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# MODELING GENERATION EXPANSION IN THE CONTEXT OF A SECURITY OF SUPPLY MECHANISM BASED ON LONG-TERM AUCTIONS. APPLICATION TO THE COLOMBIAN CASE

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*Abstract*

*In an attempt to provide electricity generation investors with appropriate economic incentives so as to maintain quality of supply at socially optimal levels, a growing number of electricity market regulators have opted for implementing a security of supply mechanism based on long-term auctions.*

*In this context, the ability to anticipate and analyze long-term investment dynamics is a key issue not only for market agents, but also for regulators. This paper, describes a model developed to serve this purpose. A general methodology has been designed to be able to analyze these long-term auction mechanisms in the formats presently in place. A real-size simulation based on the Colombian system has been developed to illustrate the capabilities of the model.*

*Keywords: Security of supply, long-term auctions, electricity market modeling*

## 1 INTRODUCTION

Though motivations may differ in each specific case, the universal *leit motiv* in electric power industry reform has been the need to seek new vehicles, new

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regulatory models, to channel the necessary strategic expansion of electric infrastructure in general and generation facilities in particular. Since the outset in the nineteen eighties, the question posed in power system reform has been whether the market, of its own accord, can ensure satisfactory security of supply from the standpoint of power generation. When the conclusion is that this is not the case, and an additional regulatory mechanism is found to be necessary, the subsequent question consists in deciding which the most suitable approach to tackle the problem is. No international consensus has been reached in this regard, but as time passes, an in-depth analysis of electric power systems worldwide, see (Batlle and Rodilla, 2009) has shown that in almost every electricity market the regulator has designed some manner of rule to drive or delimit natural market developments in an attempt to guarantee short-, medium- and long-term supply.

***Long-term auctions as mechanisms to ensure security of supply***

Orthodoxly speaking, the theoretical justification for liberalizing generation was to promote efficiency at all levels: operation, planning and expansion. That objective cannot be met, however, unless risks are allocated efficiently among the agents involved. Decision-making risk is high in power generation and failures[1] are likely. Risk, although to a lesser extent, also plays a key role in resource management decision-making.

[1] By investment failures is meant investments generating less net social benefit than other available possibilities. The uncertainty involved in investment decision-making in the electric power industry is primarily responsible for these suboptimal (when evaluated *ex-post*) investments.

Under the market-oriented paradigm, the new role of regulation is to ensure that the economic incentives in place for each activity can guarantee that quality of supply is maintained at socially optimal levels. In pursuit of ways to provide such incentives for investment in generation (the extra income or hedging instruments needed), a growing number of electricity market regulators have opted for implementing a security of supply mechanism based on long-term auctions.

Although each security of supply mechanism features certain particularities, roughly speaking, this approach entails assuring new entrants an extra payment or hedge for a number of years from the time they become operational. In the auction-based approach, specifically, the market authority calls a publication auction to buy (or orders the Load Serving Entities to buy), on behalf of demand all (or at least acquire a partial hedge over) the expected consumption for a number of years. This asset/instrument/product, the so-called reliability contract, may adopt any of several forms, ranging from a fixed payment in exchange for guaranteed production in times of scarcity, e.g. the so-called reliability option, see (Vázquez, 2002), to a more "plain vanilla" future power supply contract (i.e., a sort-of contract-for-differences).

***Main elements of auctioned reliability contracts***

The design of such reliability contracts critically conditions the final outcomes of the mechanism (Batlle and Pérez-Arriaga, 2008). Two key elements can be distinguished in this regard: time terms and the measure used to evaluate compliance with the terms of the contract.

- First, since the objective is to provide investors with a sufficient hedge to implement their projects, a suitable definition of the time terms is of vital importance:

  - "lag period", i.e. the time lapsing from the date the deliverability commitment is signed to the actual delivery date. Allowing the awardee investors sufficient time to build the generating unit after winning the auction (e.g., four years) is a key element.

  - contract duration, i.e. the duration in years of the commitment stemming from the auction (e.g. ten years).

- Regulators must also define a methodology to evaluate and take account of each generating unit's actual contribution to system reliability. Two very simple (and simplistic) criteria would be "installed capacity" [MW] or monthly energy production [MWh/month]. This definition, however, is usually based on a measure of the availability of units during critical periods when the likelihood of scarcity is highest. Hence the appearance of the concept "firm supply" which, depending on system requirements and the specific details of the incentive, is termed "firm capacity" (Spain), "firm energy" (Brazil), "adequacy capacity" (Chile) or even "efficient firm offer" (Guatemala).

These long-term auction-based mechanisms are intended to largely guarantee the investments required to maintain an adequate and stable generation reserve margin. Agents' bids, along with the quantity of "firm supply" defined by the regulator to be necessary to ensure future supply, determine the price of the reliability contract, i.e. the hedge that allows investors to make project financing feasible.

As noted above, mechanisms of this nature are already in place in a significant number of electricity systems[2], namely in Brazil, Colombia, Chile and Peru in Latin America and New England and PJM in the US[3].

***The need for models to analyze long-term security of supply auctions***

In this context, the ability to anticipate and analyze long-term investment dynamics is a key issue not only for market agents, but also for regulators. For the latter, analysis should support the auction design process, weighing the impact of the elements comprising the reliability contract (lag period, contract duration, optionalities, penalties, etc.). Contract terms and certain other characteristics of the mechanism, if not carefully designed, have been shown to lead on occasion to undesirable results.

From the market agents' perspective, the need for tools to support decision-making in connection with these auction mechanisms is evident. Simulation models are necessary in this new market framework to analyze the suitability of

[2] See (Batlle and Rodilla, 2009) for a detail enumeration and discussion of the mechanisms in place worldwide.

[3] No European market has yet implemented a solution of this nature, but Directive 2005/89/EC explicitly envisages resort to them by regulators if needed ('the possibility of imposing public service obligations on electricity undertakings, *inter alia*, in relation to security of supply').

investment in a new generating facility as well as to help define the most fitting auction strategies.

This paper describes a model developed to serve this purpose. A general methodology has been designed to analyze these long-term auction mechanisms in the formats presently in place.

