UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE ELECTRIC POWER INDUSTRY

Development of a model to determine the optimal strategy in a hydro basin

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Madrid, July 2018

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Abstract

The extensive expansion of the installed capacity of renewables energies have changed the market conditions and the hydroelectric technology is going to play a very important role because the strong interaction between hydro and other technologies. Hydro technology enables the system to absorb the short-term variations introduced by renewables technologies. For that reason, it is fundamental to manage this type of facilities in an optimal way.

The aim of this master's thesis is to develop a model to compute the optimal schedule in the short-term of the hydro plants in a basin. The deterministic model tries to replicate the behavior of the Spanish electricity day-ahead market and, as a result, be an adequate tool to support the elaboration of bidding strategies.

The model is developed taking into account a whole basin what is necessary for more accurate results when we analyze the different parts of the basin. In this project I present the results obtained when comparing the solution of the model with what was carried out in the reality in two plants with a common unit which can pump or turbine water.

The results obtained by the model fulfil the proposed objectives. These results show the optimal management of the hydro plants depending on several factors, such initial and final level of the reservoirs, the time horizon, market prices, taxes and other characteristics.

Acknowledgment

I wish to express my sincere gratitude to Mr. Rubén Matey Pérez for providing me the opportunity to do my internship and master thesis in “IBERDROLA” and for the useful comments, remarks and engagement through the learning process of this master thesis.

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I am especially grateful to my friend whose respect and affection has been essential to overcome such a difficult year.

Last, but not the least, my parents, my brother and family who have always been there to support me in all the decisions along my way.

To all, thank you very much.

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Document structure

The first chapter provides an introduction to the problem we are going to solve by carrying out the present master's thesis. It also includes the description of the objectives, scope and motivations to develop the project.

In the chapter 2 a review of the state of the art of the hydro units and the state of the art of the optimization models of hydro units will be presented.

In the chapter number 3 the problem to solve will be described.

The next chapter 4 includes a brief description of the general context of the Spanish market, paying attention to the Day-ahead market to provide the reader with an overall view of the market structure.

The methodology and different steps followed to develop the model are described in the chapter 5.

The results of the model developed are presented in the chapter 6.

Ultimately, in chapter 7 are presented the conclusions deduced from the results obtained and future work.

Chapter 1: Introduction

1.1 Motivation

The source of inspiration for the development of this master's thesis is the José María de Oriol hydroelectric unit in the village of Alcántara (Cáceres) because its location in the village where I grew up allowed me to know this technology from a very young age and has been a source of inspiration to choose the energy sector as a field to develop my professional career.

FIGURE 1. JOSÉ MARÍA DE ORIOL DAM

Source: Mosingenieros

This interesting technology is present around the world and there is a vast amount of hydropower capacity installed in our country.

Furthermore, due to the considerable expansion of the installed capacity of renewables energies, there have been a change during the last years and the hydroelectric technology is going to play a significant role. In the market three different effects can be detected: Firstly, energy prices have going down because renewable energy sources (RES) and periods with considerable feed-in tariffs in the wind technology. Furthermore, the traditional peak-off-peak price profile varies because PV. For that reasons there is a change in the management of the existing power plants. And the final dispatch of the hydro plants is steered by water values in the short and mid -term optimization. [BRAU16]

These effects make hydro units highly important in a system due to the strong interaction between hydro and other technologies. The possibility of storing or pumping water allows better use of the water and therefore longer optimization periods.

Moreover, hydro generation is very flexible but uncertain; it is an affordable way of storing energy at large scale enabling the system to absorb the short-term variations introduced by renewables technologies which high penetration stress the system. But inflows can produce important uncertainty being clearly one of the most important factors in the Spanish electric system.

1.2 Objective

The aim of this thesis is to develop a model to compute the optimal schedule in the short-term of the hydro plants in a basin, the model will be based on the water value and considering inflows in the units, the height or the maximum and minimum level of water in the units, the maximum and minimum output in MW available, and a market price forecast. In other words, the optimization model of the day-ahead Spot Auction market is considered by calculating water values and an optimal production schedule.

The model tries to replicate the behavior of the electricity market and the scheduling of the hydro plants, determining the optimal operation subject to uncertainty in hydro inflows and prices. But even though, the model is going to be a deterministic model.

A deterministic model will be simple and direct. We also believe that it would be more interesting to focus our efforts on adding more features to the project rather than making a stochastic model.

To achieve the objective the first step is to define the objective function; this function wants to obtain profits as a maximization of the difference between the revenues and cost of the plant for each hour of the day:

$$Max\ Benefit\ = \sum_i (Income_i - \ Costs_i)$$

Maximizing the profit requires an adequate tool to support the elaboration of bidding strategies. The tool developed during this thesis will obtain the water value which helps to generate offers that are set up to trade the energy of the hydro power plants on the day-ahead market.

The project has a two-week time-frame; this limited scope responds to the objective to obtain an accurate forecast of the optimal schedule of the hydro plants. As the inputs introduced will be more precise the nearest we are to the real time, this short scope allows us to make a more accurate forecast of the offers we should realize in the market.

Therefore, the optimization will follow a two-weekly cycle, taking advantage of high prices during peak hours to produce electricity with the water stored in the reservoirs.

Chapter 2: State-of-the-art

2.1 Introduction

Finding information about hydro plants is very easy due to the maturity of the technology and the high level of implementation worldwide. However, the available information about optimization models of hydro units is not easy to find.

2.2 State-of-the-art of hydro reservoirs

Hydro technology is one of the oldest forms of energy use.

Hydro energy sources take advantage of the natural water flow to generate electricity. Thus, hydropower is generated by first converting the potential energy stored in water into the kinetic energy of running water, which is then converted into electrical energy via turbines.

It is considered that its first use was by means of the hydraulic wheel, device formed by a set of blades where the water collides and impels them achieving the movement of the whole.

This technology has been susceptible to countless advances in the last century which has converted this technology as the most mature and consolidated renewable technology. The development of this technology in Spain has allowed us to occupy a relevant role in the hydroelectric area at European level allowing us an exploitation of the national orography with a significant number of dams. The current installed capacity in Spain of 17,792 MW assumes a contribution to the national electricity production around 15% reaching a considerable hydroelectric potential as a result of the development achieved.

The main hydropower technologies are:

- Run-of-river hydropower plants: This technology obtains energy from the continuous flow of the river. In this kind of facilities the flowing water from a river is channel through a canal or penstock to spin a turbine. Typically, these facilities have no or little storage and it will provide a base load supply. [IHA_18]

- Reservoir hydropower plants: Use water stored in an artificial reservoir in the river's basin. Energy is produced by releasing water from a reservoir through a turbine. The storage capacity provides the ability to operate for many weeks or even months, independently of the inflows arriving to the reservoir.

- Pumped-storage plants: Water is pumped from a lower reservoir into an upper reservoir to turbine it afterwards. The combination of power and capacity is the key of this technology. In addition, the response time is an important factor. This time can vary for pumped hydro systems, having slower response times in the older facilities and faster response times in the modern facilities being able to respond within minutes.

These technologies can be frequently combined to take advantage of the resources. E.g., Reservoir hydropower plants can often involve an element of pumping water and Run-of-river hydropower plants may provide some storage capability. [IHA_18]

2.3 State-of-the-art of optimization model of hydro units

Sebastian Braun has written several papers regarding the optimization models for hydropower technology. Some of them are going to be used as a reference for the development of the model in this master's thesis.

In the "*Hydropower Storage Optimization Considering Spot and Intraday Auction Market"*, Sebastian realizes a case-study based analysis of short-term hydro power optimization considering Spot and Intraday Auction markets.

In that paper, the optimal production schedules and bidding strategies are calculated.

The literature proposes two separated categories for solving hydro power scheduling problems. Firstly, a system economic-based approach: for example, Oliviera solved a MILP in integrating cost-efficient storage capacity. The alternative category focuses on the operation of the individual plants or a portfolio of hydro storages. Both alternatives are based on the calculation of the optimal strategy through the wholesale electricity prices.

In addition, Pereira (1991) introduces a SDDP (Stochastic Dual Dynamic Programming) approach, then Wallace (2003) introduces stochastic models and Labadie (2004) the optimization of the operation in the reservoirs. Löhndorf (2013) including stochastic prices and inflows. Abgottspon (2012 and 2013) includes the long-term future and the hourly day-ahead market into one optimization and discusses the influence of a price maker. [BRAU16]

2.3.1 Trading hydro on the Spot market

As discussed in Braun (2015) the evaluation of hydro power storages on the German electricity market highly depends on the chosen input factors and the optimization method itself. The most important value drivers identified were market prices, followed by balancing energy provision, the optimization model itself and inflows. [BRAU16]

2.3.2 Spot optimization characteristics

- The day-ahead spot prices' auction to determine the optimal generation and pumping schedule have an hourly time resolution, t = 1h.

- The spread between generation and pumping prices is essential to maximize the profit. .

- The reservoir balancing equations means that the water level in t is a summation of the water level in t-1 and the water that has been released from an upper reservoir and subtracting the water that has been released into a lower reservoir.

  [BRAU16]

2.3.3 Conclusions and decisions

Being able to find similarities between the German (the market studied by Sebastian Braun) and the Spanish markets, it can be concluded that the strategy followed by Braun can be applied to the development of a similar test for a hydraulic portfolio in Spain. This test will follow the category that focuses on individual plants or portfolios based on using wholesale electricity prices and calculating an optimal control strategy.

In general, the papers found opt for a stochastic price analysis. However, for the development of this work I have decided to make a deterministic analysis for two reasons:

The first one is the trust in the source that provides me the data and the second one is the possibility of spending more hours to make a more robust model instead of trying different scenarios. Similarly, for the inflows a deterministic analysis will be carried out.

Chapter 3: Problem Description

3.1 Presentation of the problem

The problem proposed for the development of this master thesis is located at the confluence of several rivers, where the portfolio of hydroelectric technology is a mix of large scale reservoirs for seasonal storage and small reservoirs for daily storage.

Taking advantage of the hydraulic resource efficiently will be the main objective of this work and to achieve it is going to be necessary the development of a tool which makes it possible. This tool will follow the logic of pumping in low prices scenarios and generate energy during high prices scenarios therefore the actual problem is to decide how or when to allocate the pumping and generating program in the given horizon.

This tool should also be able to work with the singularities that the hydrographic basin presents and which are the following ones:

One of these rivers is characterized by its huge variations of the flow and because it is a fast-flowing river. The dam located in this river, Unit 3, is not able to store large amounts of water. Therefore, to avoid spillages the water is pump trough a common unit towards the Unit 2, which is located in other river and received as an input the water turbined in a previous unit, Unit 1, the spillages and other inflows.

