtained as inputs from the company's front office management.

As for the hydro resources modelling, considering the entire catchment systems in detail would give rise to a very complex problem that falls outside the bounds of this work. Consequently, an aggregate model is proposed for each basin so that instead of storing water, it receives, stores and produces equivalent energy. Pumping facilities of each basin are considered as independent aggregate catchments.

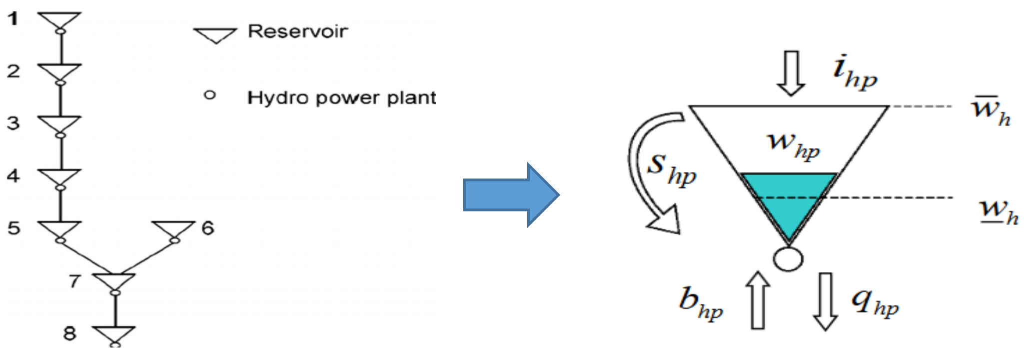


Figure 35 Equivalent single basin

These are the aggregated catchment facilities finally considered:

Hydro units
A
B
C
D
E
F

A_bomb
D_bomb
E_bomb
F_bomb

The rated power from the considered units are not shown due to confidential issues. Those units whose name include "bomb" corresponds to the independent pumping facilities considered. Note that only 70% of the pumped energy can be subsequently converted to electric power. However, this is something already internalized in the water values that are used for the resources valuation.

Taking into account these aggregate model for each one of the basins, along with the hourly values of the P48 and the day-ahead market bids, a direct procedure is built for valuating the water resources used for imbalances regulation. Below, the different steps for that purpose are specified:

- For each of basins it is computed the scheduled production that is assumed to be regulation output (including daily modulation output) according to the classification made in section 3. This is calculated subtracting the non-dispatchable and conditioned output from the P48. Although it was not mentioned until now, both non-dispatchable and conditioned output can be identified as that energy blocks offered at a price of 0 €/MWh in the day-ahead market. For this very reason, the bids considered in this regulation staircases building process are those one with price different from 0.

$$Adjustable\ output = P48 - (non - dispatchable\ output + conditioned\ output)$$

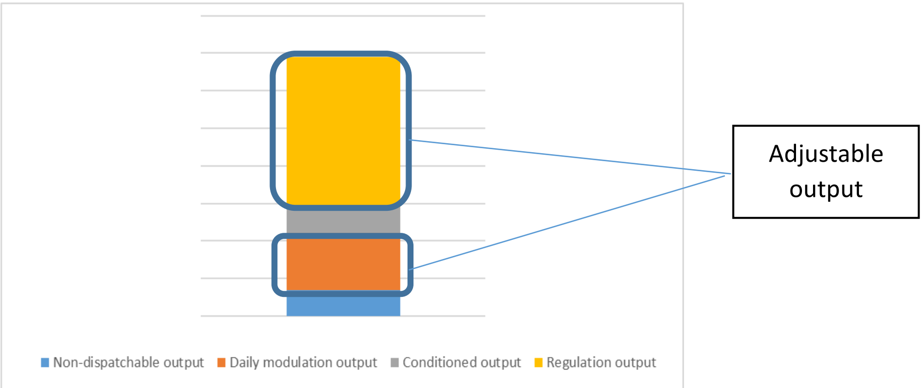


Figure 36 Adjustable output

Table 3 Hydro P48

DAT_FECHA	DAT_HORA	P48_A_bomb	P48_A	P48_B	P48_C	P48_D_bomb	P48_D	P48_E	P48_E_bomb	P48_F_bomb	P48_F
xx/xx/xxxxx	1	-590	320	0	0	-190	0	80	-294	-54	0

- At the same time, taking the energy bids blocks from the day-ahead market (assumed as the available energy in the given basin and period) an individual staircase is built and translated into the corresponding variables within the VBA program.

FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	A	160	60,71
XX/XX/XXXX	1	A	160	61,23
XX/XX/XXXX	1	A	170	62,58
XX/XX/XXXX	1	A	170	63,15
XX/XX/XXXX	1	A	170	67,88
XX/XX/XXXX	1	A	100	75,51
XX/XX/XXXX	1	A	100	76,51
XX/XX/XXXX	1	A	100	78,87
XX/XX/XXXX	1	A	100	79,11
XX/XX/XXXX	1	A	50	82,51
XX/XX/XXXX	1	A	1000	160

FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	E	80	61,12
XX/XX/XXXX	1	E	80	62,08
XX/XX/XXXX	1	E	75	62,52
XX/XX/XXXX	1	E	70	64,08
XX/XX/XXXX	1	E	70	65,25
XX/XX/XXXX	1	E	75	65,47
XX/XX/XXXX	1	E	75	68,75
XX/XX/XXXX	1	E	80	77,15
XX/XX/XXXX	1	E	80	86,75
XX/XX/XXXX	1	E	700	160

FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	A_bomb	110	20,11
XX/XX/XXXX	1	A_bomb	150	38,11
XX/XX/XXXX	1	A_bomb	110	45,11
XX/XX/XXXX	1	A_bomb	110	47,11
XX/XX/XXXX	1	A_bomb	110	48,11
XX/XX/XXXX	1	A_bomb	110	49,11

FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	E_bomb	68	38,22
XX/XX/XXXX	1	E_bomb	78	41,22
XX/XX/XXXX	1	E_bomb	72	43,22
XX/XX/XXXX	1	E_bomb	72	44,22
XX/XX/XXXX	1	E_bomb	72	45,22

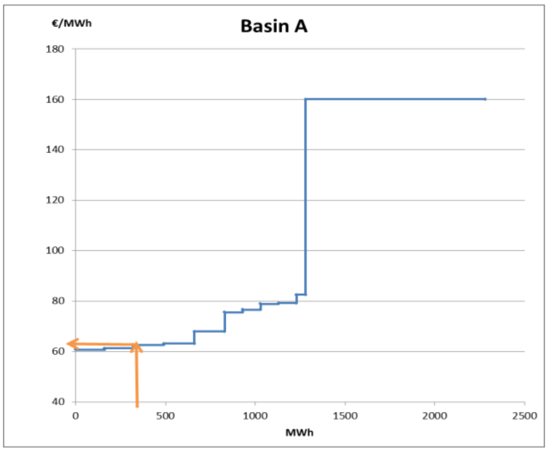
FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	F	55	67,15
XX/XX/XXXX	1	F	55	69,21
XX/XX/XXXX	1	F	55	70,25
XX/XX/XXXX	1	F	100	79,49
XX/XX/XXXX	1	F	100	80,04
XX/XX/XXXX	1	F	100	80,55
XX/XX/XXXX	1	F	100	80,96
XX/XX/XXXX	1	F	110	159,9
XX/XX/XXXX	1	F	700	160