The model is inspired by system dynamics methodology (Sterman, 2000). System dynamics is one of the modeling techniques that has been shown to successfully analyze the long-term dynamics of liberalized systems, particularly in terms of how new generation capacity enters the market. A number of approaches have been proposed for accommodating this theory to the long-term analysis of electricity systems, see for instance (Ford, 1997), (Ford, 2002) or (Bunn and Larsen, 1997). In particular, system dynamics-based models have been proven useful in identifying and characterizing the so-called boom-and-bust investment cycles that tend to characterize generating investment decisions in the absence of any additional adequacy regulatory mechanism. They have also been used to analyze the effect of regulatory long-term security of supply mechanisms as in (Bunn and Oliveira, 2001) or (Park *et al.*, 2007).

Secondly, section 2 contains a description of the main features of the model, which is inspired by the guidelines and basic structure of the approach set out by (Sánchez, 2009). Certain additional refinements of key importance have been developed to deal with the complexities stemming from the differences in electricity system structures and market and auction designs. In this regard, for instance a multi-scenario analysis tool and an approach to assess new hydro plants investments have been introduced in the standard model.

Lastly, section 3 illustrates the potential of the methodology with a real-size case study. This exercise analyzes the long-term results obtained when the model is used to simulate long-term generation expansion in the Colombian system, in the presence of Reliability Charge Auctions. The reason for choosing this particular case is that it is the widest ranging example available, for it combines a market structure in which several technologies compete to enter the system (hydro, coal, gas, fuel) with the most sophisticated auction design (aimed to deal with such technology diversity).

# 2 METHODOLOGY

## 2.1 Model overview

As mentioned, the aim of long-term auction-based mechanisms is to maintain investment at the level required to ensure an adequate and stable generation reserve margin. The *boom-and-bust* cycles that characterize generating investment decisions in the absence of any additional adequacy regulatory mechanism are therefore expected to disappear when such mechanisms are in place. By reducing the frequency of scarcity episodes, they also purpose to narrow price volatility. This does not, however, eliminate uncertainty altogether, by any means.

In this type of regulatory mechanisms market agents must still indispensably be able to estimate future market conditions in the presence of an auction-based security of supply mechanism. The ultimate objective for the regulator is to be able to anticipate the future structure of the expansion portfolio and predict system evolution. For market agents, in turn, the aim is to assess the profitability of their potential investments. It is in response to this need that forecasting tools can play an important role.

In light of the foregoing, a methodology has been developed in this study. Inspired by system dynamics, it also draws from a short-term game-theory model By simulating electricity market agents' interaction in the spot market, this latter model reflects their strategies as well as supply function building and market clearing and predicts future market conditions (prices and output).

As the initial simplified conceptual overview of the model in Figure 1 shows,. it consists of three distinct but inter-connected modules.

- The first, which concerns regulator decision-making, serves to assess the need to call an auction for new reliability contracts with generators to hedge future demand requirements. This module also determines the demand curve, i.e. the price-quantity curve calculated by the regulator on behalf of demand to reflect the utility function (the maximum value/price of the contracts to be signed).
- The second module calculates the generating companies (or GenCos) bid curves. This second module constitutes the core of the model and, as shown in the figure, embeds the game-theory spot market model used to simulate the short-term market.

- Finally, the third module calculates long-term auction matching and updates all the relevant variables (new generating units entering the system as a result of the auction, new debt issued by GenCos, etc.).

These modules are run sequentially on a year-by-year basis. Consequently, the cyclical process simulated includes determining demand requirements, assessing potential new investments, calculating the respective bids in the auction, and performing the clearing operation.

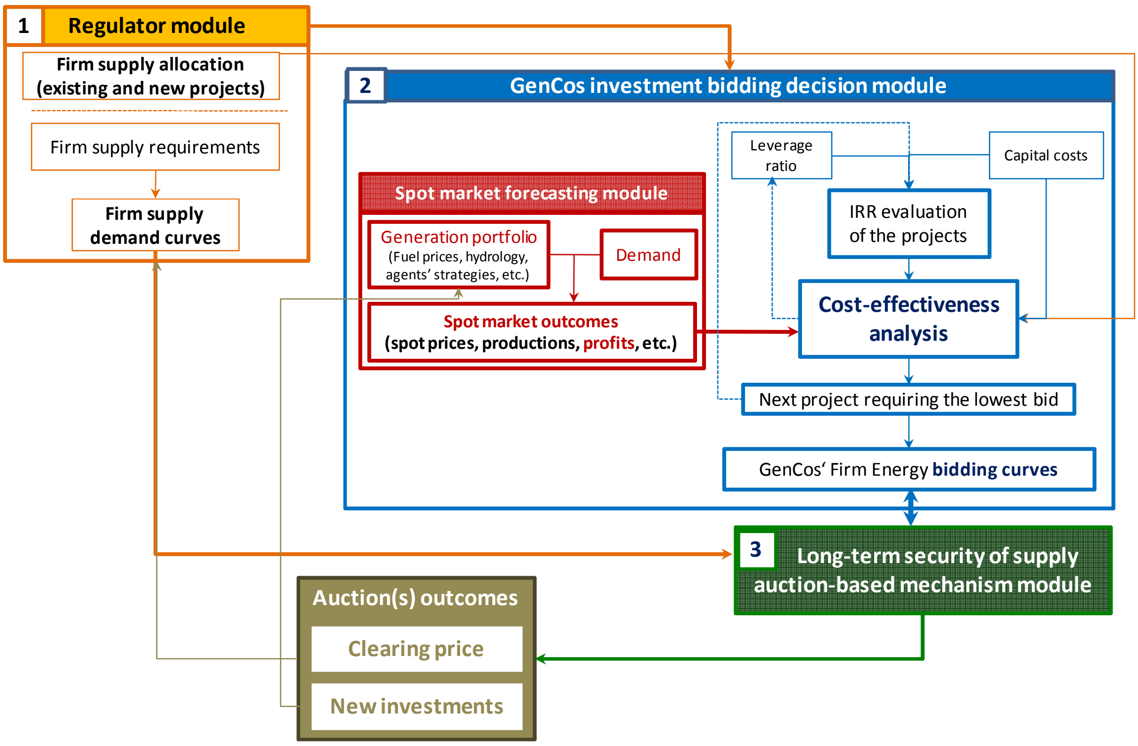


Figure 1. Model diagram

These three components are discussed in greater detail below.

