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An agent-based modelling approach for the design of Power Generation Company: application to the Colombian day-ahead market

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Sommario

La Colombia sta sperimentando un periodo di profondi cambiamenti dovuti ad un veloce sviluppo economico e tecnologico. Questi cambiamenti coinvolgono anche il settore energetico che, prossimamente, vedrà l'introduzione di un mercato di bilanciamento e l'inclusione nel mix energetico di un'importante componente rinnovabile non-convenzionale, ancora (quasi) del tutto assente e per la quale c'è un forte potenziale.

In tutti i paesi il mercato energetico rappresenta un importante snodo delle attività economico-industriali e condiziona, più o meno direttamente, tutti i suoi abitanti. Di conseguenza il suo buon funzionamento costituisce un imprescindibile condizione per lo sviluppo e la stabilità non solo economica ma anche sociale.

Per questo, l'implementazione di un modello che permetta lo studio delle attività che caratterizzano il mercato elettrico colombiano, simulandone lo svolgimento, rappresenta un motivo di grande interesse, soprattutto in questa fase di profondi cambiamenti.

Il sistema multiagente è un metodo di modellazione che ha riscosso un importante successo nell'applicazione ai mercati energetici, ed è ha stimolato lo sviluppo di diverse piattaforme che ne riproducono lo svolgimento. Queste piattaforme però trascurano un aspetto che, nel caso del mercato colombiano e di molti altri, risulta imprescindibile e la cui omissione ne compromette la fedele rappresentazione: il principio per cui le compagnie proprietarie di diverse centrali di generazione, dirigono congiuntamente l'attività di queste per massimizzare il profitto totale.

Lo scopo di questo lavoro è quindi di rispondere a tale questione con lo sviluppo di un algoritmo che riproduca la gestione coordinata di diversi agenti, i quali, rappresentano centrali che agiscono singolarmente nel mercato, ma che sono amministrate dalla compagnia che persegue la massimizzazione del suo profitto globale.

In aggiunta, la preponderanza delle centrali idroelettriche nella generazione, ha reso necessario lo sviluppo di un algoritmo dedicato all'attività di queste, che tenesse conto del loro specifico principio di correlazione tra successive sessioni di mercato.

L'implementazione di queste funzioni permette così lo sviluppo di un modello che rappresenti lo svolgimento del mercato elettrico colombiano e le attività dei suoi principali attori. Il modello verrà quindi usato per lo studio di due criticità del mercato colombiano: la situazione di oligopolio nella generazione e gli effetti dell'esercizio del potere di mercato da parte delle compagnie dominanti; la volatilità dei prezzi di mercato durante i periodi di carenza di apporto idrico, a causa di periodici eventi climatici di forte siccità, e i possibili benefici derivanti dall'installazione di parchi eolici.

Parole Chiave: mercato elettrico colombiano, sistemi multi-agente, algoritmo, compagnia di generazione, centrale idroelettrica, oligopolio, volatilità prezzi mercato.

Abstract

Colombia is going through a period of deep changes due to the fast economic and technological growth. These changes involve also the energy sector which will soon experience the introduction of a balancing market and the aggregation to the energy mix of non-conventional renewable energy systems, still (almost) absent in spite of their strong potential.

The energy market represents in each country an important turning point of the economical and industrial activities and it conditions, more or less directly, all the citizens. Thus, its good functioning constitutes an essential condition for the social-economic development and stability. For these reasons, the improvement of a model which allows the study of the Colombian energy market activities, by the simulation of its operations, represents a very interesting theme, especially in this moment of deep changes.

The multi-agent system is a modelling approach which obtained significant achievements in the application to the energy market, and it stimulates the development of several platforms that reproduce the market activities. However, these platforms neglect an essential aspect that, for the cases as the Colombian market and many others, compromises their realistic representation: the principle for which the companies that own different power plants, manage jointly the activities of their plants to maximize the whole profit.

Therefore, the aim of this work is to fill the gap with this question by the development of an algorithm that reproduces the coordinated management of different agents; those represent power plants that act individually in the market, but they are administered by the companies that pursue the target to maximize its global profit.

In addition, the prevalence of the hydropower plants in the energy generation, requires the development of an algorithm dedicated to the representation of their activities; this has to include the peculiar principle of correlation that characterizes hydro-plants' consecutive market sessions. The implementation of these features allows the development of a model that represents the operation of the Colombian energy market and the activities of the main participants. Then, the model is exploited to perform the analysis of two critical issues of the Colombian market: the situation of oligopoly in power generation and the effect of the power exercised by the dominant companies; the volatility of the market prices during the period of water shortage, due to the periodical climatic event of strong drought, and the possible benefits derived by the installation of wind farms.

Keywords: Colombian energy market, multi-agent system, algorithm, power generation company, hydropower plant, oligopoly, market prices volatility.

Extended Abstract

INTRODUCTION

Today Colombia is experiencing a phase of changes that involves also the energy sector. In the next years, important changes will occur, revolutionizing the current dynamics, as the introduction of a balancing market and the aggregation to the energy mix of non-conventional renewable energy systems.

However, the energy market is still organized with a very basic structure and simple rules; in general, it is licit to affirm that the market configuration is inadequate to receive the significant innovation planned for the next years.

To accomplish the process of maturation, two onerous questions have to be solved soon to lay the foundations for the future structure of the market: the clear oligopoly in energy generation, and the volatility of the market prices due to the periodical climatic event of drought, known as "El Niño" or ENSO (El Niño-Southern Oscillation), which provoke strong shortage of water supply. The solution of these two issues represents an essential condition for the market development and it will improve significantly its efficiency and its reliability.

As regards these motivations, the improvement of a platform that allows the study of the market operations and the activities of its participants, especially the generators, is a reason of strong and current interest. To realize that, it is necessary to represent the generators and their real behaviour, including the presence of oligopoly in generation. This aspect has always been neglected in the development of all the other existent platforms (for the energy market).

For this reason, the purpose of this thesis is the implementation of an algorithm capable of reproducing this essential aspect of the market trading. To realize that, the agent-based modelling approach has been selected. The AMES framework [13], in which a very promising

structure is organized, was chosen to inspire the algorithms developed in this thesis.

After the realization of the required algorithms, they will be exploited to build a model of the Colombian day-ahead market. The model allows the analysis of the mentioned critical points:

- **OLIGOPOLY**. The objective is to demonstrate that the current oligopoly increases the market prices with respect to the situation in which the competition is guaranteed;

- **WATER SHORTAGE**. The target is to observe and to measure the possible benefits deriving from the installation of wind farms capacity and to verify if this will solve the problem of price volatility.

INTRODUCTION TO AGENT-BASED MODELLING

Agent-based modelling (ABM) is a modelling approach proposed in the late 1940s but, the large amount of calculations required had restricted the use of ABM until the arrival of the first modern calculators in the late 1980s. The core concept of Agent-Based Modelling is that the representation of a certain phenomenon or system can be modelled describing the interaction among entities, the agents, and environment.

Agents can be set in order to change and even adapt their strategy, in this case the terminology Multi-Agent System (MAS) is more appropriate.

U. Wilensky and W. Rand in "An introduction to agent-based modelling" [7], describe effectively the most important peculiarities of this approach with respect to the more common equation-based model (EBM). These characteristics perfectly fit the needs of the energy market modelling. Thus, the wide range of useful results and the way in which the modelling attributes match the market components, makes ABM strongly exploited for the energy markets. Through the application of learning algorithms, the agents can improve their

strategy to gain larger profits, turning the model into a MAS for all intent and purpose.

In 2007 J. Sun and L. Tesfatsion published "Market Power and Efficiency in a Computational Electricity Market With Discriminatory Double-Auction Pricing" [13] in which they describe the AMES framework that inspired the algorithm developed in this work. The target was to reproduce the characteristics of the Californian wholesale power market. To represent accurately the activities of the generators that sell energy in the market, the authors had associated to them a variation of the RE RLA, the Roth-Erev Reinforcement Learning algorithm (VRE RLA).

The learning algorithm has to meet the needs of bid selection recognizing the result obtained, in term of profit. This perfectly fits the purpose of A. Roth and I. Ever work [11]: the basic intuition underlying any reinforcement learning algorithm is that the tendency to implement an action should be strengthened (reinforced) if it produces favourable results or weakened if it produces unfavourable results [12].

Regarding the algorithm working principles, the beginning is the initialization of the *propensities (q)*, i.e. at the time *t=0*, with the same value *q(0)* for each of the N options. The *propensities* quantify the will or predilection for a certain option; each option is associated to a propensity value. At the following iteration these are updated depending on the selection and the result obtained. The following equations expose the operation of the Modified RE RLA (MRE RLA), used in the Colombian market model, for the choice of an option *k* at the time *t* and the consequent update of the propensities at the time *t+1*:

$$q_j(t+1) = (1-r) \times q_j(t) \qquad (0.1)$$
$$+ RESPONSE_j \quad \forall j$$

$$RESPONSE_j = \pi_k(t) \times (1-e) \quad if\ j \qquad (0.2)$$
$$= k$$

$$RESPONSE_j = q_j(t) \times \frac{e}{N-1} \quad if\ j \qquad (0.3)$$
$$\neq k$$

$$r \in [0;1] \qquad (0.4)$$

$$e \in [0;1] \qquad (0.5)$$

The choice probability of each action a_k at the time *t* is defined as:

$$p_j(t) = \frac{q_j(t)}{\sum_{i=0}^{N-1} q_i(t)} \qquad (0.6)$$

where:

• $q_j(t)$ is the propensity of action j at time t;

• $\pi_k(t)$ is the reward obtained by the chosen action k at time t;

• *r* is the recency parameter;

• *e* is the experimentation parameter;

• $p_j(t)$ is the probability choice of the action j at time t.

THE COLOMBIAN CASE

Colombia has a liberalized energy market since 1995 when Generation, Transmission, Distribution and Commercialization were unbundled; transmission is the only one activity in which there is not competition among the participants.

The energy trades can be realized by transaction in the day-ahead market, the only energy market existing, for the short-term commitments, and through bilateral contract for the long-run agreements.

There are two issues particularly debated about the Colombian electricity market: the question of the Oligopoly and the reliability of the energy supply during the period of "El Niño". These two points are becoming over time more and more significant. The first because the Colombian market price is rather high, because of the oligopoly, in despite of the large share of hydro power plants.

With reference to the second point, in the last decades the frequency and the intensity of the phenomenon have been increasing. As consequences, it provokes energy emergencies more frequently and also more dangerous for the energy supply.

Thus, the model developed can offer an important instrument to study these two topics and maybe can it help finding possible solutions.

MODELLING PROCESS
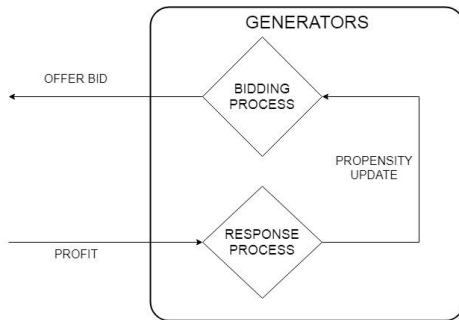
Figure 4.2-Generators modules and informations flow

The environment focuses on the generators activities. Therefore, the demand was designed as a passive entity that represents market energy volume that has to be fulfilled. The *Figure 4.2* shows the modules that drive the generators action: the "Bidding process" reproduces the act of bid submission; the "Response process" receives and elaborates the market results. This general scheme refers to all kind of generator agent (hydro, thermal and company), but they have differences within the modules. Their target is to maximize the profit gained through their participation in the market.

The Colombian generators pattern is composed of hydro and thermal power plants, with a significant prevalence of the first one; thus, the model of the market has to include both types of generator agent. Their algorithm cannot be the same because of notable differences steering their activities. The algorithm described in the AMES framework is suitable to design a thermal generator agent. Whereas, to realistically simulate the activity of the hydro plants, it is necessary to implement a specific procedure.

The Oligopoly in generation also cannot be represented. In fact, AMES and all the other platform that provide an energy market environment, design only generator agents which act autonomously with respect to the other market participants; that is not the case of the power generation companies that manage multiple plants. Considering the planned organization of a balancing market, it was of interest to develop a parallel platform able to simulate also real-time trading. To realize this environment, the algorithm

modules (Bidding Process and Response process) used for the day-ahead market was properly adapted to the real time operation.

Matlab was chosen as computing platform to make more accessible the usage of the tool and to facilitate possible future development.

The execution of the algorithm requires the following data input to define the agent profile and to allow the accomplishment of all the calculation:

$\underline{ID}$-The identification number of the agent;

$\underline{AREA}$-The area in which the generator act;

$\underline{TRADER}$-The identification number of the agent group/company membership;

M1-The number of possible different bid price;

$\underline{M2}$-The number of possible different bid energy;

$\underline{e}$ (Experimentation Parameter)-MRE RLA parameter;

$\underline{q}_{in}$ (Initial Propensity) -MRE RLA parameter;

$\underline{RI}_{MIN,c}$ –Range Index that represents the bid prices spectrum;

$\underline{RI}_{MAX,l}$ –Range Index that represents the bid energy spectrum;

$\underline{CAP}_L$, $\underline{CAP}_U$ (Production limits [MWh])-Lower and upper production limits;

$\underline{a}$, $\underline{b}$, $\underline{FC}$ (Cost function parameter) –The production cost function parameters (only thermal agents);

$\underline{C}_W$ (Cost of water [€ /MWh]) – This value represents the marginal cost of production for the hydro power plants (only hydro agents);

$\underline{V}_{RESERVOIR}$ (Reservoir volume [MWh]) –This value represents the availability of the water reservoir (only hydro agents);

$\underline{V}_{RES,MAX,techn}$, $\underline{V}_{RES,MIN,techn}$ (Reservoir technical limits[MWh])–The values representing the technical limits of the reservoir capacity (only hydro agents);

$\underline{REFUEL}$ [MWh/h]-The value representing the quantity of water recovery for the plant reservoir (only hydro agents).

- **Bidding process for thermal agents**

The module that perform the bidding process follows three steps:

a. Action Domain Matrix (ADM) construction;

b. Probability definition and Stochastic process;

c. Bid report.

The execution of these steps is exposed in "Dynamic testing of wholesale power market designs: An open-source agent-based framework" [14] and it provides the procedure for the submission in the market of a single offer composed of bid price and a bid energy.

- **Bidding process for hydro agents**

The hydro power plant production depends on the water availability but the AMES framework doesn't consider the variation of the production constraints. Hence it was necessary to consider the variation of the water availability and to include the correlation among the choices taken by the agents.

The idea for the updating of the water availability is to consider the reservoir volume variation due to the power production and a possible degree of water refill, represented by the term *REFUEL*. The control of the reservoir volume is set in order to maintain it over a certain minimum level $V_{RES,MIN,techn}$, so that the energy offered in the market cannot exceed the water availability. However, the correct representation of the hydro plants' market operations requires to consider not only the production constraint variation, but also the inter-dependence of different bids due to the water consumption and its effects on the decision-making process. For these reasons a system that allows the selection and the submission of multiple interdependent bid offers, was implemented.
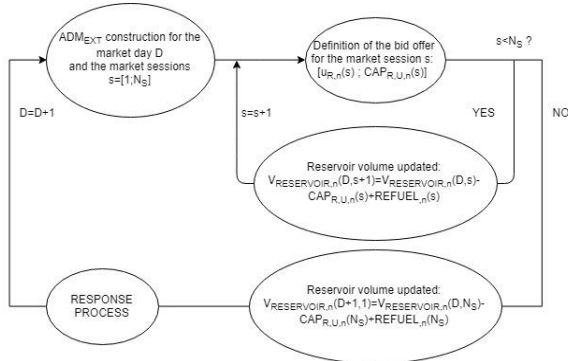
Figure 4.3-Flux diagram representation of the general bid process for hydro agent

The *Figure 4.3* summarizes the algorithm execution for the general case in which the hydro agent submits N_S consecutive bid offers in the generic day D.

Here is described the general algorithm executed for the submission of N_S consecutive bids for a certain N_A number of different agents *n*, even if in this case it makes reference to a single agent ($N_A=1$). The values $M_{1,n}$, $M_{2,n}$, $RI_{MAX,L,n}$ and $RI_{MIN,c,n}$, associated to the agent *n* are received as input and they are used to build as much $vM_{1,n}^s$ and $vM_{2,n}^s$ as *s* consecutive bid to submit in the market. $vM_{1,n}^s$ and $vM_{2,n}^s$ are the groups of values related to respectively the bid price and the bid energy of agent *n* for the market sessions *s*. The combinations of each values of $vM_{1,n}^s$ and $vM_{2,n}^s$ compose the extended *ADM* (ADM_{EXT}) of dimension $[M_{EXT}; N_S \times N_A \times 2]$. The following pseudo-code provides the construction of ADM_{EXT} and the calculation of M_{EXT} that expresses the number of possible different bids *m* that the N_A agents can submit in the market (in this case the single agent) for N_S market sessions.

$algorithm: ADM_{EXT}\ construction$
$input: N_A;\ N_S;\ M_{1,n};\ M_{2,n};RI_{MAX,L,n};\ RI_{MIN,c,n}$
$output: M_{EXT};ADM_{EXT}[M_{EXT}; N_S \times N_A \times 2]$

$for\ each\ n = [1:N_A]$
  $if\ M_{1,n} = 1$
    $for\ s = [0:N_S - 1]$
      $vM_{1,n}^s = 0$
    end
  $else$
    $for\ each\ s = [0:N_S - 1]$ 0.7
      $Inc_{1,n} = \dfrac{RI_{MAX,L,n}}{M_{1,n} - 1}$ $vM_{1,n}^s$
          $= [0: Inc_{1,n}: RI_{MAX,L,n}]$
    end
  end
  $if\ M_{2,n} = 1$
    $for\ each\ s = [0:N_S - 1]$
      $vM_{2,n}^s = 0$
    end
  $else$

$$Inc_{2,n}$$
$$= \frac{1 - RI_{MIN;c,n}}{M_{2,n} - 1} \quad vM_{2,n}^s$$
$$= [RI_{MIN,c,n} : Inc_{2,n} : 1]$$
$$end$$
$$end$$
$$end$$

$$M_{EXT} = \prod_{n=1}^{N_A} (M_{1,n} \times M_{2,n})^{N_s}$$

$$for\ each\ kk = [1:M_{EXT}]$$
$$for\ each\ n = [1:N_A]$$
$$for\ each\ s = [1, N_S]$$
$$for\ each\ k_{1,n} = [1:M_{1,n}]$$
$$ADM_{EXT}(kk, (n-1) \times N_s \times 2$$
$$+ 2 \times (s-1) + 1)$$
$$\leftarrow vM_{1,n}(k_{1,n})$$
$$end$$
$$for\ each\ k_{2,n} = [1:M_{2,n}]$$
$$ADM_{EXT}(kk, (n-1) \times N_s \times 2 +$$
$$2 \times (s-1) + 2) \leftarrow vM_{2,n}(k_{2,n})$$
$$end$$
$$end$$
$$end$$
$$end$$

$$return\ ADM_{EXT}$$
$$return\ M_{EXT}$$

At this point, from the selection of m_{choice}, 4 values are determined:

$$ADM_{EXT}(m_{choice}; (n-1) \times N_s \times 2$$
$$+ 2 \times (s-1) + 1) \quad \text{0.8}$$
$$\rightarrow RI_{L,n}^s$$

$$ADM_{EXT}(m_{choice}; (n-1) \times N_s \times 2$$
$$+ 2 \times (s-1) + 2) \quad \text{0.9}$$
$$\rightarrow RCAP_{U,n}^s$$

Now, can be defined the reported bid prices u_R and bid energies $CAP_{R,U}$ for the 2 market sessions:

$$CAP_{R,U,n}(s) = RCAP_{U,n}^s \times (CAP_{U,n} - CAP_{L,n})$$
$$+ CAP_{L,n} \quad \text{0.10}$$

$$if\ CAP_{U,n}(s)$$
$$> (V_{RESERVOIR,n}(s) - V_{RES,MIN,techn,n}) \quad \text{0.11}$$
$$\rightarrow CAP_{R,U,n}(s) = 0$$

$$u_{R,n}(s) = \frac{C_{W,n}}{1 - RI_{L,n}^s} \quad \text{0.12}$$

$$V_{RESERVOIR,n}(s+1) = V_{RESERVOIR,n}(s)$$
$$- CAP_{R,U}(s) \quad \text{0.13}$$
$$+ REFUEL_n(s)$$

$$CAP_{R,U}(s+1) = RCAP_{U,n}^{s+1} \times (CAP_{U,n}$$
$$- CAP_{L,n}) + CAP_{L,n} \quad \text{0.14}$$

$$if\ CAP_{U,n}(s+1) > (V_{RESERVOIR,n}(s$$
$$+ 1) - V_{RES,MIN,techn,n}) \quad \text{0.15}$$
$$\rightarrow CAP_{R,U,n}(s+1) = 0$$

$$u_{R,n}(s+1) = \frac{C_{W,n}}{1 - RI_{L,n}^{s+1}} \quad \text{0.16}$$

$$V_{RESERVOIR,n}(s+2) = V_{RESERVOIR,n}(s+1)$$
$$- CAP_{R,U,n}(s+1) \quad \text{0.17}$$
$$+ REFUEL_n(s+1)$$

• Response process

This process is the same for thermal, hydro and groups of generators. After the market closing, the agents receive the results of the dispatch and calculate the profit gained. AMES indicates to calculate the profit as it is shown in eq. 0.37 but this is not appropriate for the case of Colombian market. In fact, with the submission of a unique price offer, it is necessary to make the agent sensible to both the result of the market and the merit of the submitted bid. So, a different way to calculate the profit, exposed in eq. 0.38, has been created. Consequently, the response process is the same exposed by the MRE RLA. The following equations compare the 2 different forms of profit calculation:

$$PROFIT = \sum_{s=1}^{N_s} [(Q_{MRK,s} * p_{MRK,s})$$
$$- TC(Q_{MRK,s})] \quad \text{0.18}$$

$$PROFIT_{VAR} = \sum_{s=1}^{N_s} \{(Q_{MRK,s} * p_{BID,s})$$
$$+ [Q_{MRK,s}$$
$$\times (p_{MRK,h} - p_{BID,s})$$
$$\times (\frac{p_{BID,s}}{p_{MRK,s}})] \quad \text{0.19}$$
$$- TC(Q_{MRK,s})\}$$

where:

• $Q_{MRK,s}$ is the energy sold in the market session s;

• $p_{MRK,s}$ is the market price for the session s;

• $p_{BID,s}$ is the bid price for the market session;

• $TC(Q_{MRK,s})$ is the total cost of production of the energy $Q_{MRK,s}$ sold in the market;

The updated propensities are then used in the stochastic process that lead to the choice of the bid for the next market day.

Only for the hydro agents, it is necessary to update the water availability. In case of some bid would not be accepted, the reservoir volume has to be corrected:

$$V_{RESERVOIR}(D+1) = V_{RESERVOIR}(D) - \sum_h CAP_{R,U,D}(h) - Q_{sold,D}(h)$$ 0.20

where:

• $CAP_{R,U,D}(h)$ is the bid energy reported in the market at the day D for the hour h;

• $Q_{sold,D}(h)$ is the energy sold in the market at the day D for the hour h.

• **Company agent**

The structure of AMES cannot reproduce the dynamics occurred in situation of Oligopoly. In fact, in AMES, the agents, representing the power plants, act autonomously and pursue the maximization of their profit in competition with all the other agents. This does not correspond to the reality when different plants pertaining to the same ownership/group participate in the market.

For this reason it was necessary to implement a specific algorithm able to coordinate and to submit the bid for the different agents belonging to the same company.

This point represents an innovation because all the platforms that recreate models of energy market, as AMES but not only, neglect the possible collaboration among the agents. On the other hand, a realistic representation of the interaction occurring in the market operations cannot neglect this partnership.

The only other work about coordination between agent in an energy market is [23] where Kun Zhang et al. set a sort of communication among the agents, reflected in the cooperative communication reinforcement learning algorithm (CC-RL). However, even this feature is not suitable to design the activity of company agents for which it subsists an actual coordination of the agent bids.

To recreate these dynamics, a company-agents that manage several plants was created. This company-

agent follows the same procedure of the simple-agent, but it subscribes bids for all the power plants member of the company and account for the total of their profits. In this way, this new agent acts de facto as owner or manager of entities that previously were set as independent.

To reproduce the company-agent activities the structure of AMES was adjusted starting from the Bidding Process; this would determine the prices submitted from the different plants. To do that the three steps were changed as follow:

Step a. The *ADM* is extended (ADM_{EXT}). It is composed of all the groups of values related to the bids s of the N_A plants of the company, implying that also all their consecutive bids are included. So, for each generic agent n of the company c, it is received as input data $M_{1,n}$, $M_{2,n}$, $RI_{MAX,L,n}$ and $RI_{MIN,c,n}$ for the submission of N_S consecutives bids. The ADM_{EXT} is computed as it is exposed in eq. 0.7, through the combination of each values of $vM_{1,n}^s$ and $vM_{2,n}^s$, related to each n agent for each s market session. Contrary to the case of the hydro agent, the number of agent considered is $N_A > 1$.

The dimension M_{EXT} express the number of possible different combinations of bid price and bid energy, for the N_A plants controlled and the N_S consecutive bids, that the company-agent can submit in the market.

Step b. According to the MRE RLA, the probability calculation remains the same. The execution of the stochastic process also does not change, and it provides as much values of RI_L and RI_C as much consecutive bids, through the selection of a unique m_{choice} (eq. 0.8 – eq. 0.9).

Step c. From the definition of these values it's possible to determine the bid prices and the bid energy for the different agents with the same procedure of the simple-agent.

The successive Response Process follows the same procedure described previously, but the profit calculated for the company-agent c accounts for the earnings of all the plants n pertaining to the group of generation:

$$PROFIT_{VAR,c} = \sum_{n=1}^{N_A} PROFIT_{VAR,n} \qquad 0.21$$

The procedure described is able to submit bid price and bid energy for different agents who relate to the same company and to elaborate the relative results.

• Balancing market model

Everything that was described up to now represents the whole set of operation performed by the agents to participate in the day-ahead market. The same also have to be executed to participate to the balancing market sessions. However, it is necessary to adjust some point to make the platform coherent with the activities of balancing. Thus, here below all the algorithm sequences are not reported as previously, but the following 3 points describe the modifications applied:

1.DATA INPUT. In this case the platform receives as input data 2 sets of demand: the forecast demand for the day-ahead operation and the real demand for the balancing market operation. The difference between them defines the energy trades in the balancing market sessions;

2.BIDDING PROCESS. The algorithm follows the same procedure[1], but it computes a bid offer for a single market session. However, it is necessary to assign a specific set of propensities to each market sessions;

3. RESPONSE PROCESS. Consistently with the mentioned modification, the response process will also be performed for each market session.

• CASE STUDY: Algorithm improvement

Testing the algorithm through the execution of a simple Case Study two main concerns had emerged: a) the numerical divergence, b) the reward calculation.

a) Firstly the algorithm was executed exactly as illustrated in the AMES framework. That includes

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[1] For the hydro agents will be not consider the refuel already computed for each hour.

the application of the VRE RLA. This variation of the algorithm provides the use of the operator exponential to calculate the choices probability:

$$p_j(t) = \frac{e^{\frac{q_j(t)}{C}}}{\sum_{i=0}^{N-1} e^{\frac{q_j(t)}{C}}} \qquad (0.22)$$

Where c is the Boltzmann cooling parameter. The exponential is a very sensible operator and in many computing environments it is easy to run into numerical problems because of very large numbers.

Thus, the following solutions were tested, but they did not permit to solve the issue:

1. Containment of the PROFIT through the change of the orders of magnitude:

$$(MWh \rightarrow GWh) - (€ \rightarrow k€ \rightarrow M€) \qquad 0.23$$

2. Containment of the *PROFIT* applying a scaling to its value by a fix factor k_p:

$$\begin{aligned} q_m(t+1) \\ = (1-r) \times q_{m(t)} \qquad 0.24 \\ + RESPONSE_m \quad \forall m \end{aligned}$$

$$\begin{aligned} RESPONSE_m = \frac{PROFIT_{VAR}(t)}{k_p} \\ \times (1-e) \quad if\ m \qquad 0.25 \\ = m_{CHOICE} \end{aligned}$$

3. Containment of the propensities applying a scaling (k_q) before the calculation of the probabilities.

$$q_{NORM} = \frac{q}{k_q} \qquad 0.26$$

$$p_j(t) = \frac{e^{\frac{q_{NORM,j}(t)}{C}}}{\sum_{i=0}^{N-1} e^{\frac{q_{NORM,j}(t)}{C}}} \qquad 0.27$$

Considering all the results and the observation made with these different tests, the MRE RLA was chosen to be used in the developed model. The trade-off of this version of the algorithm is the increase of the converging time to a permanent position.

b) The rule of the Colombian market, for which the participants submit a unique bid price for all the 24 market hours/sessions, affects the capability of

the agents in recognizing the merit of their own choices for the result obtained in the market. This requires the development of another system of profit calculation showed in eq 0.19: *PROFIT$_{VAR}$* . This is composed of two parts: the first contribution $(Q_{MRK} \times p_{BID})$ that remunerates depending on the bid price; the second contribution $(Q_{MRK} \times (p_{MRK} - p_{BID}) \times \left(\frac{p_{BID}}{p_{MRK}}\right))$ that remunerates the remaining difference between the bid price and the market price. The aim of this important modification is to reproduce the human cognition that allows to discern the reward obtained by merit of the bid submitted, from the reward obtained because of the action/position of the other competitors.

The following points summarize the difference emerged from the use of the two forms:

1.when PROFIT$_{STD}$ is used some agents are not capable of recognizing the best option for them, because their choice has a small weight with respect the whole results;

2. when PROFIT$_{VAR}$ is used those agents recognize the effect of their choice so it prefers to increase the mark-up, helping to increase their profit.

COLOMBIAN DAY-AHEAD MARKET MODEL

The daily demand for the Colombian market model was reduced to 3 hours selected from the demand curve in correspondence of the base load (H1), ramp (H2) and peak load (H3) to represent on average the demand of a generic working day.

• Oligopoly analysis

To realize this analysis, 2 scenarios are set: in the first one, the Competition Scenario, the generators act autonomously in the market and they pursue the maximization of their profit; in the second one, the Oligopoly Scenario, the company agents arrange the bid of their plants to maximize the company profit.

The previsions about the possibility to exert the market power were confirmed: the oligopolistic companies increase the prices over the outcome provided by the (almost) perfect competition in the first scenario. The mark-up increases with the energy demand because the higher the demand, the higher the freedom to exert the market power is. *Table 5.8* summarizes the gap of the two Scenario's statistical data: all the parameters show the grew of the market prices.

	DEVIATION COMPETITION-OLIGOPOLY [%]		
HOUR	TREND	MEDIAN	AVARAGE
H1	72,73	61,00	58,22
H2	78,42	78,42	76,79
H3	93,61	93,61	89,88

Table 5.8-Percentage deviation between the result of the Competition Scenario and the Oligopoly Scenario

• Water supply shortage analysis and integration of NC RES

During the period of ENSO, the hydro plants water supply strongly decreases because of the rainfall reduction. To solve this problem Colombia decided to develop NC RES to sustain the energy production during this period.

In the generation-transmission Expansion Plan 2016-2030 [17] the UPME (Mine-Energy Planning Unit) approved the realization of three wind farm projects. This reason convinces to analyse the possible impact on the energy market of the installation of these wind farms capacity, during the period of ENSO.

The same Competition Scenario itself and the Oligopoly Scenario are considered but other generator agents will be added to the energy mix: the wind farms.

It will be investigated if the availability of the cheap wind farms capacity succeeds to contain the raise of the market prices and the possible differences in the two Scenarios.

In order to study the impact of the wind farms and to evaluate the benefits of the UPME project, the water supply shortage is simulated in two different situations:

1.NOWIND scheme. There is no wind capacity in the energy mix;

2.WIND scheme. Three wind farms are included in the energy mix and their capacity respects the projects planned by UPME.

a) COMPETITION SCENARIO.

In normal conditions, NO ENSO, the (almost) perfect competition provides the lowest prices for all the three charges. In the ENSO condition the prices decrease by increasing the wind farms capacity. The percentage deviations between the NO ENSO and the ENSOs schemes outcomes, shown in *Table 5.18*, give a detailed proportion of the difference among the scenarios.

	ENSO-NOWIND			ENSO-WIND		
HOUR	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]
H1	20,27	23,47	26,42	4,40	4,40	6,70
H2	498,34	498,34	478,26	99,43	107,98	189,70
H3	498,34	498,34	513,08	498,34	498,34	487,02

Table 5.18 Percentage deviation with respect to the No Enso Competition Scenario

b) OLIGOPOLY SCENARIO.

As expected the market prices are always higher than correspondent values of the Competition Scenario. Because of the prices' mark-up performed by the oligopolistic company, the wind capacity is even able to reduce the market prices with respect to the NO ENSO condition where there were no wind farms. For this reason the related percentage deviations, in *Table 5.20*, assume negative values. About the demands H2 and H3 the same observations of the Competition Scenario are valid also in this case: the WIND scheme permits to contains the mark-up of H1.

	ENSO-NOWIND			ENSO-WIND		
	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]
H1	7,83	36,05	32,62	-13,74	-9,23	-12,00
H2	222,12	222,12	221,65	222,12	222,12	124,55
H3	209,04	209,04	214,24	209,04	209,04	211,87

Table 5.20-Percentage deviation with respect to the No Enso Oligopoly Scenario

CONCLUSION

• Methodology analysis

a) COMPANY OF GENERATION.

The implemented company-agent determines simultaneously the bid offer for each plant managed and it accounts for the global profit gained; exactly as the power generation company that owns many different plants. This is a total innovation because currently all the existent energy market platforms, neglect this kind of coordination and retain sufficient to introduce only the single-agent profit maximization. The outcomes from the Oligopoly analysis of the Colombian market model, successfully show the effect of the developed feature and the large deviation of the results by its omission. This analysis proved that the future development of platforms that reproduce the market activities has to include this essential aspect of the trading. In this sense, the scheme implemented in this thesis outlines the principles that could drive the innovation of the design of the generator agents behaviour in the market;

b) HYDRO PLANTS.

To represent adequately the profile of the hydro generators, it was necessary to define all the parameters that characterize the aspect of their energy production. The outline of those attributes of the hydro generation was essential to represent realistically the largest part of the Colombian generation mix. However, that was not enough to outline the hydro agents' activities. In fact, the water consumption creates an inter-connection among successive bid offers, because of the

variation of the water availability. To deal with this peculiarity, the concept of ADM was again extended including the set of parameters required to determine simultaneously multiple bid offers, and not only a single one as provided by AMES. In this way the decision-making process involves different consecutive offers considering the inter-dependence that characterize successive bids;

c) REWARD CALCULATION and BALANCING MARKET.

The Colombian day-ahead market rules establish that the participants can submits a unique bid price for the 24 market sessions. This requires an improvement of the reward/profit calculation; otherwise the agents would not be sensible to the merit of its bid with respect to the profit gained. The implemented calculation system reproduces the human cognition that discerns the reward obtained by merit of the bid submitted from the contribution due to the bid/position of the other competitors.

As the last step, the forthcoming opening of a market dedicated to the real-time trading encourage the development of a parallel platform able to simulate this kind of exchanges. To realize this, the structure of the day-ahead market was preserved, but the market rules and the results updated were adapted to reproduce the peculiarities of the balancing transaction.