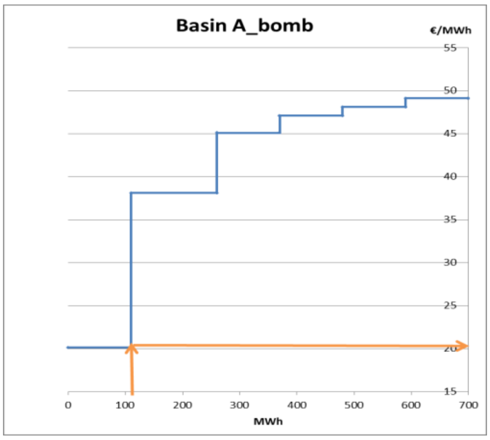
FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	D	80	59,11
XX/XX/XXXX	1	D	80	59,26
XX/XX/XXXX	1	D	80	59,41
XX/XX/XXXX	1	D	80	59,67
XX/XX/XXXX	1	D	80	59,82
XX/XX/XXXX	1	D	80	60,07
XX/XX/XXXX	1	D	80	60,62
XX/XX/XXXX	1	D	80	61,27
XX/XX/XXXX	1	D	80	61,92
XX/XX/XXXX	1	D	80	62,67
XX/XX/XXXX	1	D	80	63,52
XX/XX/XXXX	1	D	80	64,51
XX/XX/XXXX	1	D	80	65,51
XX/XX/XXXX	1	D	80	66,51
XX/XX/XXXX	1	D	70	160

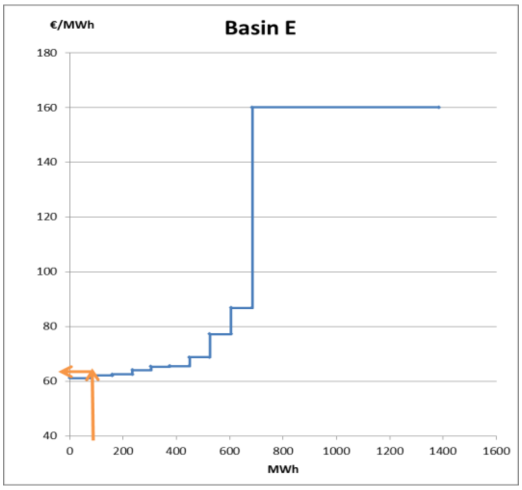
FECHA	HORA	UNIDAD	ENERGÍA	PRECIO
XX/XX/XXXX	1	D_bomb	205	34,09
XX/XX/XXXX	1	D_bomb	205	34,84
XX/XX/XXXX	1	D_bomb	205	35,49
XX/XX/XXXX	1	D_bomb	205	36,04
XX/XX/XXXX	1	D_bomb	190	36,78
XX/XX/XXXX	1	D_bomb	190	37,33
XX/XX/XXXX	1	D_bomb	190	37,88

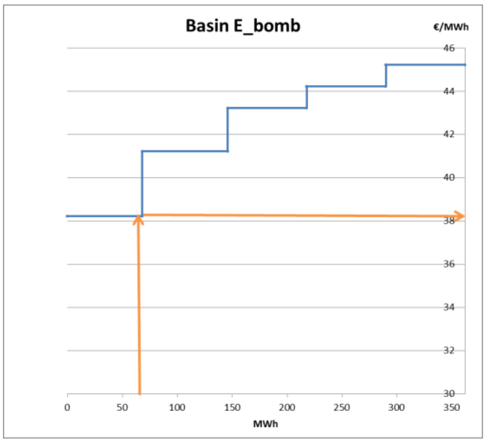
Figure 37 Hydro energy bids

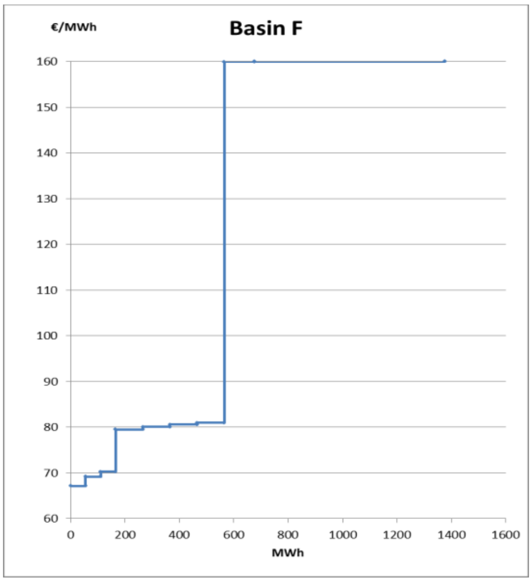
- With the adjustable output and the staircase for each basin already defined, it is possible to obtain the functioning point for that aggregate hydro unit (simplified basin).

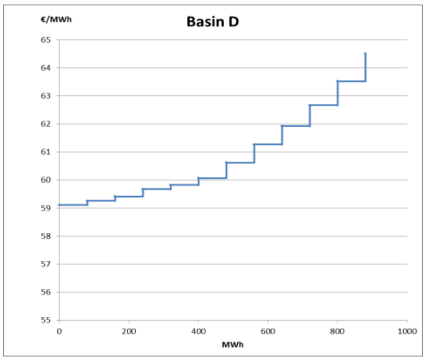


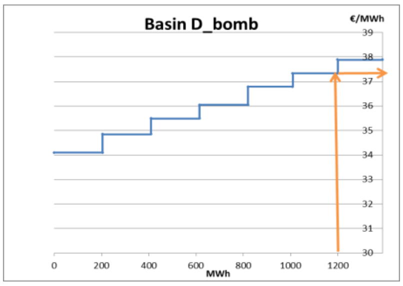












- Once the functioning points are established for each basin, the different upward and downward energy steps are pinpointed and saved as new variables in the VBA program.

- All the obtained energy steps from the different basins are mixed in an independent way for the upward and downward steps.

- The combination of the energy steps from different basins is carried out by sorting them out according to a price ascending criterion in the case of the upward energy and according to a priced descending criterion in the case of the downward energy. With the implementation of this stage in the VBA program it has already been obtained two integrated staircases (upward and downward) that gather the available regulation energy from all the basins.

Upward staircase		
Energía	Precio	
150	38,11	A_bomb
190	38,11	D_bomb
78	41,22	E_bomb
72	43,22	E_bomb
72	44,22	E_bomb
110	45,11	A_bomb
72	45,22	E_bomb
110	47,11	A_bomb
110	48,11	A_bomb
110	49,11	A_bomb
80	59,11	D
80	59,26	
80	59,41	
80	59,67	
80	59,82	

E_bomb should reduce the consumption in only 8 MWh, but due to its discrete characteristic that is not possible

D generates 64 MWh to compensate the discrete functioning of pumping units

Figure 38 Example of upward staircase

In the above figure, those cells in yellow correspond to the energy steps used from the aggregate upward staircase in order to regulate the wind power imbalance .