The common unit, shared by Unit 2 and Unit 3, cannot pump and turbine water at the same time. Thus, an optimal schedule is needed to take advantage of opportunities across the time horizon to operate the units in the most profitable way as possible considering the technical and economical parameters and constraints that both market and generations units present.

There is another unit, Unit 4, which receive the water turbined and the spillages of Unit 2, Unit 3 and Unit 7 that should be consider as an input because the power generated will depend on the volume of water stored in this unit. This unit is a seasonal unit with a big capacity to store water enabling the system to absorb the short-term variations introduced by unexpected inflows which can stress the basin.

In the remaining river Unit 5, Unit 6 and Unit 7 are located. Two of these reservoirs are able to pump and turbine water, but cannot do it at the same time, and the water release in Unit 7 finally reach de reservoir 4.

In addition, one of these units is located in an irrigated area; consequently, the conditions of exploitation, i.e. minimum and maximum level of water in the reservoir are subject to other restrictions. According to which and depending on the current level of water and the time of the year the unit should be operated in one way or another.

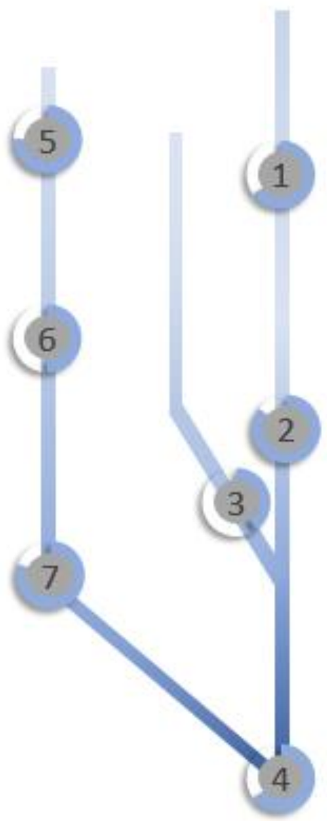


FIGURE 2 SCHEME OF THE BASIN

3.2 Summary of the units

	Turbine	Pump	River
Unit 1	x		1
Unit 2	x		1
Unit 3		x	2
Unit 4	x		1, 3
Unit 5	x	x	3
Unit 6	x	x	3
Unit 7	x		3

Unit 1: Located in River 1, the water is release (turbined + spillages) to Unit 2.

Unit 2: Located in River 1, the water is release to Unit 4.

Unit 3: Located in River 2, the water is pump from reservoir 3 to reservoir 2.

Unit 4: Located in the confluence of rivers 1 and 3, the water is released to a non-modeled unit.

Unit 5: Located in River 3, the water is release to Unit 6. This unit is able to pump water from Unit 6.

Unit 6: Located in River 3, the water is release to Unit 7. This unit is able to pump water from Unit 7.

Unit 7: Located in River 3, the water is release to Unit 4.

Chapter 4: Market context

4.1 Introduction

Generally, the larger part of the consumed electricity is traded in the day-ahead market. Therefore, it is fundamental to understand how the day-ahead market works in the Spanish electricity market because is the market in which is based the optimization model that we will see in the following chapters.

4.2 Historical overview

The liberalization of the Spanish electricity market began with a Protocol negotiated by the Ministry of Industry and the major electric utilities in Spain before 1997. The Protocol is carried out because the need of the Ministry to reach an agreement with the utilities.

Based on the Protocol and on the Electricity Directive, the Electric power Act 54/97 was approved in 1997, this Protocol establishes a general framework of the liberalized electricity sector and scheduled it beginning for the 1st January 1998.

This process expects to increase the competitiveness of the electricity companies and to create a more efficient system for all markets participants ensuring a transition toward the liberalization and establishing the appropriate rates for regulated activities.

The essence of this process can be summarized in the following points:

Unbundling of activities: This concept shows an attempt to create a separation of functions between the regulated activities (transmission and distribution) and the ones that can be opened up to competition (generation and retailing).

The basic rule for separating or unbundling activities in the new regulatory environment is that no single agent should be allowed to conduct a regulated activity (such as transmission or distribution) and an activity open to competition (such as generation or retailing) simultaneously.

In Spain a company was created to separate the generation and transmission parts. "*Red Eléctrica de España, S.A. was founded in 1985 in application of Law 49/1984 of 26 December. It was the first company in the world exclusively dedicated to the transmission of electricity and the operation of the electricity system*".

[www.ree.es/en/about-us]

This unbundling make sense since transmission and distribution networks are subject to significant economies of scale, which makes them a natural monopoly, making the introduction of competition inefficient.

Subsequently, in 2010 a legal separation between Distribution System Operator and retailing was performed.

Liberalization: In most countries, a step by step process was carried out to obtain a change from a vertically integrated monopoly in the electricity industry to a market where regulated and competitive activities are.

Prior to liberalization, in most countries in Europe, state power companies governed the electricity sector. Therefore, privatization reduces the ability of the governments to use the electricity companies as a tool to achieve their political agendas and at the same time enhances a most efficient performance.

Deregulation: Generating and retailing activities were deregulated to increase efficiency forcing them to participate in a more competitive market. A wholesale electricity market was created where buyers and sellers can conduct transaction according to the rules of free trading but under the supervision of public bodies to ensure transparency, objectivity and free competition.

To manage the wholesale market an electricity market operator (OMEL) is needed. And to ensure that the market is working properly and to avoid market power, a regulatory and independent authority, National Commission of Market Competition (CNMC), was created.

Deregulation in retailing activities make possible to all consumer to choose supplier.

Third-Party Access (TPA): Some measures must be taken to ensure that all market agents have access to the transmission and distribution grid. These measures aim to increase competitiveness in the electricity sector by providing access to the different agents.

4.3 Spanish electricity market

The Spanish electricity market is divided or structured in several different markets:

Future markets: Organized markets managed by OMIP. In these markets the contracts signed are a legal agreement to buy or sell something at a predetermined price at a specified time in the future.

Spot markets: There is a day-ahead market and six intraday markets both organized and managed by OMIE. In this market the electricity is traded for immediate delivery. The day-ahead market is carried out the previous day and the intraday market is carried out the delivering day.

In the Spanish electricity market energy is traded mainly in the day-ahead market. This market is very liquid and there is a huge amount of volume trade in the day-ahead market because is compulsory to all the agents to offer their generation available. Then in the six intra-day markets the agents can adjust their offers.

Balancing markets: These markets are required for system adjustment services and are managed by the System Operator, REE, which is responsible for the security and integrity of the system. The purpose of these markets is to adapt the programs of the production units, resulting from the participation in the previous energy markets and to solve the technical constraints of the system modifying the generation programs to ensure compliance with the conditions of safety and quality requirements at the minimum cost for the system.

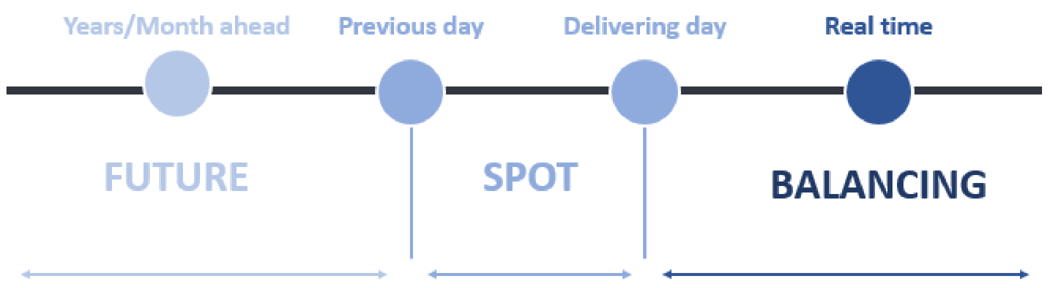


FIGURE 3. TYPE OF ELECTRICITY MARKET AS A FUNCTION OF THE TIME WHEN ENERGY IS PURCHASED

Bilateral markets: An unorganized market where the terms and conditions of the physical contracts are agreed between the parties involved.

4.4 Day-ahead market

The day-ahead market is the most important mechanism to sell and buy electricity in the Iberian Peninsula, thus, this market has a great liquidity. After the matching algorithm, EUPHEMIA (Pan-European Hybrid Electricity Integration Algorithm), is run, the result provides a single marginal price where price and volume in each hour are established according to the point where the supply and demand curves cross. This marginal price becomes the reference for all market participants disregarding the price bided by each agent.

It is remarkable to know that all generating agents must submit their available generation offers in the day-ahead market and only the generation capacity declared unavailable in advance may not be offer.

4.4.1 The bid format

Bids are sent to the market operator and consist of 24 hourly bids that make up the 24 consecutive hours of the next day.

All players must submit their offers for the following day until 12:00 pm. Then, the optimization algorithm, EUPHEMIA, is run, and the price will be obtained.

Those offers can be simple or include additionally complex conditions.

Sellers indicate an amount of power and a price for each time period and generating plant. But they can include some constraints in their bids creating what is known as a complex bids which include one or some the following technical or economic conditions:

- Indivisibility
    - The indivisibility condition enables agents to define that they will only be matched for the whole amount of the energy specified or more.
    -
- Load gradients
    - As some generation technologies cannot cope with sharp variations of delivered power, the load gradient allows them to specify the maximum variations of power (in MW/minute).

- Minimum income

    - This condition enables bids to be presented in all hours but they will only be matched if the total production obtained in the day is below a defined threshold, defined by: fixed amount (€) and a variable amount according to the matched energy (€/MWh).

In addition, there are other types of complex bids.

4.4.2 Pricing design

In Spain, the electricity sold or purchased gets the same price for all agents. This uniform price, also known as market clearing price, results from the intersection of the aggregated supply and demand curves and present some advantages and drawbacks.

Advantages:

- It provides a reference price for other markets.
- The mechanism is transparent and simple.
- It provides the right short-term signal (dispatch) and long-term efficiency (investment recovery).

Drawbacks:

- It is subject to market power because agents can withhold capacity increasing the clearing price. This may happen if the market is not competitive enough.

Chapter 5: Day-ahead market optimization model

5.1 Introduction

The model developed during this thesis will only consider the day-ahead market.

During this chapter we will see the proposed optimization model to obtain the optimal programming of the basin considering the layout of the basin and the technical and physical constraints of each reservoir. The model will determine the optimal schedule for each hour of the following two weeks which means determine the optimal offers to sell or purchase energy for each hour of the day.