## 2.2 The regulator module

### *The decision to call an auction*

The model performs this assessment annually (as regulators do in real life) bearing in mind the lag period defined in the contracts. The regulator calls a long-term auction to acquire the reliability product contracts needed (for instance: energy swaps, financial options or any other long-term instrument) to hedge the future supply of electricity. These auctions only make sense in the event of a negative imbalance between the quantity covered under reliability contracts in effect (from former auctions) and expected future requirements. In other words, if at any given time the regulator deems that the market, left to its own devices, is able to provide sufficient generation availability when needed, no auction is required.

### *Firm supply allocation criteria*

The firm supply assigned to each plant is the amount of the reliability contract[4] that the regulator regards each unit to be capable of providing under scarcity conditions, based on historical records or estimates of future values.

In the Peruvian system, for instance, the figure allocated to hydroelectric units is 95 % of total unit output during critical periods (assuming that the unit operates at full capacity seven hours a day every day).

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[4] For instance, energy produced in an hour in which the spot price exceeds a certain threshold, as in NE-ISO, or in a full day in the Colombian system.

***Reliability product demand curve***

After estimating future needs, i.e. the quantity to be purchased in the next auction, the regulator proceeds to calculate the demand curve.

In some systems (Colombia, NE, PJM, etc.) this curve is expressed as a piecewise linear function. A specific and indeed the simplest demand curve consists in merely determining the requirements and the so-called reserve price of the auction, such as in the long-term auctions held in the Peruvian system.

## 2.3 Investment bidding decision module

The four chief assumptions used to simulate the generator bid-building process are:

- First, from the generators' perspective, only two sources of income are considered: the spot market and the long-term security of supply auction. Other possible sources of income such as markets for ancillary services are excluded.
- Second, in the simulation new generating plants are implicitly regarded to be able to enter the system only after winning a long-term auction. Although under certain conditions a plant may recover both its operation and investment costs with spot market revenues only, it seems implausible that investors would waive the stable additional payment entailed in the security of supply mechanism.
- Third, generators' bids are calculated to obtain the so-called break-even point. In other words, bids are computed to fully recover the cost of capital plus an adequate rate of return. Therefore, strategic bidding (such as withdrawing

potential investments in new capacity) is regarded to be non-existent in long-term auctions[5].

- Fourth, all the investment costs associated with a new project are assumed to be financed exclusively by issuing new debt.

When modeling long-term dynamics under an energy-only market scheme[6], generation investments have usually been assumed to be driven primarily by the profitability expected from each project, typically measured in terms of the Internal Rate of Return (hereafter IRR). That approach obviously calls for an analysis of the expected cash flows throughout a project's life span. Under the long-term auction scheme, such a perspective does not apply because cash flows cannot be determined until the auction has been cleared. Here the traditional methodology is inverted: the IRR required by a new project is determined first, to subsequently back-calculate the bid that would ensure such profitability.

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[5] In the context of a long-term auction, the three main effects of strategic withdrawal of possible new investments are: first, prices rise during the auction; second, the spot market price is also higher because periods of scarcity are more likely; and third, these price hikes may ultimately encourage other competitors to invest. This third effect tends to offset the benefits deriving from mere price increases in the short-and long-term markets. The reason is clear: agents able to benefit directly from the withdrawal of investments may see their market share, and with it their former ability to exercise market power, shrink substantially (Sánchez, 2009).

[6] Although the term "energy only market" is somewhat vague, it is commonly used to refer to markets in which the regulator imposes no mechanism to guarantee a reliable supply.

***Internal rate of return (IRR) required of a new project***

The profitability that each agent requires of a potential new project is calculated with an empirical function that relates the IRR required to the company's leverage ratio (hereafter, the IRR function).

The characteristics of the IRR functions used in the model are shown in Figure 2, where the required rate of return grows with the company's leverage ratio. Note that the figure, identifies a critical leverage ratio that cannot be exceeded[7]. The function has to be adjusted for each agent separately to accommodate the differences in their respective investment potential (in view of their size and financial structure). The advantage of using empirical functions lies in their ability to represent most of the variables influencing companies' decisions simply and in a compact way.

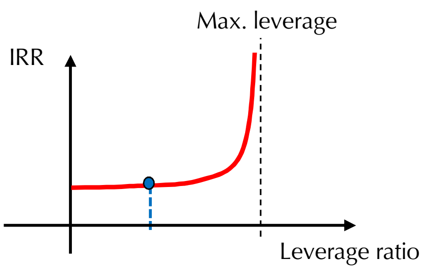


Figure 2. IRR function for a new project

In the simulation model this function is continuously updated to enable each company to assign a different IRR to each project submitted in any given auction, since undertaking a new project alters a company's financial structure.

[7] The strong theoretical support for such dependence can be explained by credit risk theory, see Sánchez (2009).

### *Representation of new projects*

Each potential new project has been characterized by a number of parameters, including: maximum capacity (MW), variable cost ($/MWh) throughout the simulation period, the firm supply value assigned by the regulator (MWh or MW, depending on the case), capital costs, construction period and life span and its unforced failure rate.

In the specific case of new hydroelectric projects, the expected monthly energy output (MWh) must also be entered in the model. Output is expressed as a linear function of the energy produced by hydro plants presently operational. The reason for adopting this approach is that data on the hydrological conditions historically prevailing at existing sites are readily available and are essential to computing future scenarios. In the model, several energy availability scenarios can be simulated in the same run.

### *Bidding curve algorithm*

Generators' bidding curves were built using the iterative procedure shown in Figure 3.