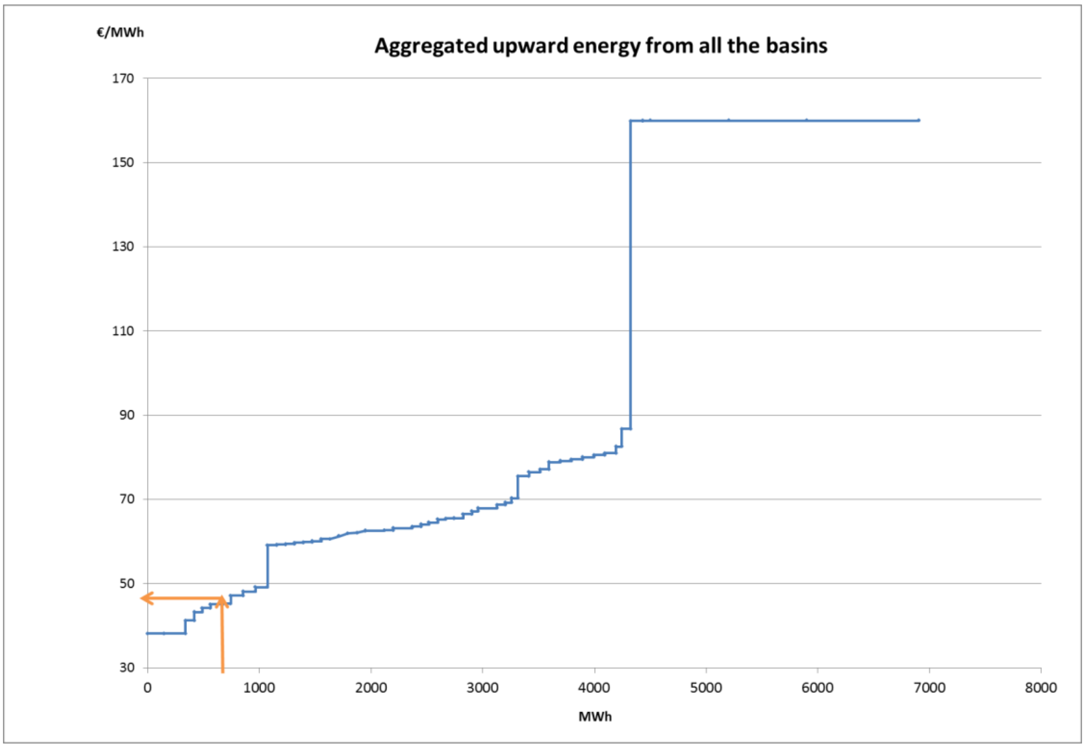


Figure 39 Example of upward staircase

5. Results

5.1 Economic comparison of wind power integration vs non-integration in the aFRR control area

As it has already been explained in previous sections, the economic assessment aims to do a comparison between the economic results of the following situations:

- Wind power portfolio is considered to settle its own imbalances in an independent way (differente Balance Responsible Party BRP) and therefore, these units are not included in the aFRR control area. In this case, the AGC does not receive the wind power imbalances as an additional setpoint to follow.

- Wind power portfolio is included in the same Balance Responsible Party as the units from the hydraulic portfolio. In this way, the imbalances from hydro and wind power are computed and settled as a whole by the TSO. This case entails the integration of the wind power units within the aFRR control area and the introduction of their imbalances as a new setpoint for the AGC in order to enable the automatic regulation of these wind imbalances by the hydraulic units.

For the analysis of the results from this economic comparison model, whose details were already explained in the methodology section, it is been considered as interesting to do a classification of the different possible cases according to the imbalances sign and the relative direction in comparison with the system needs.

Just as a reminder from what it has been described in the section 3 regardin AGC functioning, the decision by the generation control centre is either enabling the imbalances regulation tracking mode of the AGC or not ("Regular" or "Comunicar desvío"). The results spreadsheets of the Excel application shows in the column "Decisión óptima" the optimal decision to have been taken at an specific hour. The criteria are quite straightforward and defined for the different cases described in the following pages.

The economic analysis has been carried out for a period of three months. As it is explained in the initial disclaimer, the overall economic results are not shown in this document. Instead, specific examples for certain hours are used to describe the different cases that take place.

5.1.1 Imbalance in the opposite direction of the system needs

Overall economic results for the three months period analysed has revealed that the percentage of times in which the chosen decision has been the optimal one reaches **87 %** . This allows to state that the most suitable procedure to follow, if establishing a fixed decision setpoint, is to regulate the imbalance. A breakdown of different examples are detailed below.

- **Upward imbalances**

  The criterion to be considered here is:

$Wind\ power\ imbalances\ settlement > Hydraulic\ resources\ valuation$ → Notice to the TSO the deviation and disable AGC wind power imbalance tracking

$Wind\ power\ imbalances\ settlement < Hydraulic\ resources\ valuation$ → Regulate by enabling AGC wind power imbalance tracking and carry out the manual selection of which hydro basins will be activated for the tracking

In short, regulate the imbalance would be optimal as long as the imbalance price is below the average water value of the hydraulic resources used. According to this rule, examples for both possibilities as optimal decision are shown below:

- Optimal decision → regulate the imbalance

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
195,00	Upward	40,63	40,63	27			27	

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
5.265,00 €	7.922,85 €	Regular	2.657,85 €	40,63 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	48_reg_D_bom	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
-552	168	0	0	-392,5	0	35	-222	-54	0

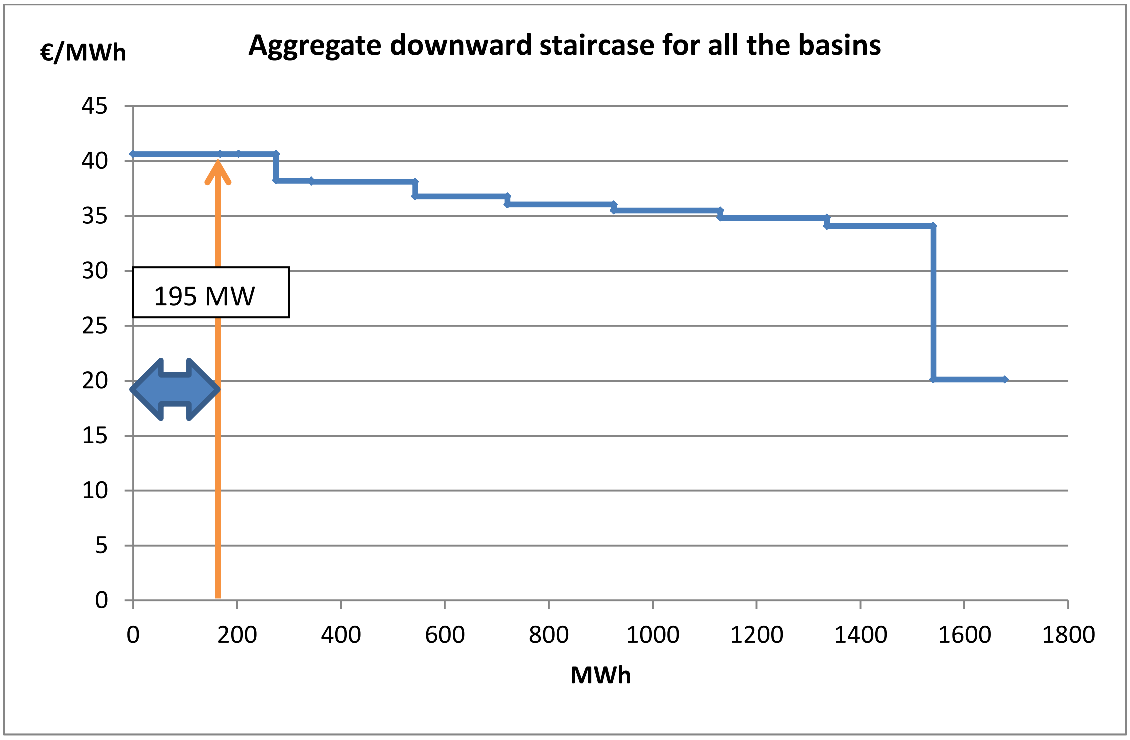


Figure 40 Case: Upward imbalance "Contra" – Optimal decision:regulate

❖ Optimal decision → incur in the imbalance and notice it to the TSO

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
234,37	Upward	46,16	46,16	42	42			

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
9.825,06 €	- €	Comunicar desvío	- 9.825,06 €	- €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
-844	70,1	0	0	-1390	0	10,9	-362	-54	0