• Algorithm limits and Future improvement

a) ADM DIMENSION.

The main concern about the ADM is to guarantee the correct exploration of the agents' set of option. This became critical when the ADM assume very large extension. To deal with this issue, a sort of filtering of the ADM could be performed so that to reduce its dimension. The idea is to progressively eliminate the options that would bring outcomes similar to others. In this way the spectrum of exploration would be reduced making the research more effective and meaningful;

b) NUMERICAL DIVERGENCE.

The advantages derived by the application of the VRE RLA were already discussed. To guarantee its correct functioning it is necessary to avoid the numerical divergence due to the use of the exponential. A possible solution in this direction could be the development of an adequate and more complex (even not static) system of scaling of the values involved, with respect to the attempt made in this work. Even the improvement of a dynamic evolution of the Boltzmann cooling parameter could manage this issue, even if it would require an enhance study of the theoretical validity of the solution;

c) COMPANY AGENTS.

The mentioned problem of the ADM dimension limits the application of this algorithm for which it was required the reasonable simplification of aggregation of different plants in a single agent. The solution of this obstacle can open the use of this algorithm to a larger number of agents without the needs to make any simplification.

d) HYDRO GENERATOR AGENTS.

To strengthen the algorithm's structure it will be necessary to solve the mentioned problem of the ADM dimension. In addition, it would be of interest to include more constraints related to the operation of the hydro power plants to make the algorithm more accurate.

CHAPTER 1

Introduction

1.1 Motivation

For the last 10 years Colombia is experiencing a phase of changes that will bring it at the level of the developed countries. It is forecasted that Colombia will soon assume a significant position in the framework of the South-America with a strong improvement of the economic and social conditions.

This transformation concerns also the energy sector in which, in the next years, important changes that will revolutionize the current dynamics will occurs. For example, the policy regulation of the subsidies directed to encourage the installation of non-conventional renewable capacity, is very recent: in Colombia this is an almost unexploited matter and an enormous opportunity of business. In particular, the wind capacity will grow very fast because of the very strong potential and the strategical role that it could assumes.

In this context, the energy market is still organized with a very basic structure and simple rules. To make some examples, it provides only a day-ahead market combined with an inefficient system of balancing of the real demand; the bid offer is composed of a single bid price for the 24 market sessions. In general, it is licit to affirm that the market configuration results inadequate to receive the significant innovation predicted and, in part, planned for the next years. It is not surprisingly that the national authority is setting several updates to renovate the whole market structure as the introduction of a balancin market.

To accomplish the process of maturation, two onerous questions has to be solved soon so that the foundations for the future structure of the market can be laid: the clear and oppressive oligopoly in power generation and the volatility of the market prices due to the periodical water shortage. The solution of these two issues represents an essential condition for the market development and it will significantly improve its efficiency and reliability.

1.2 Aim of the thesis

Regarding these motivations, the improvement of a platform that allows the study of the market operations and the activities of its participants, especially the generators, results reason of strong and current interest. To realize that, it is necessary to represent the generators and their real behaviour, because they are the most influent market players. Nevertheless, as already mentioned, the Colombian market is characterized by the presence of oligopoly in generation and this aspect was always neglected in the development of all the other existent platform (for the energy market). Thus, to build an environment that could reproduce accurately the Colombian market operations, it is necessary to deal with this issue.

In this regard, this thesis purposes the implementation of an algorithm able to reproduce this essential aspect of the market trading. To realize that, it is the agent-based modelling approach which was abundantly employed in the field of the energy market with very good results that is selected. Above all, the AMES framework built a very promising structure and it was chosen to inspire the algorithm developed in this thesis.

After the realization of that, the developed model will be exploited to study the Colombian day-ahead market. In particular, the analysis will be focused on the mentioned critical points:

- OLIGOPOLY. The objective is to demonstrate that the current oligopoly increases the market prices with respect to the condition in which the competition is guaranteed;

- WATER SHORTAGE. The target is to observe and to measure the possible benefits derived by the installation of wind farms capacity and to see if this will solve the problem of price volatility.

1.3 Structure

About the thesis stricture, it is articulated as follow:

- CHAPTER 2. In this chapter the agent-based modelling is introduced by the outline of its history and its characteristics. Then, notable examples of electricity market models are examined with a particular focus on the AMES framework and the learning algorithm exploited;

- CHAPTER 3. In this chapter it is purposed an overview about Colombia and, more in detail, about the Colombian energy sector and the energy market. The mentioned critical issued will be presented here extensively;

- CHAPTER 4. This chapter describes the different algorithms executed by the model with particular focus on the original algorithm of hydro agents and company agents. Then, the analysis of a Case Study allows the discussion of the most significant concerns faced during the implementation of the model;

- CHAPTER 5. In this chapter the Colombian market model is presented together with all the significant data researches. Then the critical issues are studied with the organization of several scenarios and the analysis of their outcomes;

- CHAPTER 6. The last chapter closes the thesis with the analysis of the methodology followed to implement the algorithms and the outcomes provided by the Colombian market model. At the end the algorithms' limits will be exposed together with their potential solution and the possible future improvements.

CHAPTER 2

Introduction to agent-based modelling

Agent-based modelling (ABM) is a modelling approach proposed in the late 1940s, but it started to be really exploited only in the early 1990s, with the development of modern calculators. The core concept of Agent-Based Modelling is that the representation of a certain phenomenon or system can be modelled describing the interaction among entities and environment. These entities take the name of "agents" which are autonomous individuals with peculiar characteristics and properties whose interactions result in information.

Agents act in a specific landscape, called "environment", which represents the background where information are elaborated and exchanged with and among the agents (*Figure 2.1*). Not only the interaction agent-agent and agent-environment can change in time, but also the intrinsic characteristics of the agents. In fact, agents can be set in order to change and even adapt their strategy or simply the way to interact. The evolution can be intelligent and in this case the terminology Multi-Agent System (MAS), which indicates a structure where computerized intelligent agents interact within an environment, is more appropriate.

Figure 2.1 – Environment and agents network

2.1 History and Applications

Before to explain the peculiarities of ABM it can be useful to go through its history looking at some famous application. The concept of an entity which the state consists of mental components such as beliefs, capabilities, choices and commitments, makes ABM suitable for application in many different field such as ecology, economy and social sciences. In these sectors the interaction among entities provides very interesting results, but the large amount of calculations required impose the use of very powerful computational capacity. As consequences, the use of ABM had been restricted until the arrival of the first modern calculators in the late 1980s.

In 1971, the American economist Thomas Schelling created the first agent-based model, the *Thomas Schelling's segregation model* [1], with the aim to explain why segregation is so difficult to combat. Although the model is quite simple, it analyses how individuals might self-segregate, incorporating the basic concept of agent-based models as autonomous agents interacting in a shared environment.

In the 1980s the interest for the ABM was expanded in many different sectors: Craig W. Reynolds investigated the aggregate motion of flock of birds in his work "*Flocks, herds and schools: A distributed behavioural model*". "The paper explores an approach based on simulation as an alternative to scripting the paths of each bird individually. The simulated flock is an elaboration of a particle system, with the simulated birds being the particles. The aggregate motion of the simulated flock is created by a distributed behavioural model; much like that at work in a natural flock the birds choose their own course" [2].

The term agent was not used before the 1990s. Ones of the firsts to purpose it were J. Holland and J. Miller presenting the paper "*Artificial Adaptive Agents in Economic Theory*" [3], in 1991, where they debate about the use of A.I. (artificial intelligent) in economy. In the meanwhile, it started to appear the first platform that was specific to work with ABM as StarLogo in 1990, and as Swarm and NetLogo in the mid-1990s, until the arrival of RePast and AnyLogic in 2000.

Social sciences received an important contribution from ABM in the 1990s; one notable example is the large-scale ABM, Sugarscape, developed by Joshua M. Epstein and Robert Axtell. In their work "*Growing artificial societies: social science from the bottom up*" [4] the authors used cutting-edge computer simulation techniques to examine fundamental collective behaviours as group formation, cultural transmission, combat and trade.

More recently, Ron Sun published "*Cognition and Multi-Agent Interaction: From Cognitive Modelling to Social Simulation*" where the author explores the intersection between individual cognitive modelling and modelling of multi-agent interaction (social stimulation) [5]. The growing attention on biodiversity and environment preservation pushes the use of ABM approach to deal with these very important topics. A notable example of that was the article "*Symmetric competition causes population oscillations in an individual-based model of forest dynamics*" in which it was explored how intra-specific competition affects population dynamics using FORSITE, an individual-based model describing tree-tree interactions in a spatial and stochastic context [6].

2.2 Why agent-based models?

To understand the reasons why to choose this approach instead of the more common equation-based model (EBM) it is necessary to explore the advantages and the differences with respect to the other technique. The authors U. Wilensky and W. Rand in their text "*An introduction to agent-based modelling*" [7], one of the most appreciated modern work about ABM, describe exhaustively the most important aspect of the method. 5 points have been chosen to represent the main advantages of ABM:

- *Heterogeneity vs Homogeneity*. Seeing that ABM approach studies individuals, it allows to model a heterogeneous population, in contrast with the equation approach which makes assumption of homogeneity. Homogeneity is often the base on which the EBM is built. Moreover, results and any information emerging are generally continuous, and continuity usually does not fit with the representation of the real word: any kind of groups, organizations or populations are composed by a discrete number of members, and ABMs respect this discrete composition. Considering the example of an energy market, different generators have different cost functions, capacities and constraints, thus they will not take the same decision given the same input from the environment;

- *Aggregate vs Individual.* The interesting and important effect of the previous point is that knowledges of the aggregate phenomena are not required because the focus is on the individual and the global pattern results as consequence. Modelling through an equation-based approach needs to have a good comprehension of the aggregate dynamics; then the hypothesis are tested out against the aggregate output. In contrast, ABM enables to set simple rules for simple entities, requiring knowledge only about individual behaviours, and then to observe the aggregate result by running the model.

Thus, not only the modelling process results easier because the basic principles are not complex, but the result also matches the real world more firmly because the relationships between individuals are better described. In general, the outcome generated by ABMs are more detailed than those generated by EBMs not only at the individual level, but also at global level. In additions ABM enables to track, and so to study, the individual evolution much more than by modelling the whole system dynamics;

- *"Bottom Up" approach.* Since ABM operates by modelling the individual characteristics and its decision-making process, it is possible to examine the evolution of any individual (or aggregate individuals) in the model and observe the global outcome. "This "bottom-up" approach of ABMs is often in contrast with the "top-down" approach of many EBMs, which tell you only how the aggregate system is behaving and do not tell you anything about individuals" [7];

- *Randomness.* Another significant difference with the other methods is that they used to be made in a deterministic way, whereas in the ABMs it is easy to include randomness: a decision-making process, or any other aspect, can be set on probability, so that the model became heuristic, again more alike to the reality;

- *Simulation running.* ABM allows to reproduce very complex interactions occurring in the system just by definition of few simple rules that guide the agents; then it can be possible to study the result with an almost infinite number of heterogeneous agent just running simulation. In the time-frame of the simulation it is easily possible to allow the agent to track the history of everything occurring in the environment and then, based on these information, set the way in which the agent change his behaviour and strategy. In the case of an environment in which the complexity is due to the sophisticated exchange of information between stationary agents and environment (more than agent with agent) the approach doesn't change: the interactions environment-agent and agent-agent have the same power and value;

2.3 Trade-offs of ABM

ABM provides many advantages and benefits over other methods but there are some peculiarities and requirements that must be respected in order to exploit effectively this approach. Firstly, considering systems that can be described by simple equation-based models, the execution of the correspondent agent-based models can result computationally

intensive and this requires a powerful calculator. In fact, running an elementary EBM necessitates repetitive mathematical calculations, a light load for the calculator. However, when the level of complexity grows the EBM can even result heavier, in term of calculation, then an ABM, taking more time and effort to run the model.

The significant computational expense paybacks detail individual data, which are tracked and recorded during their development. The inevitable fee is the same of any kind of simulation: the deeper the level of detail, the stronger the computational power required. In case of decision-making process this can imply a wider range of decision to make possible.

To ensure a correct operation of the model, the variables that control his working have to be well set. In the equation-based modelling these variable pre-determined by the modeler are called "free parameters". In ABM, more free parameters are used than EBM, not only because of the high level of detail, but also because they control the assumptions of the model and they make possible many different actions. It follows that the modeler has to have enough information about the individual and how it interacts within the system. Building the model without these knowledges is not possible. In contrast with the EBM, which requires the only understanding of the whole system operations, ABM requires the same and an additional effort to gain the knowledge about the micro-behaviour of the system. In fact, the validation of the result of the ABM is performed by comparison with the known description of the entire system. The advantage with respect to the EBM approach is that a causal description at the aggregate level is not required because the modelling focus is on the individual, the single agent.

If the results produced by running the model are considered valid thus it is possible to affirm that these represent at least one potential way in which the system works.

2.4 Agent-based modelling in electricity market

Now, considering all the characteristics and peculiarities of ABM (and MAS), it is easier to understand the reasons why the approach can be so useful for the case of a power market, electricity and gas. In principle the agent-based model is built designing a certain number of agents, which represent the demand and/or the offer, and the entities managing the market. The interaction among all the agents produces the price and the volume of energy exchanged as outcome. Through the application of learning algorithm, the agents can improve their strategy to make larger profits, making the model a MAS for all intent and purpose.

The same model can serve many different goals: for instance, monitoring the market price and volumes, tracking the strategies of each agent, evaluate the efficiency and the level competition of the market. The wide range of useful results and the way in which the

modelling attributes fits the market components, makes ABM strongly exploited for this purpose. To show the possible application of ABM three recent and significant works, which exploit ABM method with different purposes, will be presented, it follows the detail analysis of the AMES framework that inspire the design of the generators agents.

- *Agent-based price simulation of the German wholesale power market [8].* In this paper the authors apply an agent-based model and monitor the resulting market price. They design 4 kind of agents representing thermal power plants, pumped storages plants, renewable generators (RES) and demand; each one is characterized by its specific decision process. The thermal power plants submit their bid considering the cost and the availability of the production, and the expected price, corresponding to the predicted scarcity. Hydro power plants, operating as both customer and supplier, decide how to act in the market only depending on the forecast market price, because they have almost no production cost; RES generators are aggregated in a single agent and bid almost zero because of the low marginal cost of generation; demand as well is aggregate in a single agent which act as price taker. The bidding decision-making process of thermal power plants can be modelled either as cost based[2] or strategic mark-ups to the price which the plants is intended to bid. The interactions, together with the optimization of the dispatch, provide the spot market price which is then benchmarked with the historical data. The results of the simulation, shown in *Figure 2.2*, demonstrate the correspondence between the simulation and the historical data. Moreover, the coincidence between the simulations with cost based bids and strategical bids "is consistent to the fact that most power plants in Germany are currently legally obliged to cost based bidding because they belong to market participants with a large market share" [9].
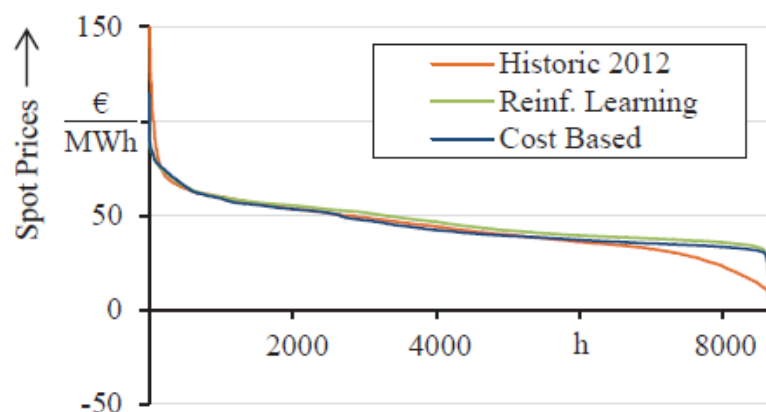
Figure 2.2-Duration curve of simulated and historic spot prices in Germany

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[2] In this case the thermal power plants bid price reflects the opportunity cost of generation

- *Modelling hydro power plants in deregulated electricity markets: Integration and application of EMCAS and VALORAGUA"[10].* The paper published by P. Thimmapuram, T. Veselka, V. Koritarov et al. in 2008 presents the study performed on the Iberian electricity market. The authors integrated the agent-based model EMCAS [10] (Electricity Market Complex Adaptive System), which simulates the operation of a deregulated market, with VALORAGUA that is an hydro-thermal coordination model which optimises the overall system operations. The aim of the work was to provide an effective instrument to deal with the management and the operation of a hydro power plant, which is very complex because of the control of the water flows and capacity. *Figure 2.3* shows the information flows between the two tools: VALORAGUA provides all the possible hydro data and, depending on that, EMCAS performs the agent activities in the markets providing the results (the capabilities includes day-ahead market, real-time market, bilateral financial contracts etc.). By setting the load profile and the generators of the Iberian Market the authors succeed to monitor the bidding offer, the residual capacity, start-up and shut-down of a hydro power plant.
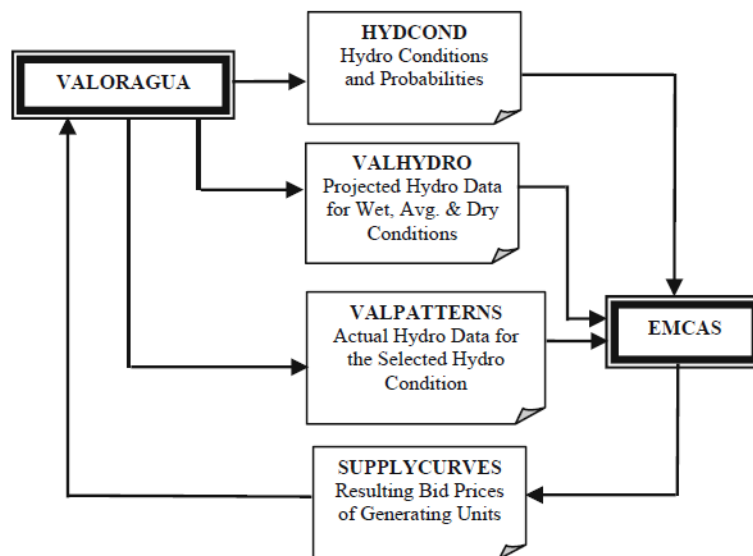
Figure 2.3- Information Flow between EMCAS and VALORAGUA

- *Agent-based model for spot and balancing electricity markets [12].* Recently published by F. Kuhnlenz and P. Nardelli, the authors present an agent-based model of the Nord-Pool[3] electricity market. The model combines spot and balancing market and allows to analyse the interaction among agents and between the markets. The authors set three kinds of agents: Producers which provides power for a certain price (per MWh); Users which generates a demand curve changing prices through the simulations depending on external or internal factors; Utilities which forecast and trade energy for its designed users and distribute balancing costs among them. The typical load curve of the Nord Pool can be effectively reduced to a sine-type curve with peak around 6 p.m.
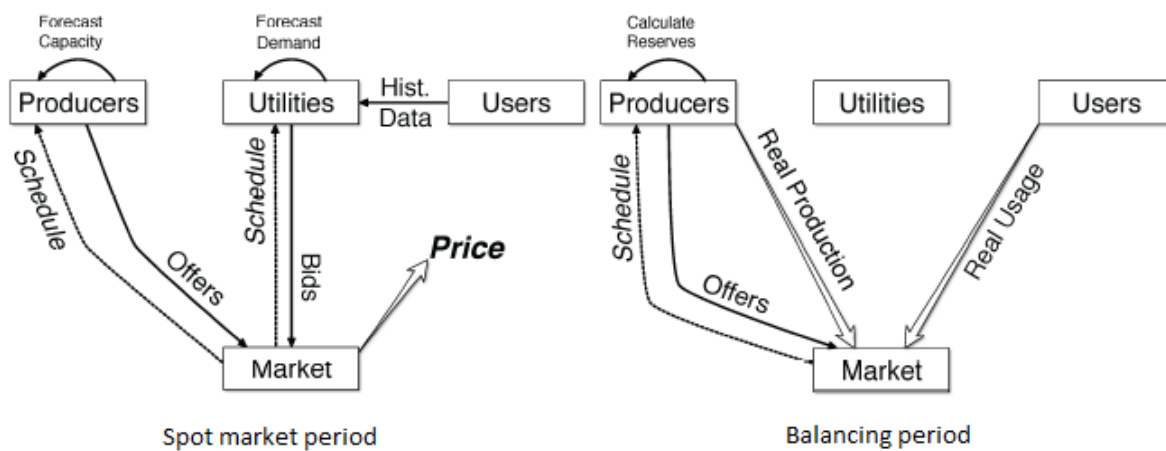
Figure 2.4-Sport and Balancing market information flows

Figure 2.4 shows the two steps of the market activities: firstly, producers and utilities submit offers according to the forecast price and demand; then the market clears the price and determines the daily schedule. Furthermore, agents can decide if a further bid on the balancing market is required, depending on the response of the market and the deviation between real usage and production. In this way the authors set an environment in which it is possible to analyse several kinds of critical results, e.g. the mark-up due to the utilities activity on the market; it is also possible to implement modification on the market mechanism and then to observe, for example in case of integration of renewable resources, the effect of shortening the spot market interval to 30 or 15 minutes. The validation of the proposed model is performed comparing market data representative of the market operation combined with some statistical survey. The results of this comparison, summarized in *Table 2.1*, show the strong affinity of the measures, which validate the model proposed by the authors.

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[3] Nord Pool is the largest European energy market and operates in Nordic and Baltic countries, Germany and UK

COMPARISON BETWEEN NORD POOL AND THE PROPOSED MODEL		
	Nord Pool (2015)	Simulation (30 days)
Avg. price	21.00 €	22.86 €
$\sqrt{\sigma^2}$	1.59%	10.62%
Avg. regulation	7.14%	1.10%
Max. regulation	13.09 h	5.02%
Intra-hour regulation	7.14 %	11.68 h
Balancing price	171% / 60%	186% / 64%

Table 2.1-Comparison between the Nord Pool and the proposed model

2.5 AMES Framework

After this analysis about ABM and its application, especially about the electricity market, the work that inspired the algorithm applied to the Colombian Market model can be discussed in detail. That is "*Dynamic Testing of Wholesale Power Market Designs: An Open-Source Agent-Based Framework*" [13] published by J. Sun and L. Tesfatsion in 2007. The authors, pushed by the restructuration and the following crisis of the California wholesale power market in the 2000, decide to implement a proper tool to reproduce the characteristics of the market. Using this software, they wanted to make possible the analysis of many critical aspect of the market operations, going in deep with technical and economic concerns. In fact, they combine a proper unit that deals with the power dispatch, considering if necessary technical constraint, with agents that represent demand and offer of the market. To represent accurately the activities of the generators, that sell energy in the market, they associate to them the learning module JReLM (Java Reinforcement Learning module), a variation of the Roth-Erev Reinforcement Learning algorithm (RE RLA). This has the aim to reproduce the strategical behaviour that characterize the generators market activities in the reality. To show the operation of the software they purpose a dynamic five-node test case; to underline the strong impact of the strategical behaviour by generators, they present two different case: The No Learning Case in which the generators have no strategical behaviour; the Learning Case in which the generators strategically select the bid steered by the RE RLA.

The framework consists in three kind of linked units that perform the main activities occurring in the market. The interaction and the mutual exchange of information, in form of interconnected input and output, recreate the execution of market sessions. These units are:

- Load Serving Entities (LSEs) are entities that submit a demand bids in the market at the beginning of each market day. They are designed as passive agents that choose with no strategical behaviour the bid power and price. The values of bid price and power are defined as data input;

- Generators are entities that submit an offer bid at the beginning of each market day. They are associated to parameters that describe their cost function; depending on the marginal cost of production (MC) they submit a certain bid price and bid power. In the No Learning Case the bid price would correspond to the MC, whereas in the Learning Case the agents will be able to mark-up the price within a pre-set range;

- ISO is a single entity representing the Market Operator which perform the market dispatch;
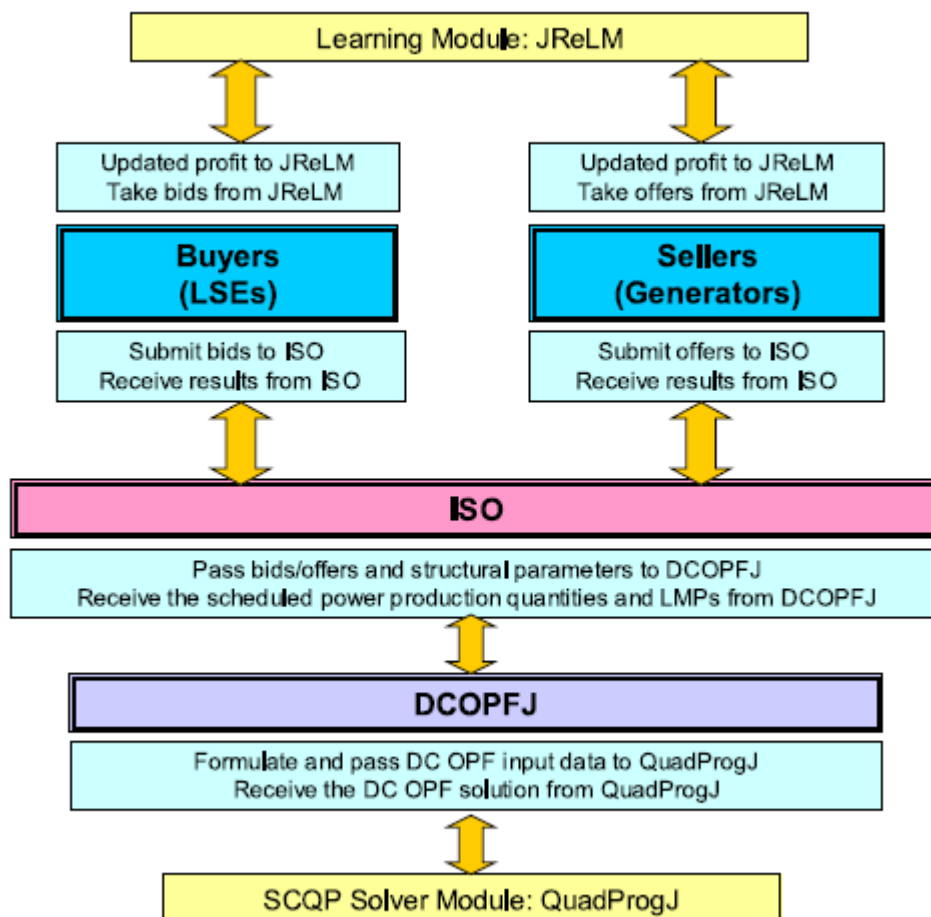
Figure 2.5-AMES framework structure

From *Figure 2.5* shows the mentioned units and the occurring information exchange. Buyers and Sellers agents submits bids in the markets thought the computation of the JReLM, they receive the market results from the ISO and then they elaborate the output updating the profit. The ISO matches the energy and price bids by the optimization of the market dispatch (DC Optimal Power Flow) performed by the solver module QuadProgJ, and then it returns the result to the Buyers and Sellers agents.

The configuration of the proposed dynamic five-nodes test case is shown in *Figure 2.6* there are five Generators agents and three LSEs. The bids[4] are crossed and the market is closed for 24 hours returning as much equilibrium prices and energy. In the No Learning Case the generator agents elaborate the bid considering only the (locational) marginal cost; in the Learning case they adopt a strategical behaviour, so the generators try to maximize their profit finding the offer with the best combination of price and energy. By trying different alternatives and learning from the result obtained in the market, in term of profit, the five agents should find each one a best choice on which they definitively converge. The different conduct of the generators affects not only their own profits, but also the market price that result bumped up with respect to the No Learning Case. This occurs because the generators, seeking for the best bid price, understand the position of the other competitors (or at least some of them) and so they increase the offer in order to maximize their profit maintaining a certain market share. The process continues until a situation of Nash equilibrium establish in the market and thus the bid offers and, consequently, the market prices are stable.
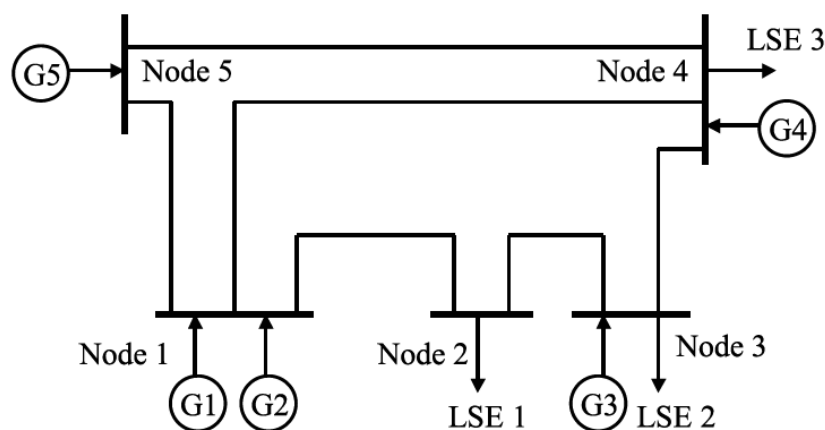
Figure 2.6-Five nodes test case pattern

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[4] In this case the bid is a couple of value (energy ; price) valid for a single hour

Figure 2.7 shows the difference in bid price and energy production for the five generators of the test case. From the No Learning Case results it can be deduced that the energy productions of Gen 3 and Gen 5 are necessary to meet the demand. This allow these agents, in the Learning Case, to exert their market power colluding (implicitly) with the other agents by reporting a bid price higher than the locational marginal cost. *Figure 2.7* shows also how the collusion involves all the generators: the bid prices of Gen 1 and Gen 5 result even five times the bid of the No Learning case. The strategical behaviour permits to the expensive generators to enter the market whereas the cheap generators reduce their share (but not their profit). It is the case of Gen 2 and Gen 4 that increase their production in each hour in detriment of the cheaper Gen 5. But even the Gen 5 increases his profit because the growth of the price compensates the reduction of the energy production.
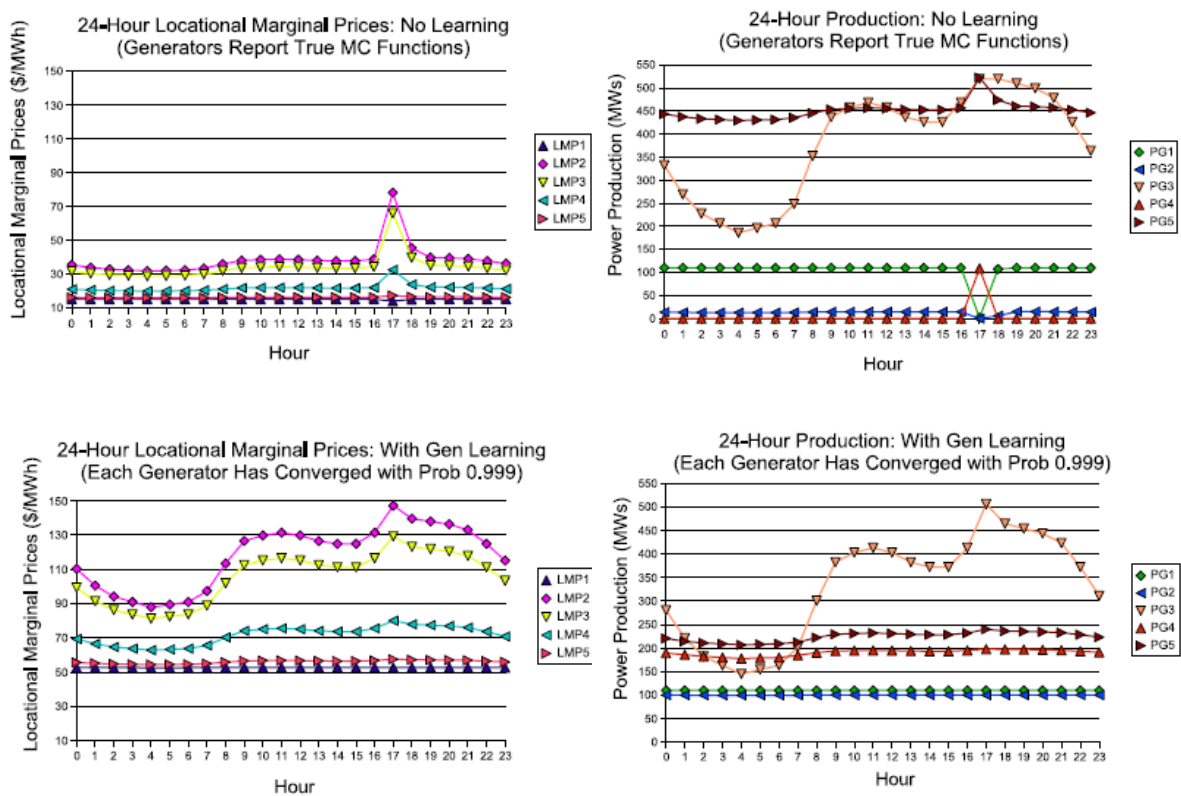
Figure 2.7-Simulation results for the No Learning Case and the Learning Case

Thus, it was proved that the outline of the generator activities represents a critical aspect of the modelling process because it's necessary to simulate the strategical conduct and the learning capacity of the agents; otherwise their behaviour would be not faithfully simulated and consequently neither the market results would be realistic. The importance of this feature is due to the significant, even dominant, influence that the generators activities exert on the market.

The structure of the AMES which manages the generators activities (bidding process and output elaboration) looks promising because it reproduces effectively the generators behaviour. However, it is suitable to represent only thermal generators activities. In fact, the algorithm does not take in account the most important constraint of hydro generators: the variation of water supply in reservoir and the consequence in the short-term bidding strategy. In an environment, as the Colombian energy market, where the hydro power plants dominate the energy pattern, the AMES framework cannot reproduce effectively the market operation. The simple and flexible structure of generators module convinces us to implement modifications in the algorithm to include this topic and to make possible the simulation of the Colombian energy market.

2.6 Reinforcement Learning Algorithm

The generator bid price should reflect the willingness of a generator to supply the energy, this includes not only the marginal cost of generation but also the risk of generation to be exposed in the market. In reality, as it was already discussed, the generators act in a strategical way and raise their bidding price to gain a larger profit. In this scenario the best bid, for the learning agent, is the one which maximize his profit. This is also coherent with the economic theory: producers tend to maximize their surplus, that is, indeed, represented by the profit. This represents one of the most significant contribution to the success of the AMES framework. Because of its importance it is reasonable to believe that a deeper analysis of the algorithm can be really useful for the study of the algorithm and its accomplishment.

2.6.1 Roth-Erev Reinforcement Learning Algorithm (RE RLA)

The learning algorithm has to meet the needs of bid selection recognizing the result obtained, in term of profit. This perfectly fit the purpose of A. Roth and I. Ever work [11]: they focus on the individual behaviour in a game with multiple interacting players. The basic intuition underlying any reinforcement learning algorithm is that the tendency to implement an action should be strengthened (reinforced) if it produces favourable results and weakened if it produces unfavourable results [12]. The observation of individual learning in MAS brings to the definition of two principles that leads the research of the best strategy: *experimentation* and *recency*. The first describes the inclination to explore the possibilities not chosen; the second deals with the "forgetting" effect of the decision-making process, i.e. the disposition to neglect the effect of the past decisions. Both are described by specific parameter, respectively *e* and *r*, that define the profile of the agent. The RE RLA results from the

incorporation of all these observations and the authors show that it is able to reproduce, successfully and effectively, the intermediate-term human behaviour of research of the best option over multiple possibilities.