The offers to sell energy determine the minimum amount of money we are willing to receive to generate electricity and the offers to purchase means the maximum price at we are willing to buy energy to pump water from the lower to the upper reservoir.

5.2 Objective function

The objective function is the first step to be defined when developing a model.

This function obtains a profit maximization of the difference between revenues obtained and cost incurred when pumping for each hour.

The revenues are the product of the energy produced and the market price at each hour and the cost involved in this type of facilities are the product of the amount of energy pumped and the market price at each hour of the day. The taxes applied to the generation of electricity which depends on the type of installation and the incomes obtained from the generation and the cost incurred in the network access tariff.

$$Max\ Benefit = \sum_i [P_i\ x\ e_{i,t} - \left(P_i\ x\ e_{i,p} + T_t\ x\ e_{i,t} + T_p\ x\ e_{i,p} + t\ x\ \left(P_i\ x\ e_{i,t}\right)\right)]$$

Where:

- P_i = Electricity price for day-ahead market.
- $e_{i,t}$ = Energy generated.
- $e_{i,p}$ = Energy pumped.
- T_t = Access tariff for generation.
- T_p = Access tariff for consumption.
- t = Taxes per income.

5.3 Energy balance equations

These equations are needed because the energy currently stored in one reservoir is a function of the energy stored in the reservoir in the previous period and the schedule of generation and pumping. Furthermore, the inflows expected, and the programmed spillages are considered.

These equations impose constraints that define the amount of energy transferred between the linked reservoirs by generating and pumping water.

$$\text{ereserv}_{i,n} = \text{ereserv}_{i-1,n} + \text{app}_{i,n} - e_{i,t,n}/\mu_n + e_{i,t,n-1}/\mu_{n-1} + e_{i,p,n}/\varepsilon_n - e_{i,p,n-1}/\varepsilon_{n-1} - s_{i,n} + s_{i,n-1}$$

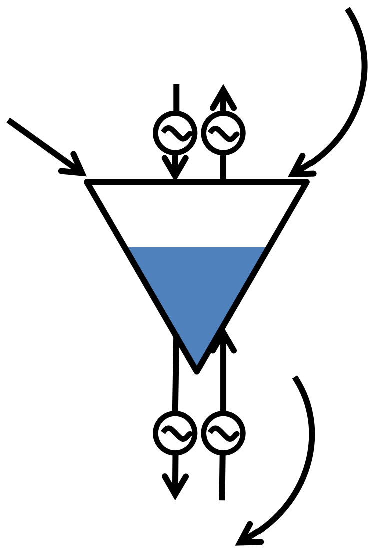


FIGURE 4. ENERGY BALANCE

Where:

- ereserv = Energy stored in the reservoir.
- app = Inflows.
- $e_{i,t}$= Generation.
- $e_{i,p}$ = Pumping.
- s = Spillages.
- μ = Performance of turbine machine.
- ε = Performance of pumping machine.
- n = Reservoir.
- n-1 = Previous reservoir.
- i = Period.
- i-1 = Previous period.

5.4 Constraints

Once the equations have been defined, it is necessary to introduce the constraints in the optimization model because the optimum program will be achieved by means of the forecast of market prices, demand and considering the technical constraints related with the units and the basin.

These constraints are mainly defined by the physical characteristics of the units but also there are some market constraints:

Physical constraints:

- Capacity constraints (lower and upper limits)
  - These restrictions are those that impose limitations of the equipment (limited generating and pumping capacity) and the capacity of the reservoirs (reservoirs cannot hold more than a maximum capacity and sometimes it is required a minimum capacity).

Lower limits:

$$e_{i,t} \geq 0$$

$$e_{i,p} \geq 0$$

$$ereserv_i \geq ereserv_i\_min$$

Upper limits:

$$e_{i,t} \leq e_{gen\_max}$$

$$e_{i,p} \leq e_{pump\_max}$$

$$ereserv_i \leq ereserv_i\_max$$

- Energy constraints (see section 5.3)
  - Energy balance that takes place in the reservoir at each hour.

- Lag time (during the change from generation to pumping mode and vice versa)
  - This constraint requires use of binary variables to establish the period which the machine must be turned off if during the immediate previous period the machine was working and we want to change the mode.

$$u_{1,p} \leq 1 - u_{2,p-1}$$

$$u_{2,p} \leq 1 - u_{1,p-1}$$

Where:

- u_1 = Decision to turbine.
- u_2 = Decision to pump.

<u>Market constraints:</u>

- Medium- and long-term signal.
  - This constraint also requires binary variables to compare the market price forecast with the medium- and long-term signals.

$$P_i - u_3 * Signal \geq 0$$

5.5 Availability

The availability of the hydro plants depends on the availability of the different groups that compose the plant. These groups can have the same or different power and the power may vary if the units turbine or pump the water. The generating or pumping groups may be unavailable one, several or all of them. The unavailability of the groups may be because of maintenance, breakdowns or lag time. Thus, the model should take into account the availability of the different groups.

During the development of the model, the constraints related to the availability have been one milestone because the shared unit between reservoirs 2 and 3 has a lag time during the change from generation to pumping mode or vice versa. And this should be also considered in the model (see section 5.4).

5.6 Time horizon

Following the logic of pumping in low prices scenarios and generate energy during high prices scenarios, the actual problem is to decide how or when to allocate the pumping and generating program in the given horizon.

Thus, make sense to have a minimum scenario of one-week time horizon in the optimization model. However, it is more interesting to extend it to two weeks because we can take advantage of additional opportunities when analyze a larger horizon. Therefore, when executing the model, it will be done with a time horizon of two weeks.

The two-week' time horizon allows the model to adapt the optimal schedule in a more profitable way considering a huge variety of possible extraordinary situations such as high demand or scarcity of renewable resources.

5.7 Input data

Once the equations of the optimization model have been developed and considering the constraints of the problem, it is necessary to define the values that the model needs to know in and this data will be introduced before to run the model. This data is collected from several sources.

The main inputs introduced are:

- Unit characteristics and availability.
- Inflows (forecast).
- Day-ahead prices (forecast).
- Initial level of water.

5.7.1 Unit characteristics and availability

The maximum capacity of energy able to turbine or pump each of the installed machines and the number of machines in every units should be introduced.

At the same time, it is necessary to introduce the number of unavailable machines in every unit at each hour.

The maximum capacity is calculated as the difference between the numbers of machines minus the unavailable machines, multiplied by the power of the machines.

$$Pmax_{i,t} = \left(m_{i,t} - v_{i,t}\right) x\, P_{max}$$

$$Bmax_{i,t} = \left(m_{i,t} - v_{i,t}\right) x\, B_{max}$$

Where:

m = Total number of machines in the unit.

v = Unavailable number of machines.

P_{max} = Maximum generating capacity of the machine.

B_{max} = Maximum generating capacity of the machine.

These formulas are used to determine both the maximum available generation power and the maximum available pumping power.

5.7.2 Inflows

A daily forecast of the inflows, in m^3/s, for the defined time horizon has to be introduced for each reservoir. This data is provided by an external company.

The data present certain uncertainty but are robust enough in the short-term to make a deterministic use of them avoiding the simulation of different scenarios.

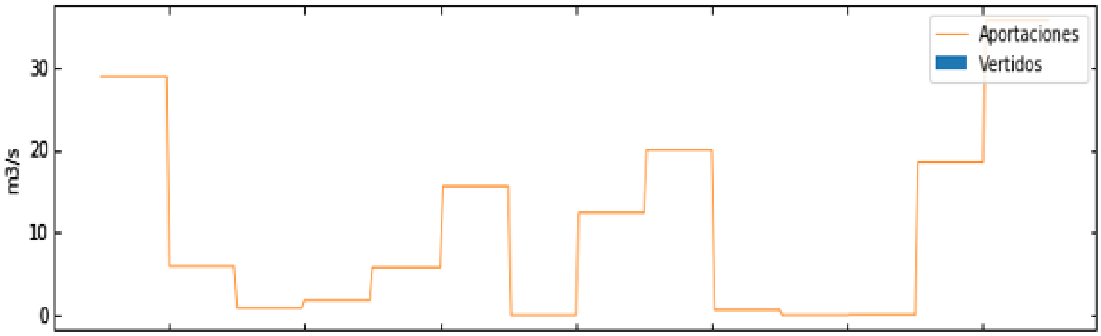


FIGURE 5. EXAMPLE OF INFLOWS FORECAST

5.7.3 Day-ahead prices

The market price forecast of the day-ahead for the defined time horizon has to be considered. This forecast is calculated and provided by the company and introduced in the model. This forecast helps us to find the optimum scheduling during the time horizon established and to generate offers to sell or buy in the day-ahead market. The price of each hour can be estimated analyzing the historical information of the electricity market, the meteorological data, etc.

For the 2 weeks' time horizon this hourly price forecast consists in 336 different prices.

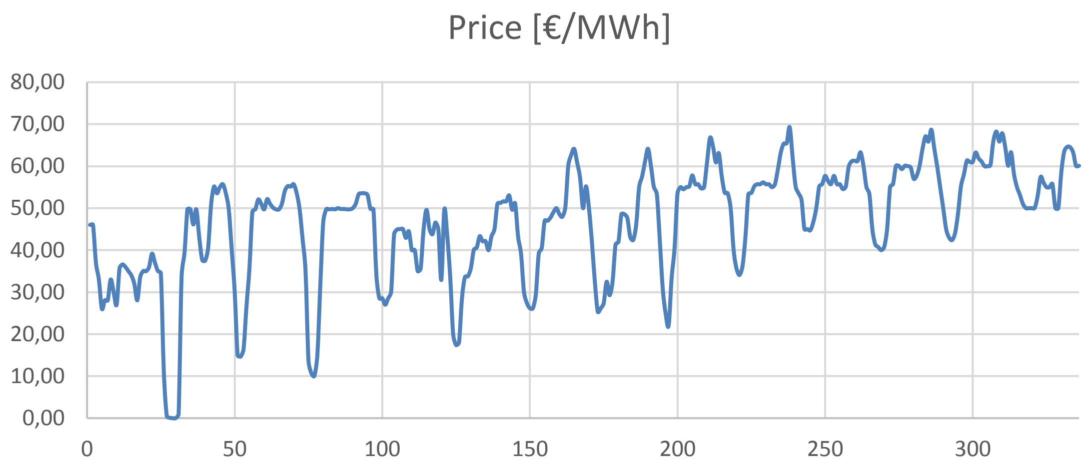


FIGURE 6. EXAMPLE OF DAY-AHEAD PRICES

5.7.4 Initial level of water

The initial level of water is the current level in each reservoir in the moment we will run the model. This data will be introduced manually but this data will be provided by the model in the previous simulations, in other words, once we run the model we obtain the level of every reservoir at the end of the period selected. This data will be an input in the next simulation of the optimization model.