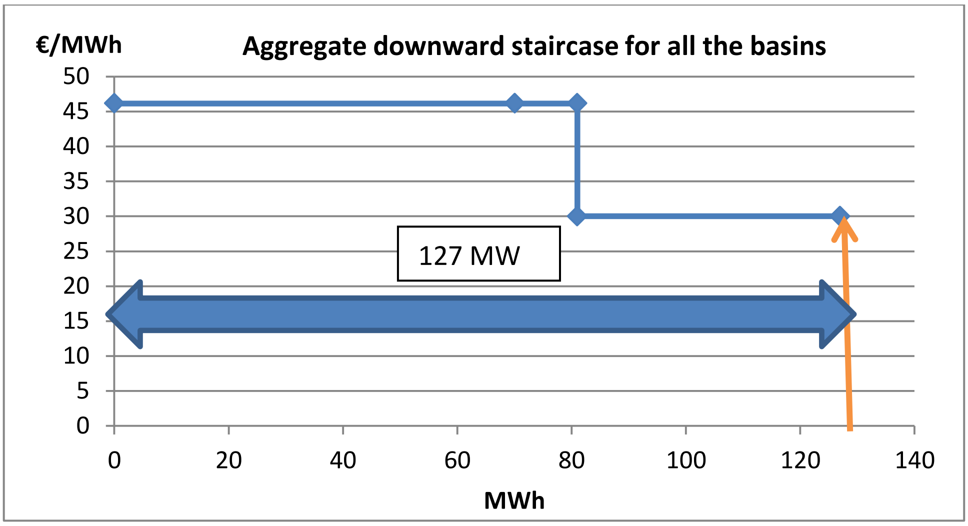


Figure 41 Upward imbalance "Contra" – Optimal decision:deviate

In this example a limitation on the available downward reserves appears because most pumping units are coupled and consuming close to the upper limit. Only 127 MW of pumping consumption can be increased, having no gap for turbine generation decrease. Therefore, it is not possible to regulate the imbalance (234,37 MWh) This is a case that may take place during certain valley periods.

- **Downward imbalances**

  The criterion to be considered here is :

Wind power imbalances settlement < Hydraulic resources valuation → Notice to the TSO the deviation and disable AGC wind power imbalance tracking

Wind power imbalances settlement > Hydraulic resources valuation → Regulate by enabling AGC wind power imbalance tracking and carry out the manual selection of which hydro basins will be activated for the tracking

In short, regulate the imbalance would be optimal as long as the imbalance price is above the average water value of the hydraulic resources used. According to this rule, examples for both possibilities as optimal decision are shown below:

❖ Optimal decision → regulate the imbalance . This example is used to clarify the already commented hypotheis about the continuous functioning of the pumping aggregated units. As it is described below, the economic effect of this assumption is neglectable→

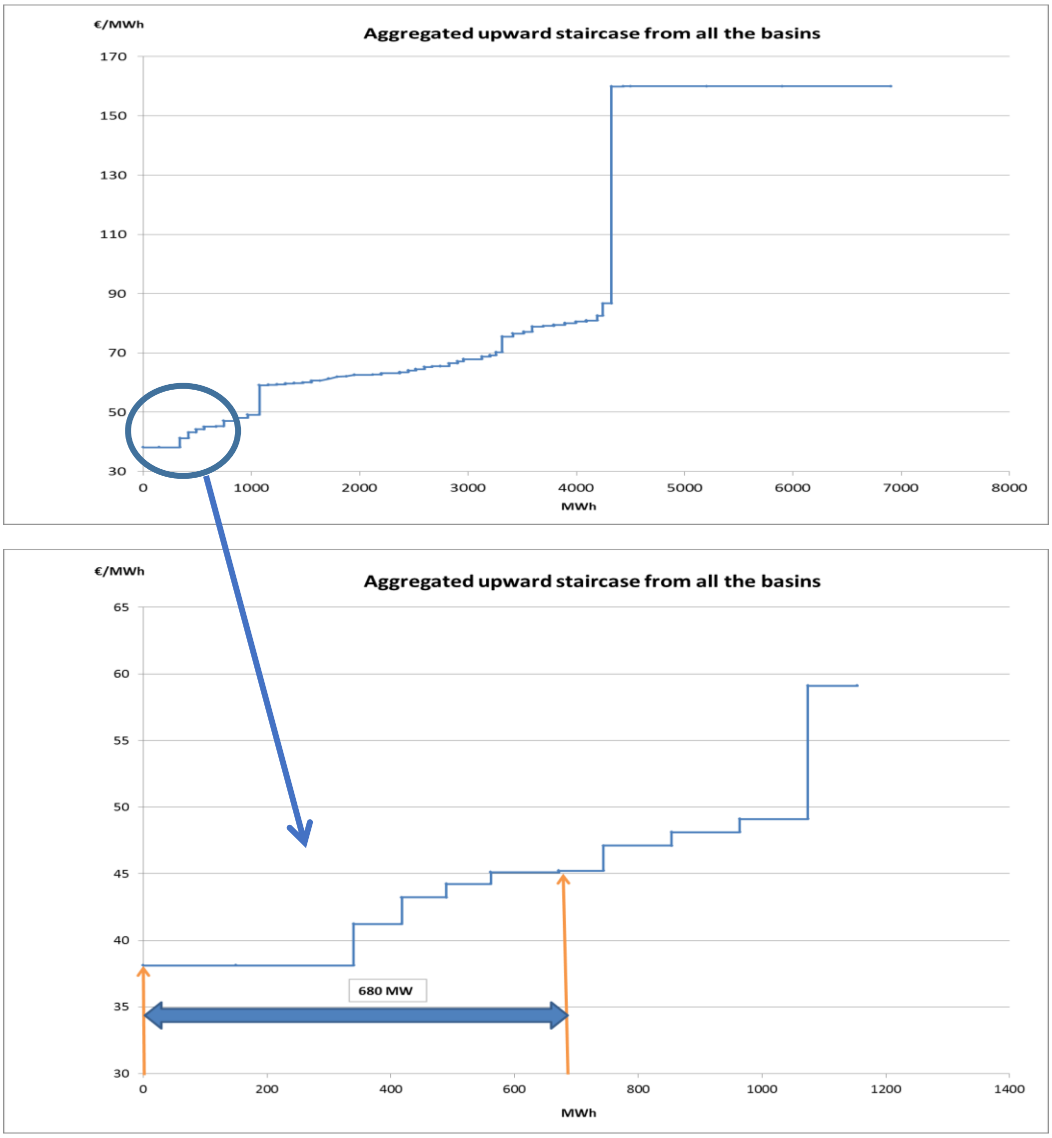
- Conitnuous pumping

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
-680	Downward	38,11	46,8	38,11				52,8

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
-31.824,00 €	- 27.792,10 €	Regular	4.032,00 €	40,87 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
-590	320	0	0	-190	0	80	-294	-54	0

In this case, the first block of upward energy that is used would correspond to a reduction in the pumping consumption. This reduction would match the wind power imbalance (-650 MW) under the assumption of continuous functioning of the pumping aggregate units, which was commented in section 4 .