Looking at the algorithm working principles, the beginning is the initialization of the *propensities (q)*, i.e. at the time *t=0*, with the same value *q(0)* for each of the N options. The *propensities*, as is suggested by the same word, quantify the will or predilection for a certain option; each option is associated to a propensity value. At the following iteration t=1,2,… these are updated depending on the selection and the result obtained. For example, if the option *k* is selected at the time *t*, then the propensities at the time *t+1* are updated as follow:

$$q_j(t+1) = (1-r) \times q_j(t) + RESPONSE_j \quad \forall j \tag{2.1}$$

$$RESPONSE_j = \pi_k(t) \times (1-e) \quad if\ j = k \tag{2.2}$$

$$RESPONSE_j = \pi_k(t) \times \frac{e}{N-1} \quad if\ j \neq k \tag{2.3}$$

$$r \in [0; 1] \tag{2.4}$$

$$e \in [0; 1] \tag{2.5}$$

The choice probability of each action a_k at the time *t* is defined as:

$$p_j(t) = \frac{q_j(t)}{\sum_{i=0}^{N-1} q_i(t)} \tag{2.6}$$

Where:
- $q_j(t)$ is the propensity of action j at time t;
- $q_j(0)$ is the propensity of action j at time t = 0, also known as initial propensity;
- $\pi_k(t)$ is the reward obtained for action k at time t; the authors indicate that it has to be necessarily a monotonically increasing function;
- *r* is the recency parameter;
- *e* is the experimentation parameter;

2.6.2 Modified Roth-Erev Reinforcement Learning Algorithm (MRE RLA)

It was observed that the algorithm developed by Roth and Erev fails to learn in case of action rewarding with zero profit/payoff. For this reason Nicolaisen, Petrov and Tesfatsion [13] developed a modified version of the RE RLA. They also proved that, in the context of electricity market auction, the market efficiency is considerably higher when traders use the MRE RLA.

Looking at the propensities update it can be observed a light difference whereas the probabilities computation remains unchanged.

$$q_j(t+1) = (1-r) \times q_j(t) + RESPONSE_j \quad \forall j \tag{2.7}$$

$$RESPONSE_j = \pi_k(t) \times (1-e) \quad if \ j = k \tag{2.8}$$

$$RESPONSE_j = q_j(t) \times \frac{e}{N-1} \quad if \ j \neq k \tag{2.9}$$

$$p_j(t) = \frac{q_j(t)}{\sum_{i=0}^{N-1} q_i(t)} \tag{2.10}$$

2.6.3 Variant Roth-Erev Reinforcement Learning Algorithm (VRE RLA)

It could happen that the reward assumes negative value so that to lead problems in probabilities calculation. In order to avoid that J. Sun and L. Tesfatsion in [14] purpose an additional modification to the RE RL algorithm by changing the probability calculation, based now on the exponential of the propensity of each option. The VRE RL algorithm is currently used in the AMES framework.
Here it is showed the form of the algorithm:

$$q_j(t+1) = (1-r) \times q_j(t) + RESPONSE_j \quad \forall j \tag{2.11}$$

$$RESPONSE_j = \pi_k(t) \times (1-e) \quad if \ j = k \tag{2.12}$$

$$RESPONSE_j = q_j(t) \times \frac{e}{N-1} \quad if \ j \neq k \tag{2.13}$$

$$p_j(t) = \frac{e^{\frac{q_j(t)}{C}}}{\sum_{i=0}^{N-1} e^{\frac{q_j(t)}{C}}} \tag{2.14}$$

Where c is the (new) Boltzmann cooling parameter: it is used to control the degree to which differences among the propensities are emphasized in the calculation of probabilities from the propensities. "If the variations in the action propensities are not too large, a judicious selection of the cooling parameter allows the differences between the propensities to be amplified in the probability calculations" [15].

CHAPTER 3

The Colombian case

The aim of this work is to provide an adequate instrument to analyse the operations of the Colombian electricity market. Colombia is going through a period of deep changing that is affecting both the energy mix and the market functioning.

In fact, only in 2014 with the important law 1715 [16], the government had started to stimulate the growth of the non-conventional renewable energy system (NC RES) by official regulation of the subsidies. The ambition, as shown in *Figure 3.1,* is to expand the installed capacity of photovoltaic (PV) systems and wind farms, for which there is a very strong potential in the North of the Country [17]. This can help not only to reduce the high cost of energy but, it can also improve the quality of energy supply reducing the outages.
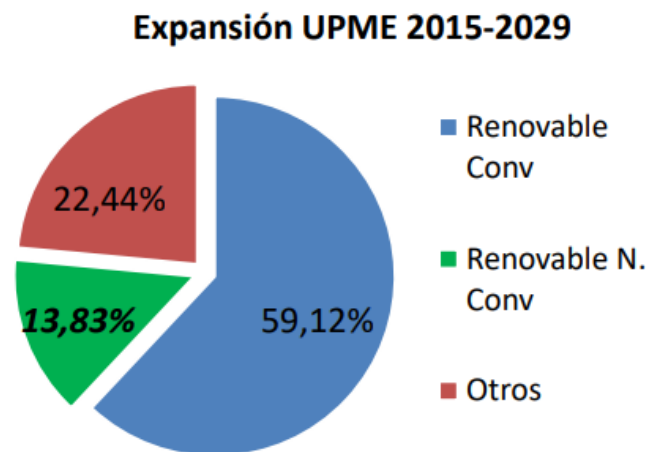
Figure 3.1- Capacity expansion plan to 2030

Furthermore, the market structure will go through a period of deep changes too. In the last years, for example, the need to have a balancing market, together with the existing day-ahead market, started to be more pressing because of the high cost of the inefficiencies. The reason of this change is the ineffectiveness of the system to manage the deviation of real-time operation from the scheduled generation profile with the day-ahead auction.

Thus, in the next section, the Country's characterization will be introduced focusing on the energy and electricity sector. Then, the Colombian energy market will be described with a particular attention on its critical points.

3.1 Overview on the Colombian energy sector

GDP **282.36$BN**
FIVE-YEAR ECONOMIC GROWTH RATE **-24.00%**
POPULATION **48.65M**
TOTAL CLEAN ENERGY INVESTMENTS, 2012-2016 **0.49$BN**
INSTALLED POWER CAPACITY **16.64GW**
RENEWABLE SHARE **6.00%**
TOTAL CLEAN ENERGY GENERATION **3,903.25GWh**
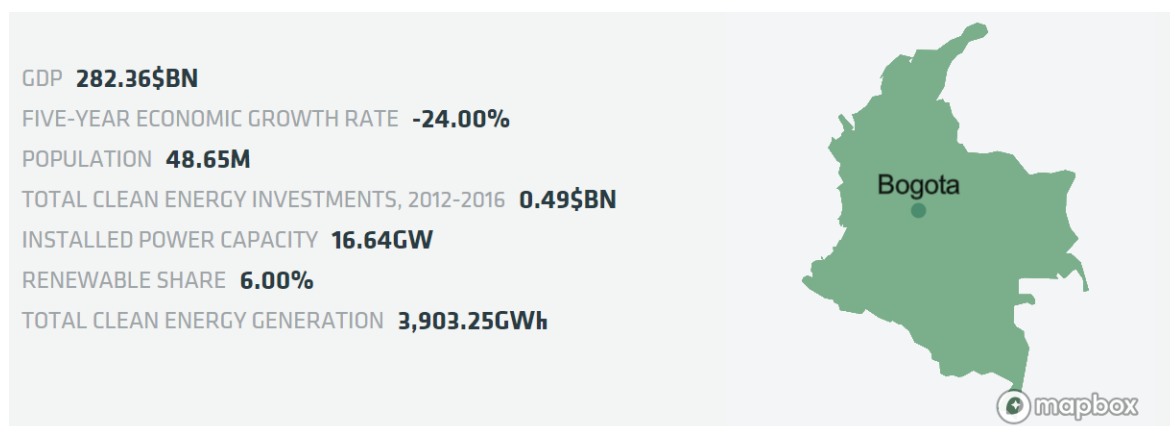
Figure 3.2- Colombian significant indicators

Colombia is an important developing country and it is consolidating its status of regional power despite the crisis experienced in 2014, with the last fall of the oil price started. The principal country's indicators can be observed in *Figure 3.2*. Colombia is the second most populated country of South-America with a young population, and a very dynamic economy. Colombian economy is one of the top 25 in the world, the third best in the continent behind the bigger Brazil and Argentina. The export is constantly increasing, and the country is one of the largest coal exporter; the first economical partner is the US which is both first exporter and first importer.

The growth is rapidly changing Colombia from the social, economic and environmental points of view. The historic peace agreement clinched with the Farc[5] in 2016, which closed the oldest existing internal conflict, represents the transformation that are occurring in the Colombian society. The country is trying to reduce the social inequities together with the economic development, paying particular attention on the sustainability of its expansion.

This transition affects also the energy sector, for which an important development is expected. In fact, the economic growth of the country is reflected on the expansion of the energy demand, shown in *Figure 3.3*; its recent slow down is due to the mentioned economic difficulties occurred during the oil crisis.

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[5] It is a Marxist-Leninist guerrilla movement active from the end of 60s
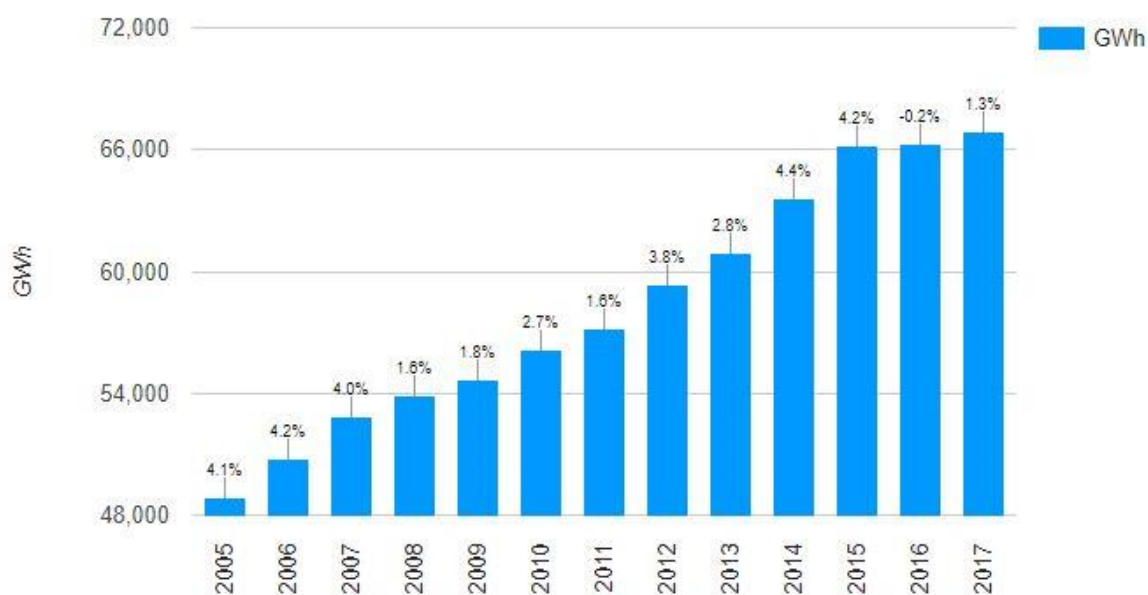
Figure 3.3-Electricity demand historical data

The electricity supply in Colombia relies on the National Interconnected System (SIN) and several isolated local systems in the Non-Interconnected Zones (ZNI). The *Figure 3.4* shows the topology of the transmission network: the SIN crosses the country in correspondence with its valleys, and most of the eastern zones are not connected. The SIN provides energy to the 96% of the population even if the area covered accounts only the 30% of the national territory. The electricity transmission is managed only by public companies, among which the largest is ISA that belongs to the government. The total coverage of energy supply is an important topic in the Country because its goal is to develop solutions that integrate NC RES with traditional systems to provide energy all over the nation.

Colombia is not only rich of fossil fuels, but it has the world largest water reserves pushing the exploitation of the water resources. In fact, the increasement of the energy demand was followed by the expansion of hydro power plants. As it can be observed from the *Table 3.1*, large hydro plants dominate the power capacity and the electricity generation.
Nevertheless the thermal plants result very important; they contribute to the energy reliability, by the control of the congestion, and to the energy security, by guaranting the service in period of water shortage. This last point represents a critical concern for Colombia which is periodically afflicted by an extreme climate phenomenon called "El Niño". When this occurs the water reservoirs are dryied out, so that the energy supply is stressed and the electricity market price explodes. In 2016 this almost leaded to the rationing of the electricity supply [18].

Figure 3.4-Colombian national transmission system

TECHNOLOGY	INSTALLED CAPACITY [MW]	SHARE [%]	GENERATION [GWh]	SHARE [%]
Hydroelectric	11891	70.8	57342	86.0
Thermal (gas)	2129	12.7	5280	7.9
Thermal (coal)	1329	7.9	3303	5.0
Liquid	1148	6.8	491	0.7
Gas-Liquid	264	1.6	248	0.4
Wind	18.42	0.1	3.1	0.004
TOTAL	16779	100	66667.1	100

Table 3.1-Colombian energy capacity and generation in 2017

As it can be deduced from the presented data, Colombia has no needs to integrate the energy mix with NC RES as Solar of Wind power plant to reduce the exploitation of fossil fuels, or the pollution due to generation. They can also really help with some important concerns, as the "Niño" question. For this reason the country has planned and is stimulating the installation of new NC RES and this will change both the transmission system and the energy market.

3.2 The Colombian energy market

Colombia has a liberalized energy market since 1995 when Generation, Transmission, Distribution and Commercialization were unbundled; transmission is the only activity in which there is not competition among the participants.

Three institutions deal with the management and control of the market activities:

- UPME (Unit for Mining and Energy Planning), a specific compartment of the Ministry of Mine and Energy, which is in charge for the long term National Energy Plan and the Expansion Plan;
- CREG (Regulatory Commission for Gas and Energy), public commission responsible for the efficiency of the energy supply and the market competition;
- XM, the private company that acts as Market Operator; it manages the market closing and all the activities connected to the energy dispatch.

The energy trades can be realized by transaction in the day-ahead market, the only energy market existing, for the short-term commitments, and through bilateral contract for the long-run agreements. Only generators with capacity exceeding the 20 MW are obligated to offer in the market their daily power availability, whereas the generators with capacity between the 10 and 20 MW are free to participate. The market participants are *centrally dispatched*.

At the beginning of the day-ahead market the participants submit an offer for the 24 hours sessions of the next day, they declare the power availability for each of the 24 hours related to an unique bid price. This represents a significant peculiarity with respect to the market rules of the European countries where it is possible to diversify the bid price for each different market sessions.

The retail agents also can participate in the market, but they do not submit bid price, they can only declare their power application. The market clearing is executed without considering any kind of technical or operative constraint.

After the market closing, XM performs the market dispatch optimizing the generation for the 24 hours, respecting the result of the day-ahead market and considering also the forecast (technical and operative) constraints. The result of this activity is the *ideal generation* profile for the following day.

Then, during the dispatch operations, it can happen to face unexpected events as plants generation problems, congestion, line damages etc. In this case, XM is appointed to organize the daily *re-dispatch* within 1 hour and a half from the event. The generators are allowed to deviate from the programmed dispatch, without being penalized, no more than the 5% of the committed *ideal generation* [19].

Between 1 and 6 days from the operation, XM effectuate the settlement: the market operator pays for the power that the agent sold in the market, at the market price; then, according to a mechanism called *Reconciliación* (literally reconciliation), the deviation of the *real generation* from the *ideal generation* is compensated[6].
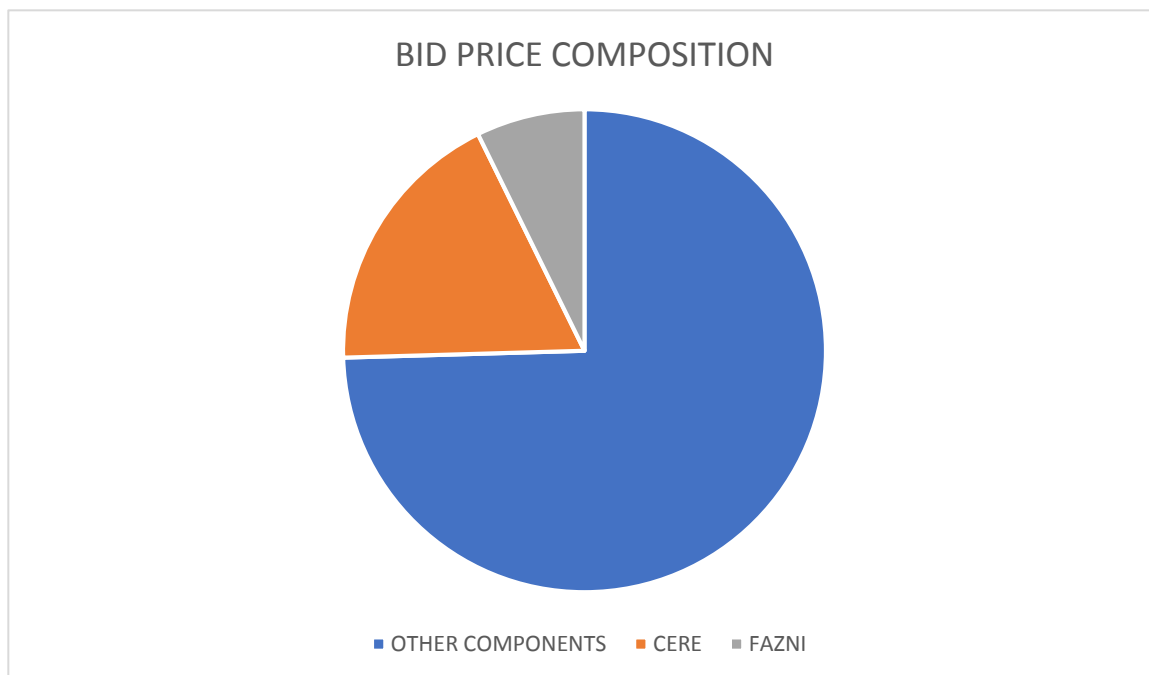
Figure 3.5-Bid price components

The bid price of the generators should reflect the current risk to provide energy and the long-run required capacity installed in the country. But, as shown in *Figure 3.5*, the generator has to include two components to the final bid price: the FAZNI - Financial Support Fund for Electrification of Non-interconnected Areas, and the CERE – Equivalent Real Cost of Energy. The first one is a contribution to support the energy supply and the construction of

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[6] If the generator has produced more than the energy programmed it receive the relative payments; on the contrary if the generator has produced less it pays back the correspondent amount to the market operator

infrastructure to include the non-interconnected zones into the SIN; the second one is the contribution to sustain the "*Cargo por confiabilidad*" system that will be discuss in section 3.3.2.

Colombia has always been an exporter of energy, mostly to Panama and Ecuador. In 2005 the energy export amounted to 1.76 TWh. But from 2015 to 2017 the exportations decreased from 460 GWh to only 0.44 GWh because of the effect of the "El Niño" that affected the water reserved and gradually reduced the production of the cheap hydroelectrical energy. The international transactions are not considered in the spot market definition, but they determine another market price, the *TIE*, that concerns only the agents involved in the import/export of energy. The *Figure 3.6* summarises the process and the contribution to the market prices formation.
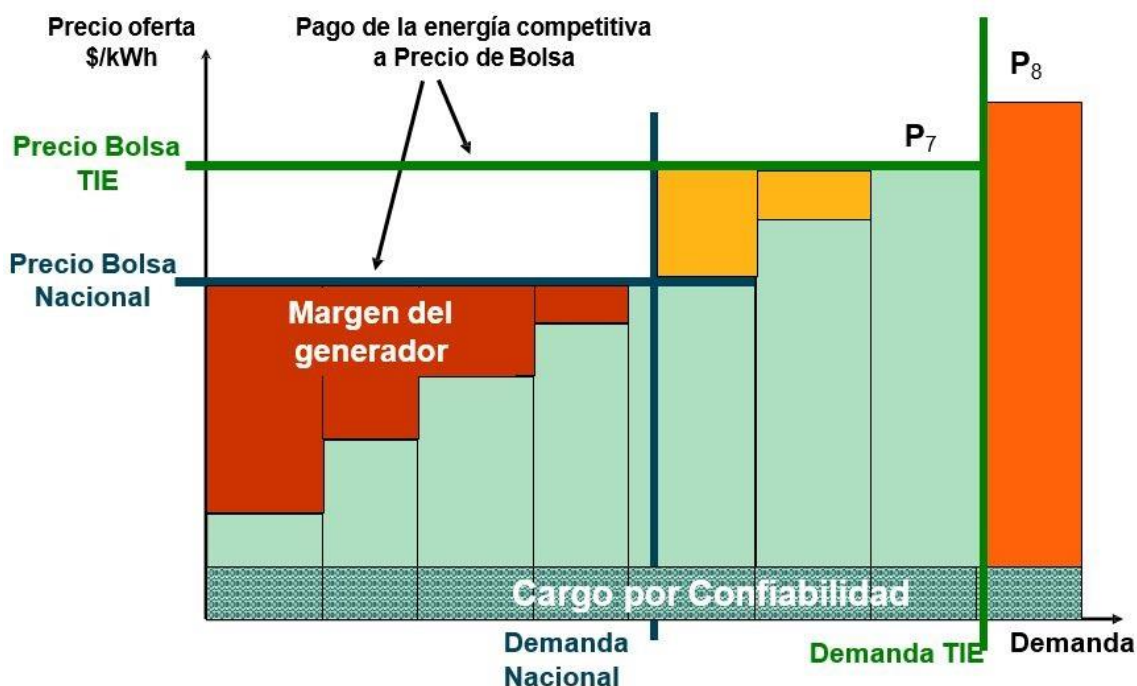
Figure 3.6-Market prices formation

3.3 Critical issues of the Colombian energy market

To know in detail the Colombian energy market it is necessary to analyse two important topics largely debated from years: the question of the Oligopoly and the reliability of the energy supply during the period of "El Niño". These two points are becoming over time more and more significant. For the first point, it is because the dominant companies continue to expand their power capacity, and it strongly affects the efficiency in the energy supply. In

fact, the Colombian market price is rather high considering the large share of hydro power plants and so the consumers demand for cheaper prices.

About the second point, in the last decades the frequency and the intensity of the phenomenon increases, even if it would require a larger time frame data to deduce more accurate conclusions. What is clear is that the energy emergencies are not only more frequent but also more dangerous for the energy supply. The NC RES, especially the wind energy, can offer a perfect solution to the problem since they are almost unexploited although the strong potential of the Country.

Thus, the model development can offer an important instrument to study these two topics and it could help to find possible solutions.

3.3.1 Oligopoly

Figure 3.7-Power plant geography of Colombia

Colombia has a liberalized market since 1995 but the generation unbundling was never totally accomplished because few company still owned the majority of the power installed. Even if the 60% of the capacity belongs to private companies, only 3 groups, Empresas Públicas de Medellín – ISAGEN – EMGESA[7], currently own more than the 60% of it and they accounts for almost the 70% of the generation in 2017. This is shown in *Table 3.2* where the data for the 10 most important energy groups are summarized.

COMPANY	COMPANY POWER [MW]	COMPANY POWER SHARE [%]	COMPANY GENERATION SHARE [%]	HYDRO POWER [MW]	THERMAL POWER [MW]
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	3316	21,17	23,16	2910	406
EMGESA S.A. E.S.P.	3179	20,29	22,25	2971	208
ISAGEN S.A. E.S.P.	3005	19,18	22,92	2705	300
AES CHIVOR & CIA. S.C.A. E.S.P.	1000	6,38	5,78	1000	0
EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	955	6,10	6,03	955	0
TERMOBARRAN QUILLA S.A. E.S.P.	918	5,86	5,56	0	918
ZONA FRANCA CELSIA S.A. E.S.P.	777	4,96	1,41	0	777
GENERADORA Y COMERCIALIZADORA DE ENERGIA DEL CARIBE S.A. E.S.P.	450	2,87	1,53	0	450
EMPRESA URRA S.A. E.S.P.	338	2,16	2,44	338	0
GESTION ENERGETICA S.A. E.S.P.	172	1,10	1,44	0	172
TOTAL	14110	90,07	92,52	10879	3231
TOTAL COLOMBIA	15665	100	100	10944	4721

Table 3.2-Capacity and generation of the leading companies

[7] Empresas Públicas de Medellín and ISAGEN are public companies whereas EMGESA is private (part of the ENEL group)

These 3 first leader companies distribute their capacity among the 25 power plants summarized in *Table 3.3*. Each one of these 25 participates in the market through submission of independent bids. It is reasonable to think that this large capacity share allows the oligopolistic company to mark-up the market price because they are aware of beeing essential to meet the power demand.

PLANT	COMPANY	TYPE	CAPACITY [MW]
BETANIA	EMGESA S.A. E.S.P.	HYDRO	540
DARIO VALENCIA SAMPER	EMGESA S.A. E.S.P.	HYDRO	150
EL QUIMBO	EMGESA S.A. E.S.P.	HYDRO	396
GUAVIO	EMGESA S.A. E.S.P.	HYDRO	1250
LA GUACA	EMGESA S.A. E.S.P.	HYDRO	324
PARAISO	EMGESA S.A. E.S.P.	HYDRO	276
SALTO II 2	EMGESA S.A. E.S.P.	HYDRO	35
TERMOCARTAGENA	EMGESA S.A. E.S.P.	TERMO	208
ESMERALDA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	30
GUADALUPE 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	270
GUADALUPE 4	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	225
GUATAPE	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	560
LA TASAJERA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	306
PLAYAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	207
PORCE II	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	405
PORCE III	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	730
SAN FRANCISCO	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	135
TRONERAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	HYDRO	42
TERMOSIERRA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	TERMO	460
AMOYA LA ESPERANZA	ISAGEN S.A. E.S.P.	HYDRO	80
JAGUAS	ISAGEN S.A. E.S.P.	HYDRO	170
MIEL I	ISAGEN S.A. E.S.P.	HYDRO	396
SAN CARLOS	ISAGEN S.A. E.S.P.	HYDRO	1240
SOGAMOSO	ISAGEN S.A. E.S.P.	HYDRO	819
TERMOCENTRO	ISAGEN S.A. E.S.P.	TERMO	300

Table 3.3–Power plants of the oligopolistic companies

For this reason, in section 5.2, the model developed will be used to simulate the market operation both when these 25 power plants participate in the market independently and when their bids are arranged by the respective company. The comparison of the results will demonstrate if the autonomous action of these plants coincides with the profit maximization of their company, or if the companies exert the power market increasing the bid price so that to compromise the market competition.

3.3.2 Energy supply during period of "El Niño"
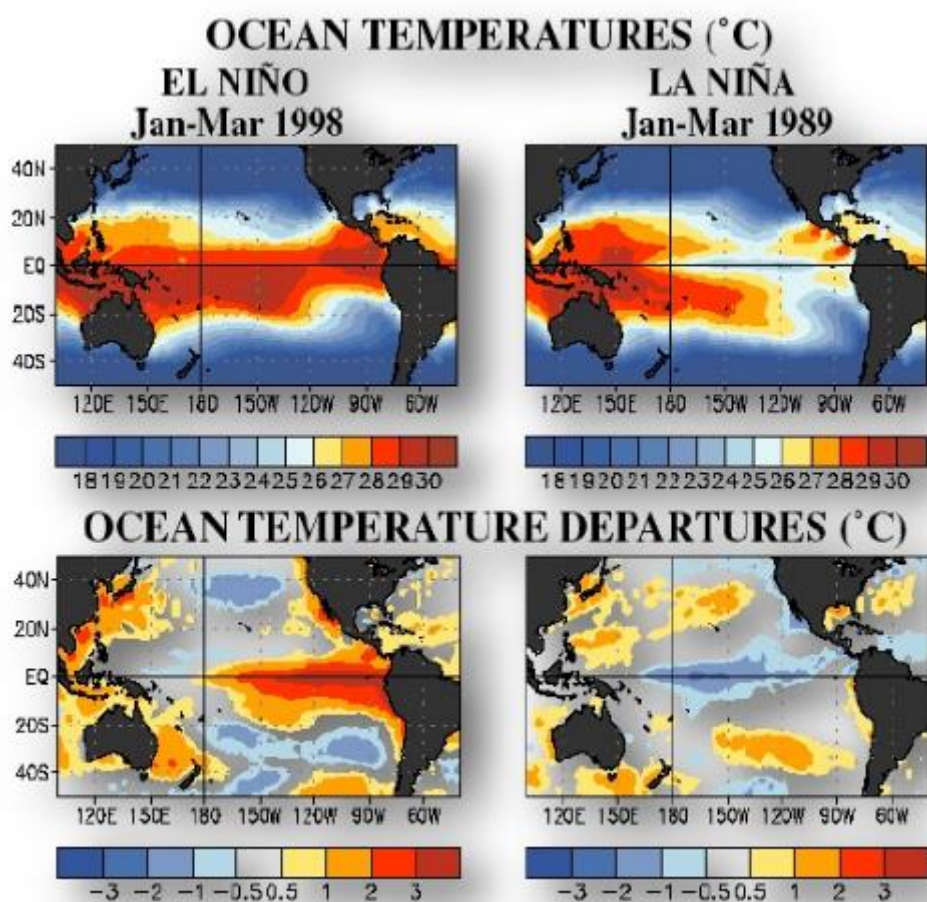
Figure 3.8-Anomalies distribution of El Niño and La Niña

"El Niño", also referred as ENSO (El Niño-Southern Oscillation), is a climatic phenomenon related to the warming of the eastern-central zone of the Pacific Ocean. It takes place periodically each 3-8 years, even if in the last decades the frequency seems to have grown; it arises between December and January (the name "El Niño" refers indeed to the Nativity). The effect of this event affects not only the countries exposed to the Pacific Ocean, but it has consequences at a global level. This phenomenon occurs because of the interaction of the ocean with the atmosphere and it consists in an anomalous warming of the ocean surface

temperatures due to the reduction of the trade winds circulation. This provokes the decrease of the oceanic water circulation, also called Walker circulation.

"El Niño" is usually followed by its counter- phenomenon "La Niña". In this case the trade winds circulation increases so that to increase also the Walker circulation. It can be easily deduced that the effects would be opposite with respect to the ones of "El Niño", in term of climatic condition and about the areas involved.
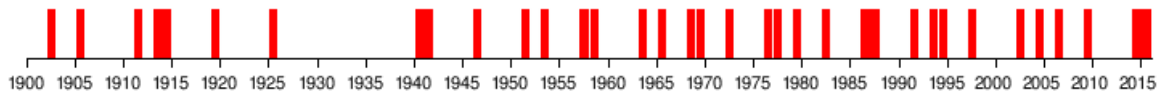
Figure 3.9-El Niño historical data

Figure 3.9 shows the frequency and intensity of the events occurred in the last century. Even if the time frame is too short to make reliable hypothesis, most of the scientists agree about the stabilization of the phenomenon and about the strong diseases that it is bringing at global level. The possible connection with the global warming is also still debated.
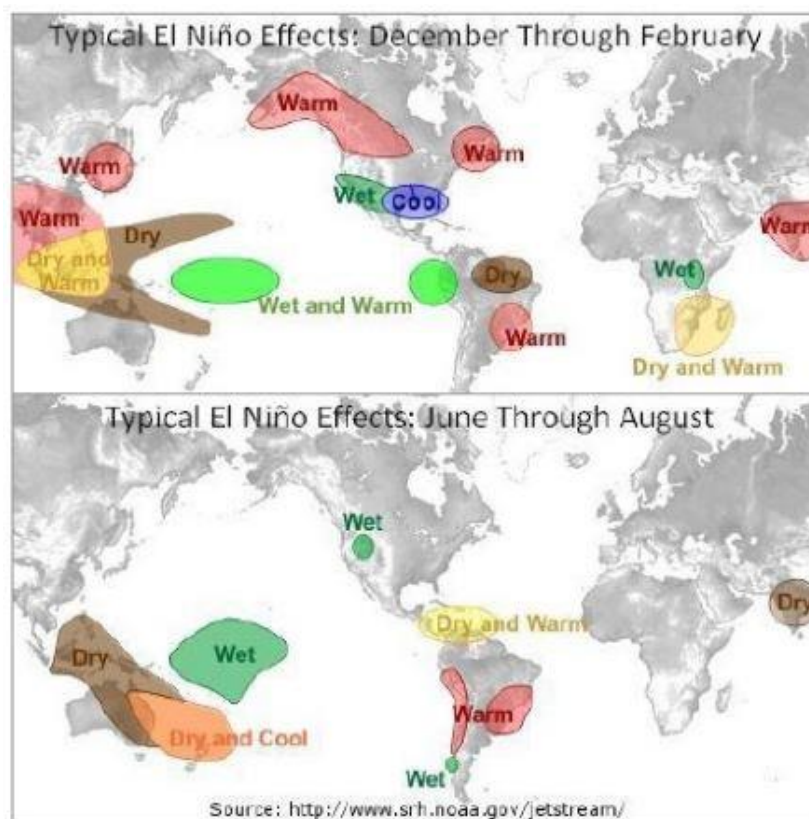
Figure 3.10- El Niño global effects

The *Figure 3.10* depicts the consequences of this climatic event that can be observed all over the world. In Colombia it provokes a strong decrease of the rainfall and the humidity rate. This affects not only the energy supply but also the agriculture and increases the amount of fires. During the 15 months of El Niño between the 2015 and 2016, the Country's temperatures raised of 2.5°C over the correspondent historical average; 14 fires burned 188650 hectares of forests and many rivers reached their minimum historical level, in particular the important river Rio Magdalena that feeds also many hydro power plants [20].

The strong reduction of the precipitations, that can reach also values around -40/-50%, results a very critical issue for the Colombian generation system that counts more than the 70% of hydro capacity share. The *Figure 3.11* shows the strong decrease of the generation from hydro plants occurred during the beginning of last episode of El Niño.
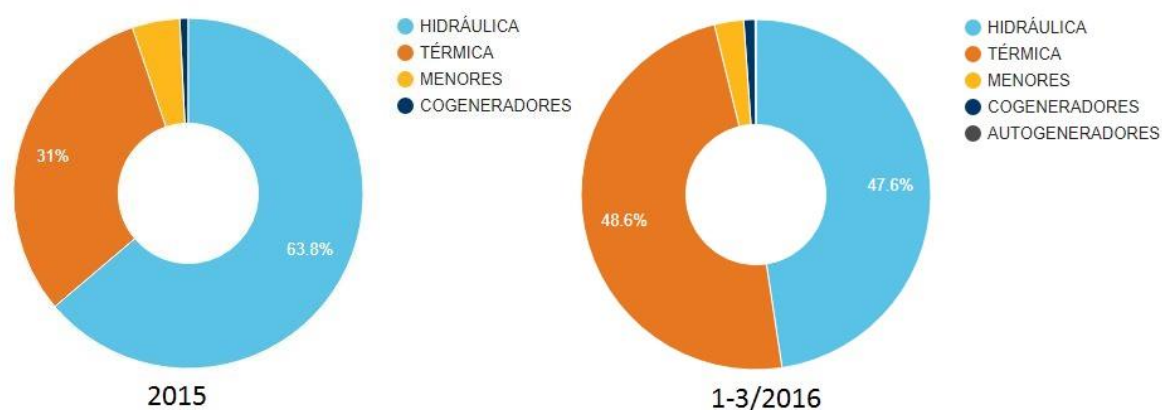
Figure 3.11 – Power generation in 2015 and first trimester of 2016

These critical circumstances strongly increased the volatility of the market price that raised up because thermal generators with very high production costs entered the market. Without the power generation from these plants the Country have to ration the energy supply.
To prevent these circumstances, Colombia developed in 1996 a scheme called "Cargo por Capacidad" (literally "Capacity Charge") [21]; that was then updated in 2006 with the "Cargo por Confiabilidad" (literally "Reliability Charge") [22].