5.8 Model

For the development of this thesis different softwares have been used, of which we used the necessary tools to streamline and facilitate the implementation of the model.

These softwares are presented briefly before explaining the methodology.

FIGURE 7. SOFTWARES

5.8.1 Microsoft Excel

"Microsoft Excel is a software program produced by Microsoft that allows users to organize, format and calculate data with formulas using a spreadsheet

system. This software is part of the Microsoft Office suite and is compatible with other applications in the Office suite."

[www.scribd.com]

5.8.2 Python

"Python is an interpreted, object-oriented, high-level programming language with dynamic semantics. Its high-level built in data structures, combined with dynamic typing and dynamic binding, make it very attractive for Rapid Application Development, as well as for use as a scripting or glue language to connect existing components together. Python's simple, easy to learn syntax emphasizes readability and therefore reduces the cost of program maintenance. Python supports modules and packages, which encourages program modularity and code reuse. The Python interpreter and the extensive standard library are available in source or binary form without charge for all major platforms and can be freely distributed."

[www.scribd.com]

5.8.3 GAMS

"The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows you to build large maintainable models that can be adapted quickly to new situations. GAMS is specifically designed for modeling linear, nonlinear and mixed integer optimization problems.

GAMS allows its users to formulate mathematical models in a way that is very similar to their mathematical description. Through this, GAMS lets the user concentrate on modeling. But since the model is formulated in a way that is similar to its mathematical description, it can be understood and maintained not only by programmers".

[www.gams.com]

5.8.4 Methodology

The model will follow the methodology shown in Figure 8 with the programs presented in section 5.8.

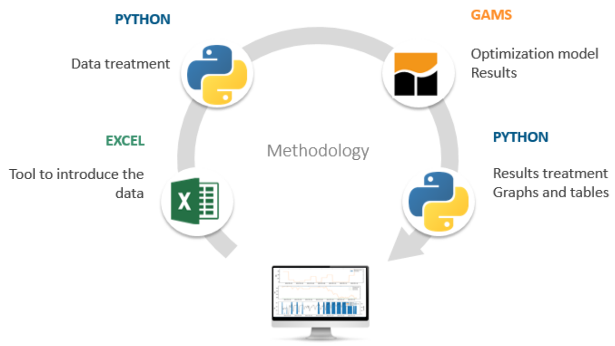


FIGURE 8. SUMMARY OF THE METHODOLOGY

The first program used in the development of the master thesis is Excel. In Excel we introduce all the initial data, the inputs, that is, the characteristics of each of the hydraulic plants, the unavailability, the daily inflows, the price forecast and the initial level in each of the dams. In addition, in Excel we will have other data such as the evolution of the maximum and minimum level during the year in the reservoirs, the calculation of the energetic coefficients of turbine and pumping, etc.

Below are several examples of how we found the Excel spreadsheet to introduce the necessary data.

Date	Inflows (m3/s)						
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
01/01/2018	60	9,06	11,69	10.07	3,495	0,498	1,389
02/01/2018	43,08	0,01	5,17	10.54	3,507	0,359	1,771
03/01/2018	50,9	0,01	15,07	10.32	1,748	0,498	1,389
04/01/2018	51,7	0,21	12,88	11.69	3,519	0,498	1,4
05/01/2018	75,81	0	11,64	7.12	13,923	0,878	2,87
06/01/2018	45,22	0	11,04	7.69	15,938	0,498	3,6
07/01/2018	41,04	0	11,06	8.21	7,118	0,498	2,87

TABLE 1. EXAMPLE OF INFLOWS DATA

Hourly	Available Power (MW)						
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7
01/01/2018 0:00	150	80	0	500	60	60	30
01/01/2018 1:00	150	80	0	500	120	60	30
01/01/2018 2:00	100	80	0	500	120	60	30
01/01/2018 4:00	150	80	0	0	120	60	30

TABLE 2. EXAMPLE OF AVAILABLE POWER

Once we have all the inputs introduced in the Excel spreadsheet, we execute the Python script, this script will format the data and generate an output which will be used by GAMS to proceed with the optimization. It will be the Python script itself that executes GAMS and collects the data obtained during the optimization to proceed to an easy visualization of them generating the necessary graphics and tables with all the results.

Among the results obtained we will obtain the optimal generation and pumping schedule of each of the plants and the water level in each of the reservoirs in a hoary way. In addition, we will obtain the tables that will indicate both the hourly and daily schedule of the turbine and pumping programs and the offer price of the same.

In the following figures we can se an example of the results obtained by the optimization model treated and visualized with Python.

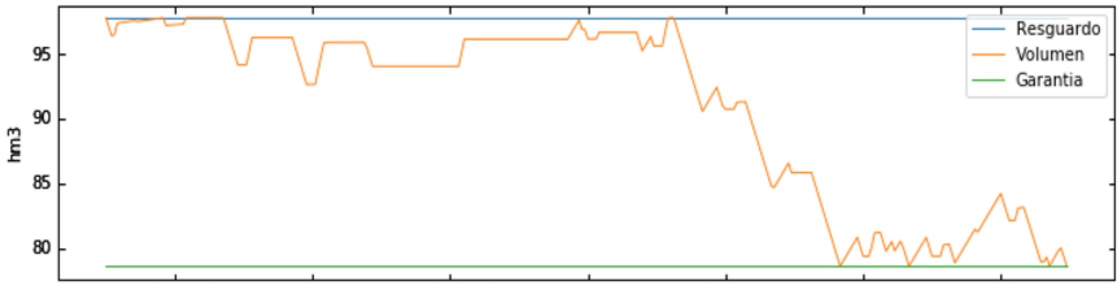


FIGURE 8. EXAMPLE OF OPTIMIZATION WATER LEVEL RESULT

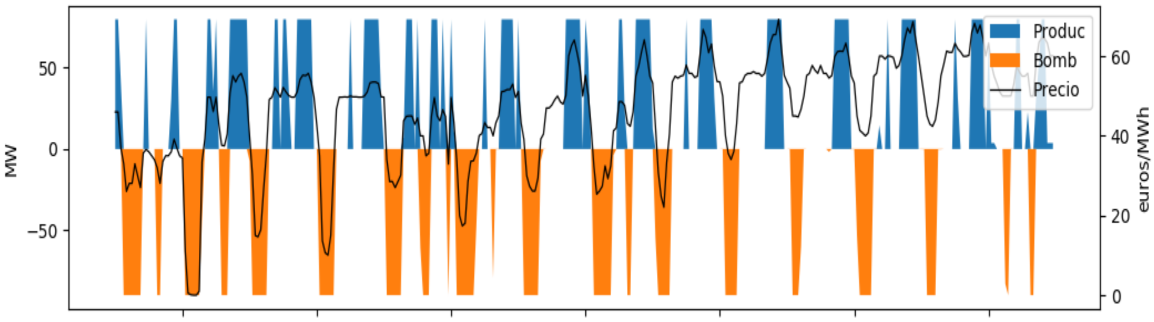
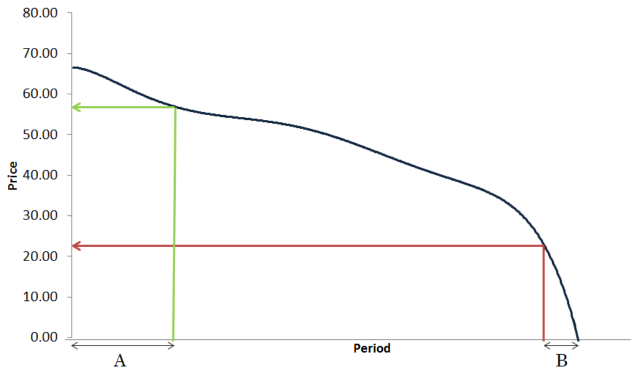


FIGURE 9. EXAMPLE OF OPTIMIZATION SCHEDULE RESULT

5.8.5 Water Value

To calculate the value of the water once we have obtained the schedule of generation and pumping, we deal with the Python results.

From the calculation of a price monotone curve depending on the period, we introduce the periods of generation and pumping, using this method we can easily obtain the value of water, or what is the same the price at which we should offer our production or the price at which we are willing to pump in each day of the two-week temporal horizon.



Where:

- A=Generation periods.
- B = Pumping periods.

FIGURE 10. PRICE MONOTONE CURVE

5.9 Outputs

The outputs of the model can be divided into two groups.

The graphs are obtained by python and the tables are obtained through and excel file previously generated by python.

5.9.1 Graphs

The main output obtained by the model, considering the previous inputs can be observed below for several units.