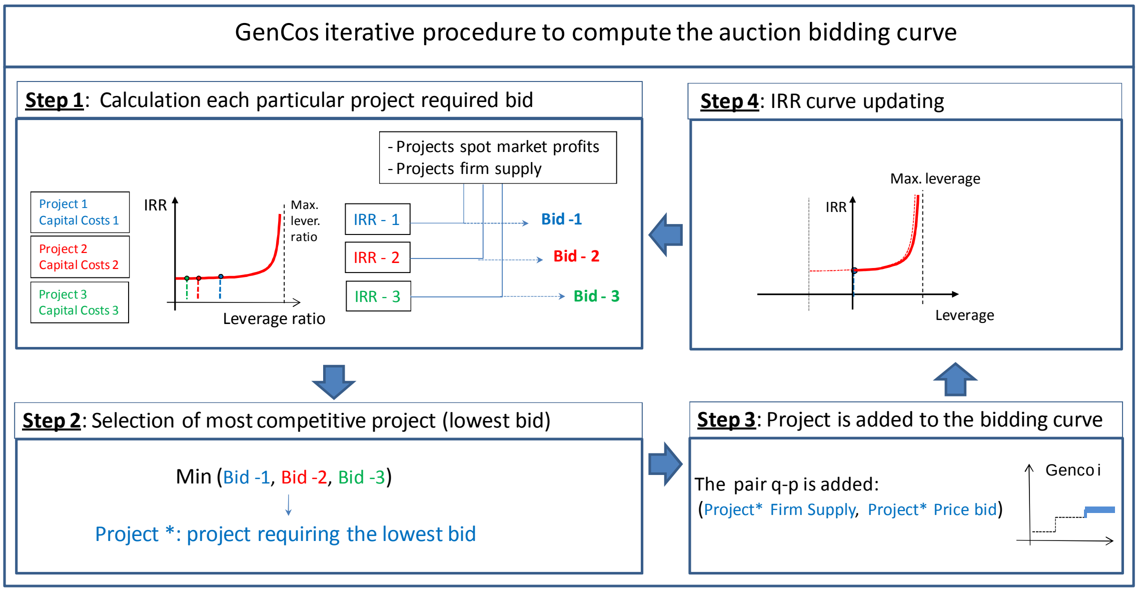


Figure 3. Iterative procedure for computing auction bidding curves

- Step 1: calculate the individual bids that ensure break-even for potential new projects.

  Each firm's IRR for its potential new projects is calculated on the grounds of its financial structure. This is done with the IRR function introduced above. The IRR value is used together with the cash flow expected from the spot market (computed using the game-theory simulation model described below) to determine the bids that would be submitted for the reliability contract.

- Step 2: identify the project with the lowest bid.

  The most competitive project, the one with the lowest bid, is the next project included in the bidding curve.

- Step 3: add the aforementioned project to the bidding curve.

  The firm supply for the most competitive project and its respective bidding price represent the next quantity-price pair on the generator's bidding curve.

- Step 4: update the IRR function.

  The IRR function is updated to take into consideration the rise in IRR attendant upon company investment in another project

The entire process is then repeated from the first step on for the project with the next lowest bid, and so on until all potential new projects[8] have been entered in the model or the critical leverage ratio (the maximum leverage ratio allowed for each company in the simulation) is reached.

***Short-term market income forecasting: spot market price module***

The spot market price is modeled using the SPCM (Strategic Production Costing Model) described in (Batlle and Barquín, 2005). This model further develops the classic Production Costing Model approach to more accurately simulate agents' strategies in a liberalized context by considering the slope of the residual demand function in bid building.

Compared to other oligopolistic models, the main advantage of the SPCM is its computational speed. This is a key feature in long-term modeling, where simulations are very time-consuming when several scenarios are computed. The three main characteristics of the SPCM model are:

- The expected demand in each period (e.g. week or month) is represented as a load duration curve.

[8] The number of projects in which a firm can invest per year can be limited. Such limits can be imposed on a technology-by-technology basis.

- The energy to be dispatched by the hydro units in each period is determined by an exogenous model that provides hydro output scenarios. Plants' production profiles in each period are calculated with an algorithm that peak-shaves the demand monotone[9].

  Although such hydroelectric dispatching constitutes perfect competitive behavior, hydro output is subsequently regarded (on a company-by-company basis) to be inframarginal production when calculating the strategic (oligopolistic) bids submitted by thermal plants.

  Each hydro plant's maximum (and also minimum) output is calculated as a function of the weekly power produced. Historical data are required to calibrate such functions.

- The thermal units are ranked along the monotone by order of merit on the basis of their bid prices. These bids are calculated by internalizing the slope of the residual demand to be faced by each agent, considered as an exogenous variable in the SPCM model.

[9] The peak-shave algorithm is applied to the equivalent demand monotone. This equivalent demand is calculated by summing the power demand and the energy corresponding to non-available units submitting bid prices below the resulting system's marginal price. This serves to show that identical load levels may lead to different marginal prices due to thermal plant failures. Unit availability is computed on a time block-by-time block basis (where each time block consists of10 hours of similar demand over the monotone).

The market model is run for different values of two uncertain variables that play a key role in price formation in hydro-thermal system markets: the hydrological scenario and thermal plant availability (using Monte Carlo).

### 2.4 Auction module

Once both the demand and the bid curves for the generating companies are plotted, the auction is cleared. The information delivered by this module is, on one hand, the price to be paid (the auction marginal price) and on the other, the awardees, i.e. the new investments entering the system.

After simulating the auction, each GenCo leverage ratio must be updated. The IRR curve is thereby modified to provide for future assessments. The new plants must be entered as part of the generation mix in the system in accordance with the lag period established in the regulations.

## 3 LONG-TERM SIMULATION OF THE COLOMBIAN AUCTION-BASED SECURITY OF SUPPLY MECHANISM

This section describes a full-scale simulation designed to study the expected growth trend in Colombian generation capacity in the next few decades in the presence of an auction-based security of supply mechanism. The discussion first addresses the main elements of the regulatory design, then the input data defining the scenario considered and finally the results and chief conclusions.

## 3.1 Ensuring long-term resource adequacy in the Colombian system: a brief description of Reliability Charge Auctions

So-called Reliability Charge Auctions were introduced in Colombia in 2006 (the first auction was called in May 2008). The mechanism ensures generators a fixed payment in exchange for producing in critical periods (also known as scarcity periods) at a pre-established or strike price. Since a period is defined to be critical whenever the spot price exceeds the strike price, the reliability contract (called the Firm Energy Obligation) implies a commitment that adopts the form of a financial call option.

If the generator fails to comply with the production committed to in such periods, it must purchase energy on the spot market (to make up for the shortage created by its failure to comply with the commitment acquired). Thus, the incentive to be available during tight conditions is high, for the mechanism institutes an implicit penalization for non-compliance.

Both the generators that receive such payments and the payments themselves are determined by market forces in a public auction. The quantity (the total amount of Firm Energy Obligations) to be purchased in the auction, i.e., the amount of power that would have to be produced whenever a critical period is declared, is determined by the regulator (acting on behalf of regulated demand).