The "Capacity Charge" scheme had the purpose to make convenient the investment in power plants that guarantees the energy supply, at reasonable price, during period of water shortage. It consists in the distribution of a certain amount of money so that to support the production of energy even when the cost of production, and consequently also the bid price, is higher than the scarcity price. In addition, this makes the investment in thermal power plants beneficial because it guarantees a "backup-profit" even in normal conditions. In fact, usually,

the large share of hydro plants is sufficient to fulfil the energy demand and so to do not allow the thermal power plant to sell enough energy to return of the investment in a reasonable time.

However, during the ENSO of 2005, this scheme failed because some power plants refused to produce energy since the unexpected very high fuel cost made the marginal cost of production too high to trade energy under the scarcity price.

Thus, in 2006, the "Reliability Charge" system was implemented. This relates the distribution of the money to the purchase of "OEF - Obligación de Energía Firme" (literally Firm Energy Obligation). When the market price exceeds the scarcity price for at least 1 hour during the day, the generator assignee of OEF has to produce a certain amount of energy. The OEF can be acquired by selected agents through proper auction. The money distributed is paid by all the generators through the collection of the mentioned CERE contribution that is included in their bid prices.

Even with this last implementation the scheme results very expensive for the consumers and even rather inefficient. For these reasons, Colombia starts to stimulate the development of NC RES as wind farms and PV power plants by the launch of the subsides ratified through the law 1715 of 2014. In fact, both PV and wind plants would not be affected by the occurrence of "El Niño" so that to offer an important alternative to the thermal generation.

Thus, different scenarios of NC RES capacity will be simulated in section 4.3 to study the impact of the installation of wind and PV power plants during ENSO's period of water shortage.

CHAPTER 4

Modelling process

Figure 4.1-The market environment representation

To analyse and discuss the critical issue of the Colombian energy market, exposed in section 3.3, a model able to reproduce the market operations has been built. According to the ABM approach, the model consists of agents whose interactions reflect the actual activities occurring in the market.

As the case of AMES, the environment developed focuses on the generators activities, so the demand was designed as a passive entity which represents the market quantity to be fulfilled. Although, the generators agents elaborate a bid to subscribe in the market and then, depending on the demand and the position of the other agents, they receive the output and elaborate the correspondent reaction. Their target is to maximize the profit gained by the participation in the market.

As shown in section 3.1, the Colombian generators pattern consists of hydro and thermal power plants, with a significant prevalence of the first; thus, the model of the market has to include both the type of generator agent. However, their algorithm cannot be the same because of notable differences steering their activities. The algorithm described in the AMES framework is suitable to design a thermal generator agent. Whereas, to realistically simulate the activity of the hydro plants, it is necessary to include in the algorithm its primary concern: the variation of its water availability. To realize that proper modifications were applied to the general structure of the AMES algorithm, so that to represent this specific feature. These modifications will be described in detail in the next sections 4.1.3.

There is another important aspect of the Colombian energy market, discussed in section 3.3.1, that cannot be reproduced by the AMES algorithm: The Oligopoly. In fact, AMES and all the other platforms that provide an energy market environment, design generator agents able to act autonomously with respect to the other market participants. But this does not correspond to the reality when different plants pertaining to the same ownership/group that participate in the market. In this case the generators do not pursue the maximization of its own profit, but they contribute to the maximization of the company profit. This implies that the agents that are related to the same ownership do not compete between themselves. For these reasons it was necessary to implement a specific algorithm, shown in section 4.2, to coordinate and to submit the bid for the different agents belonging to the same company.

As already discussed, the intention of Colombia is to couple the day-ahead market with a balancing market in order to optimize the activity of re-despatch (section 3.2). Thus, it is reason for interest to develop a parallel platform able to simulate real-time trading so that to make feasible the test of the possible reaction of the market. To realize this environment, the algorithm modules (Bidding Process and Response process), used for the day-ahead market, were properly adapted to the real time operation.
The market rules cannot be the same as (the ones of) the day-ahead market, in particular because different bid prices have to be allowed to be subscribed in the different hourly market sessions. However, imposing this restriction couldn't be realistic regarding real-time trading, where the energy exchanged could assume also negative values.

The MRE LA [15] was selected to perform the learning process of all the types of agents. This choice, in contrast with the AMES framework that applies the VRE LA, will be discussed in detail in section 4.4.2.

Matlab was chosen as the computing platform to make more accessible the usage of the tool and to facilitate possible future development.

Therefore, this chapter will go through the definition of the model and the development of all its components. To describe better the modelling process, the first analysis will concern the thermal agent algorithm; the second analysis will continue on the modification applied to the hydro agents and with the description of the algorithm to manage groups of generators. The chapter ends with two critical concerns that have been faced during the test of the model.

4.1 Thermal & Hydro Generator Agent
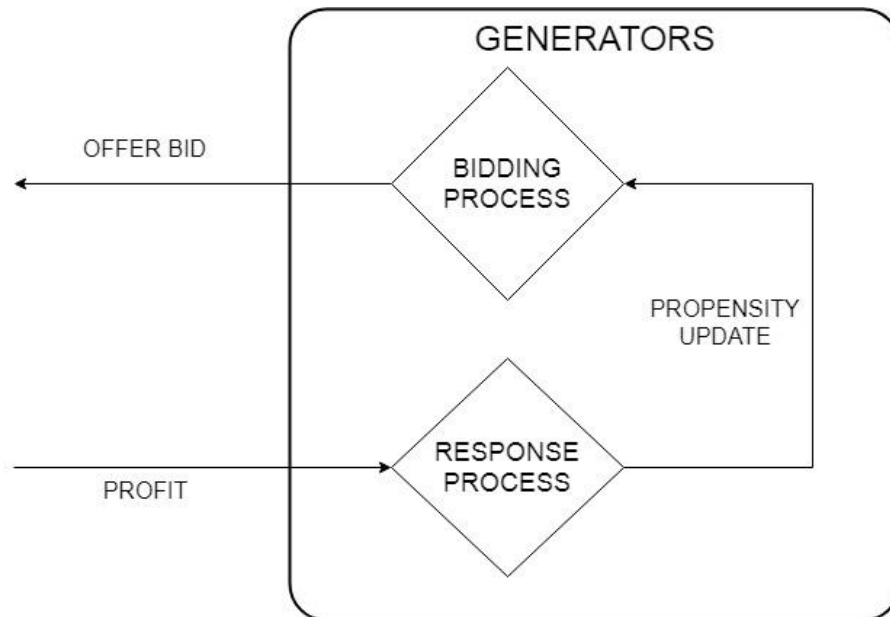
Figure 4.2- Generators modules and informations flow

The algorithm that manages the generators' activity performs different functions which, all together, have the target to find the market position that maximize the profit gained of the energy sold.

Figure 4.2 shows the modules that drive the generators action: the "Bidding process" reproduces the act of bid submission; the "Response process" receives and elaborates the market results. This general scheme is applied to all kind of generator agent (hydro, thermal and company) but they have differences within the modules.

This section presents, firstly, the data input that define both thermal and hydro generators, and then, the description of the two modules steered by the MRE RLA.

4.1.1 Agents Data Input

The execution of the algorithm requires the data input necessary to define the agent profile and to allow the accomplishment of all the calculations.

Parameter	Description/Function
ID	The identification number of the agent.
AREA	The area in which the generator act[8].
TRADER	The identification number of the agent group/company membership.
M1	The number of possible different bid price.
M2	The number of possible different bid energy.
e – Experimentation Parameter	Modified Roth-Erev Reinforcement Learning Algorithm parameter.
q_{in}- Initial Propensity	Modified Roth-Erev Reinforcement Learning Algorithm parameter.
$RI_{MIN,c}$ – Range index	Range Index that represents the bid price spectrum by estimation of the mark-up on the marginal cost of production.
$RI_{MAX,I}$ – Range index	Range Index that represents the possible variation of bid energy with respect the production limits.
CAP_L , CAP_U [MWh] – Production limits	Lower and upper production limits.
a , b , FC – Cost function parameter (only thermal agents)	The production cost function parameters.
C_W [€/MWh] – Cost of water (only hydro agents)	This value represents the marginal cost of production for the hydro power plants
$V_{RESERVOIR}$ [MWh] – Reservoir volume (only hydro agents[9])	This value represents the availability of the water reservoir.
$V_{RES,MAX,techn}$, $V_{RES,MIN,techn}$ [MWh] – Reservoir technical limits (only hydro agents[8])	The values representing the technical limits of the reservoir capacity.
REFUEL [MWh/h] (only hydro agents[8])	The value representing the quantity of water recovery for the plant reservoir.

Table 4.1 – Agent data input

4.1.2 Bidding Process for Thermal agents

The module that performs the bidding process follows three steps:
   a.   Action Domain Matrix (ADM) construction;
   b.   Probability definition and Stochastic process;
   c.   Bid report.

---

[8] It could be taken in consideration to perform the market dispatch with respect to the transmission and/or other market constrains

[9] In case of Run-of-the-river power plants it is supposed artificial values for all the amount related to a reservoir.

Step a. The *ADM* represents the set of options from which the bid has been determined: it is composed of two groups of values: one, to derive the bid price (vM_1), the other, to derive the bid energy (vM_2); M_1 and M_2 correspond to the number of values respectively for vM_1 and vM_2. The following equations summarize the composition of the two groups depending on the value of M_1 and M_2:

$$if\ M_1 = 1 \rightarrow vM_1 = 0 \tag{4.1}$$

$$if\ M_2 = 1 \rightarrow vM_2 = 1 \tag{4.2}$$

$$if\ M_1 > 1 \rightarrow vM_1 = \big[vm_{1,1};\ \dots\ ; vm_{1,M1}\big] = [0:Inc_1:RI_{MAX,L}] \tag{4.3}$$

$$if\ M_2 > 1 \rightarrow vM_2 = \big[vm_{2,1};\ \dots\ ; vm_{2,M2}\big] = [RI_{MIN,C}:Inc_2:1] \tag{4.4}$$

Where $vm_{i,j}$ is the generic element j of the vector vM_i.

All the possible combinations among the values of vM_1 and vM_2 compose the *ADM,* which dimensions will be $M \times 2$; where $M = M_1 \times M_2$. M is also the number of possible different bids m that the agent can submit in the market.

$$ADM = \begin{bmatrix} 0 & 0 \\ 0 & \vdots \\ 0 & vm_{2,j} \\ 0 & \vdots \\ 0 & RI_{MAX,L} \\ \vdots & 0 \\ vm_{1,j} & \vdots \\ vm_{1,j} & vm_{2,j} \\ vm_{1,j} & \vdots \\ vm_{1,j} & RI_{MAX,L} \\ vm_{1,j} & 0 \\ \vdots & \vdots \\ RI_{MIN,C} & vm_{2,j} \\ RI_{MIN,C} & \vdots \\ RI_{MIN,C} & RI_{MAX,L} \end{bmatrix} \tag{4.5}$$

$$M = M1 \times M2 \tag{4.6}$$

N.B. The following ADMs built with more than two groups of values are built in the same way: combining, as shown, all the elements of each group that compose the matrix.

Step b. Then, according to the MRE RLA, the probabilities $p_{i,m}$ related to each bid option m, for the agent i, is calculated:

$$p_{i,m} = \frac{q_{i,m}}{v} \qquad\qquad v = \sum_{m=1}^{M} p_{i,m} \qquad\qquad\qquad 4.7$$

Through the execution of a stochastic process in form of "*roulette wheel*", that considers the probability related to each option, the couple of values RI_L and $RCAP_U$ are chosen from the *ADM*:

$$ADM(m_{choice}, 1) \rightarrow RI_L \qquad ADM(m_{choice}, 2) \rightarrow RCAP_U \qquad\qquad 4.8$$

These values have a specific meaning as regard to the bid report:

$$RI_L = 1 - \frac{MC}{u_R} \qquad\qquad RCAP_U = \frac{CAP_{R,U} - CAP_L}{CAP_U - CAP_L} \qquad\qquad 4.9$$

Step c. From the definition of these two values it is possible to determine the bid price and the bid energy. The bid energy reported in the market ($CAP_{R,U}$) is derived directly from the previous equation:

$$CAP_{R,U} = RCAP_U \times (CAP_U - CAP_L) + CAP_L \qquad\qquad 4.10$$

Assuming a quadratic cost function for the thermal generators of the form:

$$TC(Q) = FC + a \times Q + b \times Q^2 \qquad\qquad 4.11$$

where Q is the energy produced by the generator.

The bid price reported in the market (u_R) results from the marginal cost of production:

$$MC(CAP_{R,U}) = a + 2 \times b \times CAP_{R,U} \qquad\qquad u_R = \frac{MC(CAP_{R,U})}{1 - RI_L} \qquad\qquad 4.12$$

This procedure refers to the submission of a single bid for a certain market session. In fact, the set of propensities is associated only to the operation and to the results of that specific market session. Thus, it is supposed that there are not significant constraints, in term of energy production, that correlate different market sessions. This is realistic for the thermal generators, except for exceptional cases like when the plant is switched off. Therefore, in a market day with 24 market sessions, this procedure is executed 24 times elaborating as much independent set of propensities.

4.1.3 Bidding Process for Hydro agents

The hydro power plant production depends on the water availability and its scarcity is reflected (also) on the bid price. For these reasons the short-term bid strategy for hydro generators represents a critical aspect for the design of the agent profile. The AMES framework doesn't consider the variation of the production constraints. Hence, it was possible to preserve the structure of the modules shown previously in *Figure 4.2*, but it was necessary to consider the variation of the water availability and to include the correlation among the choices taken by the agents.

The idea of the updating of the water availability is to consider the reservoir volume variation that is due to the power production and to possible water supply. The control of the reservoir volume is set in order to maintain it over a certain minimum level $V_{RES,MIN,techn}$, so that the energy offered in the market cannot exceed the water availability.
The submitted bid energy is calculated in the same way but monitoring the water availability:

$$CAP_{R,U}(s) = RCAP_U \times (CAP_U - CAP_L) + CAP_L \qquad 4.13$$

$$if\ CAP_U(s) > (V_{RESERVOIR}(h) - V_{RES,MIN,techn}) \rightarrow CAP_{R,U}(s) = 0 \qquad 4.14$$

where *s* is the generic market session of the day *D*.

Then, the update of the reservoir volume $V_{RESERVOIR}$ is computed, considering the water consumption due to the potential power production and a certain degree of water refill, represented by the term *REFUEL*. The "refuelling" is calibrated on the effective water supply received by the reservoir.

$$V_{RESERVOIR}(s+1) = V_{RESERVOIR}(s) - CAP_{R,U}(s) + REFUEL(s) \qquad 4.15$$

The production cost for the hydro agent would not be the same of the thermal agent because the most significant contribution represented by the fuel consumption is missing. Consequently, it was chosen to consider a linear cost function and to summarize the marginal cost of production in the unique term C_W, that serves as reference for the calculation of the submitted bid price:

$$TC(CAP_{R,U}) = C_W \times CAP_{R,U} \qquad 4.16$$

$$u_R = \frac{C_W}{1 - RI_L} \qquad 4.17$$

The previous equations describe the peculiar principles that have been defined for the management of the hydro plants' activities. These passages, in the procedure, are being considered for the submission of the agents' bid offers.

The bidding process for thermal agents provided by AMES, shown in the previous section, allows the definition of a single independent bid offer. For the correct representation of the hydro plants' market operations it was required to consider not only the explained production constraint variation, but also the inter-dependence of different bids due to the water consumption and its effects on the decision-making process. For these reasons, a system was implemented, allowing the selection and the submission of multiple interdependent bid offers. To realize this feature, the concept of ADM was extended to include the set of all the possible multiple bid offers.

As regards the procedure exposed in section 4.1.1, here is described the general algorithm executed for the submission of N_S consecutive bids for a certain N_A number of different agents n, even if in this case it is referring to a single agent ($N_A=1$). The values $M_{1,n}$, $M_{2,n}$, $RI_{MAX,L,n}$ and $RI_{MIN,c,n}$, associated to the agent n are received as input and they are used to build as much $vM_{1,n}^s$ and $vM_{2,n}^s$ as s consecutive bid to submit in the market. $vM_{1,n}^s$ and $vM_{2,n}^s$ are the groups of values related to, respectively, the bid price and the bid energy of agent n for the market sessions s. The combinations of each values of $vM_{1,n}^s$ and $vM_{2,n}^s$ compose the extended ADM (ADM_{EXT}) of dimensions $[M_{EXT}; N_s \times N_A \times 2]$. The following pseudo-code provides the construction of ADM_{EXT} and the calculation of M_{EXT} that expresses the number of possible different bids m that the N_A agents can submit in the market (in this case the single agent) for Ns market sessions.

$algorithm: ADM_{EXT}\ construction$

$input: N_A;\ N_S;\ M_{1,n};\ M_{2,n}; RI_{MAX,L,n};\ RI_{MIN,c,n}$

$output: M_{EXT};\ ADM_{EXT}[M_{EXT}; N_S \times N_A \times 2]$

$for\ each\ n = [1:N_A]$

  $if\ M_{1,n} = 1$

    $for\ each\ s = [0:N_S - 1]$

      $vM_{1,n}^s = 0$

    end

  $else$

    $for\ each\ s = [0:N_S - 1]$

      $Inc_{1,n} = \dfrac{RI_{MAX,L,n}}{M_{1,n} - 1} \quad vM_{1,n}^s = [0:Inc_{1,n}:RI_{MAX,L,n}]$

      end

    end

   $if\ M_{2,n} = 1$

     $for\ each\ s = [0:N_S - 1]$

       $vM_{2,n}^s = 0$

     end

    $else$

     $for\ each\ s = [0:N_S - 1]$

       $Inc_{2,n} = \dfrac{1 - RI_{MIN;c,n}}{M_{2,n} - 1} \quad vM_{2,n}^s = [RI_{MIN,c,n}:Inc_{2,n}:1]$

       end

    end

end

4.26

$$M_{EXT} = \prod_{n=1}^{N_A} \left(M_{1,n} \times M_{2,n} \right)^{N_S}$$

$for\ each\ kk = [1:M_{EXT}]$

  $for\ each\ n = [1:N_A]$

   $for\ each\ s = [1, N_S]$

    $for\ each\ k_{1,n} = [1:M_{1,n}]$

      $ADM_{EXT}(kk, (n-1) \times N_S \times 2\ +\ 2 \times (s-1)\ +\ 1) \leftarrow vM_{1,n}(k_{1,n})$

     end

    $for\ each\ k_{2,n} = [1:M_{2,n}]$

      $ADM_{EXT}(kk, (n-1) \times N_S \times 2\ +\ 2 \times (s-1)\ +\ 2) \leftarrow vM_{2,n}(k_{2,n})$

    end

   end

  end

end

$return\ ADM_{EXT}$

$return\ M_{EXT}$

Thereafter, from the selection of m_{choice}, a couple of values $RI_{L,n}$ and $RCAP_{U,n}$ are determined for each market session s of the generic agent n:

$$ADM_{EXT}(m_{choice};(n-1) \times N_s \times 2 + 2 \times (s-1) + 1) \rightarrow RI_{L,n}^s \qquad 4.27$$

$$ADM_{EXT}(m_{choice};(n-1) \times N_s \times 2 + 2 \times (s-1) + 2) \rightarrow RCAP_{U,n}^s \qquad 4.28$$

At this point the reported bid prices $(u_{R,n})$ and bid energies $(CAP_{R,U,n})$ of the generic agent n, for consecutive market sessions s and $s+1$, are computed as follow:

$$CAP_{R,U,n}(s) = RCAP_{U,n}^s \times (CAP_{U,n} - CAP_{L,n}) + CAP_{L,n} \qquad 4.29$$

$$if\ CAP_{U,n}(s) > (V_{RESERVOIR,n}(s) - V_{RES,MIN,techn,n}) \rightarrow CAP_{R,U,n}(s) = 0 \qquad 4.30$$

$$u_{R,n}(s) = \frac{C_{W,n}}{1 - RI_{L,n}^s} \qquad 4.31$$

$$V_{RESERVOIR,n}(s+1) = V_{RESERVOIR,n}(s) - CAP_{R,U}(s) + REFUEL_{,n}(s) \qquad 4.32$$

$$CAP_{R,U}(s+1) = RCAP_{U,n}^{s+1} \times (CAP_{U,n} - CAP_{L,n}) + CAP_{L,n} \qquad 4.33$$

$$if\ CAP_{U,n}(s+1) > (V_{RESERVOIR,n}(s+1) - V_{RES,MIN,techn,n}) \rightarrow CAP_{R,U,n}(s+1) = 0 \qquad 4.34$$

$$u_{R,n}(s+1) = \frac{C_{W,n}}{1 - RI_{L,n}^{s+1}} \qquad 4.35$$

$$V_{RESERVOIR,n}(s+2) = V_{RESERVOIR,n}(s+1) - CAP_{R,U,n}(s+1) + REFUEL_{,n}(s+1) \qquad 4.36$$

Figure 4.3 summarizes the algorithm execution for the general case in which the generic hydro agent n submits N_s consecutive bid offers in the generic market day D.
This feature allows the agent to control more in detail the short-term bid power strategy. The pay-off is the strong increase of the *ADM* dimension which is a critical concern for the algorithm functioning. This issue will be discussed in detail in section 6.1.
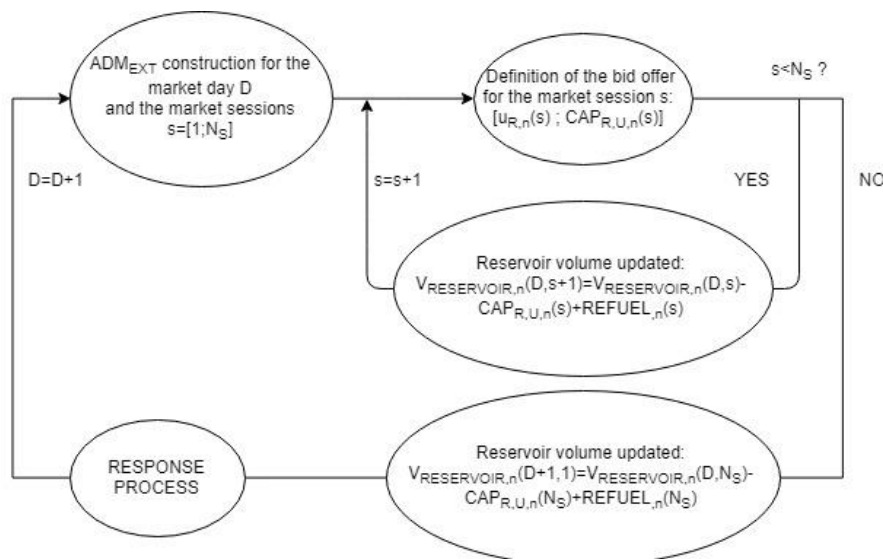
Figure 4.3-Flux diagram representation of the general bid process for hydro agent

4.1.4 Response Process

This process is the same for thermal and hydro generators and companies of generation. After the market closing, the agents receive the results of the dispatch and calculate the profit gained. The profit is used as basis for the calculation of the RESPONSE that updates the propensity set related to the option chosen m_{choice}.

AMES indicates to calculate the profit as the product between the market price and the energy sold (*PROFIT*: eq. 4.37), but this is not appropriate for the case of the Colombian market. In fact, with the submission of a unique price offer, it is necessary to make the agent sensible to both the result of the market and the merit of the submitted bid. So, as explained in detail in section 3.4.3, a different way to calculate the profit exposed in eq. 4.38, was created : *PROFIT$_{VAR}$*. Thereafter, according to the MRE RL algorithm described in section 2.6.2, the *RESPONSE* for each *m* option is calculated (eq. 4.39 and 4.40) and it is used to update the propensities for the following market day (eq. 4.41). The next equations summarize the entire process:

$$PROFIT = \sum_{s=1}^{N_S} [(Q_{MRK,s} * p_{MRK,s}) - TC(Q_{MRK,s})] \qquad 4.37$$

$$PROFIT_{VAR} = \sum_{s=1}^{N_S} \{(Q_{MRK,s} * p_{BID,s}) + [Q_{MRK,s} \times (p_{MRK,h} - p_{BID,s}) \times (\frac{p_{BID,s}}{p_{MRK,s}})] \qquad 4.38$$
$$- TC(Q_{MRK,s})\}$$

$$RESPONSE_m = PROFIT_{VAR}(D) \times (1 - e) \quad if\ m = m_{CHOICE} \qquad 4.39$$

$$RESPONSE_m = q_m(D) \times \frac{e}{M - 1} \qquad if\ m \neq m_{CHOICE} \qquad 4.40$$

$$q_m(D + 1) = (1 - r) \times q_m(D) + RESPONSE_m \quad \forall m \qquad 4.41$$

Where:

- $Q_{MRK,s}$ is the energy sold in the market session *s*;
- $p_{MRK,s}$ is the market price for the session *s;*
- $p_{BID,s}$ is the bid price for the market session *s;*
- $TC(Q_{MRK,s})$ is the total cost of production of the energy $Q_{MRK,s}$ sold in the market;
- *M* is the *ADM* dimension (eq. 4.6 – eq. 4.26 (M_{EXT} - ADM_{EXT})).

The updated propensities are then used in the stochastic process that leads to the choice of the bid for the next market day.

Only for the hydro agents, it is necessary to update the water availability because, in their bidding process, the reservoir volume was updated considering to sell all the energy bid in the market sessions. But, in case of some bid would not be accepted, the reservoir volume has to be corrected:

$$V_{RESERVOIR}(D+1) = V_{RESERVOIR}(D) - \sum_{s=1}^{N_s} CAP_{R,U,D}(s) - Q_{sold,D}(s) \qquad 4.42$$

Where:

- $CAP_{R,U,D}(s)$ is the bid energy reported in the market at the day D for the market session s;

- $Q_{sold,D}(s)$ is the energy sold in the market at the day D in the market session s.

This procedure describes the process that updates the propensities associated to the agent's bid options. For the case of a thermal agent, a single s market session would be considered because, as already mentioned, it submits independent bid offers; thus, the result related to m_{choice} corresponds to the profit gained only in that single market session. On the contrary, for the case of hydro agents which submit h_i multiple interconnected bid offer through m_{choice}, the procedure would add up the profit gained in the different h_i market sessions.

4.2 Company Agent

A realistic representation of the Colombian energy market cannot neglect the situation of Oligopoly that affect the market activities. As it was shown in the section 3.3.1 only three companies own the 60% of the capacity installed in the country and they account for almost the 70% of the yearly generation; this allow the companies to exert the power on the market.

The structure of AMES cannot reproduce the dynamics occurred in a situation of Oligopoly. In fact, the agents, representing the power plants, pursue the maximization of their profits in competition with all the other agents. Even if the market rules impose independent bid for single plants, this do not correspond to the actual situation. In reality, the companies arrange the bids of all the plants owned in order to collect the largest total possible profit, and not the largest profit for each single generator. This implies that these agents would not be in competition. So, it is required a new structure that could represent and manage the interest of a group of agents.

This point represents an innovation because all the platforms that recreate models of energy market, as AMES but not only, neglect the possible collaboration among the agents.

Differently, a realistic representation of the interaction occurring in the market operations cannot neglect this partnership. When the power share of these groups is not too significant, their influence can be neglected; contrarily, for the cases like the Colombian market in which subsists a strong and clear Oligopoly, it is necessary to consider the agents association to simulate realistically the market activities.

The only other work about the coordination between agents in an energy market is "Social Interaction of Cooperative Communication and Group Generation in Multi-Agent Reinforcement Learning Systems" [23]. Kun Zhang et al. set a sort of communication among the agents, reflected on the cooperative communication reinforcement learning algorithm (CC-RL). Changes in the agents' state or in the environment state, stimulate the generators to send an undefined signal; the receiving agents, through the CC-RL, learn to optimize their profit considering the reception of the signal. The authors proved that the involvement of this signal in the decision-making process establishes an implicit collusion that would help to increase the agents' profit.

However, even this feature is not suitable in our conditions because in case of Oligopoly the "collusion" is explicit and subsists an actual coordination of the agent bids.
To recreate these dynamics, a company-agents that manage several plants has been created. This company-agent follows the same procedure of the simple-agent, but it subscribes bids for all the power plants members of the company and account for the total of their profits. In this way, this new agent acts de facto as owner or manager of entities that previously were set as independents.

To reproduce the company-agent activities, the structure of AMES was adjusted starting from the Bidding Process which would determine the prices submitted from the different plants. To do that, with reference to the structure of the algorithm showed in the section 4.1.2, the three steps have been changed as follow:

Step a. The *ADM* is extended (*ADM$_{EXT}$*) and in this case, it is composed of all the groups of values related to the bids s of the N_A plants pertaining to the company; this implies that also all their consecutive bids would be included. So, for each generic agent n of the company c, the input data are: $M_{1,n}$, $M_{2,n}$, $RI_{MAX,L,n}$ and $RI_{MIN,c,n}$ for the submission of N$_S$ consecutives bids. The *ADM$_{EXT}$* is computed in the same way exposed in eq. 4.26, through the combination of each values of $vM_{1,n}^s$ and $vM_{2,n}^s$, related to each n agent for each s market session. Contrarily to the case of the hydro agent, the number of agents considered is $N_A > 1$.

The dimension M_{EXT} expresses the number of possible different combinations of bid price and bid energy, for the N_A plants controlled and the N_S consecutive bids that the company-agent can submit in the market.

Step b. According to the MRE RLA, the probability calculation remains the same. The execution of the stochastic process also does not change, and it provides as much values of $RI_{L,n}^s$ and $RCAP_{U,n}^s$ as consecutive bids through the selection of a unique the m_{choice}:

$$ADM_{EXT}(m_{choice}; (n-1) \times N_s \times 2 + 2 \times (s-1) + 1) \to RI_{L,n}^s \qquad 4.43$$

$$ADM_{EXT}(m_{choice}; (n-1) \times N_s \times 2 + 2 \times (s-1) + 2) \to RCAP_{U,n}^s \qquad 4.44$$

Step c. From the definition of these values it's possible to determine the bid prices and the bid energy reported in the *s* session market by each *n* agent with the same procedure of the simple-agent:

$$CAP_{R,U,n}^s = RCAP_{U,n}^s \times \left(CAP_{U,n} - CAP_{L,n}\right) + CAP_{L,n} \qquad 4.45$$

$$u_{R,n}^s = \frac{MC\left(CAP_{R,U,n}^s\right)}{1 - RI_{L,n}^s} \qquad if\ n: Thermal\ plant \qquad 4.46$$

$$u_{R,n}^s = \frac{C_{W,i}}{1 - RI_{L,n}^{+s}} \qquad if\ n: Hydro\ plant \qquad 4.47$$

For the company agents also, the hydro plants' bid energy is calculated depending on the results of the algorithm described in the section 4.1.3, that determines the available capacity relying on the water reserve.

The successive Response Process follows the same procedure described in the previous section 4.1.4, but the profit calculated for the company-agent *c* accounts for the earnings gained by all the plants *n* that belong to the group of generation:

$$PROFIT_{VAR,c} = \sum_{n=1}^{N_A} PROFIT_{VAR,n} \qquad 4.48$$

The procedure described in this section is able to submit bid price and bid energy for different agents who pertain to the same company and to elaborate the relative results. In theory there are no limits about the number of agents that can be managed by a single company-agent but, in practise, it is necessary to deal with the usual problem of the *ADM* dimension. Assuming that the agents submit in the market, their entire energy availability could be reasonable, so that the *ADM* dimension would be reduced because there are no options associated to the bid energy

4.3 Balancing market model
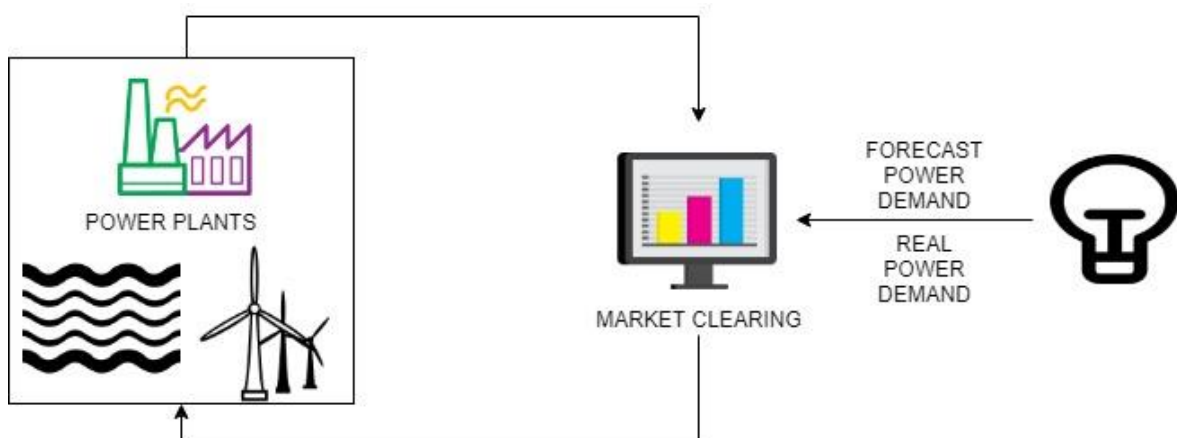
Figure 4.4- The day-ahead market and Balancing market environment representation

Everything that was described so far, represents the whole set of operation performed by the agents to participate to the day-ahead market. The same thing has to be executed also to participate to the balancing market sessions, because the agents submit bid and elaborate the relative output as before. But, it is necessary to adjust some point to make the platform coherent with the activities of balancing.

Thus, here below all the algorithm sequences are not reported as in the previous sections, but the modifications applied to them are highlighted and exposed:

- From *Figure 4.4* it can be observed how the platform receives, as input data, 2 sets of demand: the forecast demand for the day-ahead operation and the real demand for the balancing market operation. The difference between them, that can also be negative, defines the energy trades in the balancing market sessions;

- Bidding Process. The algorithm follows the same procedure[10], but it computes a bid offer for a single market session. However, it is necessary to assign a specific set of propensities to each market sessions. Thus, the entire module will be performed in the same way for each hour but, in the stochastic process, will be considered the proper set of propensity;

- Response Process. Consistently with the mentioned modifications, the response process will be also performed for each market session. By consequences, only the hourly profit will be calculated and it will update the related propensity set. In the same way also the reservoir volume will be properly updated.

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[10] For the hydro agents will be not consider the refuel already computed for each hour.