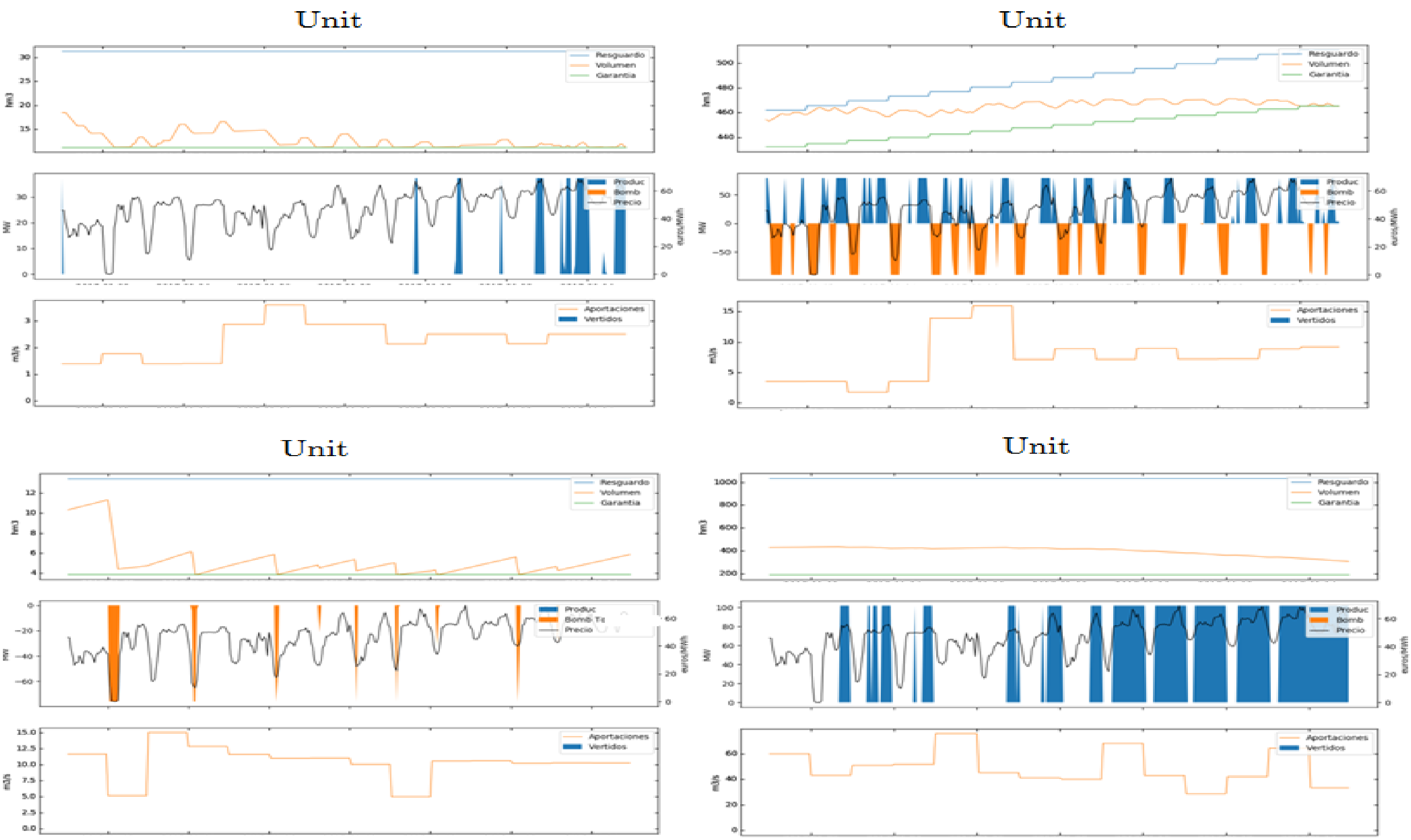


FIGURE 11. OUTPUT EXAMPLE

Chapter 6: Results

This model offers the possibility of back-testing the past, allowing us to evaluate strategies to improve them.

Taking into account the inputs presented in the previous chapter, the results obtained will be compared with real data. Several back-tests of different parts of the problem presented will be analyzed to contrast the results obtained with the actual generating and pumping programs that were carried out months before.

Two cases will be analyzed, one comparing the model results with the real schedule in a two week period when the inflows were the expected ones (#1) and the other case considering a two week period when the unexpected large amount of rain led to spillages and the schedule obtained was not the desired one (#2).

For both cases, the problem analyzed will be focused in the Units 2 and 3.

6.1 Back-test #1

To perform this first back test we analyze two situations. The first one try to replicate the reality in the model introducing the inflows, unavailability of the machines and the maximum powers during the period, as well as the initial and final levels of water that were given in the reservoirs. Then, the water levels constraints are removed it and we introduce the long term signal prices of the above and beyond the study case, in this case Unit 1 and Unit 4.

As we are going to analyze the behavior of the Units 2 and 3, we also need to model the previous and the following ones, Unit 1 and Unit 4 respectively.

The list of graphs and tables provided below shows the results obtained during the first back-test.

The following bar graphs show the difference between the real generated and pumped power scheduled in a daily basis, in MWh, and what the model would have done in that situation.

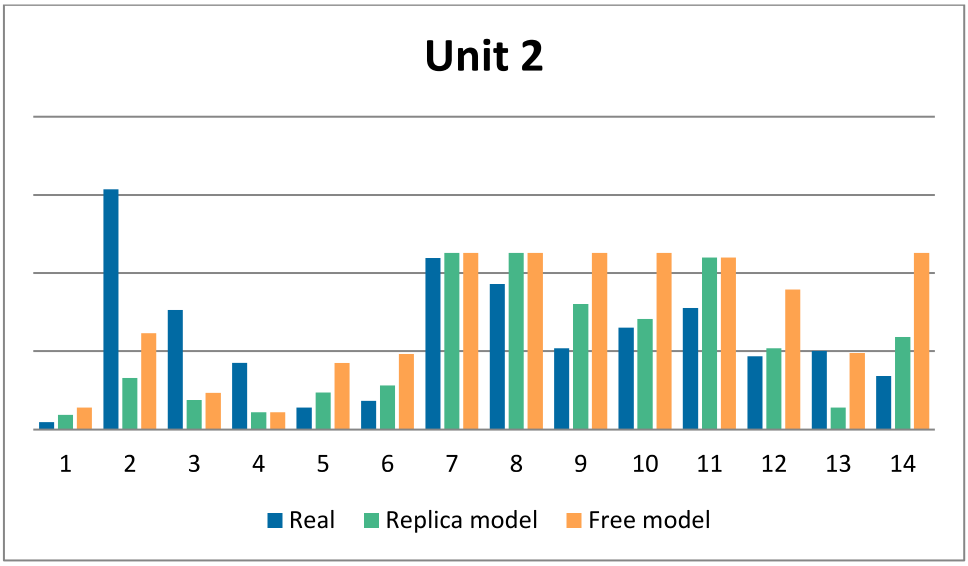


FIGURE 12. DAILY SCHEDULE OF UNIT 2. BACK-TEST 1

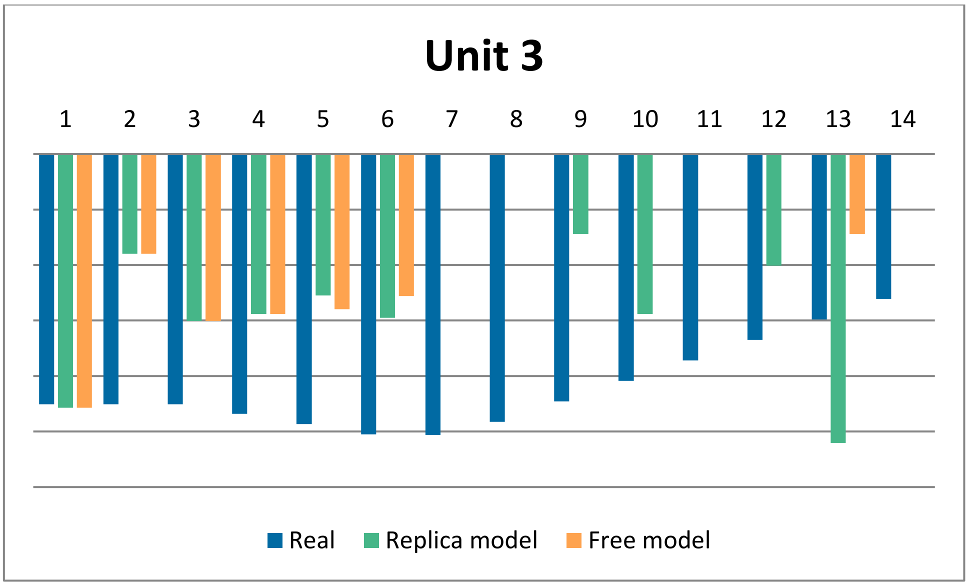


FIGURE 13. DAILY SCHEDULE OF UNIT 3. BACK-TEST 1

6.1.1 MWh

MWh - Unit 2 & Unit 3					
Real		Replica model		Free model	
Generation	Pumping	Generation	Pumping	Generation	Pumping
8384.32	5919.16	7357.84	2930.18	10142	1905

TABLE 3. BACK-TEST 1. AGGREGATED GENERATION AND PUMPING SCHEDULE.

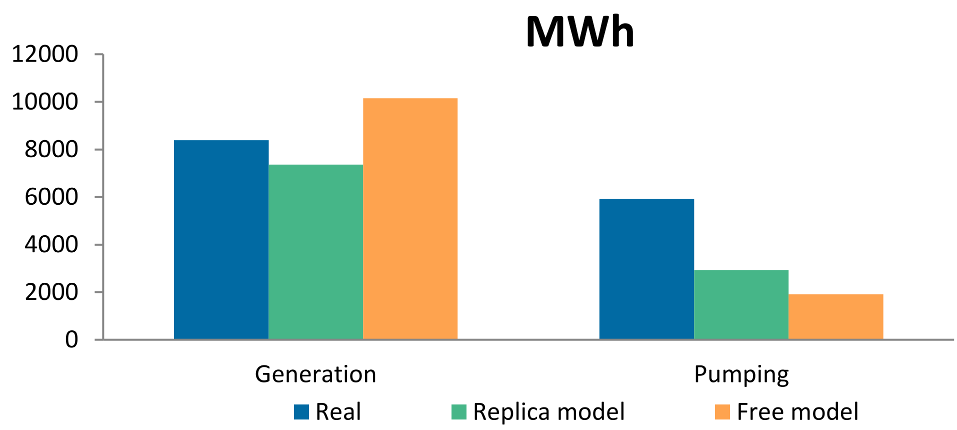


FIGURE 14. BACK-TEST 1. AGGREGATED GENERATION AND PUMPING SCHEDULE

The table above shows that the amount of power generated, in MWh, the replica model results are a bit lower than in reality but in the free model the MWh generated increases. The amount of water pumped is reduced in both cases; the reduction is considerably greater.

6.1.2 Hours

hours - Unit 2 & Unit 3					
Real		Replica model		Free model	
Generation	Pumping	Generation	Pumping	Generation	Pumping
190	96	137	99	219	56

TABLE 4. BACK-TEST 1. TOTAL NUMBER OF HOURS WORK DURING THE WHOLE PERIOD

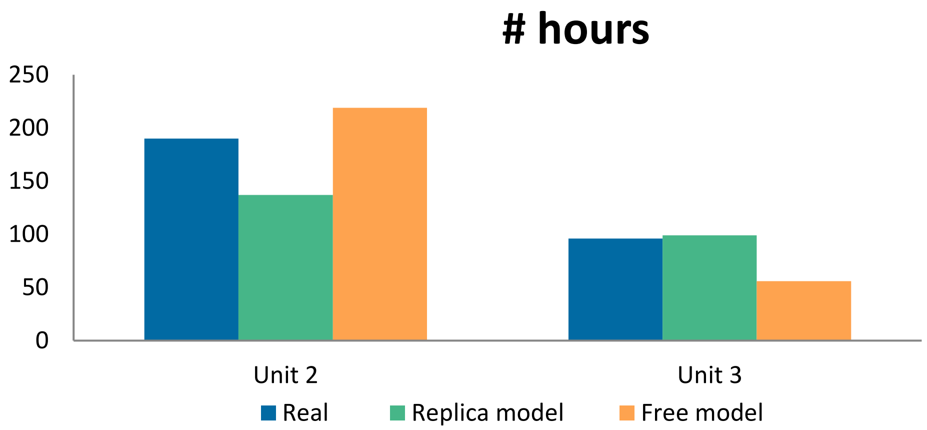


FIGURE 15. TOTAL NUMBER OF HOURS WORK DURING THE WHOLE PERIOD.