Prior to the auction, the regulator certifies the maximum quantity that each unit is entitled to offer and hence to commit to undercontract. This ceiling, previously referred to as firm supply and here as Firm Energy for the Reliability Charge[10], is calculated on the basis of preset rules and algorithms that are laid down by the regulator.

The auction is held four years (the lag period) before the power commitment may be enforced by the regulator. The Energy and Gas Regulatory Commission (CREG) must determine the existence or otherwise of an imbalance between the Firm Energy already contracted (in former auctions) and the expected demand for the year evaluated. Where this imbalance is negative, the Regulatory Commission announces its decision to call an auction.

The conditions applicable to each unit depend on its characteristics:

- Existing plants: plants already in operation at the time of the auction. The term of the contract in this case is just one year, and these plants may neither set the price nor be withdrawn during the auction (unless the auction price sinks to below a given threshold).
- New plants: plants whose construction has not begun at the time of the auction. The term of the contract may be up to 20 years. These units submit quantity-price bids and consequently determine the marginal clearing price stemming from the auction.

In Colombia, most new large-scale hydro projects need more than four years to become fully operational. To enable such projects (known as GPPS projects) to

[10] In Spanish "Energía Firme para el Cargo por Confiabilidad" (ENFICC)

participate in the mechanism as new entrants, special conditions are applied. After a standard auction is held, a second auction is called for these GPPS projects, which are eligible for lag periods of up to eight years. This auction is subject to a reserve price (a price cap), which is the clearing price established in the standard auction[11].

A comprehensive description of the rules governing the Reliability Charge mechanism can be found in CREG (2006), XM (2008) and XM and BBVA (2007).

### 3.2 Definition of scenarios

The simulation studied spot market and Reliability Charge Auction trends across a 25-year horizon, starting in 2010. Auction periodicity was assumed to be fixed, with all standard auctions being called annually.

The Firm Energy demand function (see Figure 4) was based on the definition of two parameters, M1 and M2, regarded to remain constant throughout the simulation period. The CONE (cost of the new entrant) was updated after each auction was cleared in accordance with the formula provided in the regulation, i.e., as the weighted value of the last CONE considered and the auction clearing price.

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[11] The sequential nature of these two auctions was taken into account in the simulation to enter all the information deriving from the standard auction (new investments and resulting price) in the GPPS auction. Certain simplifications were introduced with respect to these auctions: all the potential GPPS entrants were assumed to be granted the same lag period (8 years) and the same contract term (20 years).

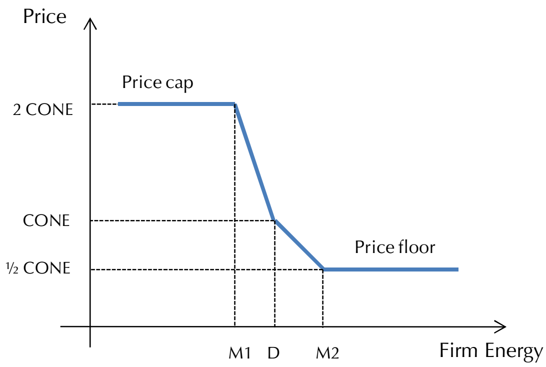


Figure 4. Firm Energy demand

Demand growth was assumed to be as forecast by the Mining and Energy Planning Unit (UPME, 2008). As shown in Figure 5, Firm Energy Obligation demand targets are assumed to follow a similar pattern.

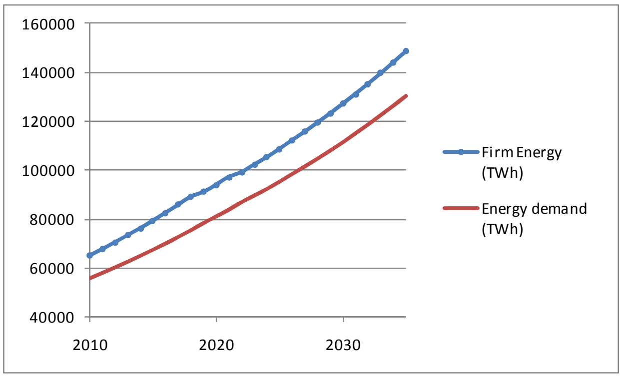


Figure 5. Expected energy demand and reference values for the Firm Energy Obligations to be purchased by the regulator

The ratio between maximum and average demand was regarded to rise at a yearly rate of 3%.

The fuel price series followed the baseline scenario described by the Energy Information Administration (EIA, 2008). Fuel price trends are shown in Figure 6. No additional environment-related costs were entered at any time in the simulation period.

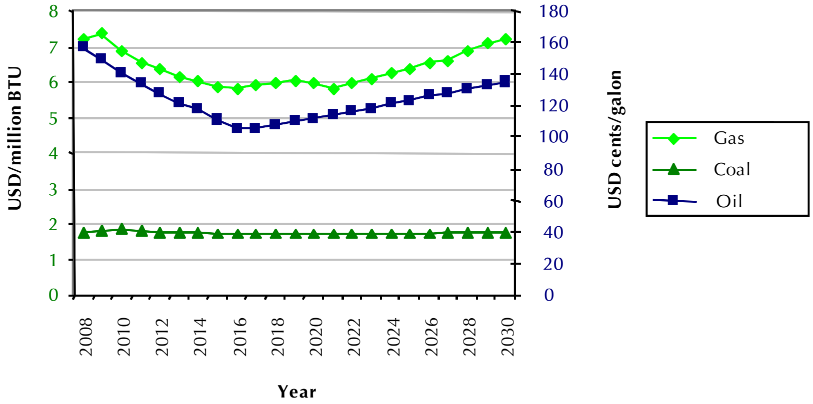


Figure 6. Fuel price forecasting scenario (source: EIA baseline scenario)

When modeling the Colombian electricity market, it is of utmost importance to reflect the system's heavy dependence on the availability of water resources. Moreover, the presence of severe (and difficult to predict) droughts during phenomena such as the El Niño-Southern Oscillation, plays a relevant role in investment decision-making. Three hydro resource scenarios were considered to take account of such hydraulic variability.

Expected yearly production for the hydro plants already installed in 2010 in the scenarios studied is shown in Figure 7.