Upward staircase		
Energía	Precio	
150	38,11	A_bomb
190	38,11	D_bomb
78	41,22	E_bomb
72	43,22	E_bomb
72	44,22	E_bomb
110	45,11	A_bomb
72	45,22	E_bomb
110	47,11	A_bomb

E_bomb reduces consumption 8 MW

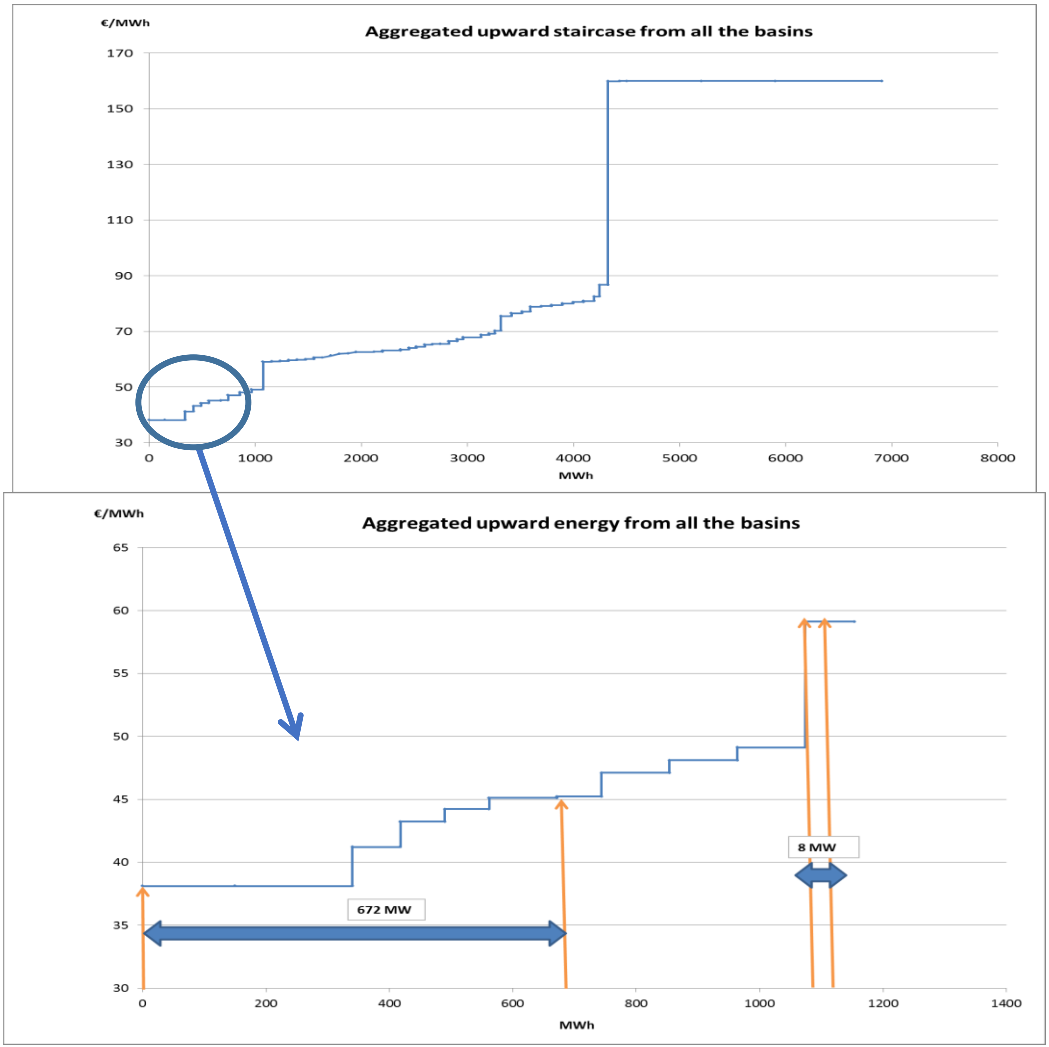
Figure 42 Case: Downward imbalance "Contra" – Optimal decision:regulate – Continuous pumping

- Discrete pumping

Due to the discrete regulation of pumping unit E_bomb here, a turbine unit (D) has to increase its output in 8 MW without complying with the theoretical merit order based on the water value. In this case, the expense of hydraulic resource would ascend to 27903,22 €, higher than in the case of continuous pumping (- 27.792,10 €). Using a relative reference, it can be said that the effect of assuming continuous pumping in the model understimates or overstimates the water valuation , if an upward imbalance takes place, in an amount equal to the difference between pumping unit bid and the next turbine bid in the staircase. For this example, this difference is 13,9 €/MWh. In terms of hyraulic resources total valuation, it represents a small percentage variation and the hypothesis of assuming continuous pumping can be regarded as acceptable.

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
- 33.611,04 €	- 27.903,22 €	Regular	3.920,78 €	41,03 €

The following figures allow to clarify the situation.



Upward staircase

Energía	Precio	
150	38,11	A_bomb
190	38,11	D_bomb
78	41,22	E_bomb
72	43,22	E_bomb
72	44,22	E_bomb
110	45,11	A_bomb
72	45,22	E_bomb
110	47,11	A_bomb
110	48,11	A_bomb
110	49,11	A_bomb
80	59,11	D
80	59,26	
80	59,41	
80	59,67	

E_bomb should reduce the consumption in only 8 MWh but due to its discrete characteristic that is not possible

D Increases generation in 8MWh to compensate the discrete functioning of pumping units

Figure 43 Case: Downward imbalance "Contra" – Optimal decision:regulate – Discrete pumping

❖ Optimal decision → incur in the imbalance and notice it to the TSO

Wind power imbalance	Sentido	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
-116,584	Downward	45,2	45,25	45,2				

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
- 5.275,43 €	- 7.077,81 €	Comunicar desvío	- 1.802,38 €	60,71 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
0	0	0	0	0	0	0	0	-54	0