The number of hours that the units should work in the 2-weeks period can vary considerably regarding the model we run.

6.1.3 Benefits

Benefit - Unit 2 & Unit 3		
Real	Replica model	Free model
267,221.56 €	303,298.98 €	469,195.69 €

TABLE 5. BACK-TEST 1. BENEFITS OBTAINED

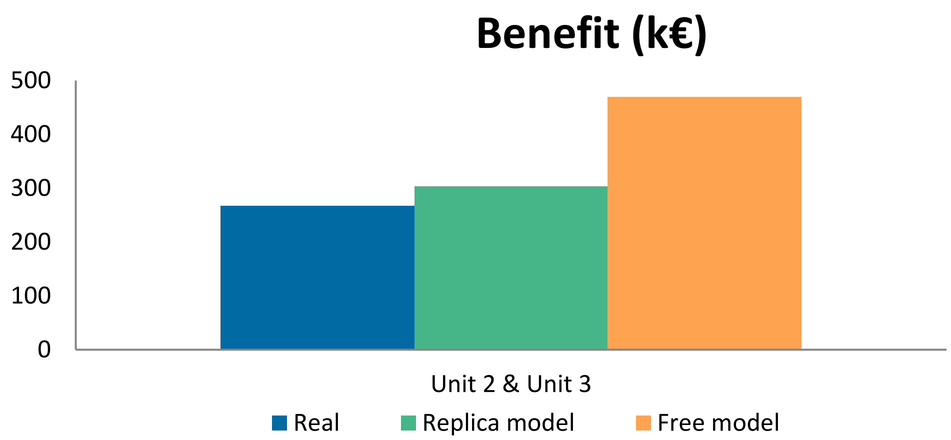


FIGURE 16. BACK-TEST 1. BENEFITS OBTAINED

6.1.4 Schedule

To conclude, it is also interesting to make a comparison between the benefits obtained. It can be seen from the tables that the benefits obtained are higher under both model assumption.

In the following figures we can see the graphs that represent the optimum programs calculated by the optimization model. Unit 2 and Unit 3 labels correspond to what was scheduled in the period back-tested.

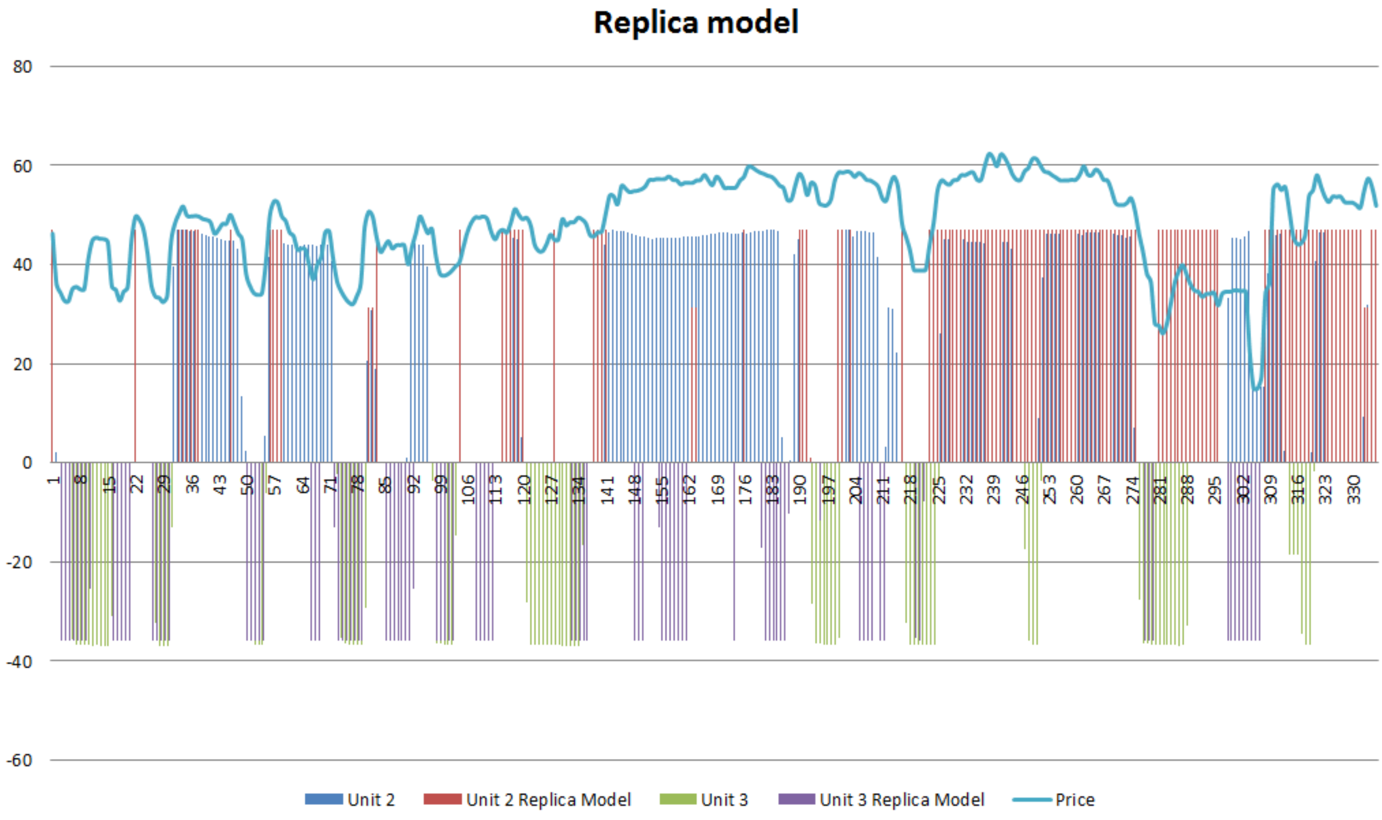


FIGURE 17. BACK-TEST 1. REPLICA MODEL SCHEDULE

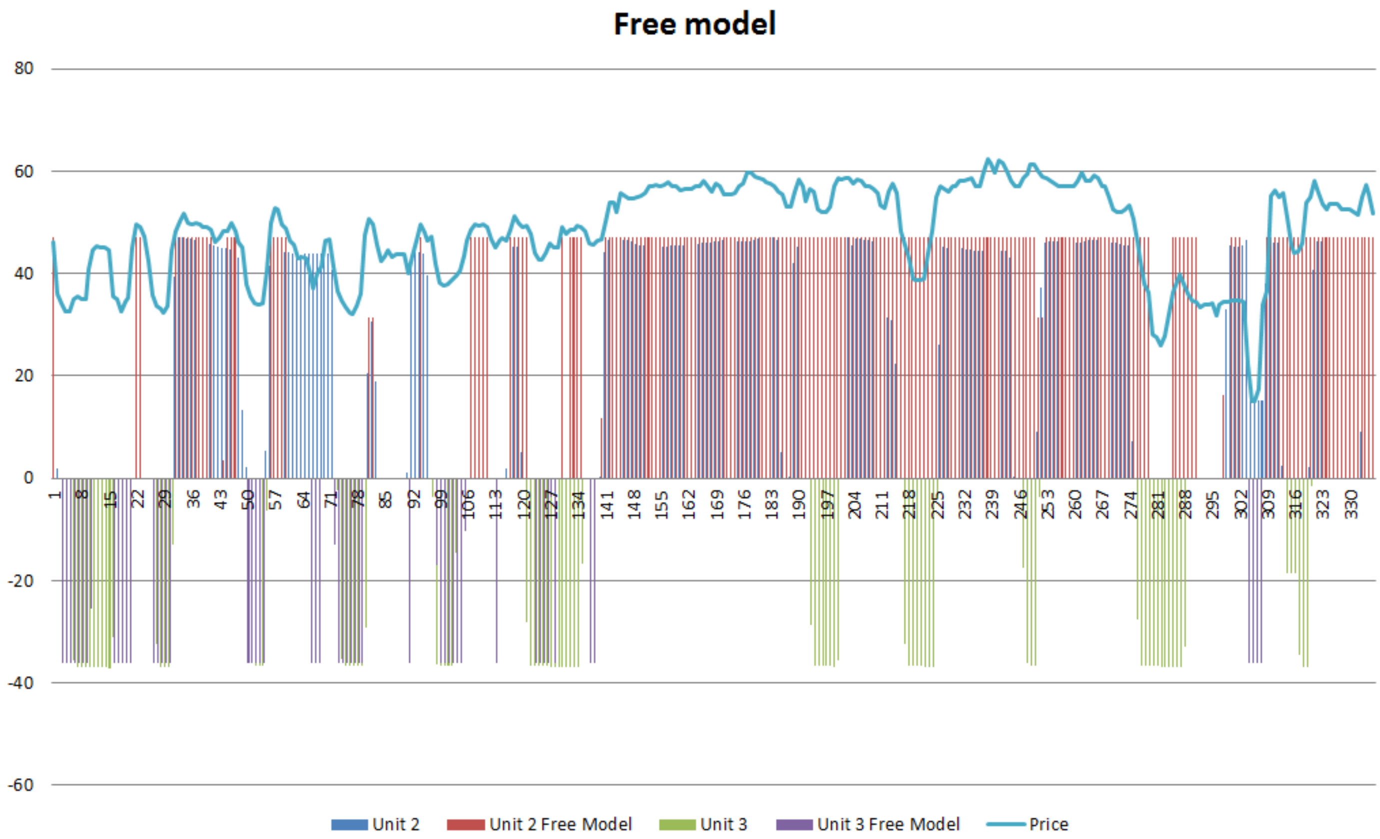


FIGURE 18. BACK-TEST 1. FREE MODEL SCHEDULE

6.1.5 Conclusions

The model developed returns the optimum generation and pumping schedule for each hour of the period. The results obtained are in line with what was expected because they comply with the restrictions, there is an increase in the benefits of the facilities obtained.

Analyzing the first situations, the replica model, it is quite interest to observe that the benefits increases although there is a clearly reduction in the amount of power generated and the numbers of hours the machine have worked. The reason is the optimal reallocation of the generation and pumping hours along the schedule.