4.4 CASE STUDY: Algorithm improvement
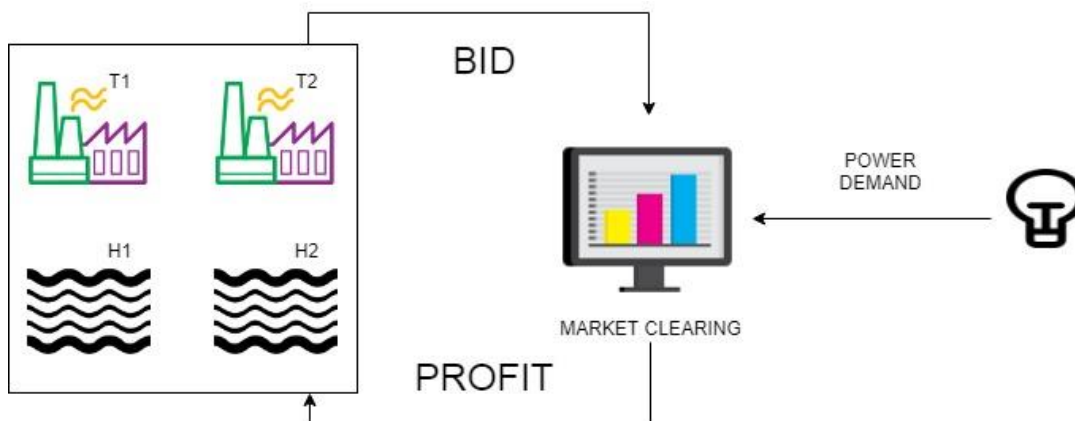
Figure 4.5- Case Study environment and information flows

With the intention to improve the algorithm and to make it suitable to the needs of the model, it was necessary to alter the AMES framework. To test the operation of each part of the algorithm, a simple Case Study was developed: 2 thermal generators and 2 hydro generators compete in a day-ahead market with 4 hours (market) sessions and a perfectly inelastic demand. The bidding rules of the Colombian day-ahead market have been applied: the agents submit a unique bid price for all the 24 hours; the market clearing is performed without considering technical or transmission constraint. So, considering the processes described in section 4.1, that steer the thermal and hydro agent activities, *Figure 4.5* depicts the outline of the market operations: bidding process for the generators agents, market clearing, profit calculation.

4.4.1 Data input and demand setting

Parameter	H1	H2	T1	T2
ID	1	2	3	4
AREA	1	2	1	2
TRADER	2	1	2	1
M_1	20	20	20	20
M_2	1	1	1	1
e – Experimentation Parameter	0.7	0.7	0.7	0.7
q_{in}- Initial Propensity	1000000	1000000	1000000	1000000
$RI_{MIN,c}$– Range index	0.75	0.75	0.75	0.75
CAP_U [MW] – Upper Production limits	1000	500	400	500
CAP_L [MW] – Lower Production limits	100	100	100	100
a [€/MWh]– Cost function parameter (thermal agents only)			44	40
b [€/MWh²] – Cost function parameter (thermal agents only)			0.02	0.04
FC [€] – Cost function parameter (thermal agents only)			0	0
C_W [€/MWh] - (hydro agents only)	20	50		
MC [€/MWh] – Marginal cost resulting from the cost function	20	50	60	80
REFUEL [MWh/h] - (hydro agents only)	1500	1000		

Table 4.2- Case Study data input
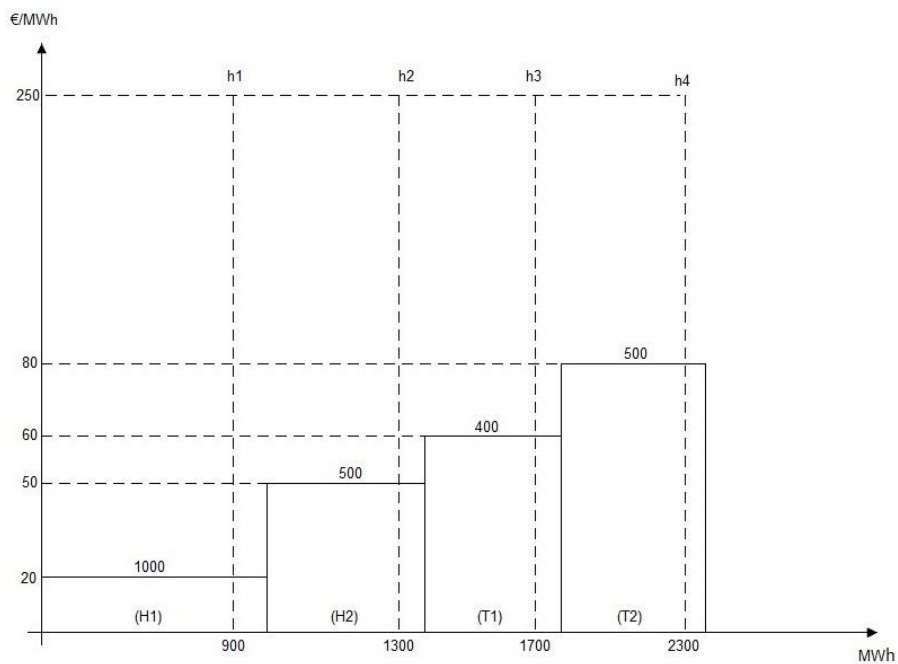
Figure 4.6- Case Study demand/offer

The simulation of this test case has the purpose to observe the behaviour of each agent, with respect to the demand and the market position of the other competitors. *Table 4.2* summarizes the parameters that design the agent profiles. *Figure 4.6* shows the cumulated offer curve considering the agents marginal cost with the power demand for the 4 hours (*h1*, *h2*, *h3*, *h4*). Considering the set of the 4 power charges, the following behaviours are expected for the agents:

- Agent *H1* should mark-up the bid price up to the *MC* of the agent *H2* to be sure to gain the maximum profit from the charge *h1*. In this way, the position of the cheapest generator is fully exploited.
- Analogously agent *T2* should mark-up the bid price up to the Price Cap set at 250 *€/MWh* and maximize the profit for the charge *h4*. In this case the agent exploits the position that is necessary to meet the demand;
- Because of the similar *MC*, the agents *H2* and *T1* compete (almost) exclusively between themselves for the power charges *h2* and *h3*.

Now, two critical aspects of the algorithm faced during the execution of the Case Study are illustrated: the numerical divergence and the reward calculation.

4.4.2 Numerical divergence

The firsts tests were performed executing the algorithm exactly as illustrated in the AMES framework. That includes the application of the VRE RLA described in section 2.6.3. This variation of the algorithm provides the use of the operator exponential to calculate the choices probability:

$$p_j(t) = \frac{e^{\frac{q_j(t)}{C}}}{\sum_{i=0}^{N-1} e^{\frac{q_j(t)}{C}}} \tag{2.14}$$

The exponential is a very sensible operator and, in many computing environments, it is easy to run into numerical problems because of very large numbers. For the case of Matlab the numerical upper limit is set around $1.7*10^{308}$; considering the operator exponential this limit is already exceeded with a rather low argument as shown in the following equation:

$$\left(\frac{q_j(t)}{c}\right)_{\text{MAX}} = \ln(1.7 * 10^{308}) < 710$$

This limit of the exponential represents a strong numerical constraint for the execution of the algorithm. Considering that *C* is defined as a constant and respecting the limits of *e* and *r* (section 2.6.1, eq. 2.2-2.4), the control of the propensity (*q)* growth becomes a very critical issue to prevent the numerical divergence.

Thus, running the Case Study market activities by testing different combination of *r-e-c* and following the structure of the VRE RLA, it always occurs a numerical interruption before the achievement of a correct solution. The main reason is the combined effect of the profit calculation in the Response Process with the accumulation of the propensities.

It would be possible to resolve this question, firstly, preserving the use of the VRE RLA because we agree the concerns, mentioned in section 1.6.3, about the possible problems when the reward assumes negative values. It is also reasonable to believe that the opportunity to control the proportions between the propensity and the probability, through the use of the Boltzmann cooling parameter, could turn the algorithm very effective.

Thus, the following solutions were tested:

1. Containment of the PROFIT through the change of the orders of magnitude:

$$(MWh \rightarrow GWh) \qquad\qquad (\text{€} \rightarrow k\text{€} \rightarrow M\text{€}) \qquad 4.49$$

   Alone, this measure does not solve the problem, so it was attempted to combine it with others. It could be observed that the calibration of the Boltzmann cooling parameter became more difficult with small numbers;

2. Containment of the *PROFIT* applying a scaling to its value by a fix factor k_p:

$$q_m(t+1) = (1-r) \times q_{m(t)} + RESPONSE_m \quad \forall m \qquad 4.50$$

$$RESPONSE_m = \frac{PROFIT_{VAR}\,(t)}{k_p} \times (1-e) \quad if\; m = m_{CHOICE} \qquad 4.51$$

   This measure permits to contain the growth of the propensities and to avoid the numerical deterioration. However, to guarantee this result, dealing with small numbers was an obligation; which, as it was already reported, complicates the control of the algorithm. This turns into an unsolvable question if it is combined with the presence of the static scaling k_p. In fact, their joined effect makes the update of the propensity values uncontrollable. Consequently, at the end, this path was abandoned.

3. Containment of the propensities applying a scaling before the calculation of the probabilities.

$$q_{NORM} = \frac{q}{k_q} \qquad\qquad 4.52$$

$$p_j(t) = \frac{e^{\frac{q_{NORM,j}(t)}{C}}}{\sum_{i=0}^{N-1} e^{\frac{q_{NORM,j}(t)}{C}}} \qquad\qquad 4.53$$

This measure as well does not solve the problem even by trying different solutions. It was observed that, by assigning to k_p a fix value, the proportion of the propensities in probability calculation is altered; this leads to a wrong execution of the stochastic process of decision-making. It was also considered the possibility to assign to k_p a variable value that would change with the propensities values (e.g. k_p=mean(q_j)) but this would bring a component of instability to the algorithm, so it was chosen to neglect this possibility for modelling reasons.

Considering all the results and the observation made with these different tests, the MRE RLA was chosen to be used in the developed model. The trade-off of this version of the algorithm is the increase of the converging time to a permanent position. On the other hand, the choice was fruitful with other advantages summarized in the following three points:

1. The absence of the operator exponential avoids any kind of numerical deterioration problem;

2. The calculation of the probabilities respects the proportion of the propensities associated to the different options;

3. The timing that the agent devotes to assume a permanent decision guarantees the correct exploration of the several different market solutions.

4.4.3 Reward calculation (PROFIT$_{STD}$ VS PROFIT$_{VAR}$)

In the AMES framework, it is suggested to calculate the reward as the profit gained in the market. Thus, according to the VRE RLA and the MRE RLA the reward that contributes to the response of the option chosen is computed as follows:

$$q_j(t+1) = (1-r) \times q_j(t) + RESPONSE_j \quad \forall j \qquad 4.54$$

$$RESPONSE_j = \pi_k(t) \times (1-e) \quad if\ j = k \qquad 4.55$$

$$\pi_k(t) = PROFIT_{STD} = p_{MRK}(t) \times Q_{MRK}(t) \qquad 4.56$$

Where:

- $p_{MRK}(t)$ is the market clearing price at time t;
- $Q_{MRK}(t)$ is the power gained in the market at time t.

We have already highlighted the rule of the Colombian market for which the participants submit a unique bid price for all the 24 market hours/sessions. This, as it was briefly illustrated in section 4.1.4, can affect the capability of the agents in recognizing the merit of their own choices for the result obtained in the market.

To better explain this point, the analysis focuses on the agent H1, and two different market outcomes were purposed to highlight the issue, "DAY A" and "DAY B":
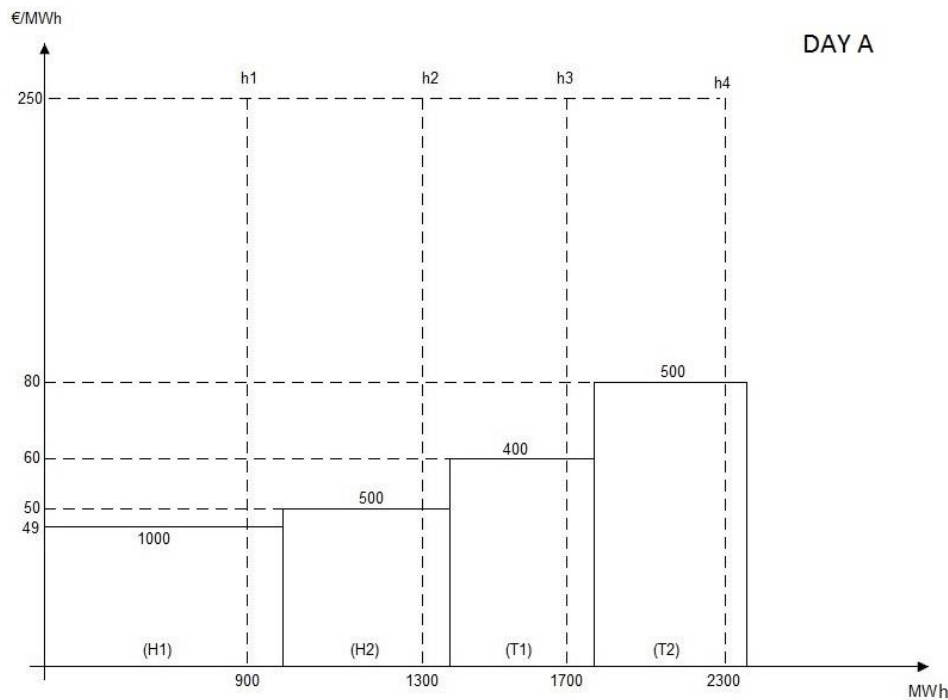
Figure 4.7-Market clearing DAY A

The "DAY A" market result showed in *Figure 4.7* depicts a situation in which the agent *H1* makes a very good choice in relation to the "limit" fixed by the *MC* of the agent *H2* at 50 €/MWh. On the contrary, the other agents make the worst choice with no mark-up of the bid price with respect to their *MC*s. With this market clearing the profit for the agent *H1* is calculated as follows:

$$PROFIT_{H1,DAY\ A,h1} = 900\ MWh \times (49-20)\frac{€}{MWh} = 26100\ € \qquad 4.57$$

$$PROFIT_{H1,DAY\ A,h2} = 1000\ MWh \times (50-20)\frac{€}{MWh} = 30000\ € \qquad 4.58$$

$$PROFIT_{H1,DAY\ A,h3} = 1000\ MWh \times (60-20)\frac{€}{MWh} = 40000\ € \qquad 4.59$$

$$PROFIT_{H1,DAY\ A,h4} = 1000\ MWh \times (80-20)\frac{€}{MWh} = 60000\ € \qquad 4.60$$

$$PROFIT_{H1,DAY\ A,TOT} = \sum_i PROFIT_{H1,DAY\ A,i} = 156100\ € \qquad 4.61$$

$$\frac{PROFIT_{H1,DAY\ A,h1}}{PROFIT_{H1,DAY\ A,TOT}} = 0.17 \qquad 4.62$$
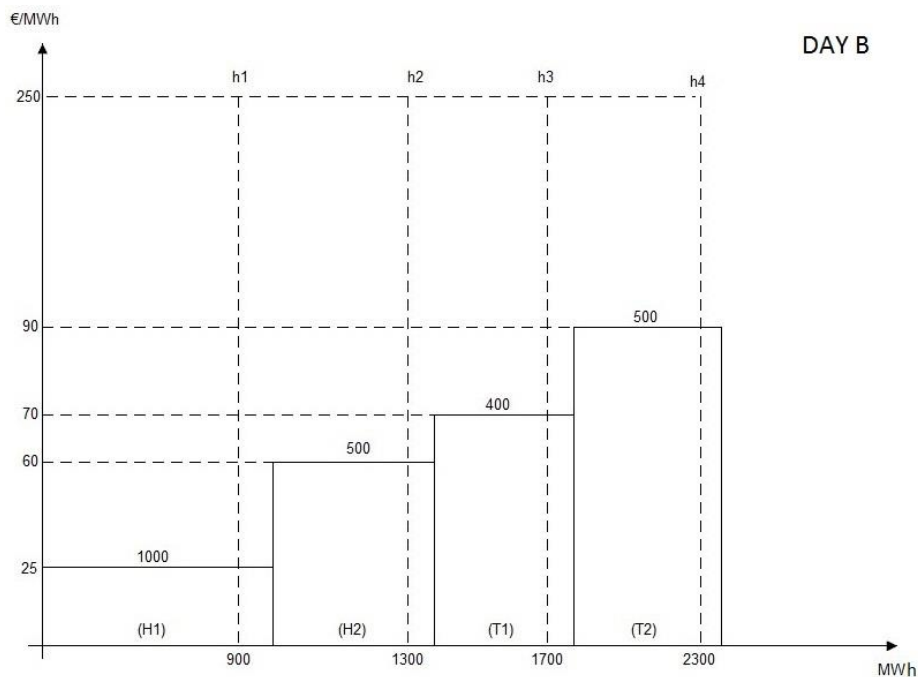
Figure 4.8-Market clearing DAY B

The "DAY B" market result, showed in *Figure 4.8*, depicts a situation in contrast with the previous one: here, the agents *H2*, *T1* and *T2* increase the bid prices over their *MC*, but quite far from the correspondent "limits"; on the other hand, the agent *H1* contains the mark-up with a bid price just over its *MC*. The resulting profit for the agent *H1* amounts to:

$$PROFIT_{H1,DAY\ B,h1} = 900\ MWh \times (25-20)\frac{€}{MWh} = 4500\ € \qquad 4.63$$

$$PROFIT_{H1,DAY\ B,h2} = 1000\ MWh \times (60-20)\frac{€}{MWh} = 40000\ € \qquad 4.64$$

$$PROFIT_{H1,DAY\ B,h3} = 1000\ MWh \times (70-20)\frac{€}{MWh} = 50000\ € \qquad 4.65$$

$$PROFIT_{H1,DAY\ B,h4} = 1000\ MWh \times (90-20)\frac{€}{MWh} = 70000\ € \qquad 4.66$$

$$PROFIT_{H1,DAY\ B,TOT} = \sum_i PROFIT_{H1,DAY\ A,i} = 164500\ € \qquad 4.67$$

$$\frac{PROFIT_{H1,DAY\ B,h1}}{PROFIT_{H1,DAY\ B,TOT}} = 0.03 \qquad 4.68$$

From the calculations of the profits it can be affirmed that the agent *H1* receives and, consequently, elaborates a stronger response from the outcome of the DAY B than from the DAY A. Although, the choice made by the agent for the DAY A is better, and almost the best, with respect to his position in the market. This is clearly due to the small weight that the profit gained in the hour *h1*, the only one in which the agent *H1* is price maker, has in respect to the total reward.

To solve this problem of sensibility with respect to the bid choice made by the agents, a modification to the reward calculation was implemented, as it was already showed in section 4.1.4:

$$\pi_k(t) = PROFIT_{VAR} = Q_{MRK} \times p_{BID} + Q_{MRK} \times (p_{MRK} - p_{BID}) \times \left(\frac{p_{BID}}{p_{MRK}}\right) - TC(Q_{MRK}) \qquad 4.69$$

where $TC(Q_{MRK})$ is the total cost of production of the energy Q_{MRK} sold in the market.

With this form of the profit, the reward constraint that imposes the function to be monotonically increasing, is attended. In fact, looking at the first derivative of the function with respect to the variable considered: the bid price, the condition is verified:

$$\frac{\partial(PROFIT_{VAR})}{\partial p_{BID}} = Q_{MRK} + Q_{MRK} - 2 \times Q_{MRK} \times \left(\frac{p_{BID}}{p_{MRK}}\right) = 2 \times Q_{MRK} \times \left(1 - \left(\frac{p_{BID}}{p_{MRK}}\right)\right) \qquad 4.70$$

$$\rightarrow \frac{\partial(PROFIT_{VAR})}{\partial p_{BID}} > 0 \qquad because \qquad p_{BID} \leq p_{MRK} \qquad 4.71$$

Looking at the form of the function $PROFIT_{VAR}$ it can be observed that the income is composed of two parts: the first contribution $(Q_{MRK} \times p_{BID})$ that remunerates depending on the bid price; the second contribution $(Q_{MRK} \times (p_{MRK} - p_{BID}) \times \left(\frac{p_{BID}}{p_{MRK}}\right))$ that remunerates the remaining difference between the bid price and the market price. It is clear that, without the fraction $\left(\frac{p_{BID}}{p_{MRK}}\right)$, $PROFIT$ and $PROFIT_{VAR}$ would be the same. The aim of this modification was to reproduce the human cognition that allows to discern the reward obtained by merit of the bid submitted, from the reward obtained because of the action/position of the other competitors. For this reason, the intensity of the second contribution was set decreasing with the gap between p_{BID} and p_{MRK}.

In the following table, the result of the profit re-calculation including this modification is summarized, and the variation of the result can be observed:

$$PROFIT_{VAR,H1,DAY\,A,h1} = 26100 \; € \qquad 4.72$$

$$PROFIT_{VAR,H1,DAY\,A,h2} = 29980 \; € \qquad 4.73$$

$$PROFIT_{H1,DAY\,A,h3} = 37983 \; € \qquad 4.74$$

$$PROFIT_{H1,DAY\,A,h4} = 47988 \; € \qquad 4.75$$

$$PROFIT_{H1,DAY\,A,TOT} = \sum_i PROFIT_{H1,DAY\,A,i} = 142051 \; € \qquad 4.76$$

$$\frac{PROFIT_{H1,DAY\,A,h1}}{PROFIT_{H1,DAY\,A,TOT}} = 0.18 \qquad 4.77$$

$$PROFIT_{VAR,H1,DAY\ B,h1} = 4500\ €$$

<div align="right">4.78</div>

$$PROFIT_{VAR,H1,DAY\ B,h2} = 19583\ €$$

<div align="right">4.79</div>

$$PROFIT_{H1,DAY\ B,h3} = 21071\ €$$

<div align="right">4.80</div>

$$PROFIT_{H1,DAY\ B,h4} = 23056\ €$$

<div align="right">4.81</div>

$$PROFIT_{H1,DAY\ A,TOT} = \sum_i PROFIT_{H1,DAY\ A,i} = 68210\ €$$

<div align="right">4.82</div>

$$\frac{PROFIT_{H1,DAY\ A,h1}}{PROFIT_{H1,DAY\ A,TOT}} = 0.07$$

<div align="right">4.83</div>

Analysing the results and comparing them with the previous ones, they can be considered as successful by making the agent sensible to both the result obtained because of its bid offers, and the effect of the other agents' position. Applying the calculation of the reward using $PROFIT_{VAR}$ the agent receives a stronger response for the choice made at DAY A, making it preferable with respect to the choice at DAY B.

To give an idea of the change of the effectiveness in the research of the best option, *Figure 4.9* provides the results of the permanent bid price of agent *H1* for the execution of the Case Study. The form of *PROFIT* was preserved firstly, then the modification of *PROFIT_{VAR}* was applied.

We easily notice the strong difference between the results of the two cases:

- when $PROFIT_{STD}$ is used agent H1 is not capable to recognize the best option for him, because its choice has a small weight with respect to the whole results (eq. 3.68). Its decision appears almost irrelevant and the consequence is a chaotic distribution of the permanent bid price;

- when $PROFIT_{VAR}$ is used, agent H1 recognizes the effects of its choice so it prefers to increase the mark-up, and this helps him increasing its profit.
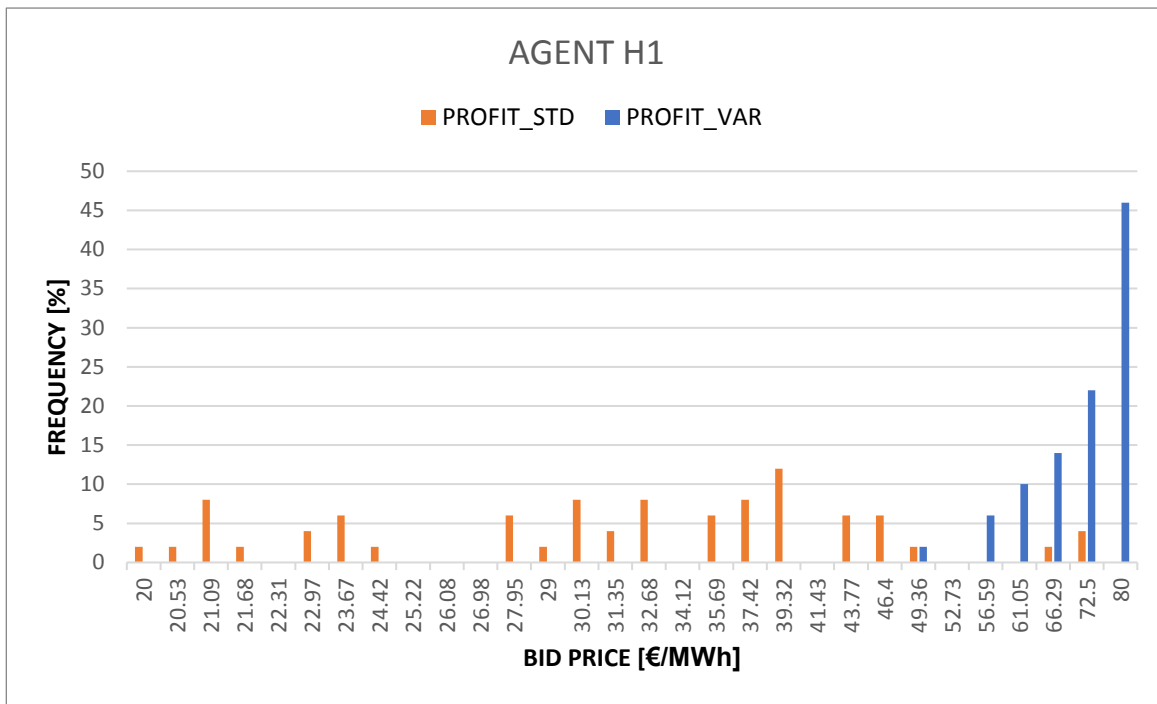
Figure 4.9-Comparison between the PROFIT CASE and the PROFIT$_{VAR}$ case

CHAPTER 5

Colombian day-ahead market model

In this chapter the model of the Colombian day-ahead market will be exploited to analyse the issues exposed in section 4.3: the effect of Oligopoly in the market and the consequences for the market of the ENSO event. The model is set in order to preserve the most significant characteristic of the market. To reproduce its operations, there are three important aspects that affect the reliability of the simulations: the generators profile, the demand data and the hydrology data.

To begin, the first section will describe these important data; then, will follow the analysis of the Oligopoly and its effects of the market price. After that the water supply will be reduced to simulate the shortage of the hydro plants typical of the ENSO period. To observe the effect of the participation in the market of NC RES, a certain capacity of wind farms will be aggregated to the energy mix. The market price tracking will show if this capacity can actually reduce the price volatility due to the deficits of the hydro plants.

5.1 Model input data

The most of the Colombian energy market data can be found on the XM web site. It provides all the hydro agents significant parameters and a complete statistics collection of the Country hydrology and energy demand. On the other side, as the thermal plants data is classified, it was necessary to encounter them manually on the related websites. In any case, it was possible to define the plants necessary to characterize all the influential market competitors.

5.1.1 Demand data
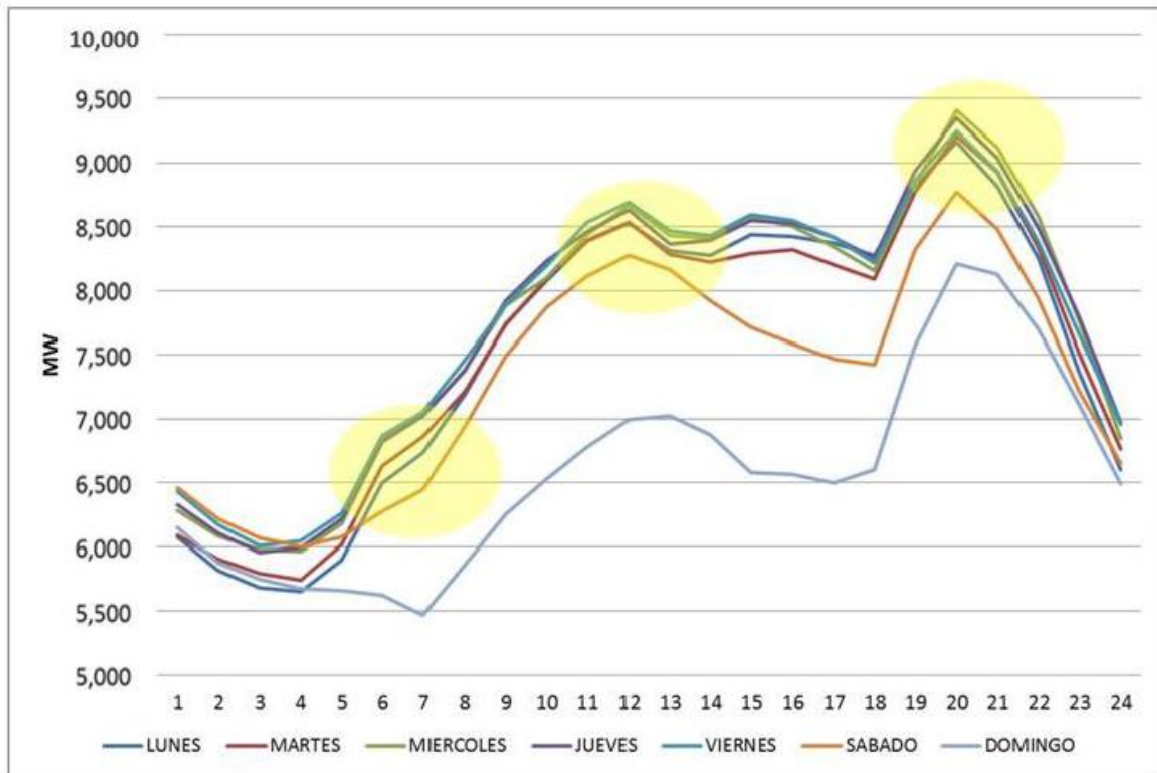
Figure 5.1-Historical average Colombian demand data

Colombia is located in the equatorial region so the demand has no seasonal changes because the day length is almost always the same. During the whole year the sun rises around 06:00 and it sets around 18:00. This articulates not only the rhythm of the human activities but also defines the hourly energy demand.

Figure 5.1 [24] shows the average of energy demand during the week. The first ramp, highlighted in the chart, starts around 06:00 and it culminates on the first peak of the lunch time, highlighted as well. The strongest peak of the day coincides with the dinner time, the moment in which everyone is back home and the sun light has already ran off.

It is interesting to evaluate the simulation results including both case of base and peak of energy demand. But, performing the execution for 24 hours would be complicated; and so would it be for the analysis of the outcome. Thus, 3 hours were selected from the demand curve in correspondence of the base load, ramp and peak load to represent the daily demand of a generic working day. *Table 5.1* summarizes the hours chosen.

HOURS	ENERGY DEMAND [MWh]
H1	6200
H2	7900
H2	9000

Table 5.1-Hourly energy demand for the Colombian model execution

5.1.2 Generator agent data

During the analysis of the Case Study the generators' data were already shown in section 4.4.1. In this case the categories remain the same but, to simplify the description, they are summarized in two groups: the "algorithm data" and "energy production" data. This division separates the data defined to calibrate the model operation and the information of the real Colombian power plant: production limits and marginal cost of production.

In *Table 5.2* the algorithm data are summarized. M_1 and the Range Index ($RI_{MIN,C}$) were chosen to provide to the generator the possibility to largely diversify the bid offer with a wide spectrum of bid prices. On the contrary M_2 was set equal to 1 in order to contain the *ADM* dimension so that it was assumed that the generator agents always submit in the market the whole available capacity. The MRE RLA parameters were calibrated to control the convergence speed and to allow enough exploration of the market combinations.

Figure 5.2-Bid price by fuel, market price and scarcity price

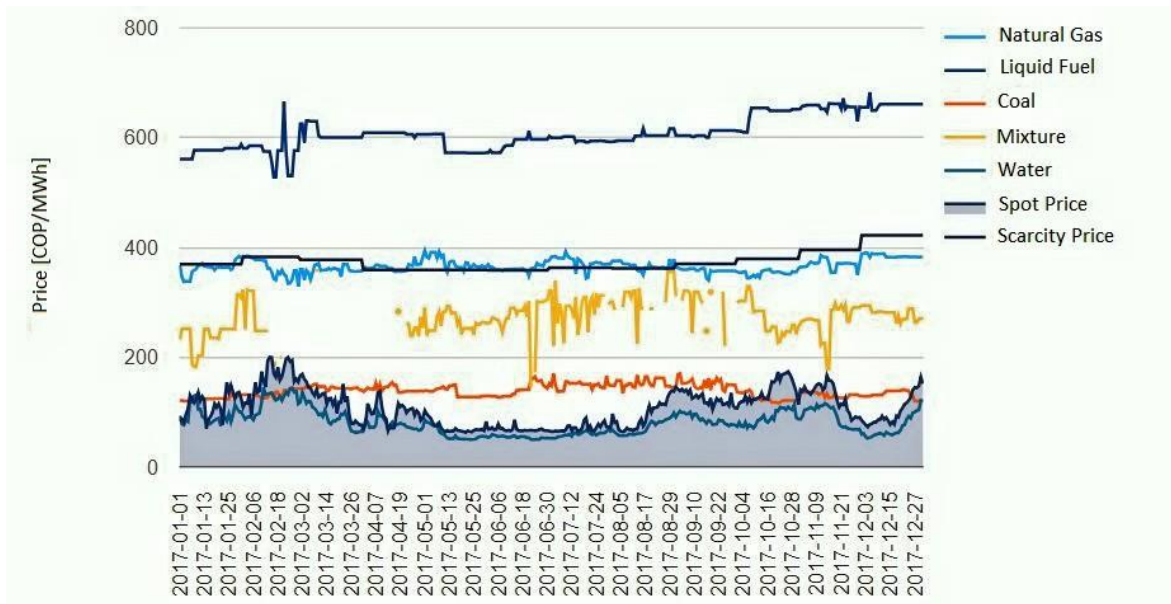| PLANT	COMPANY	M_1	M_2	r	e	q_{in}	$RI_{MIN,C}$
CHIVOR	AES CHIVOR & CIA. S.C.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
BETANIA	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
DARIO VALENCIA SAMPER	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
EL QUIMBO	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
GUAVIO	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
LA GUACA	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
PARAISO	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SALTO II 2	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
ALTO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
BAJO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
CALIMA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
CUCUANA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
PRADO	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SALVAJINA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
URRA	EMPRESA URRA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
ESMERALDA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
GUADALUPE 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
GUADALUPE 4	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
GUATAPE	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
LA TASAJERA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
PLAYAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
PORCE II	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
PORCE III	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SAN FRANCISCO	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
TRONERAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
CARLOS LLERAS	HIDROELECTRICA DEL ALTO PORCE S A S E S P	20	1	0,04	0,4	1000000	0,8
AMOYA LA ESPERANZA	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
JAGUAS	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
MIEL I	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SAN CARLOS	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SOGAMOSO	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,8
SAN MIGUEL	LA CASCADA S.A.S. E.S.P.	20	1	0,04	0,4	1000000	0,8
TERMOCENTRO	ISAGEN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOFLORES	ZONA FRANCA CELSIA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
MERILELECTRICA	ZONA FRANCA CELSIA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TEBSA1	TERMOBARRANQUILLA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TEBSA2	TERMOBARRANQUILLA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOGUAJIRA	GENERADORA Y COMERCIALIZADORA DE ENERGIA DEL CARIBE S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
GECELCA3	GENERADORA Y COMERCIALIZADORA DE ENERGIA DEL CARIBE S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOPAIPA	GESTION ENERGETICA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOTASAJERO	TERMOTASAJERO S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOCARTAGENA	EMGESA S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
TERMOSIERRA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	20	1	0,04	0,4	1000000	0,75
ZIPA	ENDESA CHILE	20	1	0,04	0,4	1000000	0,75
TERMOVALLE	TERMOVALLE S.A.	20	1	0,04	0,4	1000000	0,75
TERMOEMCALI	CONTOURGLOBAL LATAM	20	1	0,04	0,4	1000000	0,75
TERMOCANDELARIA	TERMOCANDELARIA SCA ESP.	20	1	0,04	0,4	1000000	0,75

Table 5.2-Algorithm data for generator agents

In *Table 5.3* the "energy production" data are summarized. The upper production limits (CAP_U) correspond to the actual power capacity of the power plants whereas the lower production limits (CAP_L) are considered being the 10% of the CAP_U. In the Case Study, the quadratic cost function coefficients (a, b, FC) were used to calculate the thermal agents' *MC* and then the bid price. They could be estimated for the power plants of the Colombian market but this would bring inevitable miscalculation that alters the agents' market positions. Thus, instead of estimating the cost function, it was better to refer to the data provided by XM, shown in *Figure 5.2*, where it is the bid prices by kind of plant that is summarized. The plants' *MC* is directly considered as an input referring to this chart instead of using the cost function form. It practically serves as minimum bid prices so it is sufficient to assign to the *MC* a reasonable value in order to define a realistic spectrum of bid price for each generator agent.