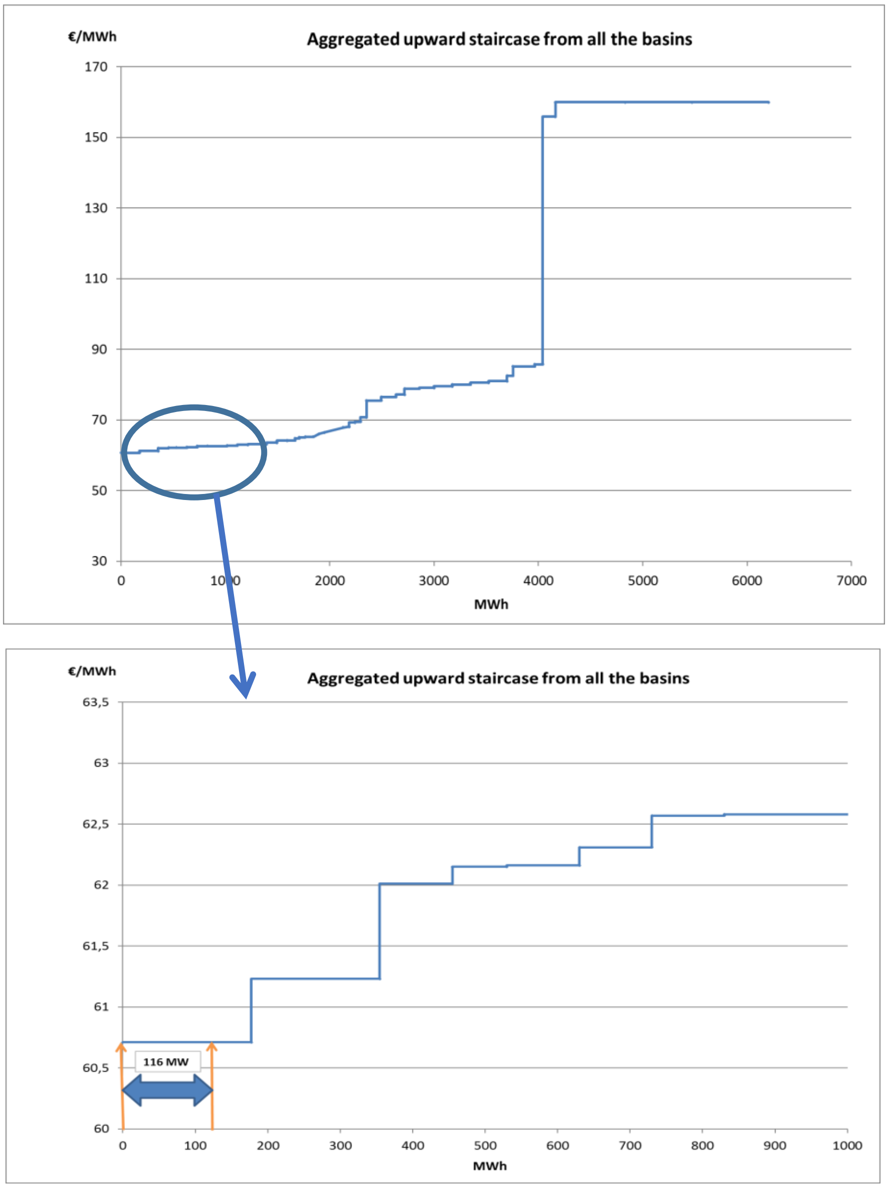


Figure 44 Case: Downward imbalance "Contra" – Optimal decision: deviate

5.1.2 Imbalances in the same direction of system needs

Overall economic results for the three months period analysed has revealed that the percentage of times in which the chosen decision has been the optimal one reaches 67 % . A fixed procedure to be established in these cases is not as straightforward as for the case of imbalances in the opposite direction of system needs. It will depend on different variables as it is explained later on. A breakdown of different examples are detailed below.

- **Upward imbalances**

The criterion to be considered here is :

$Wind\ power\ imbalances\ settlement > Hydraulic\ resources\ valuation$ → Notice to the TSO the deviation and disable AGC wind power imbalance tracking

$Wind\ power\ imbalances\ settlement < Hydraulic\ resources\ valuation$ → Regulate by enabling AGC wind power imbalance tracking and carry out the manual selection of which hydro basins will be activated for the tracking

For imbalances in the same direction of system needs it should be reminded that the imbalance price will be coincident with the day-ahead market price for the specific hour. Therefore, regulate the imbalance would be optimal as long as the day-ahead market price is below the average water value of the hydraulic resources used. According to this rule, examples for both possibilities as optimal decision are shown below:

❖ Optimal decision → regulate the imbalance

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
260,757	Upward	61,82	66,97	61,82		67,50		

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
16.121,04 €	17.601,10 €	Regular	1.480,06 €	67,50 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
0	1148,3	0	0	0	400	368,7	0	0	143,2

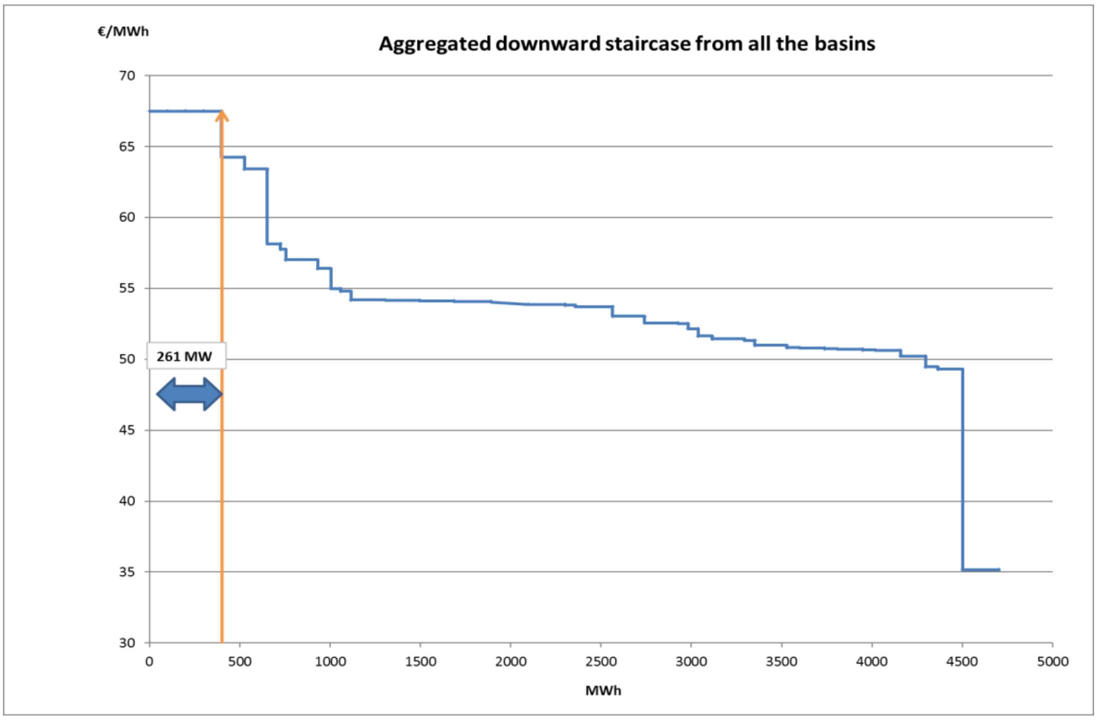


Figure 45 Case: Upward imbalance "Favor" – Optimal decision: regulate

❖ Optimal decision → incur in the imbalance and notice it to the TSO

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
152,322	Upward	43,95	44,65	43,95		42,57		

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
6.694,55 €	5.585,45 €	Comunicar desvío	- 1.109,10 €	36,67 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
0	25	0	0	-380	0	0	0	0	0