The second situation, the free model, generates considerably higher benefits because the model will try to use as much water as possible, allocating it in the most profitable periods. For that reason, the generation will be higher and the number of hours the machines will work will be higher too.

6.2 Back-test #2

To perform this second back test we analyze just one situation. The one which try to replicate the reality in the model introducing the inflows, unavailability of the machines and the maximum powers during the period, as well as the initial and final levels of water that were given in the reservoirs.

As we are going to analyze the behavior of the Units 2 and 3, we also need to model the previous and the following ones, Unit 1 and Unit 4 respectively.

The list of graphs and tables provided below shows the results obtained during the first back-test.

The following bar graphs show the difference between the real generated and pumped power scheduled in a daily basis, in MWh, and what the model would have done in that situation.

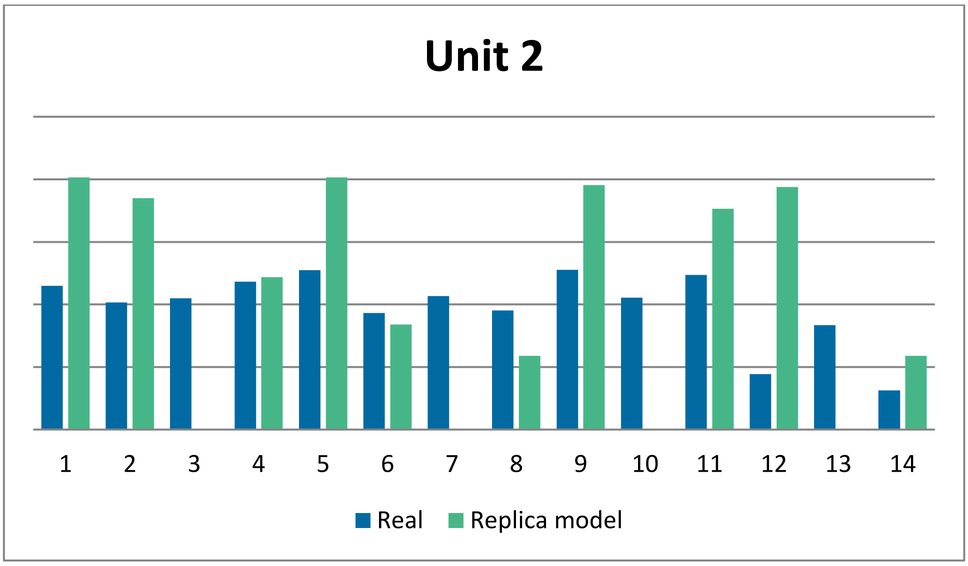


FIGURE 19. DAILY SCHEDULE OF UNIT 2. BACK-TEST 2.

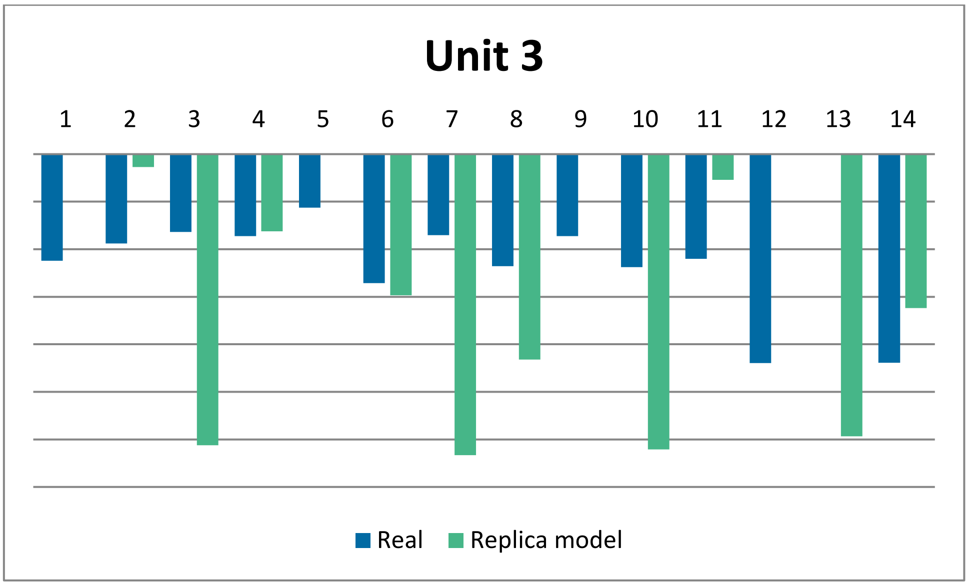


FIGURE 20 DAILY SCHEDULE OF UNIT 3. BACK-TEST 2

6.2.1 MWh

MWh - Unit 2 & Unit 3			
Real		Replica	
Generation	Pumping	Generation	Pumping
13777.661	6093.579	14768.86	7510.89

TABLE 6 BACK-TEST 2. AGGREGATED GENERATION AND PUMPING SCHEDULE.

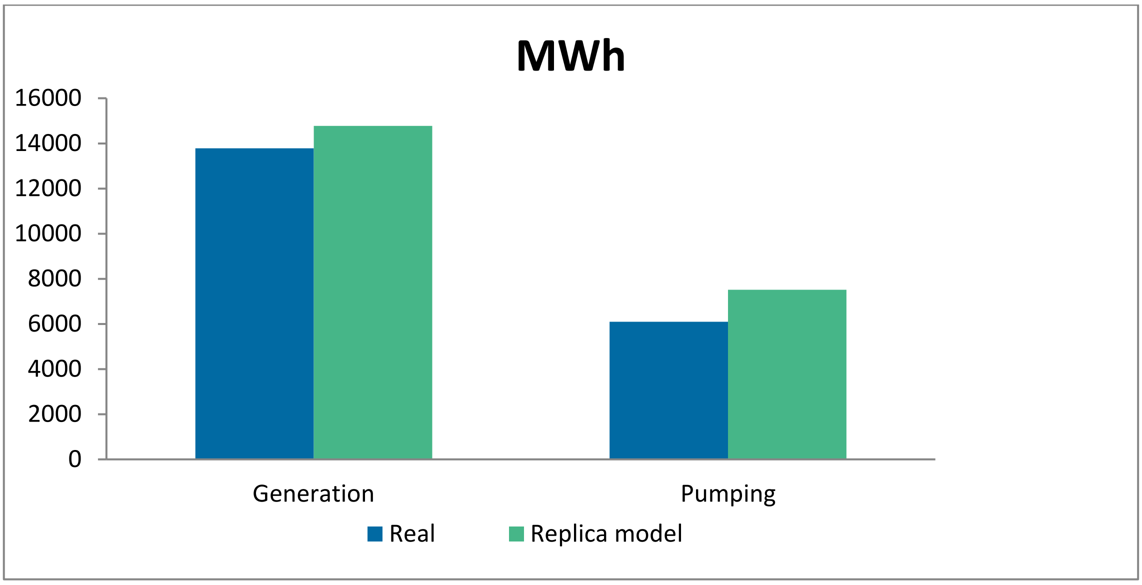


FIGURE 21. BACK-TEST 2. AGGREGATED GENERATION AND PUMPING SCHEDULE

The table above shows that the amount of power generated, in MWh, the replica model results are a higher than in reality. And the amount of water pumped is increased. This result is the desirable one because the problem during those weeks was the lack of pumping which make the company spill water. With this increase in the amount of MWh pumped we are going the reduce de spillages.

6.2.2 Hours

hours - Unit 2 & Unit 3			
Real		Replica	
Generation	Pumping	Generation	Pumping
202	*129*	*188*	*138*

TABLE 7.BACK-TEST 2. TOTAL NUMBER OF HOURS WORK DURING THE WHOLE PERIOD

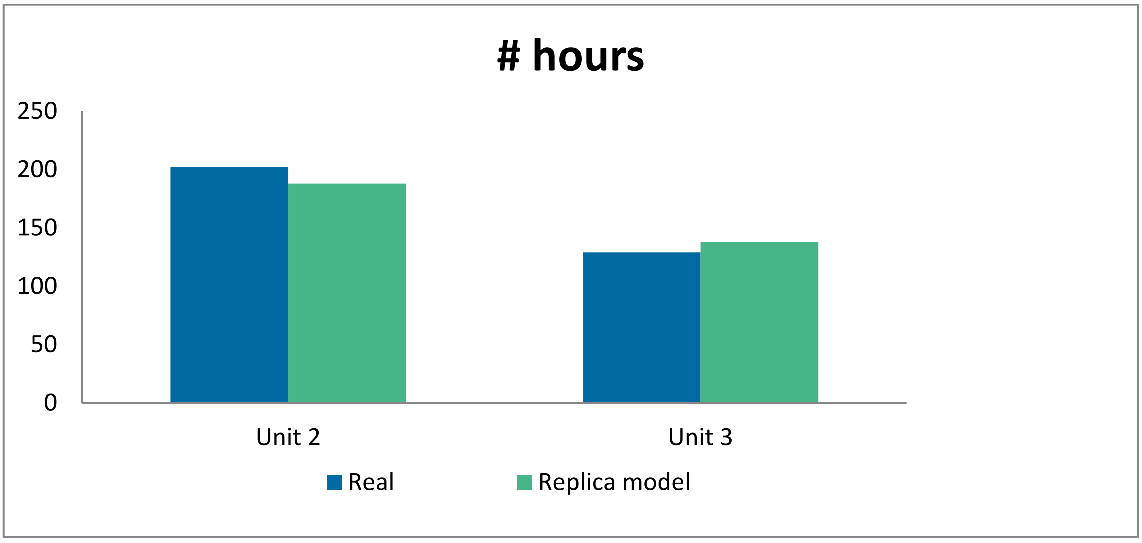


FIGURE 22. TOTAL NUMBER OF HOURS WORK DURING THE WHOLE PERIOD.

The number of hours that the units should work in the 2-weeks period shows us that the common unit is going to spend more time pumping water in exchange of a reduction of the number of generating hours.