PLANT	COMPANY	TYPE (kind-fuel)	CAP$_L$ [MW]	CAP$_U$ [MW]	MC [€/MWh]
CHIVOR	AES CHIVOR & CIA. S.C.A. E.S.P.	Hydro (dammed)	100	1000	15
BETANIA	EMGESA S.A. E.S.P.	Hydro (dammed)	54	540	15
DARIO VALENCIA SAMPER	EMGESA S.A. E.S.P.	Hydro (run-on-river)	15	150	15
EL QUIMBO	EMGESA S.A. E.S.P.	Hydro (dammed)	39,6	396	15
GUAVIO	EMGESA S.A. E.S.P.	Hydro (dammed)	125	1250	15
LA GUACA	EMGESA S.A. E.S.P.	Hydro (run-on-river)	32,4	324	15
PARAISO	EMGESA S.A. E.S.P.	Hydro (run-on-river)	27,6	276	15
SALTO II 2	EMGESA S.A. E.S.P.	Hydro (run-on-river)	3,5	35	15
ALTO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (dammed)	35,5	355	15
BAJO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (dammed)	7,4	74	15
CALIMA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (dammed)	13,2	132	15
CUCUANA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (run-on-river)	5,8	58	15
PRADO	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (dammed)	5,1	51	15
SALVAJINA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	Hydro (dammed)	28,5	285	15
URRA	EMPRESA URRA S.A. E.S.P.	Hydro (dammed)	33,8	338	15

ESMERALDA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	3	30	15
GUADALUPE 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	27	270	15
GUADALUPE 4	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	22,5	225	15
GUATAPE	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	56	560	15
LA TASAJERA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	30,6	306	15
PLAYAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	20,7	207	15
PORCE II	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	40,5	405	15
PORCE III	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	73	730	15
SAN FRANCISCO	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	13,5	135	15
TRONERAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Hydro (dammed)	4,2	42	15
CARLOS LLERAS	HIDROELECTRICA DEL ALTO PORCE S A S E S P	Hydro (run-on-river)	7,8	78	15
AMOYA LA ESPERANZA	ISAGEN S.A. E.S.P.	Hydro (run-on-river)	8	80	15
JAGUAS	ISAGEN S.A. E.S.P.	Hydro (dammed)	17	170	15
MIEL I	ISAGEN S.A. E.S.P.	Hydro (dammed)	39,6	396	15
SAN CARLOS	ISAGEN S.A. E.S.P.	Hydro (dammed)	124	1240	15
SOGAMOSO	ISAGEN S.A. E.S.P.	Hydro (dammed)	81,9	819	15
SAN MIGUEL	LA CASCADA S.A.S. E.S.P.	Hydro (run-on-river)	4,4	44	15
TERMOCENTRO	ISAGEN S.A. E.S.P.	Thermal (natural gas)	30	300	110
TERMOFLORES	ZONA FRANCA CELSIA S.A. E.S.P.	Thermal (natural gas)	61	610	110
MERILELECTRICA	ZONA FRANCA CELSIA S.A. E.S.P.	Thermal (natural gas)	16,7	167	110
TEBSA1	TERMOBARRANQUILLA S.A. E.S.P.	Thermal (natural gas)	80,1	801	110
TEBSA2	TERMOBARRANQUILLA S.A. E.S.P.	Thermal (natural gas)	11,7	117	110
TERMOGUAJIRA	GENERADORA Y COMERCIALIZADORA DE ENERGIA DEL CARIBE S.A. E.S.P.	Thermal (coal)	28,6	286	30

GECELCA3	GENERADORA Y COMERCIALIZADORA DE ENERGIA DEL CARIBE S.A. E.S.P.	Thermal (coal)	16,4	164	30
TERMOPAIPA	GESTION ENERGETICA S.A. E.S.P.	Thermal (coal)	17,3	173	30
TERMOTASAJERO	TERMOTASAJERO S.A. E.S.P.	Thermal (coal)	15,5	155	30
TERMOCARTAGENA	EMGESA S.A. E.S.P.	Thermal (oil)	20,8	208	70
TERMOSIERRA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	Thermal (coal)	46	460	110
ZIPA	ENDESA CHILE	Thermal (coal)	22,3	223	30
TERMOVALLE	TERMOVALLE S.A.	Thermal (natural gas)	21	210	110
TERMOEMCALI	CONTOURGLOBAL LATAM	Thermal (natural gas)	24,2	242	110
TERMOCANDELARIA	TERMOCANDELARIA SCA ESP.	Thermal (natural gas)	31,4	314	110

Table 5.3– Energy production agents data
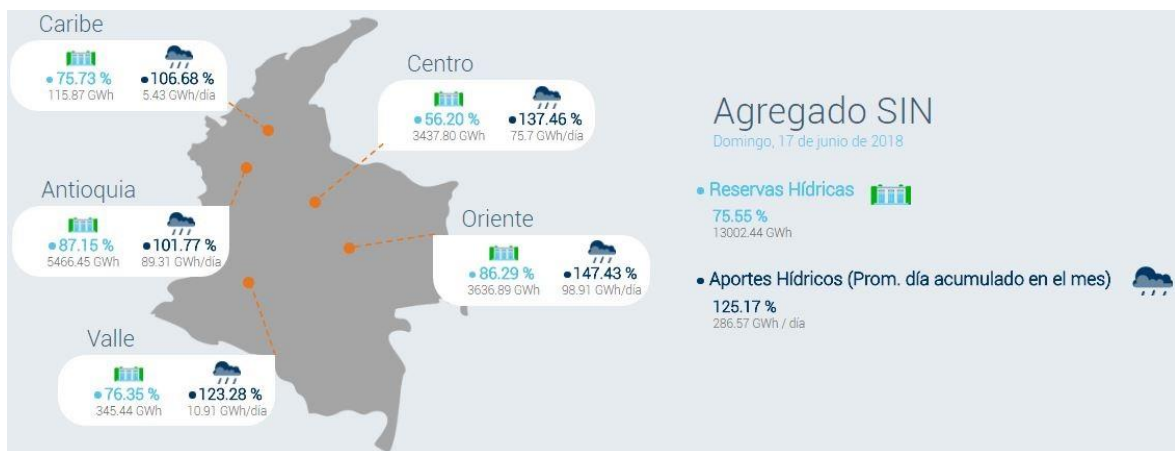
5.1.3 Hydrology

Figure 5.3-Colombian hydrology

The hydrology data of the hydro plants is very significant for the operation of the model. It refers to the reservoir dimension and the water supply received by the plants. XM provides the historical data of water supply by region, as shown in *Figure 5.3*, and the data of the maximum technical reservoir volume for the dammed hydro power plant [25]. On the other side, there are no data about the plants water supply and $V_{MIN,techn}$, so it was necessary to make an estimation of them. Because the regional water supply data are provided in form of energy, the estimated values were calculated depending on the capacity of the plant. The following equations summarize this process:

$$REFUEL_p = \frac{RWS}{24} \times \frac{CAP_{U,p}}{\sum_{REGION} CAP_{U,p}} \qquad 5.1$$

where:

- $REFUEL_p$ is the hourly water refuel for the power plant p [MWh/h];
- RWS is the average Regional Water Supply calculated by the XM data [MWh/day];
- $CAP_{U,p}$ is the upper production limit for the power plant p [MW].

For what concerns the $V_{MIN,techn}$, a symbolic value of 100 MWh was chosen for every hydro plant. All the hydrology data are summarized in *Table 5.4*.

PLANT	COMPANY	REGION	REFUEL [MWh/day]	$V_{RES,MIN,techn}$ [MWh]	$V_{RES,MAX,techn}$[11] [MWh]
CHIVOR	AES CHIVOR & CIA. S.C.A. E.S.P.	ORIENTE	14127,04	100	1171260
BETANIA	EMGESA S.A. E.S.P.	CENTRO	9301,91	100	198370
DARIO VALENCIA SAMPER	EMGESA S.A. E.S.P.	CENTRO	2583,86	100	1961608
EL QUIMBO	EMGESA S.A. E.S.P.	CENTRO	6821,40	100	1302410
GUAVIO	EMGESA S.A. E.S.P.	CENTRO	5581,15	100	2143600
LA GUACA	EMGESA S.A. E.S.P.	CENTRO	4754,31	100	42320
PARAISO	EMGESA S.A. E.S.P.	CENTRO	602,90	100	42320
SALTO II 2	EMGESA S.A. E.S.P.	ORIENTE	17658,80	100	267460
ALTO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	CENTRO	878,51	100	144934
BAJO ANCHICAYA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	VALLE	3668,46	100	101420
CALIMA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	VALLE	764,69	100	215830
CUCUANA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	VALLE	1364,05	100	197030
PRADO	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	VALLE	599,35	100	1668090
SALVAJINA	EMPRESA DE ENERGIA DEL PACIFICO S.A. E.S.P.	VALLE	2945,11	100	378540
URRA	EMPRESA URRA S.A. E.S.P.	CARIBE	3800,83	100	4242900
ESMERALDA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	459,49	100	249220
GUADALUPE 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	4135,43	100	194911
GUADALUPE 4	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	3446,19	100	4559200

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[11] $V_{RESERVOIR}(D = 0) = V_{RES,MAX,techn}$

GUATAPE	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	8577,19	100	270510
LA TASAJERA	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	4686,82	100	85820
PLAYAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	3170,50	100	1209650
PORCE II	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	6203,15	100	109950
PORCE III	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	11180,99	100	1171260
SAN FRANCISCO	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	2067,72	100	198370
TRONERAS	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ANTIOQUIA	643,29	100	1961608
CARLOS LLERAS	HIDROELECTRICA DEL ALTO PORCE S A S E S P	ANTIOQUIA	1194,68	100	1302410
AMOYA LA ESPERANZA	ISAGEN S.A. E.S.P.	ANTIOQUIA	2603,79	100	2143600
JAGUAS	ISAGEN S.A. E.S.P.	ANTIOQUIA	6065,30	100	42320
MIEL I	ISAGEN S.A. E.S.P.	ANTIOQUIA	18992,36	100	42320
SAN CARLOS	ISAGEN S.A. E.S.P.	CENTRO	1378,06	100	267460
SOGAMOSO	ISAGEN S.A. E.S.P.	CENTRO	14107,90	100	144934
SAN MIGUEL	LA CASCADA S.A.S. E.S.P.	ANTIOQUIA	673,92	100	101420

Table 5.4- Hydro power plant hydrology data

The values highlighted on red underline the run-on-river power plants. Because of the complexity to design their operation respecting the AMES framework, it was decided to suppose an artificial value that represents the $V_{MAX,techn}$. In this way, it was possible to preserve the algorithm structure and to include these hydro plants in the model of the energy mix. The values were calculated as follow:

$$V_{MAX,techn,r} = mean\left(\frac{V_{MAX,techn,DAMS}}{CAP_{U,DAMS}}\right) \times CAP_{U,r} \qquad 5.2$$

where:

- $V_{MAX,techn,r}$ is the estimated maximum reservoir volume for the run-on-river hydro plant r [MWh];
- $V_{MAX,techn,DAMS}$ is the known maximum reservoir volume for the dammed hydro plant [MWh];
- $CAP_{U,r}$ is the upper production limit for the run-on-river power plant r [MW];
- $CAP_{U,DAMS}$ is the upper production limit for the dammed power plant [MW].

5.1.4 Company agent data

The problem of the *ADM* dimension was already mentioned previously, and the section 6.3 will describe it more in detail. Because of this concern, though, it was necessary to aggregate some plants in a unique generator agent to execute the model simulation with the company agent. Otherwise, each plant would be related to a vector of values (*vM*) and the dimension *M* of the *ADM* would be too large to exploit the algorithm correctly. For this reason, the number of agent managed by each company is limited to 4.

The "energy production" data and the hydrology data for the aggregated agents correspond to the simple summation of the involved amounts.

The resulted portfolio of the oligopolistic company is summarized in *Table 5.5* together with the related "algorithm data".

COMPANY	PLANTS	M	r	e	q_{in}
EMGESA S.A. E.S.P.	BETANIA	160000	0.04	0.4	1000000
	DARIO VALENCIA SAMPER + SALTO II + LA GUACA + PARAISO				
	EL QUIMBO				
	GUAVIO				
EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	ESMERALDA + LA TASAJERA + SAN FRANCISCO	160000	0.04	0.4	1000000
	GUADALUPE 3 + GUADALUPE 4 + TRONERAS				
	GUATAPE + PLAYAS				
	PORCE II + PORCE III				
ISAGEN S.A. E.S.P.	AMOYA LA ESPERANZA + JAGUAS	160000	0.04	0.4	1000000
	MIEL I				
	SAN CARLOS				
	SOGAMOSO				

Table 5.5 – Companies' portfolio and algorithm data

5.2 Oligopoly analysis

This section studies the effect of the Oligopoly in the market. To realize that, 2 scenarios are set: in the first, the Competition Scenario, the generators act autonomously in the market and they pursue the maximization of their profit; in the second, the Oligopoly Scenario, the company agents arrange the bid of their plants to maximize the company profit, as exposed in section 4.2. In this second scenario the agents that do not belong to the oligopolistic companies are set as price taker, so their bid is blocked at the marginal cost of production. In this way these agents minimize their bid price trying to enter the market. On the opposite, the company agent plants are set as price maker because they are essential to meet the energy demand. Yet, they are free to mark-up the bid price over their marginal costs. In both cases

the thermal agents never enter the market because the hydro plants' power share is large enough to allow to cover the energy demand.

5.2.1 Competition Scenario

In this scenario, a situation near to the perfect competition should subsist because a high number of small competitors, with respect to the demand and the aggregate offer, shares the market. Thus, the market prices would tend to the *MC* of the cheapest producers.

The market price frequency for the three hours are shown in *Figures 5.4*. As expected, the market price for H1 holds on the hydro agents' *MC*; for the following market sessions H1 and H2, the market price lightly grows. The statistical data for the execution of the Competition Scenario are summarized in *Table 4.6*.
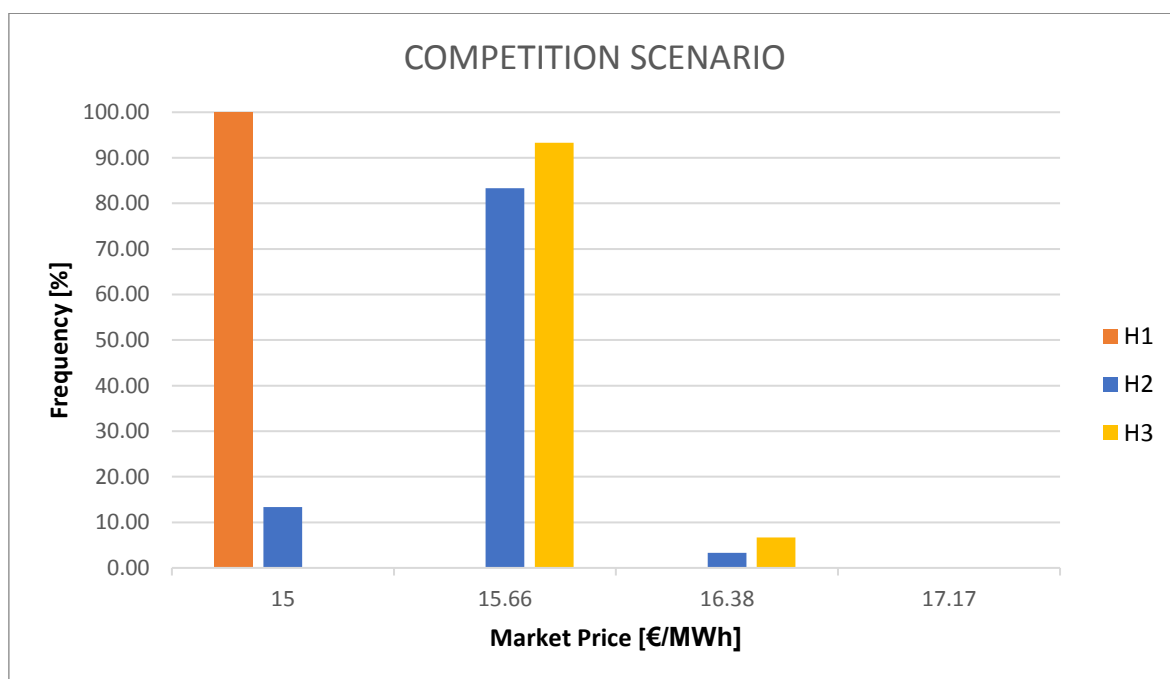

Figure 5.4-Frequency of market prices for the Competition Scenario

COMPETITION SCENARIO			
HOUR	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]
H1	15,00	15,00	15,00
H2	15,66	15,66	15,66
H3	15,66	15,66	15,66

Table 5.6- Statistical data of the market prices for the Competition Scenario

5.2.2 Oligopoly Scenario

In this Scenario, if the Oligopoly conditions were verified, the market prices would increase with respect to the Competition Scenario because the Company can exert their power on the market and mark-up the prices. To do so, the companies have a large share of the whole offer and their participation in the market is essential to meet the demand. The resulted market prices frequencies, shown in *Figure 5.5*, and the related statistical data in *Table 5.7* confirm the previsions.
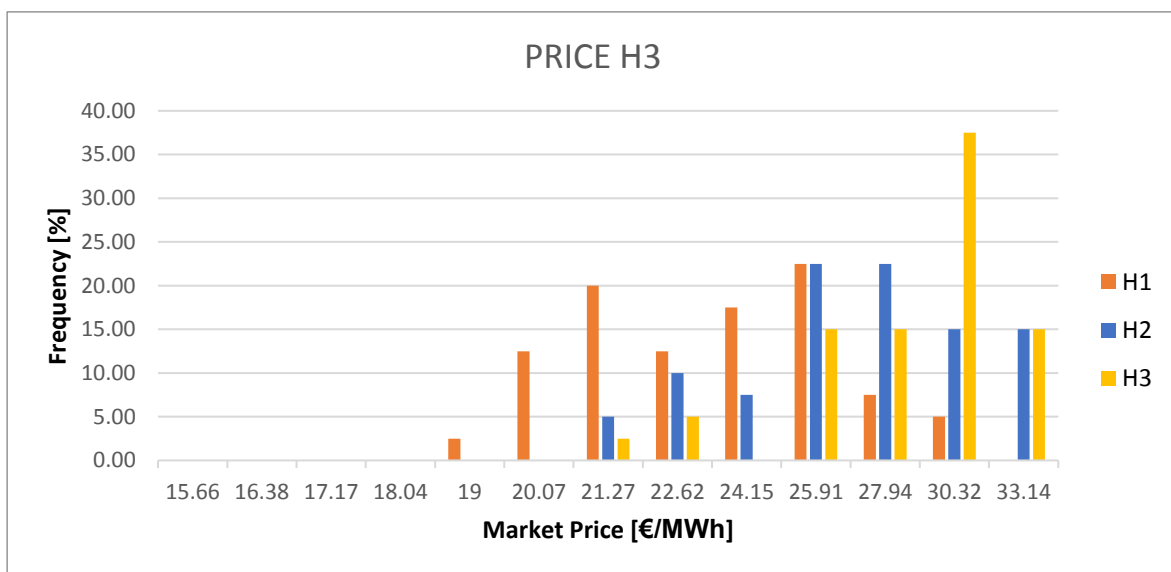

Figure 5.5-Frequency of market prices for the Oligopoly Scenario

OLIGOPOLY SCENARIO			
HOUR	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]
H1	25,91	24,15	23,73
H2	27,94	27,94	27,69
H3	30,32	30,32	29,74

Table 5.7- Statistical data of the market prices for the Competition Scenario

5.2.3 Analysis of the Scenarios' results

The previsions about the possibility to exert the market power were confirmed: the oligopolistic companies increase the prices over the outcome provided by the (almost) perfect competition in the first scenario. In the next *Figures 5.6–5.7–5.8* the differences between the correspondent market prices in the 2 scenarios are highlighted. The mark-up increases with the energy demand because the higher the demand, the higher the freedom to exert the market power is. *Table 5.8* summarizes the gap of the two Scenario's statistical data: all the parameters show the growth of the market prices.
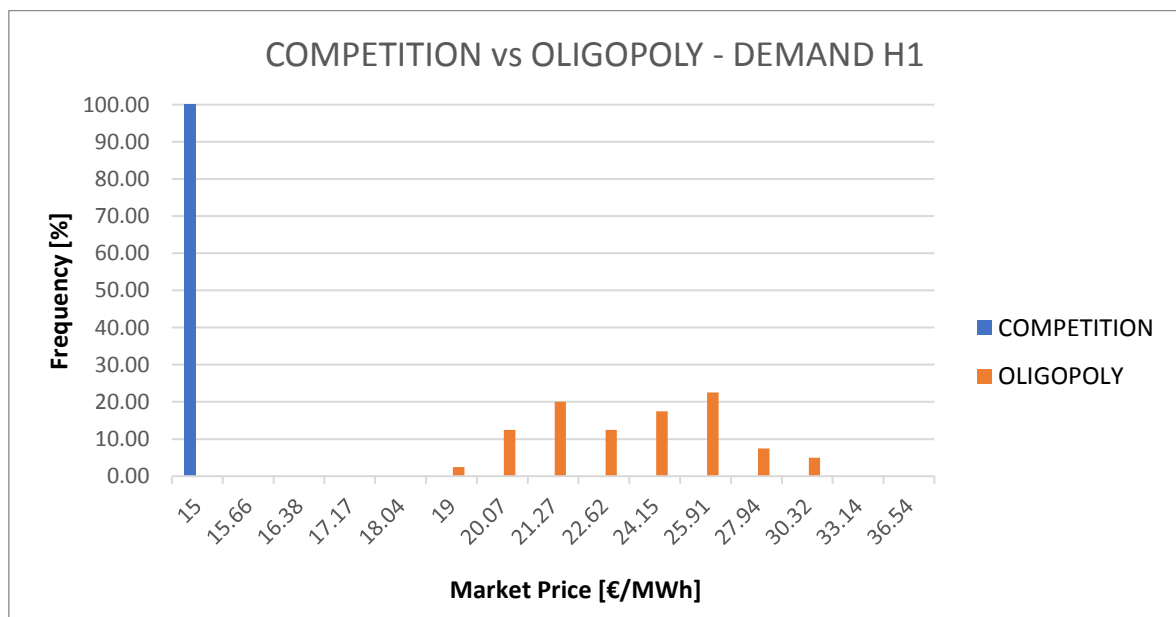

Figure 5.6-Compearison of the price for H1 between the Competition Scenario and the Oligopoly Scenario
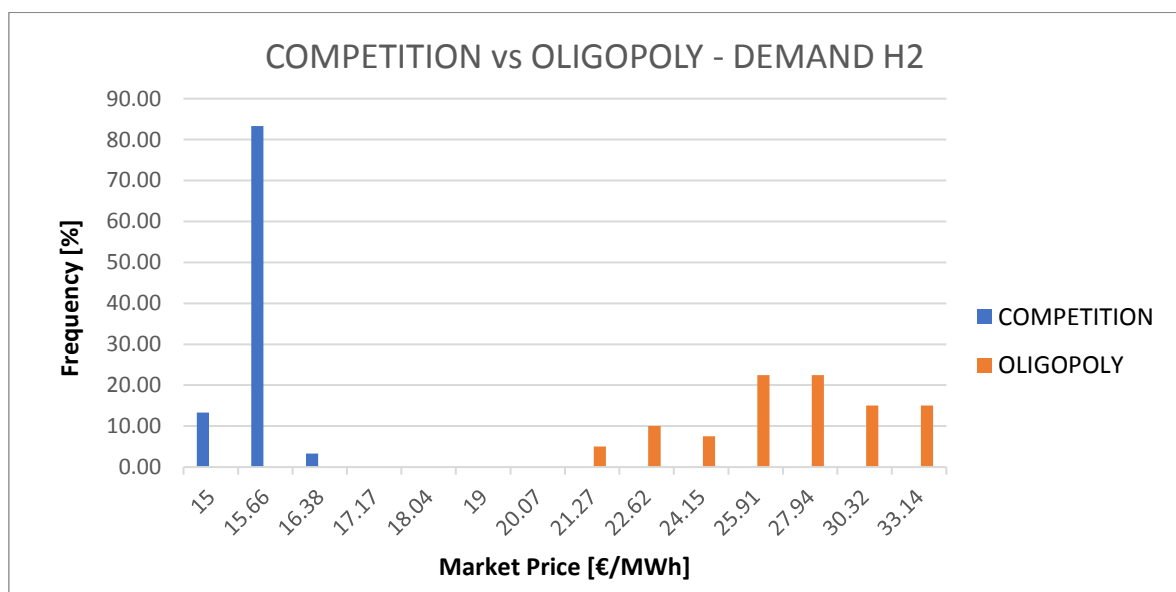

Figure 5.7-Compearison of the price for H2 between the Competition Scenario and the Oligopoly Scenario
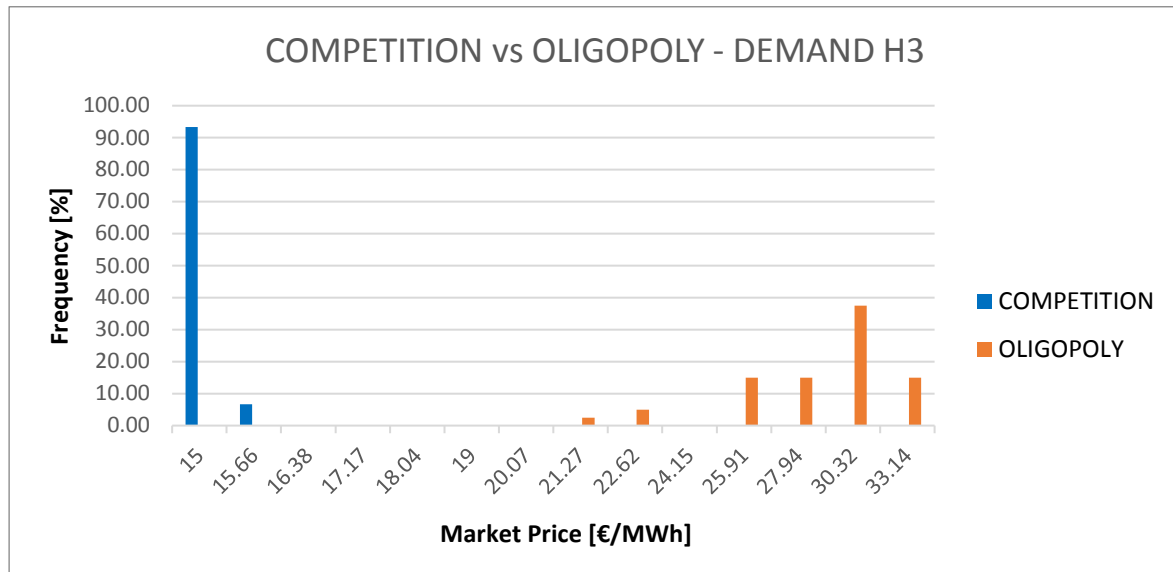
Figure 5.8-Compearison of the price for H3 between the Competition Scenario and the Oligopoly Scenario

	DEVIATION COMPETITION-OLIGOPOLY [%]		
HOUR	TREND	MEDIAN	AVARAGE
H1	72,73	61,00	58,22
H2	78,42	78,42	76,79
H3	93,61	93,61	89,88

Table 5.8-Percentage deviation between the result of the Competition Scenario and the Oligopoly Scenario

It is interesting to compare the outcome of the 2 scenarios with the Colombian market prices of 2017 shown in *Figure 5.2*: the market price holds around (and over) the 100 COP/kWh; considering the current value change ($1€ \cong 3300\ COP$), the converted market price value corresponds to almost 30 €/MWh. These values approach the outcome of the Oligopoly Scenario so that to confirm that the oligopolistic companies actually exercise their power on the market and raise the market prices.

Both *Figure 5.7* and *Figure 5.8* show the change in the price distribution from the Competition Scenario to the Oligopoly Scenario. In the first one, the condition of (almost) perfect competition pushes the prices down to the hydro plants' marginal cost. This results in the concentration of the prices' frequency around 15 €/MWh. In the second one, the price making, performed by the competition among the oligopolistic companies, provides many possible equilibrium conditions so that to determine a more chaotic distribution of the price's frequency.

5.3 Water supply shortage analysis and integration of NC RES

Figure 5.9-Location of the approved wind farm projects

During the period of ENSO, the hydro plants water supply strongly decreases for the effect of the rainfall reduction, as discussed in section 3.3.2. This decrease can achieve also values of 40% - 50%. To solve this problem Colombia decided to develop NC RES to sustain the energy production during this period. The construction of wind farm was identified as the best alternative because of the strong potential in the North of the Country and the perfect coupling with respect to the climatic condition during the ENSO period.

In the generation-transmission Expansion Plan 2016-2030 [17] the UPME (Mine-Energy Planning Unit) declares that it received demand for the installation of 3131 MW of wind capacity. It also evaluates positively the realization of three projects of 549 MW, 500 MW and 402 MW, respectively for Jemeiwaa Ka'i, Empresa Publica de Medellin and ENEL[12], because they have been retained advantageous for the final consumers in term of emission and market price. The three companies have already identified the location of their first wind farms in the northern region of "La Guajira", shown in *Figure 5.9*.

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[12] Empresa Publica de Medellin and ENEL, which is the owner of EMGESA, are two of the three oligopolistic companies.
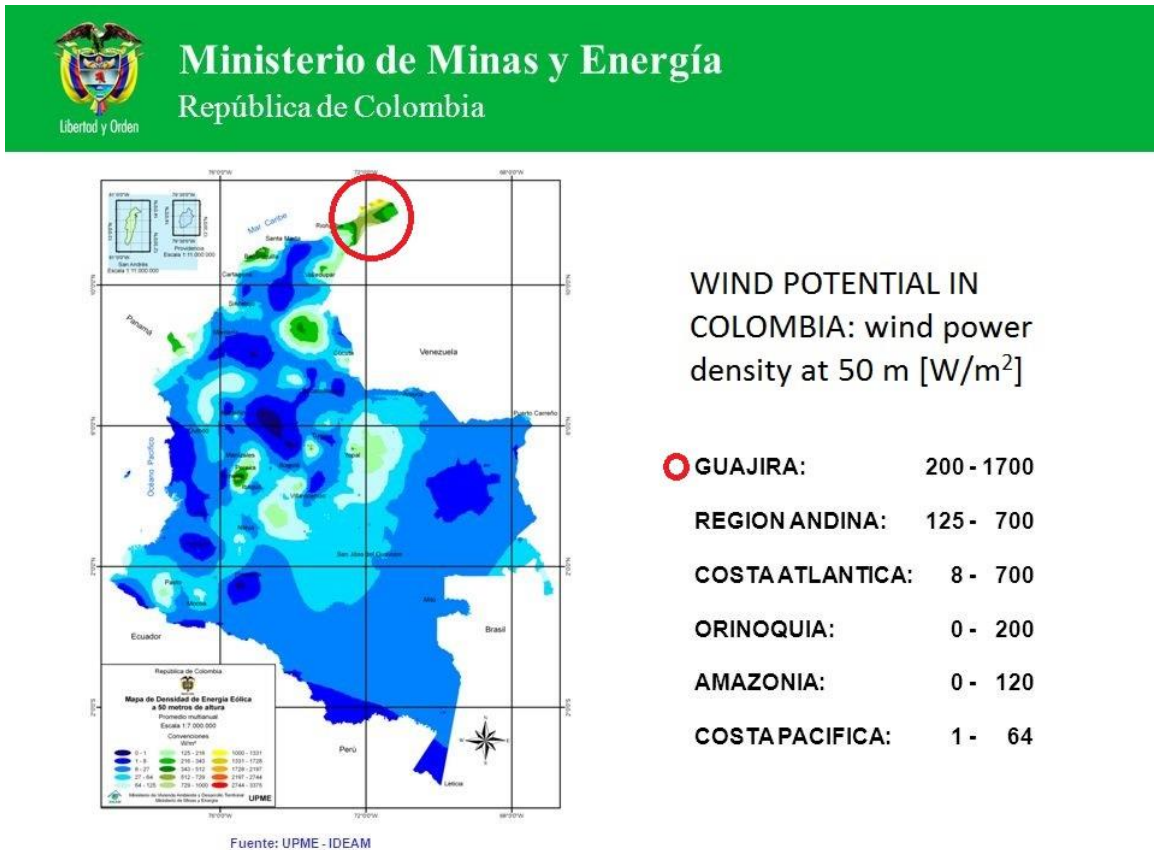
Figure 5.10-Regional wind power density in Colombia

This location was chosen because the study of the wind potential indicates this region as one of the windiest of the world. *Figure 5.10* shows the wind potential within the Country; it is possible to notice the very strong potential of the selected location.

These reasons convinced to analyse the possible impact on the energy market of the installation of the wind farm capacity during the period of ENSO through the model execution. To simulate the situation of water shortage it is necessary to alter the hydrology values: the REFUEL and $V_{RES}(D = 0)$, showed in *Table 5.4,* will be reduced respectively of 40% and 50% in order to reproduce the effect of the rainfall decrease.

The same Competition Scenario and Oligopoly Scenario are considered but other generator agents will be added to the energy mix: the wind farms. Referring to the installation project previously mentioned, it was decided to consider the capacity of these three farms and to evaluate if that capacity could actually reduce the effect of water shortage. As regards the wind power density of the project location, a capacity factor *CF* of 0.35 was assumed for all the wind farms.

The impact of the wind farm capacity will be observed through the analysis of the bid prices trend. The water shortage should allow the thermal agents to enter the market; their strategical bids would push the prices near to the Scarcity Price, set at 120 €/MWh according to the values shown in *Figure 5.2*. The study will investigate if the availability of the cheap wind farms capacity succeeds to contain the raise of the market prices and the possible differences in the two Scenarios.