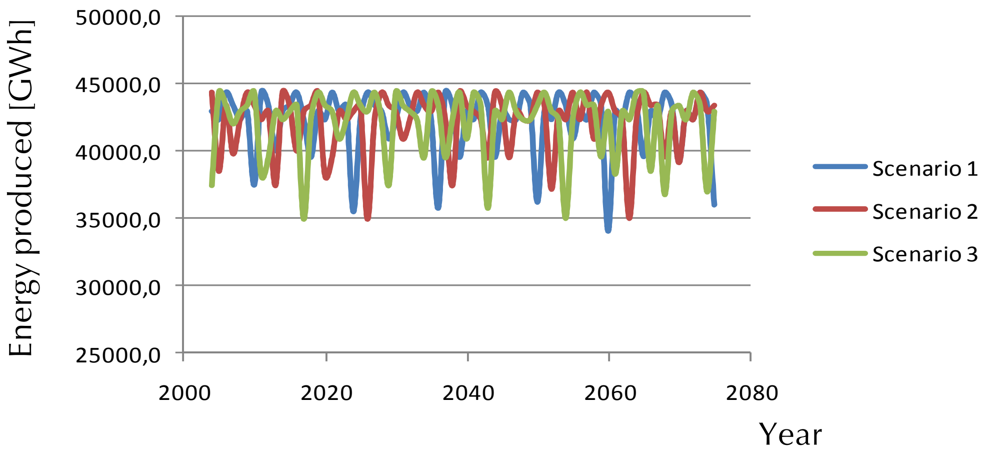


Figure 7. Hydrology data used in the simulation

The annual production of hydro power plants to be installed after 2010 was expressed as a linear function of the output of the plants already operating in the first year of the simulation (see Table i).

Table i. Coefficients for the linear function determining new generation investments

| | ALBAN | BETANIA | CHIVOR | CALIMA | GUATAPE | GUATRON | GUAVIO | MIEL | JAGUAS | TASAJERA | PAGUA | PLAYAS | PORCE II | PRADO | SALVAJINA | SAN CARLOS | URRA | Constant |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Medium size project | 0 | 0 | 0 | 0 | 0,030 | 0,030 | 0 | 0 | 0,030 | 0,030 | 0 | 0,030 | 0,030 | 0 | 0 | 0,030 | 0 | 0 |
| Amoya | 0,051 | 0 | 0,019 | -0,047 | -0,020 | 0 | 0 | 0 | 0 | 0 | 0,126 | 0 | 0,014 | 0 | 0 | 0 | 0 | -15,860 |
| Sogamoso | 1,386 | 0 | 0,192 | 0 | -0,951 | 0 | 0 | 0 | -2,164 | 0 | 0 | 0 | 0 | -3,021 | 0 | 0,858 | 0 | 47,120 |
| Pescadero | 3,078 | 0 | 0,398 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,020 | 0 | 0 | 269,800 |
| Quimbo | -0,191 | 0,507 | 0,024 | 0 | 0 | 0,106 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,161 | -18,816 |
| Cucuana | 0,124 | 0 | 0,021 | -0,060 | -0,022 | 0 | 0,008 | 0 | 0 | 0 | 0 | 0 | 0 | -0,152 | 0 | 0 | 0 | -0,508 |
| Porce4 | 0 | 0 | 0 | 0 | 0,097 | 0 | 0 | 0 | 0 | -0,043 | 0,308 | 0 | 0,722 | 1,466 | 0 | -0,102 | 0 | -27,115 |
| Miel2 | 0,346 | 0 | 0 | 0 | -0,054 | -0,093 | 0,019 | 0 | 0 | 0 | 0 | 0,206 | 0 | 0 | 0 | 0 | -0,131 | 28,193 |
| Andaquí | 0 | 0 | 0,159 | 0 | -0,236 | 0,860 | 0,099 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0,144 | 0 | -22,720 |
| El Neme | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fonce | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cabrera | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Porce3 | 0 | 0 | -0,036 | 0 | 0,2019 | 0,718 | 0 | 0 | 0 | 0,319 | 0 | -1,052 | 1,155 | 0 | 0 | 0 | 0 | 3,010 |

The model calculated short-term spot market prices for a 40-year horizon. The first 10 years were computed directly with the spot market model, while all subsequent years' prices were estimated with an interpolation function in which prices were made to converge on the very long-term system prices. These very long-term prices were also calculated with the short-term model, assuming a perfect competitive environment and the generating mix shown in Figure 8.

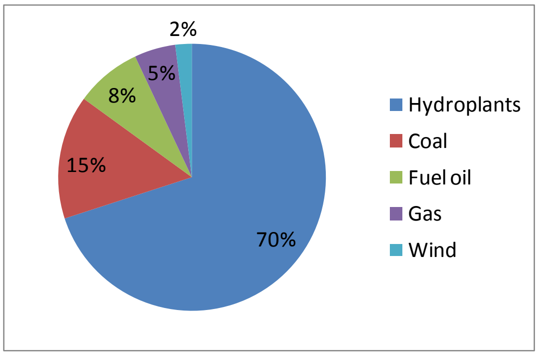


Figure 8 Very long-term generating mix

The expected evolution of the generating mix must also be roughly estimated for the spot market simulation. This roughly estimated growth was assumed to be the same for all market participants. The expected expansion hypothesis was updated after each auction to include the information on the latest investments.

The new projects evaluated included coal, fuel-oil, wind and hydro plants (of different sizes and in different locations[12]). The information on plausible future investments was taken from UPME (2008) as well as from a number of firms' expansion plans. The data on small-scale projects are given in Table ii.

Table ii. Small-scale project characteristics

| Project | Construction period | Life Span | Capacity (MW) | Investment cost (M€/MW) | Variable cost (€/MWh) | Average availability factor | ENFICC (GWh/Year) |
|---|---|---|---|---|---|---|---|
| Fuel-oil | 3 | 20 | 200 | 140 | 59 | 0,85 | 1577 |
| Coal | 3 | 20 | 325 | 400 | 22 | 0,95 | 2800 |
| Medium size hydro plant | 3 | 40 | 120 | 122 | 0 | 0,55 | 250 |
| Wind | 3 | 30 | 150 | 290 | 0 | 0,4 | 262 |

The possible entry of new generating companies in the business was not contemplated because several small companies with growth potential and characteristics similar to the features typical of a new entrant are in fact presently operating . Each firm was modeled in accordance with the function that relates the IRR required of a new investment to its financial structure (debt-to-equity ratio).