6.2.3 Benefits

Benefits - Unit 2 & Unit 3	
Real	Réplica
390,254.91 €	397,638.87 €

TABLE 8. BACK-TEST 2. BENEFITS OBTAINED

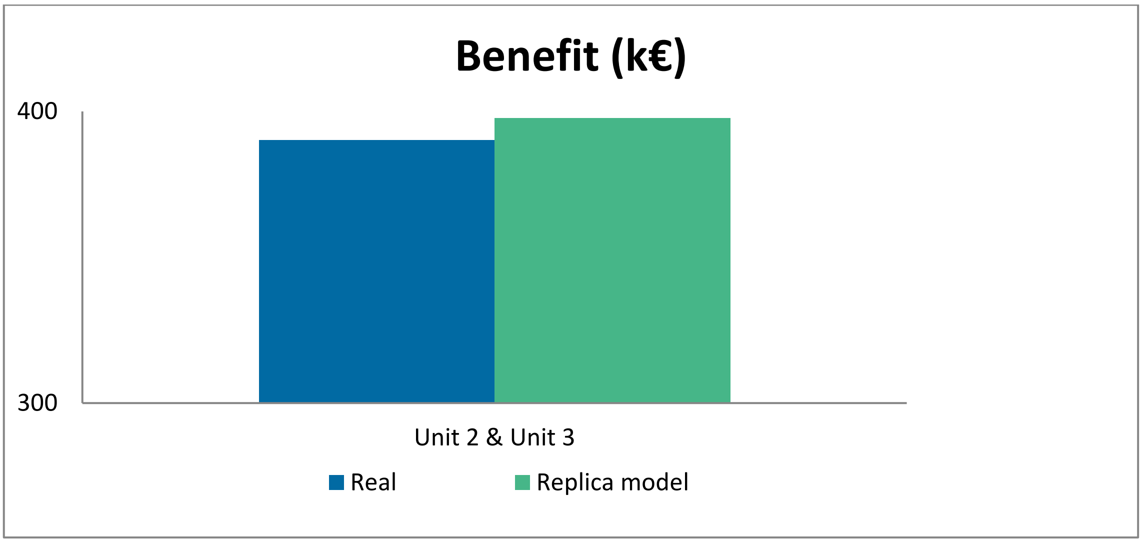


FIGURE 23. BACK-TEST 2. BENEFITS OBTAINED

6.2.4 Spillages

Spillages (m3)	
Real	Replica model
19196.832	18824.14

TABLE 9 BACK-TEST 2. SPILLAGES.

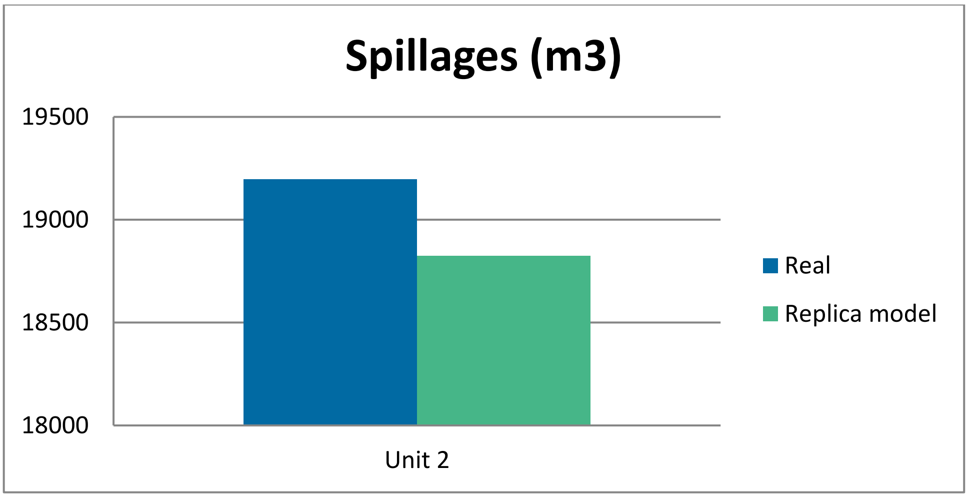


FIGURE 24. BACK-TEST 2. SPILLAGES.

6.2.5 Schedule

To conclude, it is also interesting to make a comparison between the benefits obtained. It can be seen from the tables that the benefits obtained are higher when the model is implemented.

In the following figures we can see the graphs that represent the optimum programs calculated by the optimization model. Unit 2 and Unit 3 labels correspond to what was scheduled in the period back-tested.

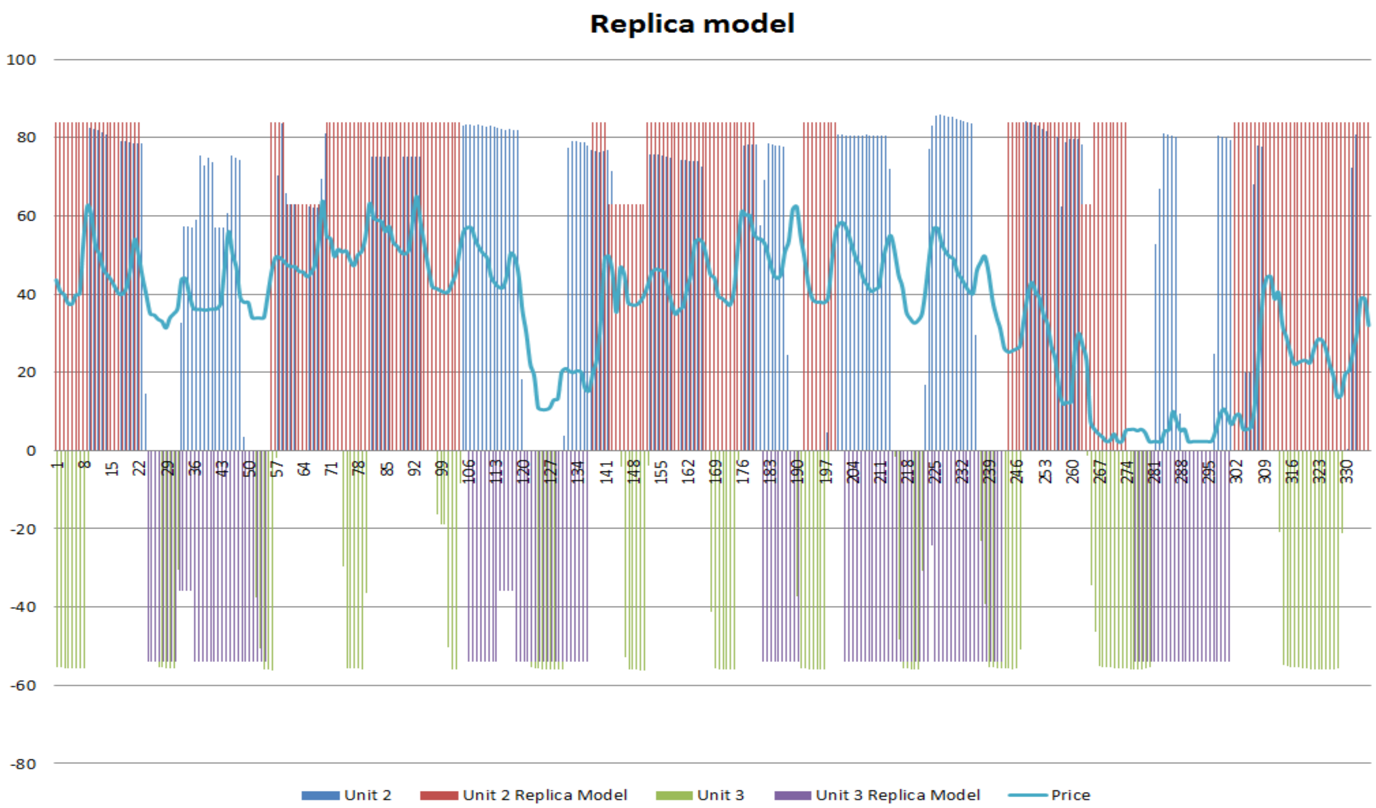


FIGURE 25. BACK-TEST 2. REPLICA MODEL SCHEDULE

6.2.6 Conclusions

The model developed returns the optimum generation and pumping schedule for each hour of the period. The results obtained are in line with what was expected because they comply with the restrictions, there is an increase in the benefits of the facilities obtained and the spillages has been reduced what was required in this period.

Chapter 7: Conclusions and future work

7.1 Conclusions

In this project an analysis and explanation of the Spanish electricity market, focusing on the day-ahead market, has been developed.

The optimization model has been developed in order to adjust the results as much as possible to the behavior of the electricity markets in the reality.

The results obtained consider the price curve. I.e. the model adjusts the pumping hours where the price is low and generates electricity in the hours with higher prices.

The marginal price for each hours of the period depends to a large extent to the volume of water traded in the market. But this factor has not been taken into account in the optimization model because the Units under study have no significant capacity to introduce huge variations in the market price. In the case that the Units studied were able to trade grater amounts of energy we should relate the prices with the volume trade through elasticity coefficients.

Ultimately, I can conclude that the optimization model comply with the objectives. The tool developed I simple to use, fast in the execution and the results obtained are optimal being able to represent the market behavior.

For that reason, I can conclude that the model developed can be used as a toll to forecast the optimal strategy for the operation of the hydro plants located in the basin studied providing us a 15-days vision.

7.2 Future work

The uncertainty and environmental factor around the electricity market makes very difficult to completely model the behavior of this market but we can try to introduce in the model as many variables as possible to get closer to the reality.

To increase the opportunities in the schedule of the basin it will be interesting to look beyond the day-ahead market, introducing the intraday and the balancing markets.

Elasticity coefficients relating marginal prices with the energy traded will also help to capture opportunities.

Last, it would be interesting to develop an hourly energetic coefficient prediction model in order to obtain a better approach to the actual production in each market sesion.

Annex A: Nomenclature and Abbreviations

Sets

i = Hours of the day [1, 2, 3...]

n = Reservoir [1, 2, 3...]

Parameters

app = Inflows [m^3/s]

B_{max} = Maximum generating capacity of the machine [MW]

$ereserv_i\_min$ = Minimum energy capacity of the reservoir [MWh]

$ereserv_i\_max$= Maximum energy capacity of the reservoir [MWh]

e_{gen_max}= Maximum turbine energy [MWh]

e_{pump_max}= Maximum pump energy [MWh]

m = Total number of machines in the unit [-]

P_i = Electricity price for day-ahead market [€]

P_{max} = Maximum generating capacity of the machine [MW]

s = Spillages[m^3/s]

t = Taxes per income [-]

T_p = Access tariff for consumption [€/MWh]

T_t = Access tariff for generation [€/MWh]

v = Unavailable number of machines [-]

μ = Performance of turbine machine [$\mathrm{MW} \cdot \mathrm{s} / m^3$]]

ε = Performance of pumping machine [$\mathrm{MW} \cdot \mathrm{s} / m^3$]

Variables

$e_{i,t}$ = Energy generated [MWh]

$e_{i,p}$ = Energy pumped [MWh]

ereserv = Energy stored in the reservoir [MWh]

u = Binary variable [0, 1]

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