In order to study the impact of the wind farms and to evaluate the benefits of the UPME project, the water supply shortage is simulated in three different situations:

- NOWIND scheme. There is no wind capacity in the energy mix;

- WIND scheme. Three wind farms are included in the energy mix and their capacity respects the project planned by UPME;

- WIND_X2 scheme. The wind farms' capacity is doubled, so that it can be possible to evaluate if could be desirable to expand the wind power.

5.3.1 Competition Scenario

In this first scenario the wind farms act autonomously in the market as all the other competitors. The farms' significant characteristics are summarized in *Table 5.9*. According to the situation of (almost) perfect competition and the water shortage condition, the farms' bid price is blocked at 1 €/MWh and the bid energy at the maximum energy availability, so that to exploit at most their presence in the market.

PLANT	COMPANY	TYPE (kind-fuel)	CAP$_L$ [MW]	CAP$_U$ [MW]	MC [€/MWh]	CF	M1	M2
EOL-GUAJIRA 1	JEMEIWAA KA'I	wind (large)	10	549 (1098)	1	0.35	1	1
EOL-GUAJIRA 2	ENEL	wind (large)	10	500 (1000)	1	0.35	1	1
EOL-GUAJIRA 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	wind (large)	10	402 (804)	1	0.35	1	1

Table 5.9-Wind farms data-Competition Scenario

Contrary to the Oligopoly analysis, the thermal agents enter progressively the market after the energy production of the hydro plants strongly had decreased because of the water supply shortage. Their high cost of production, and consequently their very high bid prices increase the market price.
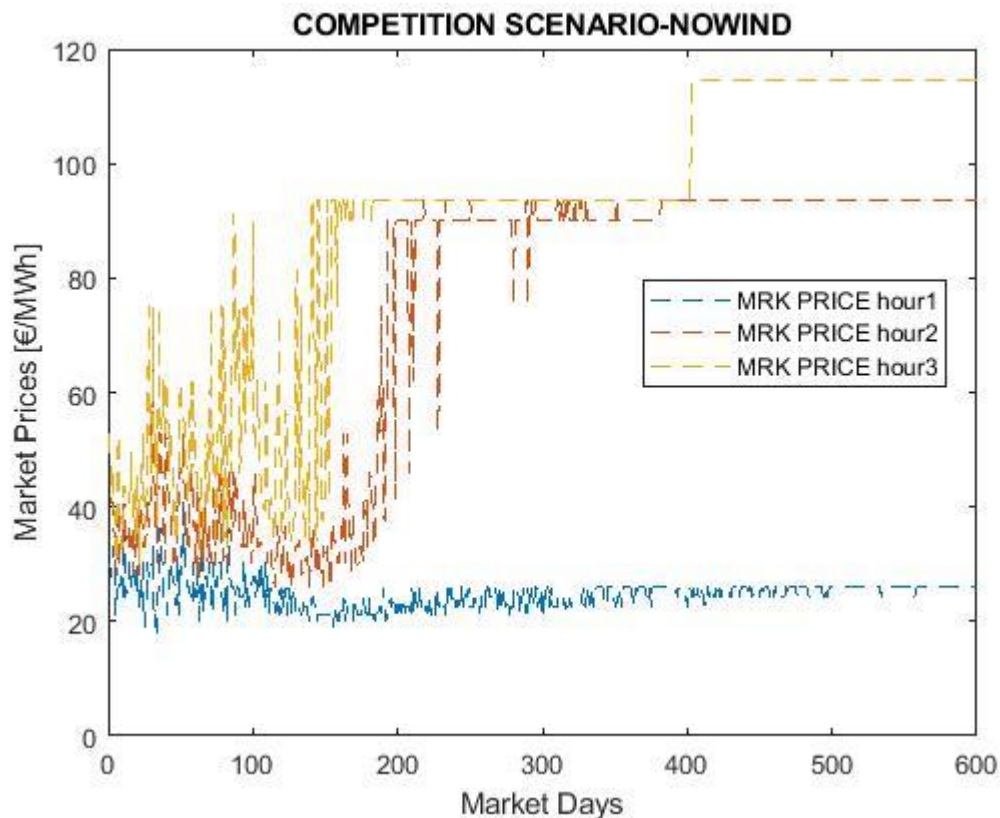
- **NOWIND scheme**

Figure 5.11-Market prices trend Competition Scenario--NOWIND scheme

As expected, *Figure 5.11* shows that in the NOWIND scheme, the H2 and H3 market prices rise quickly and approach the Scarcity Price. This is due to the strategical bids of the thermal agents that became the marginal producers. Only the base load (H1) price remains at normal level. *Figure 5.12* shows the frequencies of the market prices and *Table 5.10* summarizes the related statistical data. *Figure 5.12* shows that the price distribution became less chaotic when the values rise: this is due to the reduction of the number of participants that submits bid offer at higher level of price. Evidently the same will occur in the next scenarios.

Market Prices statistical data COMPETITION SCENARIO-NOWIND			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	18,04	18,52	18,96
H2	93,70	93,70	89,88
H3	93,70	93,70	96,10

Table 5.10-Statistical data of the market prices for the Competition Scenario-NOWIND scheme
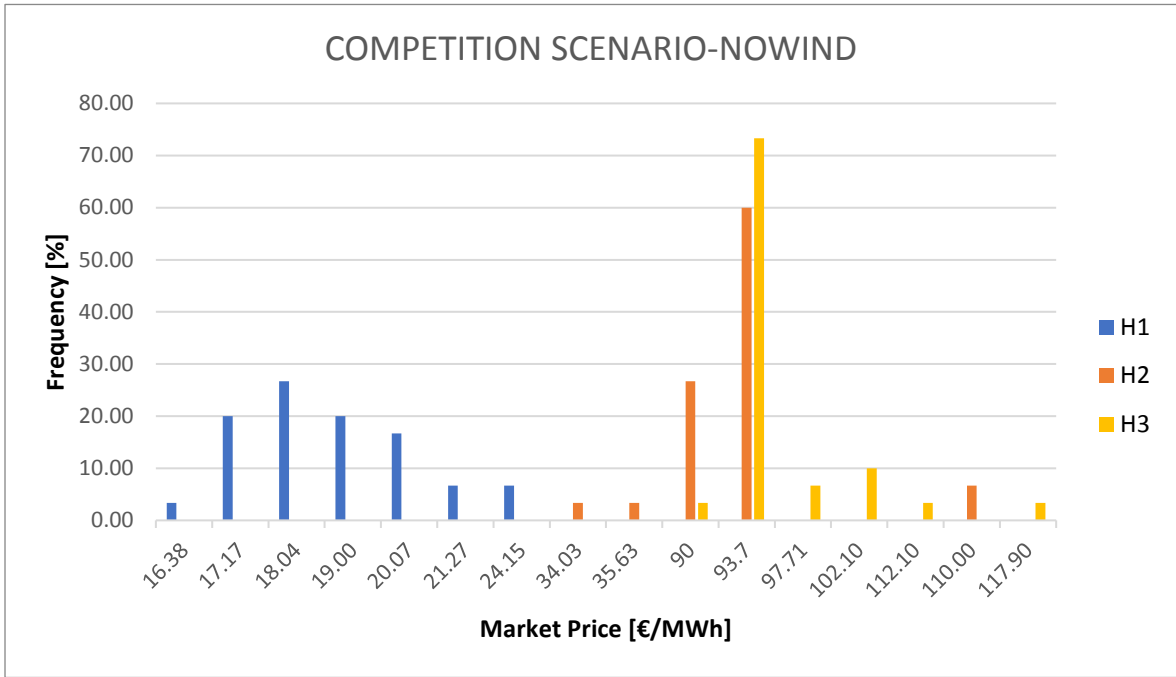
Figure 5.12-Market prices frequency Competition Scenario-NOWIND scheme
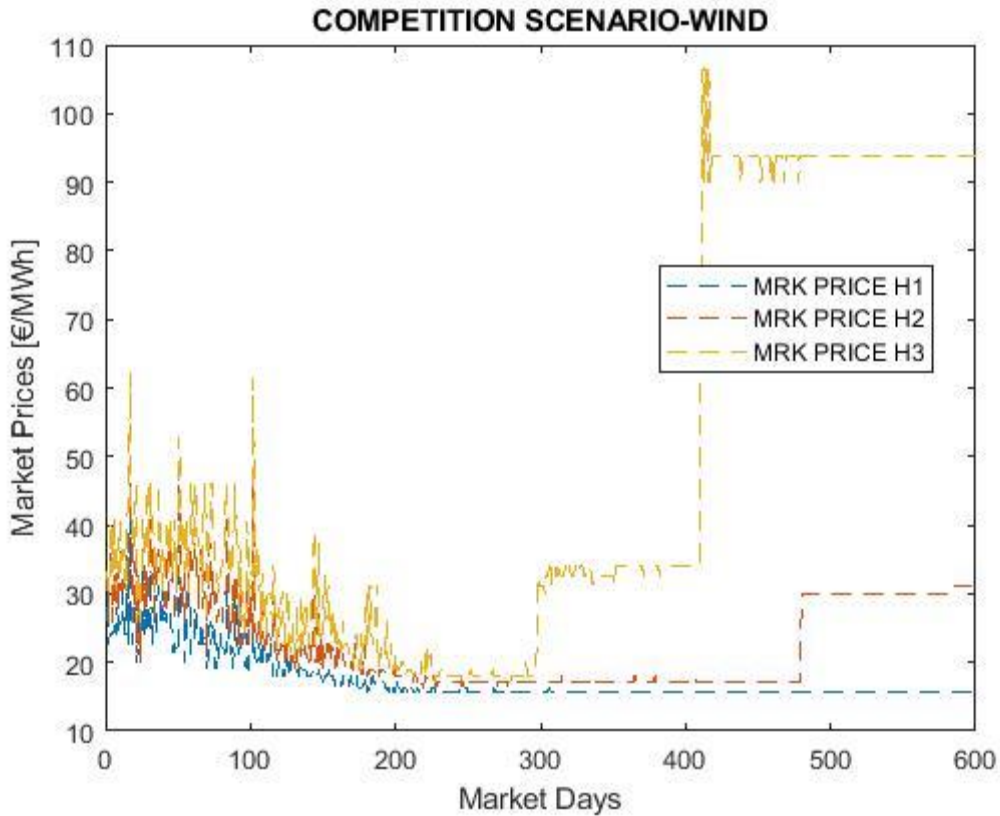
- **WIND scheme**

Figure 5.13-Market prices trend Competition Scenario-WIND scheme

With the introduction of the wind farms capacity, the situation changes as shown in *Figure 5.13*: the hydro plants crisis is delayed because the wind energy production allows to reduce the usage of hydro plants, which makes the prices remaining stable longer. As results all the three market prices decrease. In particular the H2 price because the wind capacity often permits to fulfil the related demand without the energy production of the expensive natural gas and oil thermal plants. Both *Figure 5.14*, which displays the frequencies of the market prices, and *Table 5.11* which summarizes the related statistical data, confirm the expected market price contraction.

Market Prices statistical data COMPETITION SCENARIO-WIND			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	15,66	15,66	16,01
H2	31,23	32,57	45,03
H3	93,70	93,70	92,02

Table 5.11-Statistical data of the market prices for the Competition Scenario-WIND scheme
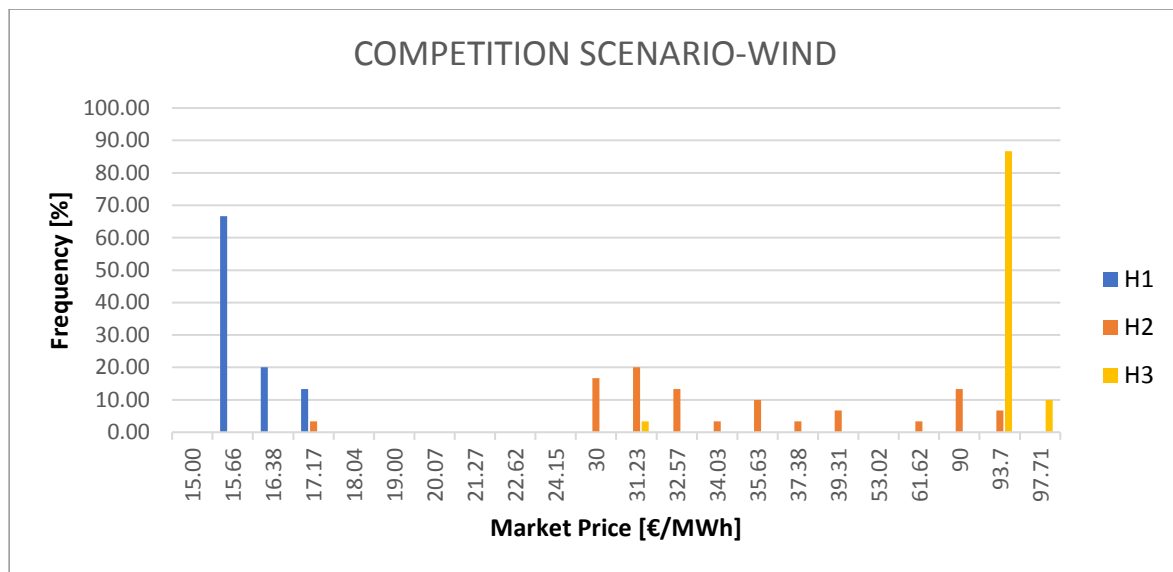

Figure 5.14-Market prices frequency Competition Scenario-WIND scheme
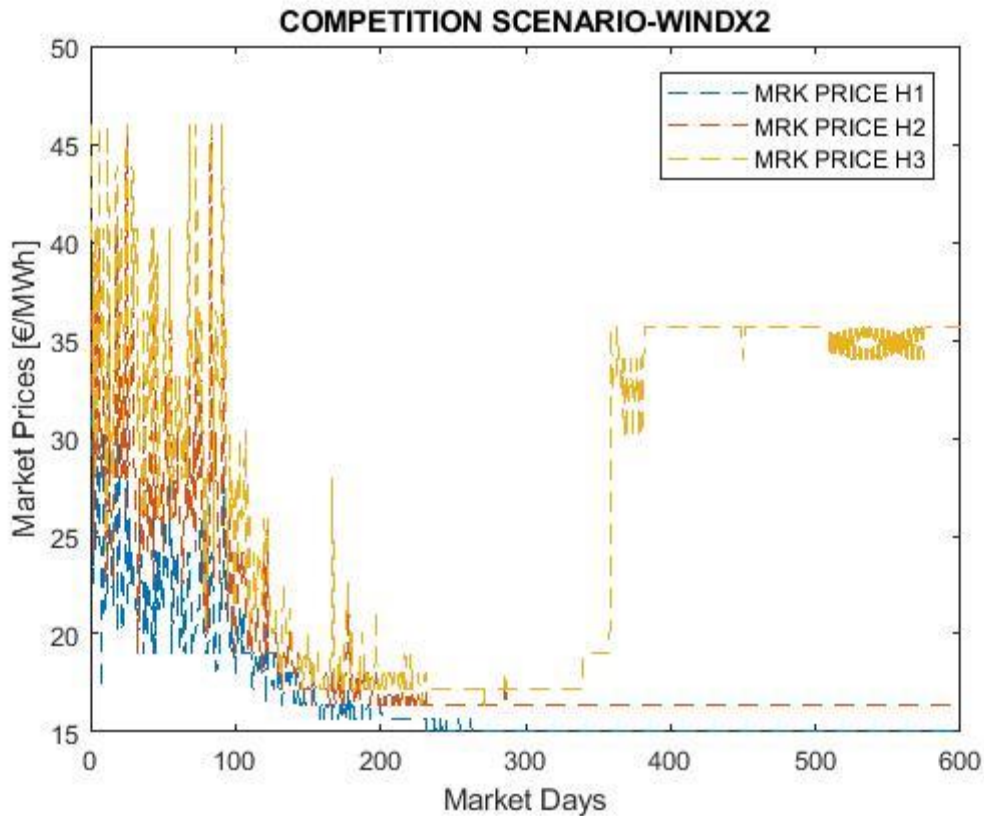
- **WINDX2 scheme**

Figure 5.15-Market prices trend Competition Scenario-WINDX2 scheme

By doubling the wind farms' capacity, the advantages strongly increase. In fact, as shown in *Figure 5.15*, the three market prices remain under control. In particular the H1 price holds on the level of no water supply shortage condition (section 5.2.1) and H2 price suffers a light mark-up. On the contrary, the peak demand (H3) price remains still higher than the normal values but frequently far from the Scarcity price. Hence, a larger wind capacity would bring very strong benefits. *Figure 5.16* shows the frequencies of the market prices and *Table 5.12* sums up the related statistical data.

Market Prices statistical data COMPETITION SCENARIO-WINDX2			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	15,00	15,00	15,20
H2	16,38	16,38	19,33
H3	93,70	67,23	59,55

Table 5.12- Statistical data of the market prices for the Competition Scenario-WIND scheme
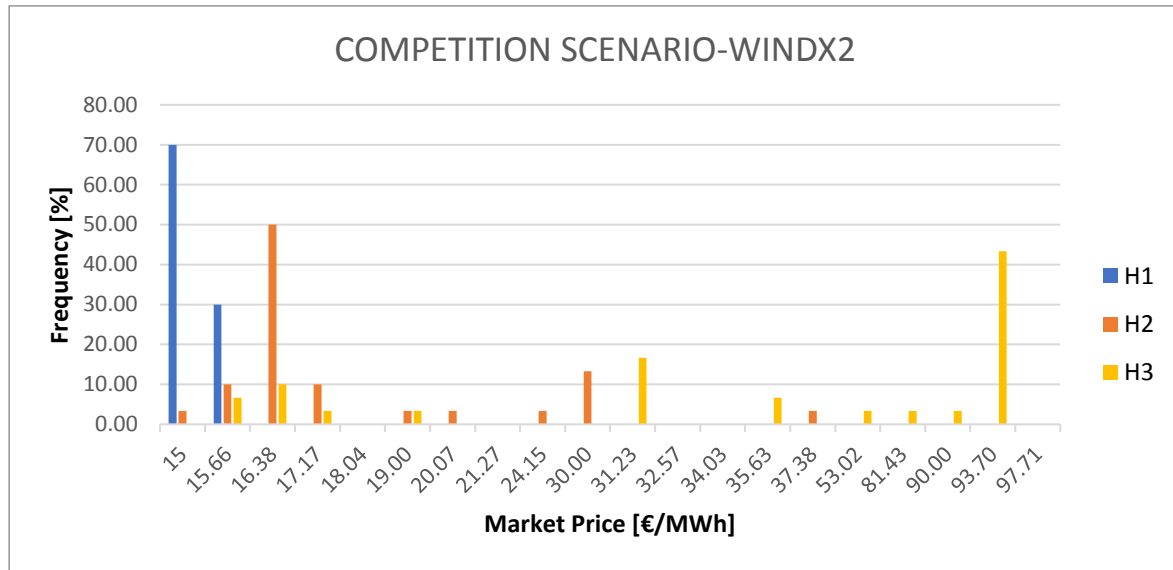
Figure 5.16-Market prices frequency Competition Scenario-WINDX2 scheme

5.3.2 Oligopoly Scenario

Two of the three projects of wind farms were purposed by two (of three) oligopolistic companies. Therefore, it is reasonable to suppose that they could be used by the companies in a strategical way and increase their power on the market. This section will verify if this condition can reduce the benefit of the wind farms installation.

Therefore, the wind farms EOL-GUAJIRA 2 and EOL-GUAJIRA 3 will be aggregated to the portfolio of, respectively, EMGESA S.A. E.S.P. (because part of the ENEL group) and EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P. The bid prices of these plants are unlocked and an arbitrary value of the MC is assumed. This will allow the company agents to submit for the wind farms strategical price bid, choosing among a realistic price spectrum. *Table 5.13* summarizes the updated wind farms' data used in the following simulations.

PLANT	COMPANY	TYPE (dimension)	CAP_L [MW]	CAP_U [MW]	MC [€/MWh]	M1	M2
EOL-GUAJIRA 1	JEMEIWAA KA'I	wind (large)	10	549 (1098)	1	1	1
EOL-GUAJIRA 2	ENEL	wind (large)	10	500 (1000)	10	10	1
EOL-GUAJIRA 3	EMPRESAS PUBLICAS DE MEDELLIN S.A. E.S.P.	wind (large)	10	402 (804)	10	10	1

Table 5.13-Wind farms data-Oligopoly Scenario

In the Oligopoly Scenario of section 5.2.2 all the bid price of the non-oligopolistic plants were blocked because they were all considered as price takers. Here, the thermal agents' bid prices are set as free because when they entered the market, they became the actual price makers.
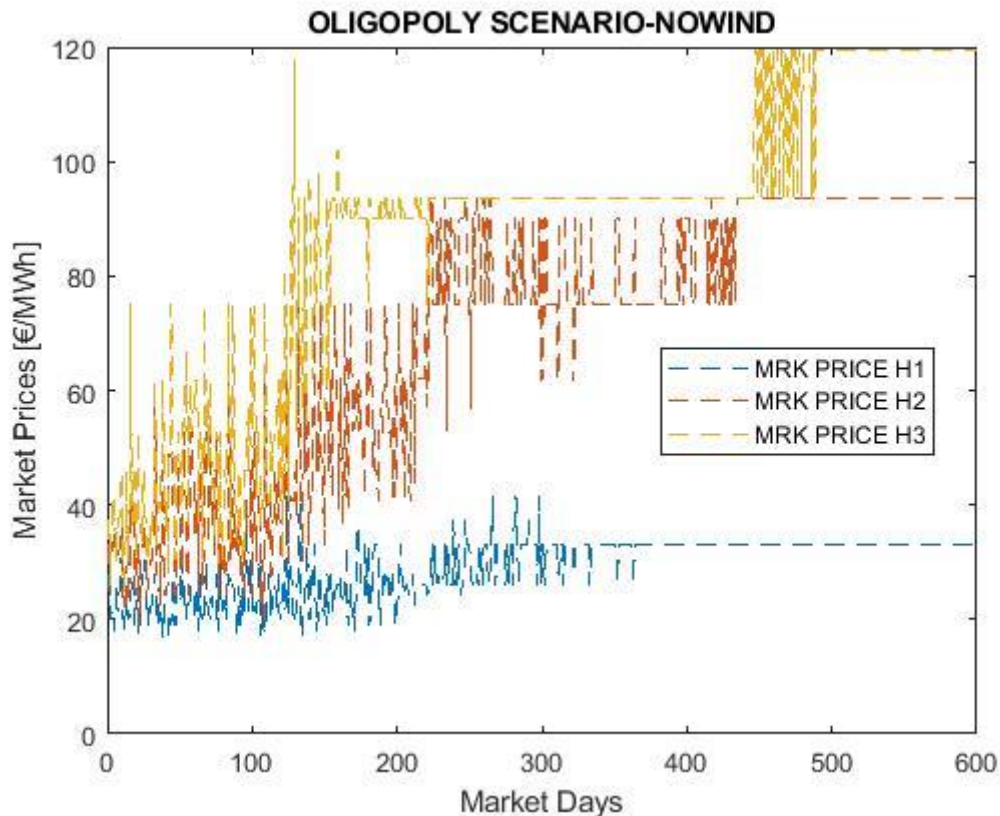
- **NO WIND scheme**

Figure 5.17-Market prices trend Oligopoly Scenario-NOWIND scheme

As for the Competition Scenario, in the NOWIND scheme, the water supply shortage progressively reduces the hydro plants energy production; so that the thermal plants enter the market and the price rises, as shown in *Figure 5.17*. The market prices frequency in *Figure 5.18*, and the statistical data in *Table 5.14*, summarize the outcomes obtained: the H1 price remain near the values of normal condition whereas the H2 and H3 prices verge on the Scarcity Price.

Market Prices statistical data OLIGOPOLY SCENARIO			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	27,94	32,86	32,38
H2	90,00	90,00	91,51
H3	93,70	93,70	95,10

Table 5.14- Statistical data of the market prices for the Oligopoly Scenario-NOWIND scheme
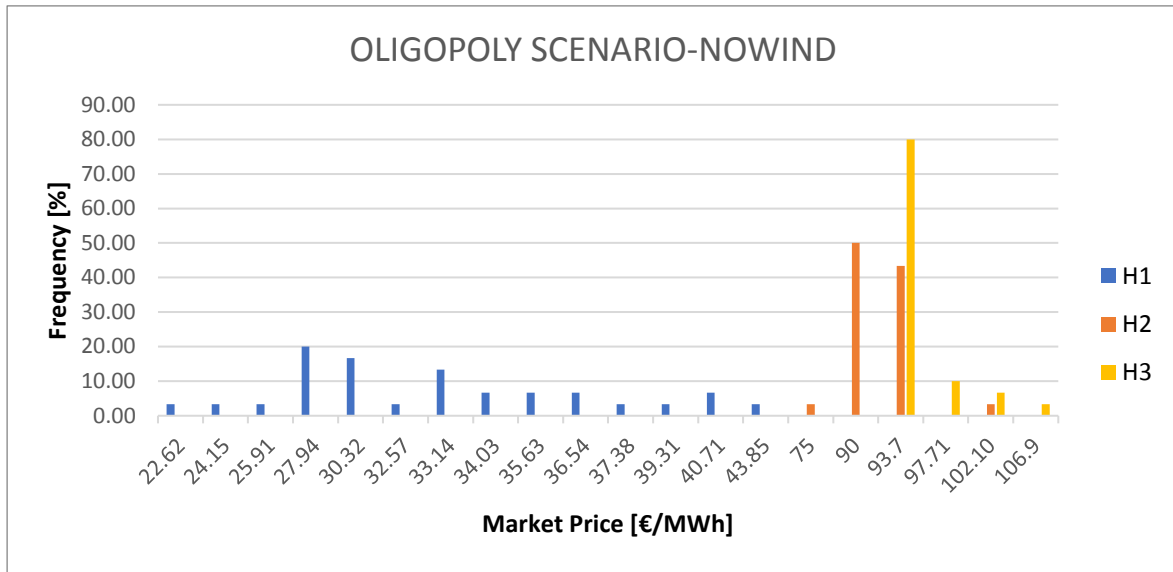
Figure 5.18-Market prices frequency Oligopoly Scenario-NOWIND scheme
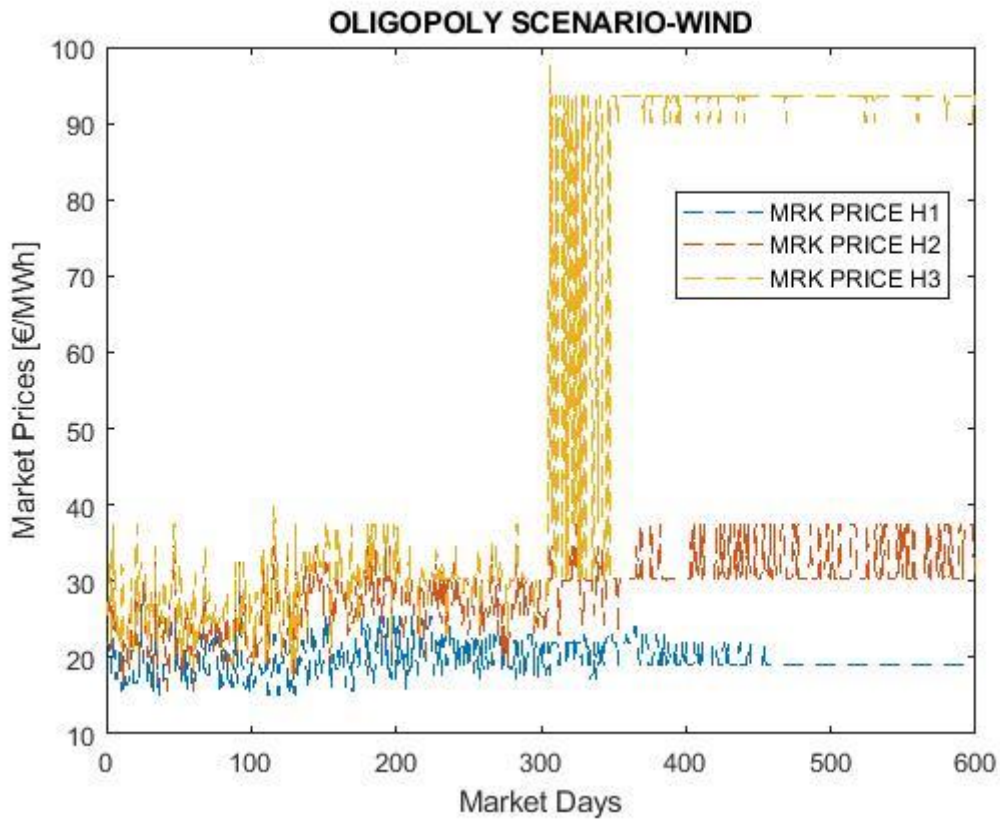
- **WIND scheme**

Figure 5.19-Market prices trend Oligopoly Scenario-WIND scheme

In the WIND scheme, it occurs the same thing than in the Competition Scenario, as shown in *Figure 5.18*: the wind capacity allows to delay the hydro plants' water shortage and to control better the market prices. In fact, the H1 price holds on the normal level and H2 prices is subjected to a not excessive mark-up whereas H3 prices still remain very high, near to the Scarcity Price. These resulted market prices are summarized in *Figure 5.20* and *Table 5.15*.

Market Prices statistical data COMPETITION SCENARIO			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	22,35	21,92	21,49
H2	90,00	90,00	63,88
H3	93,70	93,70	94,38

Table 5.15- Statistical data of the market prices for the Oligopoly Scenario-WIND scheme
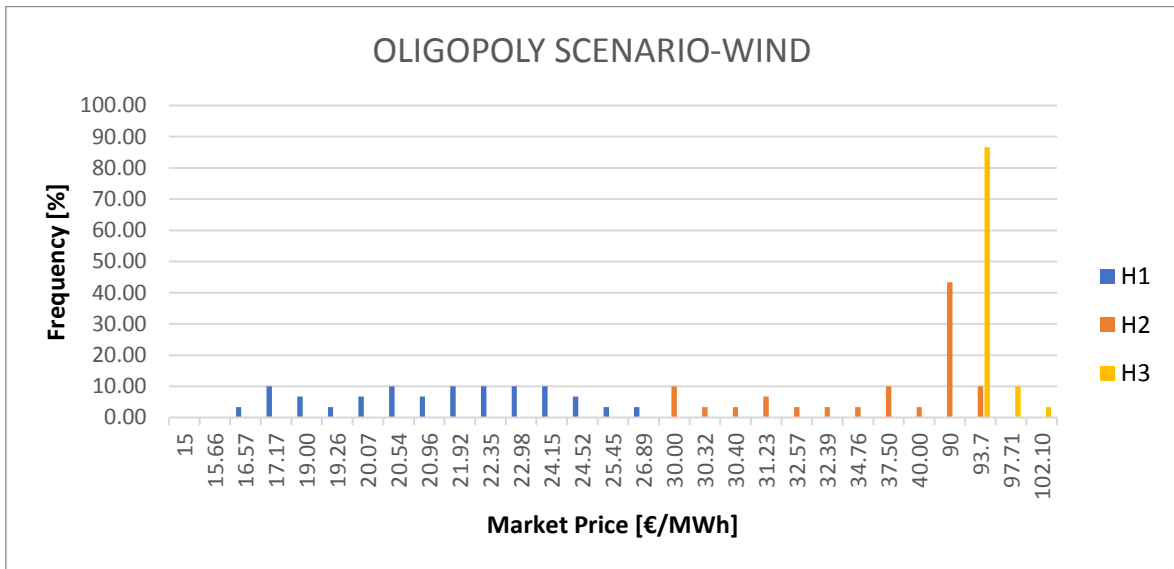

Figure 5.20-Market prices frequency Oligopoly Scenario-WIND scheme
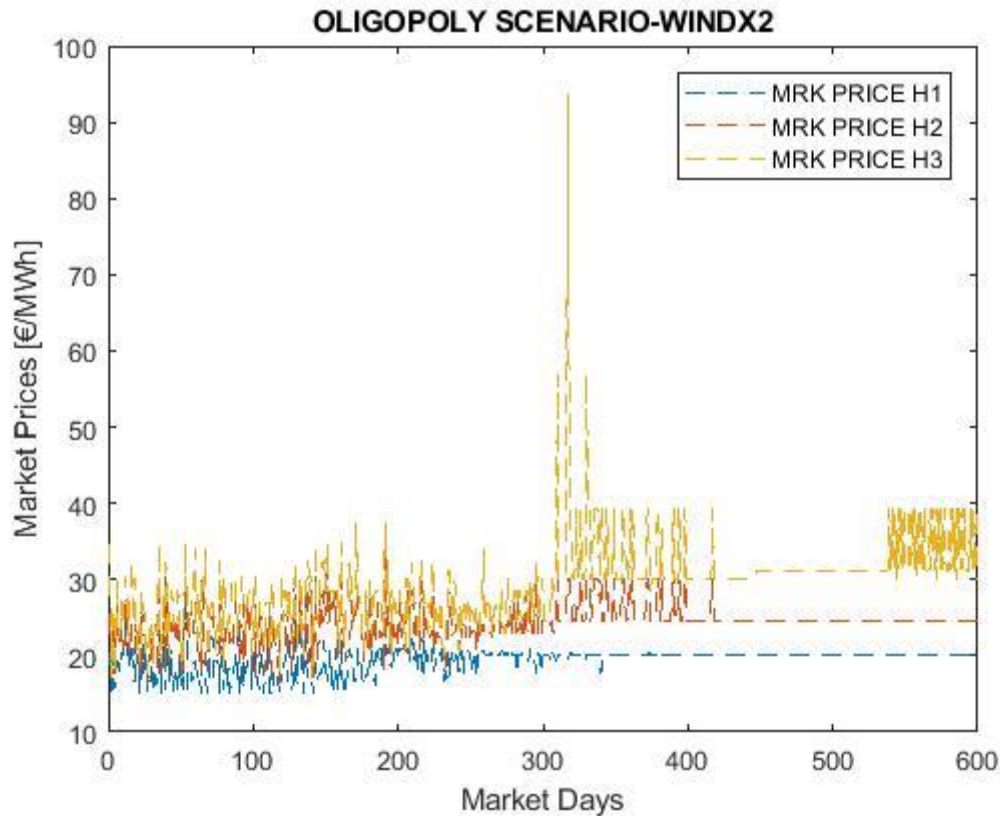
- **WINDX2 scheme**

Figure 5.21-Market prices trend Oligopoly Scenario-WINDX2 scheme

The doubling of the wind farms' capacity brings benefits even in this case because it improves the control of the market prices, as shown in *Figure 5.21*. The result is a further reduction of the prices with respect to the WIND scheme; in this regard *Figure 5.22* summarizes the market prices frequencies and *Table 5.16* the related statistical data. Nevertheless, it looks like in this case the benefit provided by the wind farms capacity is weaker than the Competition Scenario. The comparison among the two Scenarios results will confirm this impression.