### 3.3 Calibration of the spot market model

The parameters used in the spot market model were adjusted using historical market data. The agents' strategic behavior was calibrated to match market data

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[12] The location affects hydro inflows.

for 2007. The average monthly prices obtained with the calibrated model and actual market prices are plotted in Figure 9.

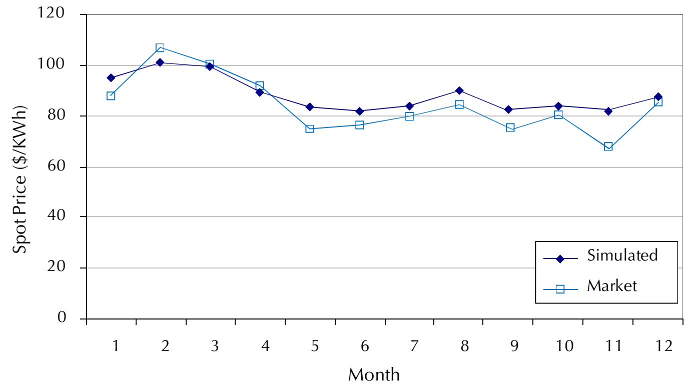


Figure 9. Mean simulated and market prices for 2007

The accuracy of hydro plant dispatch modeling (i.e. the peak-shaving algorithm) was also verified. Figure 10 shows simulated and actual dispatching for two months. While the accuracy of the approach may differ from one period to another, the trend was always fairly well reflected.

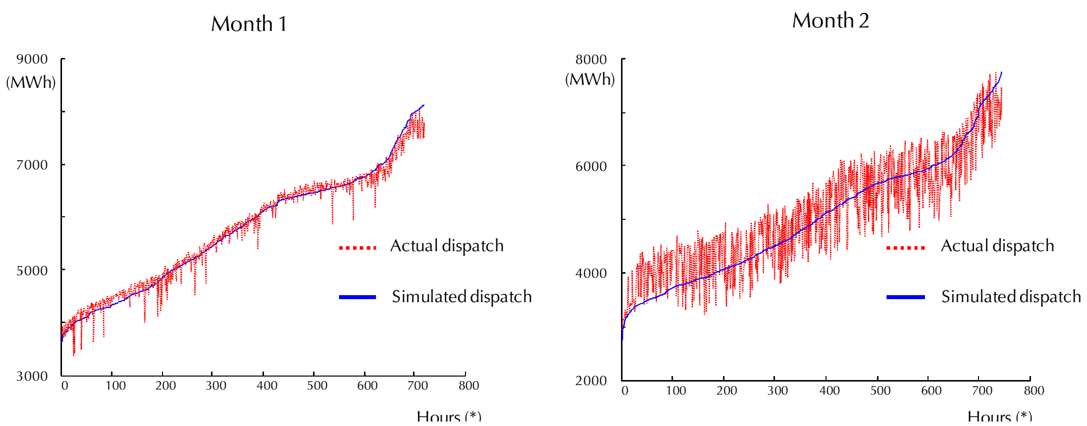


Figure 10. Verification of the suitability of the hydro plant dispatching hypothesis

## 3.4 Simulation results

The result of agents' investment decisions is plotted in Figure 11. Since the negative deviations from the regulator's Firm Energy targets were relatively small (see the graph on the right), the mechanism clearly fulfilled its main objective, i.e. to ensure sufficient long-term generating resources.

The mechanism in fact provided for a more stable investment scenario, in which boom-and-bust cycles were almost non-existent. Nevertheless, an analysis of the technologies entering the system in each year (graph on the left) revealed that each technology was subject to an investment cycle. In other words, the most profitable technology varied across the period simulated.

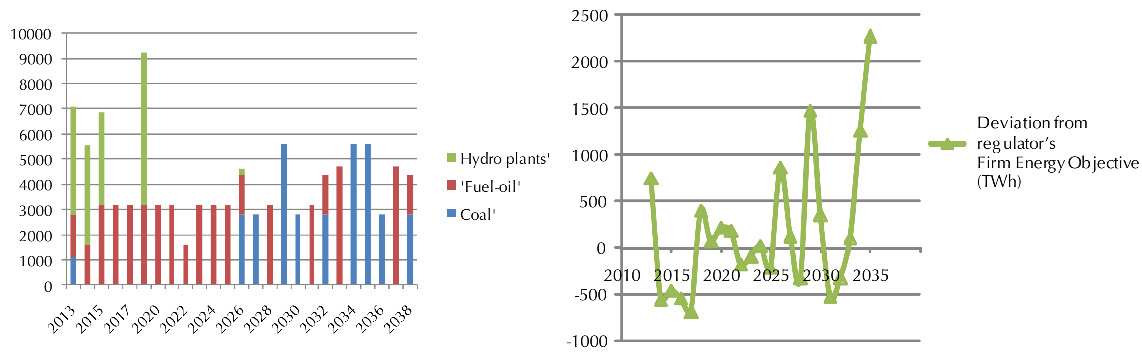


Figure 11. New investment trends

These cyclical investment trends can be explained by effect of the entry of new plants on both market prices and companies' financial structure.

***Investment cycles***

Model computations for some of the simulated years are discussed below to illustrate the long-term dynamics simulated by the investment decision module. The objective is to show how expected market income and the required IRR (which depends on each company's financial structure) determine the optimal investment.

The expected market cash flow for a given plant can be used to calculate its annualized payment (the premium resulting from the bidding price) required to fully recover its investment costs. This premium (expressed in $ per MWh of Firm Energy) was plotted versus the required IRR for some of the simulated years and for all the technologies studied (see Figure 12).