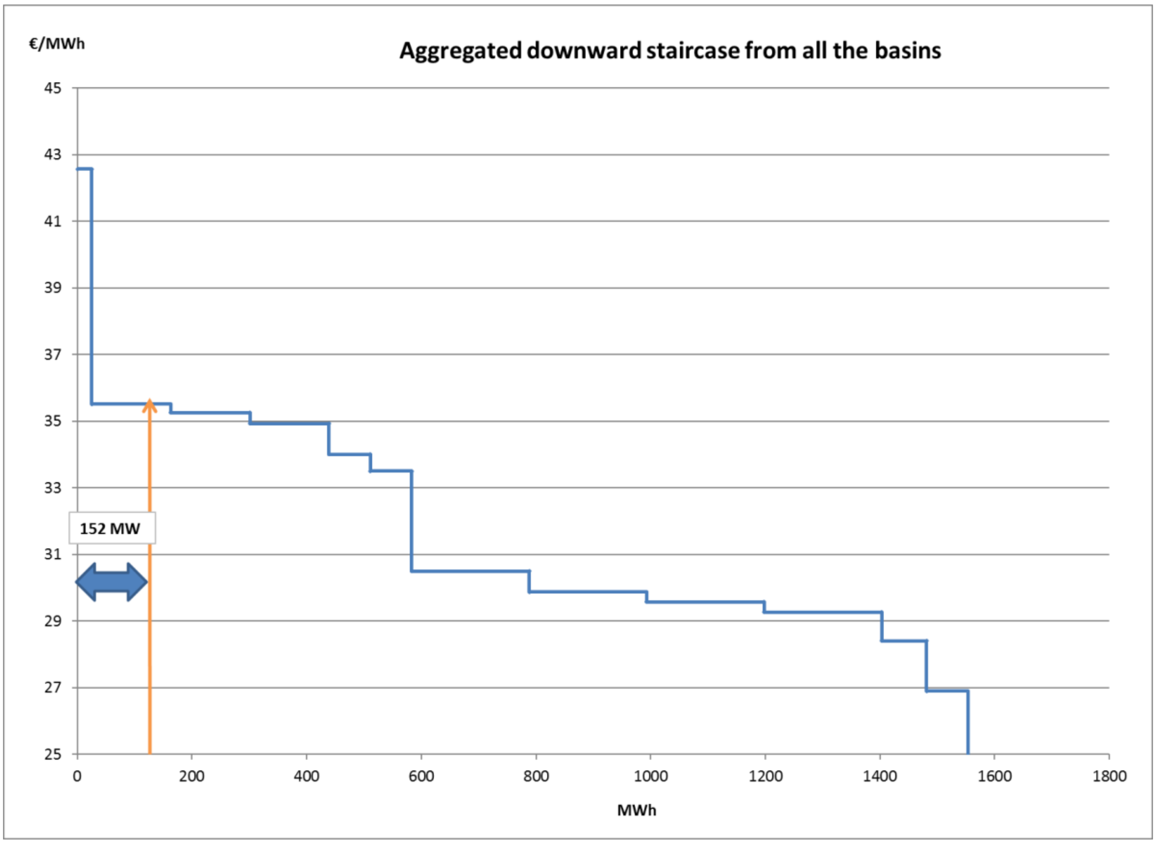


Figure 46 Case: Upward imbalance "Favor" – Optimal decision: deviate

- **Downward imbalances**

The criterion to be considered here is :

$Wind\ power\ imbalances\ settlement < \ Hydraulic\ resources\ valuation$ → Notice to the TSO the deviation and disable AGC wind power imbalance tracking

$Wind\ power\ imbalances\ settlement > \ Hydraulic\ resources\ valuation$ → Regulate by enabling AGC wind power imbalance tracking and carry out the manual selection of which hydro basins will be activated for the tracking

Regulate the imbalance would be optimal as long as the day-ahead market price is above the average water value of the hydraulic resources used. According to this rule, examples for both possibilities as optimal decision are shown below:

❖ Optimal decision → regulate the imbalance

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
-102,282	Downward	46,07	46,07	20,25	20,25			

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
- 4.712,13 €	- 2.071,21 €	Regular	2.640,92 €	20,25 €

P48_reg_A_bomb	P48_reg_A	P48_reg_B	P48_reg_C	P48_reg_D_bomb	P48_reg_D	P48_reg_E	P48_reg_E_bomb	P48_reg_F_bomb	P48_reg_F
-614	30	0	0	0	56,7	0	-72	0	0

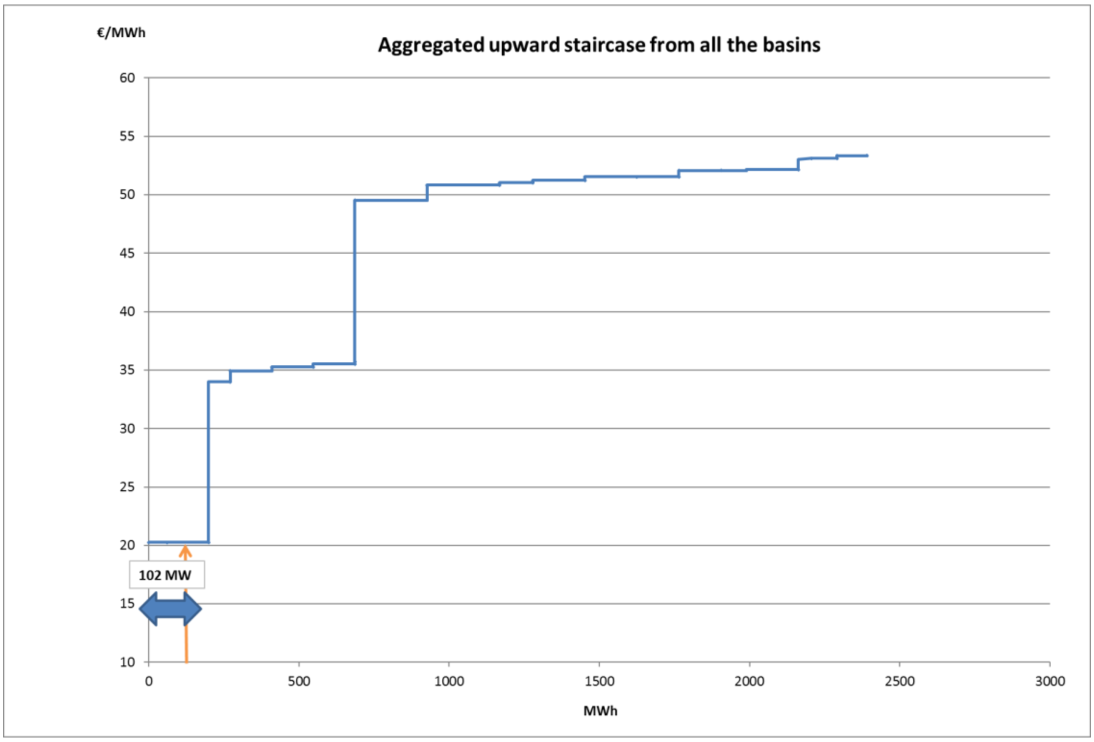


Figure 47 Case: Downward imbalance "Favor" – Optimal decision: regulate

- Optimal decision → incur in the imbalance and notice it to the TSO

Wind power imbalance	Sign	PMD	PDESVB	PDESVS	PTERB	PTERS	PGDESVB	PGDESVS
-232,635	Downward	42,71	42,71	42,71		49,5		

Imbalance valuation	Hydraulic resource valuation	Optimal decision	Savings "Regular" vs "Desvío comunicado"	Weighted average water value
- 9.935,84 €	- 11.512,18 €	Comunicar desvío	- 1.576,34 €	49,49 €

P48_reg_A_bomb	P48_reg_A	48_reg_	P48_reg_C	P48_reg_D_bom	P48_reg_D	P48_reg_E	P48_reg_E_bom	P48_reg_F_bom	P48_reg_F
0	0	0	0	0	197	0	0	0	0

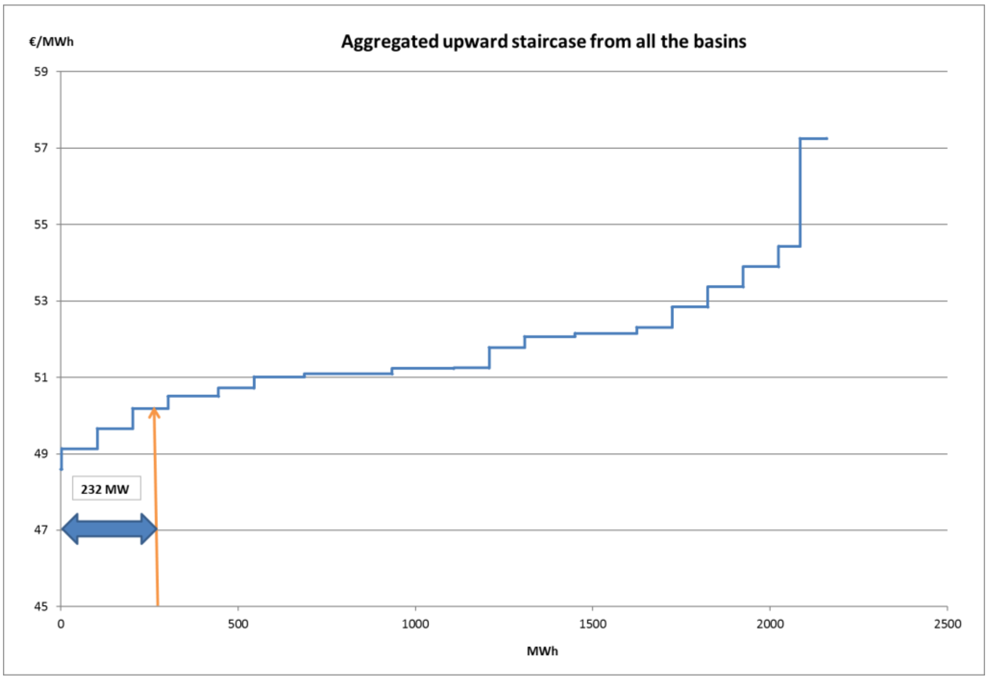


Figure 48 Case: Downward imbalance “Favor” – Optimal decision: deviate

6. Conclusions and further steps

The following points summarized the main conclusion that can be drawn from the analysis of results computed for a three month period. Besides that, some issues regarding further steps to take are also specified.