Market Prices statistical data COMPETITION SCENARIO			
HOUR	TREND[€/MWh]	MEDIAN[€/MWh]	AVARAGE[€/MWh]
H1	21,92	20,75	20,50
H2	31,23	31,23	33,03
H3	93,70	93,70	73,31

Table 5.16- Statistical data of the market prices for the Oligopoly Scenario-WINDX2 scheme
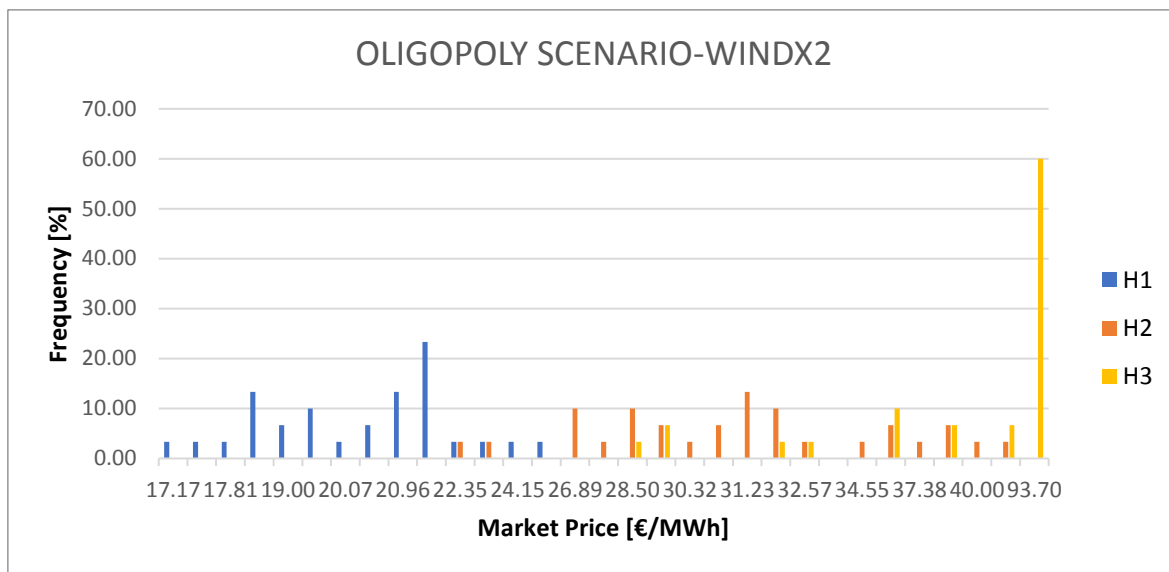
Figure 5.22-Market prices frequency Oligopoly Scenario-WINDX2 scheme

5.3.3 Analysis of the Scenarios' results

The outcomes of the two scenarios clearly show the utility to enhance the Colombian energy mix with the installation of wind farms: only for the peak of demand the electricity market continue to strongly suffer the water supply shortage due to the ENSO effect. In term of price this means a strong reduction of the market price volatility which has, as already mentioned, in the past, brought almost to the national black-out.

The comparison of the market prices outcomes is, here, divided by scenario and scheme, in order to understand better the entity of the contribution of the wind capacity:

a) COMPETITION SCENARIO
   Figure 5.23, *Figure 5.24* and *Figure 5.25* summarize the price respectively for the demand of H1, H2 and H3. In normal conditions, NO ENSO, the (almost) perfect competition provides the lowest prices for all the three charges. In the ENSO condition it is clear that the prices decrease by increasing the wind farms capacity. Also the statistical data, summarized in *Table 5.17*, depict the same. To give a more detailed proportion of the difference among the scenarios, the percentage deviations between the NO ENSO and the ENSO schemes outcomes are shown in *Table 5.18*. This table evidences that with the installation of the approved capacity (WIND scheme) only the prices of H1 would be not significantly affected by the water supply shortage; whereas by doubling the capacity it could be possible to control also the H2 prices. Nevertheless, for the charge H3, the prices remain three or four times the

normal value, as shown also from *Figure 5.25* where the price frequency for the ENSO schemes concentrates around 93.7 €/MWh.

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HOUR	NO ENSO			ENSO-NOWIND			ENSO-WIND			ENSO-WINDX2		
	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]
H1	15,00	15,00	15,00	18,04	18,52	18,96	15,66	15,66	16,01	15,00	15,00	15,20
H2	15,66	15,66	15,54	93,70	93,70	89,88	31,23	32,57	45,03	16,38	16,38	19,33
H3	15,66	15,66	15,68	93,70	93,70	96,10	93,70	93,70	92,02	93,70	67,23	59,55

Table 5.17-Summary of the market prices statistical data in the Competition Scenarios

HOUR	ENSO-NOWIND			ENSO-WIND			ENSO-WINDX2		
	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]
H1	20,27	23,47	26,42	4,40	4,40	6,70	0,00	0,00	1,32
H2	498,34	498,34	478,26	99,43	107,98	189,70	4,60	4,60	24,35
H3	498,34	498,34	513,08	498,34	498,34	487,02	498,34	329,28	279,91

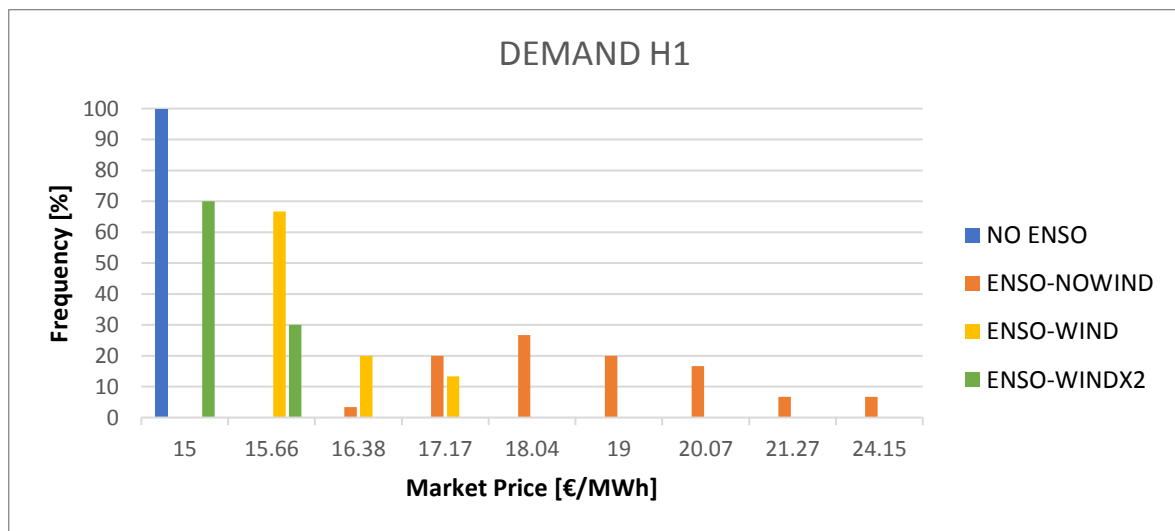*Table 5.18 Percentage deviation with respect to the No Enso Competition Scenario*

Figure 5.23-Market prices frequencies for the demand H1 in the Competition Scenario
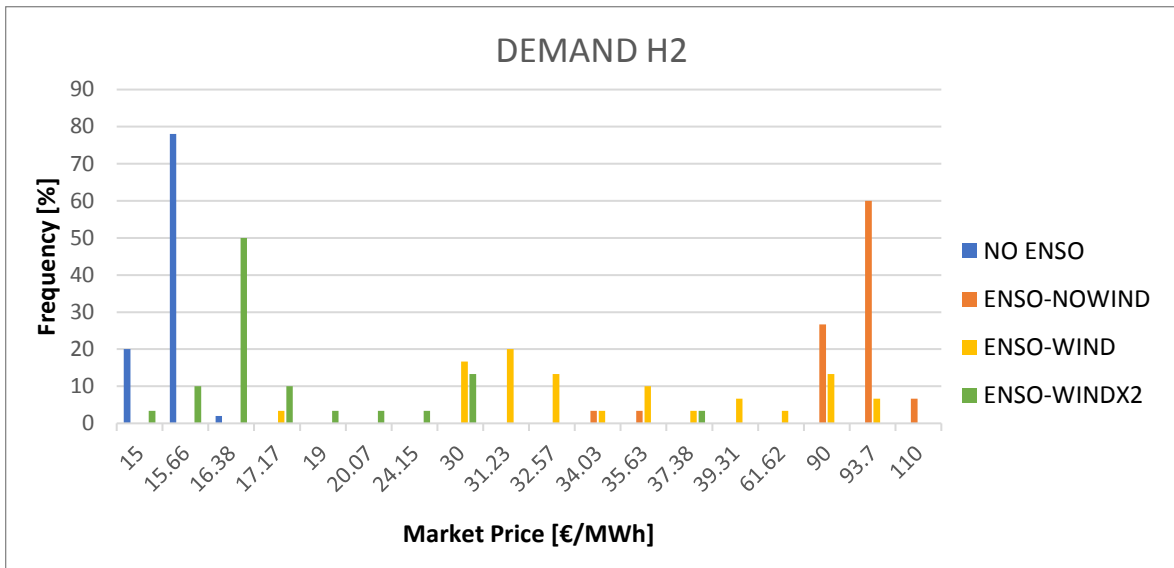
Figure 5.24- Market prices frequencies for the demand H2 in the Competition Scenario
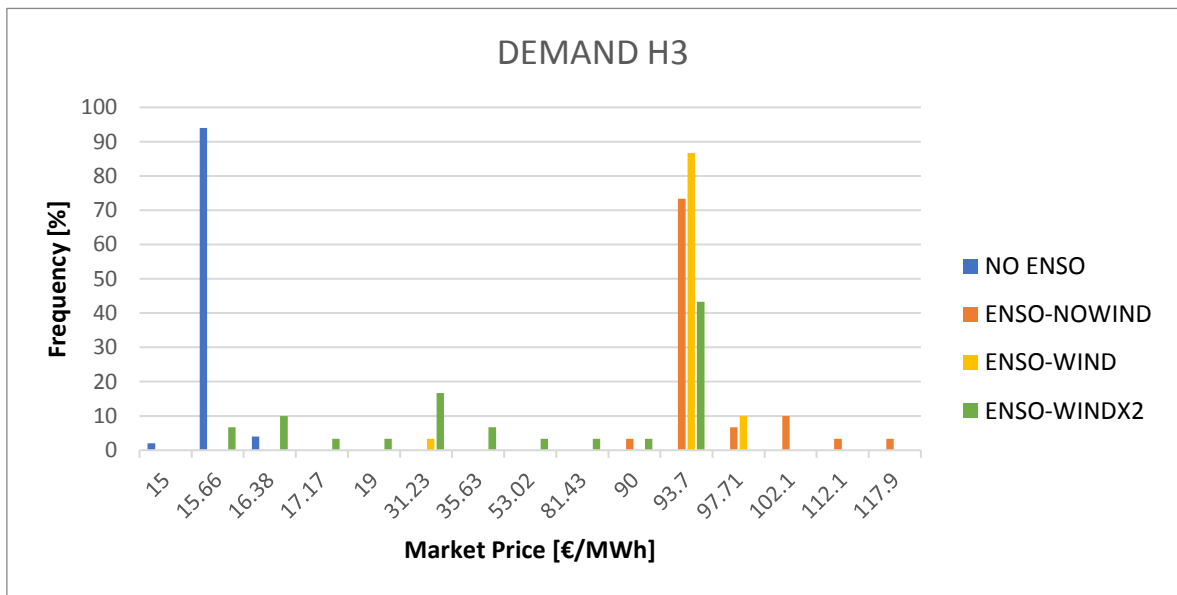

Figure 5.25-Market prices frequencies for the demand H3 in the Competition Scenario

b) OLIGOPOLY SCENARIO

As before, *Figures 5.26-5.27-5.28* summarize the price respectively for the demand of H1, H2 and H3; *Table 5.19* summarizes the prices' statistical data and *Table 5.20* contains the related percentage deviations. As expected the market prices are always higher than correspondent values of the Competition Scenario. Because of the prices' mark-up performed by the oligopolistic company, the wind capacity is even able to reduce the market prices with respect the NO ENSO condition where there were no wind farms. In fact, *Figure 5.26* shows that in both WIND and WINDX2 schemes the market have cleared prices lower than the NO ENSO outcomes for H1. For this reason, the related percentage deviations in *Table 5.19* assume negative values. About the demands H2 and H3, the same observations of the Competition Scenario can also be done in this case: the WIND scheme permits to contains the mark-up of H1 and the WINDX2 scheme reduce both the increase of H1 and H2. Comparing the percentage deviations among the three ENSO schemes, it could be deduced that the impact of the wind farms is weaker in the Oligopoly Scenario for the demands H2 and H3, because the related values do not decrease so much from the NOWIND to the WIND and WINDX2 schemes. In reality, this is not connected to the efficacy of the wind farms but it is due to the lower production of the hydro plants that belong to the oligopolistic company. These plants, used to mark-up the market prices, produce less than the Competition Scenario so that to attenuate the compensation brought by the wind farms energy production.

HOUR	NO ENSO			ENSO-NOWIND			ENSO-WIND			ENSO-WINDX2		
	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]	TREND [€/MWh]	MEDIAN [€/MWh]	AVARAGE [€/MWh]
H1	25,91	24,15	24,42	27,94	32,86	32,38	22,35	21,92	21,49	21,92	20,96	20,63
H2	27,94	27,94	28,45	90,00	90,00	91,51	90,00	90,00	63,88	31,23	30,82	33,38
H3	30,32	30,32	30,26	93,70	93,70	95,10	93,70	93,70	94,38	93,70	93,70	72,88

Table 5.19-Summary of the market prices statistical data in the Oligopoly Scenarios

HOUR	ENSO-NOWIND			ENSO-WIND			ENSO-WINDX2		
	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]	TREND [%]	MEDIAN [%]	AVARAGE [%]
H1	7,83	36,05	32,62	-13,74	-9,23	-12,00	-15,40	-13,21	-15,50
H2	222,12	222,12	221,65	222,12	222,12	124,55	11,78	10,29	17,32
H3	209,04	209,04	214,24	209,04	209,04	211,87	209,04	209,04	140,83

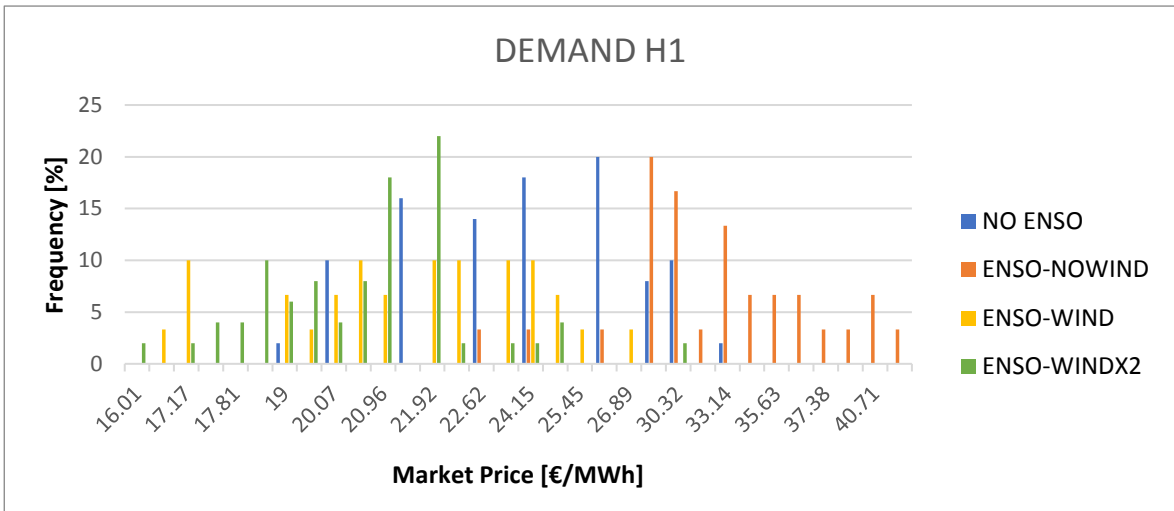*Table 5.20-Percentage deviation with respect to the No Enso Oligopoly Scenario*

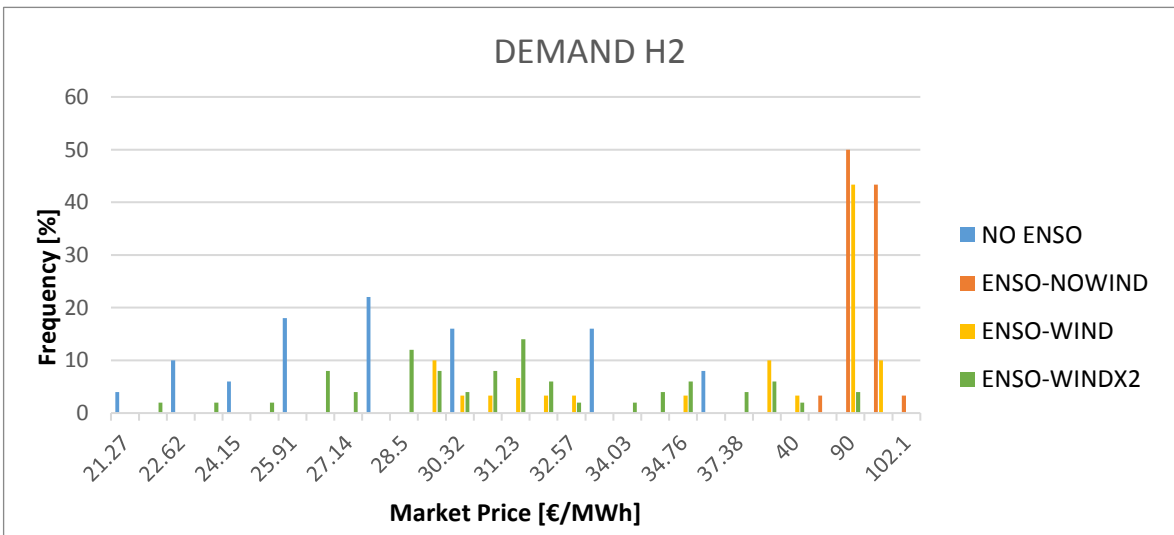*Figure 5.26-Market prices frequencies for the demand H1 in the Oligopoly Scenario*

Figure 5.27-Market prices frequencies for the demand H2 in the Oligopoly Scenario
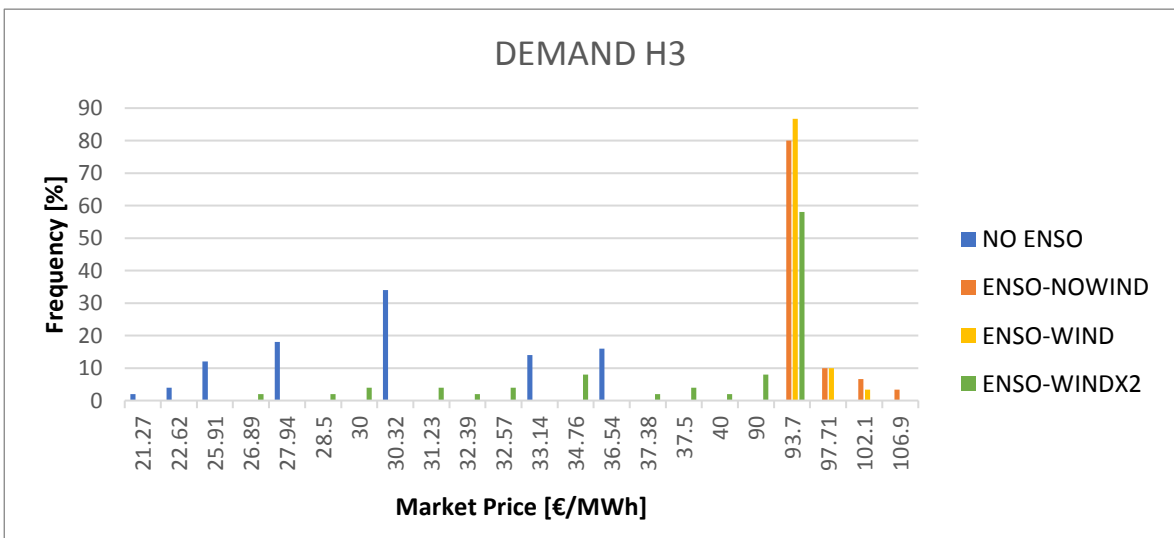

Figure 5.28-Market prices frequencies for the demand H3 in the Oligopoly Scenario

As for the outcomes of the Oligopoly analysis, the prices' distribution was, in some cases, more chaotic than others. In this regard three different situations can be identified:

- In the cases in which the competition condition is respected the hourly market prices concentrate around 15 €/MWh for the reasons previously discussed;

- When the competition condition is not respected and the price equilibrium stabilizes between 15 and 75 €/MWh, the prices' distribution results more chaotic because it corresponds to the range in which the hydro agents can submit the bid price, so the number of competitors is large and, as consequence, the number of possible market equilibrium as well;

- In case in which the competition condition is not respected and the price equilibrium stabilizes after the 75 €/MWh, the prices' distribution results less chaotic because a smaller number of competitors can bid in this range of price, reducing the number of possible market equilibrium.

CHAPTER 6

Conclusions

In conclusion of this work it is interesting to purpose the review of the methodology followed to develop the peculiar feature of this thesis, from the definition of the critical aspect of modelling the Colombian day-ahead market to the design of the dedicated algorithms. The evaluation of the results obtained from the Colombian market model will depict the field of application for the features that have been implemented. At the end, the algorithms limits will be first evaluated and then related to possible solutions and to future improvement.

6.1 Methodology analysis

The Colombian electricity market recently started to experience important changes that will make it more reliable and more efficient, approaching the level of the most developed countries. To accomplish this progress, it is necessary to deal with the most notable problems of the market: the oligopoly and the periodical water supply shortage that leads to the prices' volatility. The strong interest that these aspects have created in Colombia, motivated the development, in this thesis, of an instrument that permits the analysis of the mentioned issues.

The implementation of a model that reproduces the Colombian market operations and the activities of its participants fit perfectly the purpose of the analysis. The ABM approach was chosen because its modelling principles match the characteristics of the energy market. For these reasons many significant results have been obtained through its exploitation.

In this context, the AMES framework represents an example of successful application: it is organized with a very flexible structure and the algorithm reproduces effectively all the aspects of market trading involved in the generators' activities. In particular, the organization of all the possible bid offers (price and energy) in a unique set, the ADM, was particularly appreciated. Therefore, it has been chosen to reproduce the power plants operations taking inspiration from the procedure followed in AMES.

However, the AMES framework can be appropriate only for the representation of the behaviour of thermal agents that pursue the maximization of its own profit. Hence, for the cases, as the Colombian market or the North Pool, in which there is a dominance of hydro share, AMES cannot provide a realistic representation of market operations. Moreover, all the markets in which oligopoly in generation subsist, are also excluded because the coordination of the activities among plants that belong to the same power generation company cannot be reproduced. This last aspect represents a common characteristic to all of the other existent platforms (for the energy market representation), in which it is assumed that each agent chases autonomously its unique gain.

Those two critical issues forced the development of peculiar algorithms that allow the design of the specifications required by the Colombian energy market. Those are explained in the following three points:

- **COMPANY OF GENERATION**
  As already mentioned, the AMES framework provides the design of agents that participate in the market with the aim to maximize their only profits. In the cases in which a significant share of the participants belongs to company of generators (which is the cases of Oligopoly), it is reasonable to think that these agents would act with the purpose of maximizing the profit gained by the whole group. As regards of this, it was decided to design an algorithm able to coordinate the bid offers of different agents. To realize that the concept of ADM was extended including in this set all the possible offers of the agents that pertain to company. Therefore, the company-agent determines simultaneously the bid offer for each plant managed and it accounts for the global profit gained. In this way, an agent was implemented, that chooses the bid of different agents and seeks the best combination of them to gain the maximum total profit; exactly as the power generation company that owns many different plants. This is a total innovation because currently all the existent energy market platforms, neglect this kind of coordination and retain sufficient to introduce only the single-agent profit maximization. The outcomes from the Oligopoly analysis of the Colombian market model (section 5.2), successfully show the effect of the developed feature and the large deviation of the results by its omission. This analysis proved that the future development of platforms that reproduce the market activities has to include this essential aspect of the trading. In this sense, the scheme implemented in this thesis outlines the principles that could drive the innovation of the design of the generator agents behaviour in the market.

- **HYDRO PLANTS**

  To represent adequately the profile of the hydro generators, it was necessary to define all the parameters that characterize the aspect of their energy production. In fact, all the characteristics connected to the presence of water, as the reservoir volume with its technical limits and the refuel, are not provided by the original structure of AMES. Thus, the outline of those attributes of the hydro generation was essential to represent realistically the largest part of the Colombian generation mix.

  However, that was not enough to outline the hydro agents' activities. In fact, the water consumption creates an inter-connection among successive bid offers, because of the variation of the water availability. For this reason, an independent decision-making process to define a single bid offer was no more appropriate because each bid actually affects the following ones. To deal with this peculiarity, the concept of ADM was again extended including the set of parameters required to determine simultaneously multiple bid offers, and not only a single one as provided by AMES. In this way the decision-making process involves different consecutive offers considering the inter-dependence that characterize successive bids. The development of this feature allows the realistic reproduction of the hydro agents' short-term decision-making process and the related market activities. In this case, also the application to the Colombian market shows the successful implementation with the reproduction of the water supply shortage that periodically affects the generation mix.

- **REWARD CALCULATION and BALANCING MARKET**

  Two more issues have been faced in the modelling process. Firstly, the Colombian day-ahead market rule establish that the participants can submits a unique bid price for the 24 market sessions. This requires an improvement of the reward/profit calculation; otherwise the agents would not be sensible to the merit of its bid with respect to the profit gained. Thus, the implemented calculation system, showed in section 4.4.3, reproduces the human cognition that discerns the reward obtained by merit of the bid submitted from the contribution due to the bid/position of the other competitors. The correct functioning of this feature was successfully tested and results effective in each market context, not only concerning the Colombian market rules.

  As the last step, the forthcoming opening of a market dedicated to the real-time trading encourage the development of a parallel platform able to simulate this kind of exchanges. To realize this, the structure of the day-ahead market was preserved, but the market rules and the results updated were adapted to reproduce the

peculiarities of the balancing transaction. In this way the model of the day-ahead market was enrich with an environment dedicated to the real-time trading that, in the case of the Colombian market, can be exploited to test the possible operation.

6.2 Analysis of the Colombian day-ahead market model outcomes

Thus, after the design of the required specific algorithms and features, they were used to build a model of the Colombian day-ahead market. Then it was exploited to study the mentioned two issues of Oligopoly in generation and water supply shortage. The results obtained and the related conclusion are summarized in the following two points:

- OLIGOPOLY. The simulation and the comparison of the two scenarios in section 5.2 brought very clear results: it was proved that the activities of the three oligopolistic companies, which can exert the market power, rises the (hourly market) prices. The average mark-up with respect to the scenario of perfect competition assumes values within 60% and 90%; this suggests that the prices have actually increased also in the real market trading. Thus, it can be affirmed that the implementation of the capacity unbundling for the oligopolistic companies, or at least the application of other measures that guarantee the competition in the market, would increase the electricity supply efficiency; in addition, they would reduce both the wholesale market prices and, as consequence, the costs for the final consumers.

- WATER SUPPLY SHORTAGE. The simulation of the water supply shortage in the model brought to the expected consequent market crisis, due to the volatility of the (hourly market) prices. It was chosen to verify if the planned installation of wind farms capacity would be beneficial in this scenario. The inclusion in the model of wind farms produces very promising results: the prices volatility is reduced so that only during the peak hours the prices have significantly increased, but still under control. Thus, the execution of the market model demonstrates that the planned installation of the wind farms would be very helpful; moreover, the possible expansion of the wind capacity would increase even further the benefits in term of market prices.

6.3 Algorithm limits

Some concerns were faced during the development of all the features previously exposed. The most critical regard the computational execution of the algorithm. The following two points recap the main issues:

- ADM DIMENSION. The ADM represents the set of possible options among which the agent makes its choice determining his position (in the market). When the dimension of this set is too large, that is when the agents have to select the best option among a too wide variety of choice, it is necessary to ensure the correct execution of the research. This means that an adequate exploration of the possible options in a reasonable number of iteration must be guaranteed, even if there is no connection between the time-frame of the reality and the iteration required by the exploration. As shown in the previous section, for the case of hydro generators and company of generation, the ADM dimension grow very fast. This makes the set of possible combination of market positions enormous, so that the joined management of the options exploration and the calibration of the agents' convergence time results very tricky.

- NUMERICAL DIVERGENCE. This aspect, analysed in detail in section 4.4.2, involves the execution of the VRE RLA which uses the exponential for the calculation of the options probability. This frequently leads to numerical problem due to the achievement of amounts too large for the computing environment (MATLAB). As solution, the use of the MRE RLA was preferred. This last version of the algorithm could be considered less effective, in the research of the best option, because it requires a larger time frame in comparison with the Variant version. However, as regards the studies performed in "A comparative study of Roth-Erev and modified Roth-Erev reinforcement learning algorithms for uniform-price double auctions" [15], the VRE RLA seems to be conceived for a fast seek of the best option; in fact the convergence time in both the mentioned work and the experimentation executed to realize the Colombian market model, was very fast. The expectation is to find a computational solution that could permit the accessible exploitation of the VRE RLA, because its ability to control the probability determination, with respect to the propensities distribution, can be very helpful for the design of the agent sensibility.

6.4 Future improvement

The features implemented in this thesis were organized with a solid structure but, in relation to the mentioned limits faced in the modelling process, other improvements can increase the performance of the algorithm. The following points explicate more in detail the advantageous possible intervention:

- ADM DIMENSION. The main concern about the ADM is to guarantee the correct exploration of the agents' set of option. This became critical when the ADM assume very large extension. To deal with this issue, a sort of filtering of the ADM could be performed so that to reduce its dimension. The idea is to progressively eliminate the options that would bring outcomes similar to others. In this way the spectrum of exploration would be reduced making the research more effective and meaningful. A possible obstacle could be the dynamism of the interaction among the agents and with the environment: an option that should be potentially filtered, could actually change the related outcome after a certain number of iterations. Nevertheless, this is not true for all of the cases, and this concept could represent a valid starting point for the future works.

- NUMERICAL DIVERGENCE. The advantages derived by the application of the VRE RLA were already discussed. To guarantee its correct functioning it is necessary to avoid the numerical divergence due to the use of the exponential. A possible solution in this direction could be the development of an adequate and more complex (even not static) system of scaling of the values involved, with respect to the attempt made in this work (section 4.4.2). Even the improvement of a dynamic evolution of the Boltzmann cooling parameter could manage this issue, even if it would require an enhance study of the theoretical validity of the solution.

- COMPANY AGENTS. The creation of a single ADM and the update of the related propensities, thought the joined results (i.e. joined profit), express the concept of coordination among the bids of the agents involved. The usual problem of the ADM dimension limits also the application of this algorithm for which it was required the reasonable simplification of aggregation of different plants in a single agent. The solution of this obstacle can open the use of this algorithm to a larger number of agents without the needs to make any simplification.

- HYDRO GENERATOR AGENTS. As for the company-agents, the idea of single ADM and the updating of the related propensities express the concepts of interdependent bid and interdependent results. This approach can be extended to the required numbers of bids because there are no theoretical limits. However, to strengthen this structure it will be necessary to deal with and solve the mentioned problem of the ADM dimension. In addition, it would be of interest to include more constraints related to the operation of the hydro power plants to make the algorithm more accurate. The adequate adjustments can make the algorithm a powerful tool for the deeper study of the hydro energy producers strategy and the study of the market power.

Bibliography

[1]   T. C. Schelling, "Dynamic models of segregation," *The Journal of Mathematical Sociology*, vol. 1, no. 2, pp. 143–186, 1971.

[2]   C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," *ACM SIGGRAPH Computer Graphics*, vol. 21, no. 4, pp. 25–34, 1987.

[3]   J. H. Holland and J. H. Miller, "Artificial Adaptive Agents in Economic Theory Artificial Adaptive Agents in Economic Theory," vol. 81, no. 2, pp. 365–370, 1991.

[4]   T. A. Swanke, "Book Review: Growing Artificial Societies: Social Science from the Bottom Up," *Rev. Radic. Polit. Econ.*, vol. 31, no. 2, pp. 113–116, Oct. 1999.

[5]   R. Sun, "Cognition and multi-agent interaction: From cognitive modeling to social simulation," *Cogn. Multi-Agent Interact. From Cogn. Model. to Soc. Simul.*, pp. 1–434, 2005.

[6]   P. Caplat, M. Anand, and C. Bauch, "Symmetric competition causes population oscillations in an individual-based model of forest dynamics," *Ecol. Modell.*, vol. 211, no. 3–4, pp. 491–500, 2008.

[7]   U. Wilensky and W. Rand, *An introduction to agent-based modeling*, 10th ed., no. January. Cambridge, Massachusetts, 2015.

[8]   A. Maaz, F. Grote, and A. Moser, "Agent-based price simulation of the German wholesale power market," *Int. Conf. Eur. Energy Mark. EEM*, August 2015.

[9]   GWB, "Gesetz gegen Wettbewerbsbeschränkungen (GWB)," *Bundesgesetzblatt*, no. 32, pp. 1–64, 2013.

[10]   V. S. Koritarov, "Real-world market representation with agents," *IEEE Power Energy Mag.*, vol. 2, no. 4, pp. 39–46, 2004.

[11]   I. Erev and A. E. Roth, "Predicting How People Play Games: Reinforcement Learning in Experimental Games with Unique, Mixed Strategy Equilibria," *Am. Econ. Rev.*, vol. 88, no. 4, pp. 848–881, 1998.

[12]   R. S. Sutton and A. G. Barto, "Reinforcement learning," *Learning*, vol. 3, no. 9, p. 322, 2012.

[13]   J. Nicolaisen, V. Petrov, and L. Tesfatsion, "Market Power and Efficiency in a Computational Electricity Market With Discriminatory Double- Auction Pricing," *ISU Econ. Rep. Ser.*, vol. 53, no. 5, pp. 504–523, 2001.

[14]   J. Sun and L. Tesfatsion, "Dynamic testing of wholesale power market designs: An open-source agent-based framework" *Comput. Econ.*, vol. 30, no. 3, pp. 291–327, 2007.

[15]   M. Pentapalli, "A comparative study of Roth-Erev and modified Roth-Erev reinforcement learning algorithms for uniform-price double auctions," *ProQuest Diss. Theses*, vol. 1453051, p. 110, 2008.

[16]   Ministerio de Minas y Energia, *Ley 1715:2014*, no. Mayo 13. 2014.

[17]   UPME (Unidad de Planeación Minero Energética), "Plan de Expansión de Referencia Generación Transmisión 2016-2030," *Unidad Planeación Min. Energética UPME. ...*, p. 481, 2016.

[18]   "¿Qué tan cerca estamos de un nuevo apagón?," *EL Pais*, 2016.

[19]   CREG, *RESOLUCIÓN CREG 112 DE 1998*. COLOMBIA, 1998.

[20]   "El Niño devastó por incendios área equivalente a tres veces Cali," *El Tiempo*, 2016.

[21]   Ministerio de Minas y Energia, *Ley 143*. 1994.

[22]   Comisión de Regulación de Energía y gas (CREG), *Resolución No 071*, no. 0. 2006.

[23] K. Zhang, Y. Maeda, and Y. Takahashi, "Social interaction of cooperative communication and group generation in multi-agent reinforcement learning systems," *2011 IEEE Int. Conf. Fuzzy Syst. (FUZZ-IEEE 2011)*, pp. 1350–1355, June 2011.

[24] XM, "Curva de demanda promedio en Colombia." [Online]. Available: www.xm.com.co/Paginas/Consumo/historico-de-demanda.aspx.