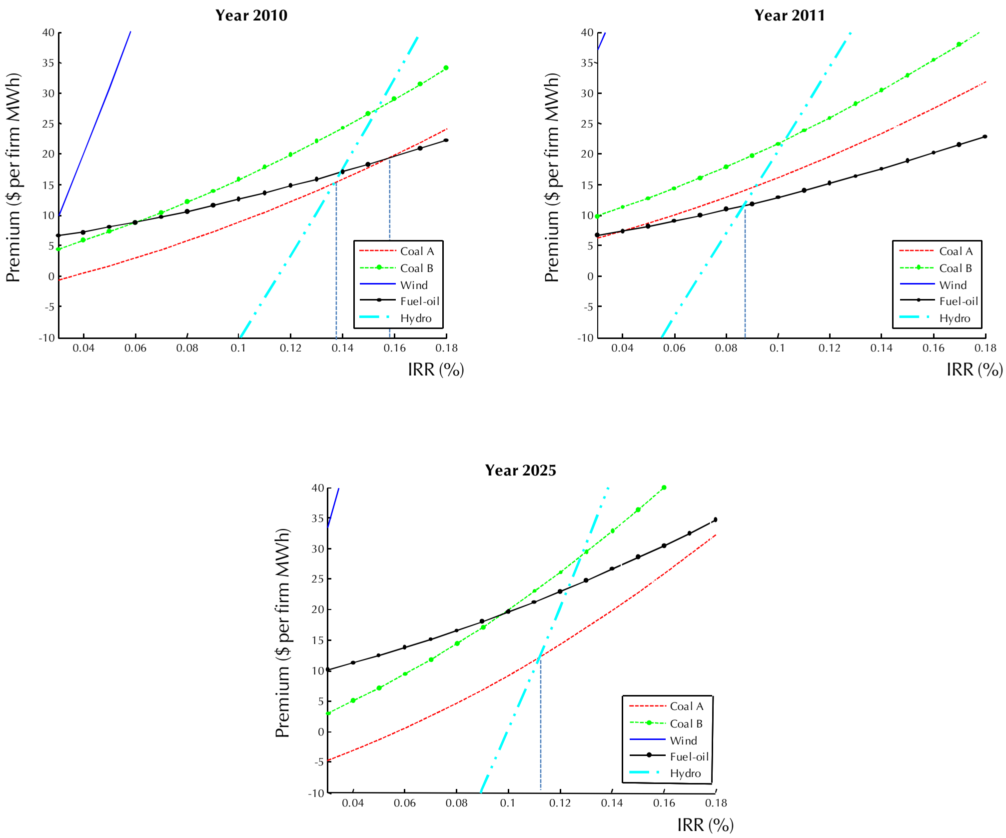


Figure 12. Premium by technology vs IRR

Although the required IRR typically ranged from 10% to 14,5%, depending on the company and its leverage ratio, in the first year of the simulation (upper-left graph in Figure 12) hydroelectric plants constituted the most profitable investment for most of the firms studied (followed first by coal-plants and then fuel-oil-fired plants). Remarkably, for certain values of the IRR the spot market prices ensured full recovery of investment costs.

Since a considerable amount of new hydro energy was committed in the first auction, spot prices could be expected to decline in subsequent periods. This led to an entirely different situation the following year (see the upper-right graph in the same figure). Note that coal-fired plants were never the most profitable technology regardless of the internal rate of return required of a new project, while fuel-oil was the optimal technology for almost the full range of IRR values.

The entry of fuel-oil plants in subsequent years caused a rise in spot prices, and as a result the reversion of the investment curves to the initial situation (see the lower graph in the figure). Under these circumstances, the expected variation in fuel prices, coupled with the expected spot market prices, made coal-fired plants the most competitive technology within the range of IRR values in question.

***Regulatory intervention***

Although this market-based mechanism has been claimed to leave the determination of the most profitable technology entirely in market agents' hands, there can be no question that certain regulatory decisions largely condition the final results[13].

In the present case study, the aforementioned results would be significantly modified if the criteria for allocating the ENFICC were slightly different for hydroelectric plants. By way of illustration, the ENFICC allocated to new medium-size hydro plant projects was raised from 250 GWh to 350 GWh, a value that is

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[13] For a general discussion of this issue see (Batlle and Rodilla, 2009), in which a number of examples are given in a broader context.

still well below the average expected plant output. The entry of new Firm Energy (GWh) under this hypothesis is graphed in Figure 13, which shows the increase in the hydro power plant share compared to the baseline scenario presented above.

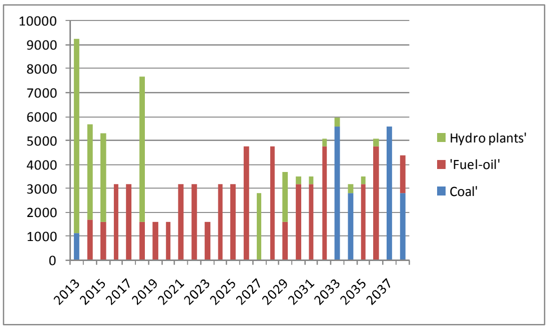


Figure 13. Entry of new investments in terms of Firm Energy

# 4 CONCLUSIONS

A brief description of the long-term auction-based security of supply mechanism was followed by the introduction of a methodology to simulate generation growth dynamics in such a context.

The simulation tool developed can be regarded to be a system dynamics-inspired model, that draws from a strategic production cost model (Batlle and Barquín, 2005) to better represent agents' interaction on the short-term spot market.

A full-scale simulation based on the Colombian system was developed to illustrate the capabilities of the model. The hydro-dominated Colombian electricity system is subject to variable hydraulic resources (due to the presence of difficult-to-forecast cyclical climate phenomena such as El Niño).

The findings led to a number of interesting conclusions:

- The present mechanism, the so-called Reliability Charge, clearly fulfils its objective of capturing new investment resources for generation. Indeed, the Firm Energy installed during the period studied tracks the regulator's objectives very closely. The price cap and the definition of the demand curve entail no entry barrier for the investments needed to meet Firm Energy requirements.
- The mechanism ensures a more stable investment environment. Nonetheless, investment cycles for each technology can be clearly identified. These cycles are occasioned by the delayed response that usually characterizes long-term investment dynamics. For example, high spot prices are a magnet for hydro plants, leading to a spot market decrease in subsequent years and changing the long-term signal conveyed by the mechanism.
- Although this market-based mechanism is purported to leave the decision on the most profitable technology entirely in market agents' hands, certain regulatory decisions are bound to condition the final results. The example given here shows that the results may vary significantly if the criteria for allocating the ENFICC were less strict for hydro plants.

Electric power system regulation is currently pursuing the optimal balance between free market initiative and centralized (sometimes called indicative) planning, see (Pérez-Arriaga and Linares, 2008). In this context, the scope for security of supply mechanisms is broadening for they should enable regulators to recover some control over the future development of their electricity systems. As a result, simulation tools such as the one discussed in this paper, able to jointly address financial criteria, economic dispatching and regulatory design for full-scale case studies, will acquire major significance in the near future.

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