- In the case of **imbalances in the opposite direction as the system needs**, it has been identified that the wind power integration within the aFRR control area becomes specially profitable for those periods in which the imbalances prices shows a high deviation from the day-ahead market price (PMD).

  - For upward imbalances, it will be possible to obtain hydraulic energy savings by reducing the final production with respect to the final scheduled energy (P48) which results in a profit whenever the corresponding water value remains above the upward imbalance price.
  - For downward imbalances, additional hydraulic energy expenses take place for the imbalance regulation. In this case, since it represent a loss, it is better to regulate whenever the corresponding water value remains below the downward imbalance price.

  Different individual analysed hours have shown that the benefits obtained here are also bound by the output limitation of the hydro units. This is closely linked to the type of hour (valley, peak) and the sign of the wind power imbalance.

- In the case of **imbalances in the same direction to the system needs**, it has been identified that the wind power integration within the aFRR control area does not result as profitable as the case of imbalances in the same direction. The explanation behind that lies in the dual pricing scheme applied in Spain for the imbalance settlement. When this case occurs, the imbalance price to face will always coincide with the day-ahead market price.

  - According to this and to the upward/downward energy regulation cases explained in the previous point, it can be easily concluded that the imbalance regulation will not be optimal to do whenever the hydraulic energy used for that purpose corresponds to the day-ahead market schedule.

  - Situations where the imbalance regulation becomes profitable take place for those periods in which tertiary reserves energy have been allocated to the agent's hydro units and the sign of the wind power imbalances allows to substitute and net the provision of that tertiary regulation.

  - Regarding the latter situation, it should be noted the difference between the dual and the single pricing scheme when the optimal decision is analysed. Under the single pricing scheme, the imbalance price to face when the deviation goes in the same direction of system needs, would be the same as the one faced by an agent whose imbalances goes in the opposite direction. Taking into account that tertiary reserves and imbalances prices are correlated (in fact, imbalance prices internalizes tertirary price) , the decision of regulate or not regulate an imbalance with energy previously allocated for tertiary reserves , would give rise to a similar economic settlement. As it is widely described in some of the papers this works has referred to, the single pricing scheme creates an incentive for the agents to incur in imbalance if its direction is the same as the system needs.

- In overall, it can be concluded that the strategy about the decision making for the wind power imbalance regulation does not allow always to follow the optimal behaviour. It has been identified that for **77 %** of hours the agent has been taken the optimal decision according to the current strategy based on establishing the fixed setpoint of regulate the whole imbalance. Therefore, there is a gap of **23 %** of cases in which the decision could have been improved. If this is translated into economic terms, this 23 % gap represent an improvement margin of **9,11%** over the current economic savings that have been computed in the model.

- In order to achieve that improvement margin, an optimization model should be developed in which all the uncertainty from the input data has to be considered. This is not an easy step to take, especially with regards to the forecast of future system needs, their direction and as a consequence, the imbalance prices at every hour. When the decision on enabling the regulation of imbalance is submitted within the AGC , all these mentioned data are unknown.

- There is also a relevant further step that should be considered for future works. This thesis has been focused on an ex-post optimization model that aimed to take the best decision among the following: compensate the wind power imbalance or notice it to the TSO. However, the decision has been linked to the total imbalance. Taking into account the simplified criterion considered for the decision making (comparison between water value and imbalance price) the optimization can be extended to decide the percentage of the imbalance to regulate and the percentage to notice to TSO, instead of taking the decision on the whole imbalance. For this purpose, some of control blocks of the AGC should be modified in order to introduce that percentage of imbalance regulation as a new setpoint.

7. References

[1] Javier García-González et al. "Stochastic Joint Optimization of Wind Generation and Pumped-Storage Units in an Electricity Market" IEEE Transactions on Power Systems, Vol. 23, No. 2, May 2008.

[2] Edgardo D. Castronuovo et al., "An integrated approach for optimal coordination of wind power and hydro pumping storage" An integrated approach for optimal coordination of wind power and hydro pumping storage. Wind Energy, Wiley, 2014, 17 (6), pp.829-852.

[3] Van der Veen, R.A.C.,Hakvoort, R.A.,. Balance responsibility and imbalance settlement in northern European evaluation. In: Energy Market, 2009, EEM 2009, Sixth International Conference on the European, IEEE, May 2009, pp.1–6.

[4] Vandezande L. Meeus L. Belmans R. Saguan M. 2010. Well-functioning balancing markets: a prerequisite for wind power integration. Energy Policy, 38(7): 3146-3154.

[5] JP Chaves-Ávila, RA Hakvoort, A Ramos The impact of European balancing rules on wind power economics and on short-term bidding strategies. Energy Policy 68, 383-393

[6] H. Holttinen, J. Ik¨aheimo, Wind prediction and bids in Denmark, Technical Report, VTT Energia, 2007

[7] J. A. P. Lopes, On the optimization of the daily operation of a wind-hydro power plant, IEEE Transactions on Power Systems 19 (2004) 1599–1606.

[8] E. D. Castronuovo, J. A. P. Lopes, Optimal operation and hydro storage sizing of a wind-hydro power plant, International Journal of Electrical Power & Energy Systems 26 (2004) 771–778

[9] J. Matevosyan, L. Söder, Short-term hydropower planning coordinated with wind power in areas with congestion problems, Wind Energy 10 (2007) 195–208

[10] J. M. Angarita, J. G. Usaola, Combining hydro-generation and wind energy biddings and operation on electricity spot markets, Electric Power Systems Research 77 (2007) 393–400

[11] Álvaro Jaramillo Duque et al. "Optimal operation of a pumped-storage hydro plant that compensates the imbalances of a wind power producer"

[12] Gardner J, Hobbs W, Lee FN, Leslie D, Streiffert D, Todd D. Summary of the panel session "coordination between short-term operation scheduling and annual resource allocations". IEEE Transactions on Power Systems 1995; 10:1879–1889.

[13] Reneses, J.; Barquín, J.; García-González, J.; Centeno, E.; "Water value in electricity markets", International Transactions on Electrical Energy Systems, vol.26, no.3, pp.655-670, 2016-03-01

[14] Reneses J, Centeno E, Barquín J. Coordination between medium-term generation planning and short-term operation in electricity markets. IEEE Transactions on Power Systems 2006; 21:43–52.

[15]OMIE. "Formación mercados" www.omie.es

[16] New intraday market (XBID) http://www.nuevomercadointradiario.omie.es/index.html#

[17] Operational procedures from Spanish TSO (REE) www.ree.es/es/actividades/operacion-del-sistema.../procedimientos-de-operacion

[18] "Reguladores de zona para el control automático de la generación". Universidad Pontificia Comillas .2008.