A tool for hydro energy scheduling and bidding in the Spanish framework

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ABSTRACT

The paper describes a unified approach for maximizing the contribution margin of each company and simultaneously determining the production of hydro units by using a stochastic nested decomposition algorithm. This approach allows keeping all the system operation details while defining the strategic or marginal behavior of the companies. Modeling characteristics of hydro units depends on the generator ownership. The internal hydroelectric reservoir chains are represented in fully detail while external hydro plants are aggregated into subsystems. The main results of the model are hydro energy quantities for the different time steps from long, medium and short-term. At the closer step this quantity is transformed by a postprocessor module into energy and price offered by each generator for each hour of the next day to be sent to the market operator.

INTRODUCTION

A restructuring of the electric energy sector all around the world is underway. Spain also is currently immersed in deep changes with a completely new regulatory framework that begun in January 1998. The Law Act [BOE, 97], already approved, establishes among other issues a day-ahead wholesale trading pool for selling and buying energy. A Market Operator (MO) determines the actual operation of the generating units, based on a simple hour by hour merit order of their bids. These are simple bids with all fixed operating costs adequately internalized[1]. The market clearing price is set hour by hour by the highest accepted bid. Different procedures have been studied to achieve the

[1]In fact it exists the so called "income constraint" which can voluntarily accompany each generation unit bid, which sets a minimum daily income for a bid to be accepted.

clearing process. All of them impose as a requirement the resulting dispatch to be technically feasible.

The former generation economic regime was an incurred costs revenue scheme based on standard costs, so that it already existed some incentives to operate efficiently, since minimizing the actual costs will mean greater profits. However, it was the System Operator (SO) who centrally dispatched the units in order to achieve the total variable costs minimization. So far, REE, owner of the high voltage transmission network, was acting as the SO and was responsible for deciding the optimal generation scheduling in the Spanish system. They used hierarchically a chain of different tools with several time horizons to achieve this purpose. The hydro scheduling for short, medium and long terms as well as all the technical constraints of thermal units were considered in this chain of models.

However under the new framework, electric firms assume much more risk, becoming responsible for their own decisions. In particular they now have to estimate their own unit commitment in order to decide, based on costs, prices and quantities, the bids that they will finally submit to the MO. So each electric company decides which amount of capacity should be offered for each hour and what the price should be. These bids will determine the actual operation of their units and their incomes. Therefore, utilities need models that fulfill their new requirements.

The answer to this problem is especially difficult for hydro units. So, currently, the electric companies are facing the need of developing new hydro scheduling tools for this purpose, that previously was partially done by the SO. The purpose of these models is twofold. On one hand, they have to consider in detail the technical operating constraints of the system and obtain the scheduling of stochastic hydro inflows. On the other hand, they must model the new competition framework with a completely new objective function, to maximize the firm’s contribution margin (revenues minus operating costs), instead of minimizing variable costs of the system. At the same time, these medium-term tools interact with short-term tools for bidding purposes.

The tool presented here is aimed at solving the contribution margin maximization problem including the scheduling of stochastic hydro inflows. Hydro scheduling is solved by the state of the art stochastic nested Benders decomposition (also called dual dynamic programming). Profit maximization is stated as an optimization problem subject to equilibrium constraints, where Cournot equilibrium represents the behavior of different competitors.

The organization of the paper is as follows. Firstly, it is presented a general overview of the model with all their functions. Afterwards, the modeling approach of hydro units is presented. Then, the hydro scheduling algorithm is depicted showing the way the contribution margin maximization has been incorporated into a traditional production model. Finally, a bidding module for hydro energy is described.

OVERVIEW OF THE MODEL

The beginning of a regulatory framework has given the opportunity to develop new models from scratch. A novel approach has been adopted in this development. A unique and integrated computer model implements all the main functions that hierarchically define the operation of the units in the following times steps:

- Long-term (a year)

  Annual budget and yearly productions for all plants are the main functions within this time horizon and the subsequent monthly updates.

- Medium-term (several months ahead)

  All the information regarding inflow stochasticity can be fully incorporated into the model at this time step because time dependencies of natural inflows usually are one or two weeks long. Hydro scheduling at this level defines policies regarding the amount of water to be offered during the next months.

- Short-term (a day-ahead)

  Capacity bidding of the units is done at this level in an hour by hour basis. Different tactics can be exploited at this level.

One of the main characteristics of this model is flexibility, allowing different types of use. For example, it can be thought as a short-term unit commitment model or as a long-term strategic model for yearly economic planning, where the representation of the electric system changes dramatically. In the short-term a period is a day and a load level is an hour while in the long-term corresponds to a month and peak, shoulder and off-peak hours, respectively. Advantages of having only one model are, for example, coherency in the origin and elaboration of data, use of similar mathematical methods, and convenient presentation of the results.

The foundations of the model are the decisions about quantities to be offered at the different time steps in order to maximize the contribution margin of the company. This objective is embedded in all the previous levels. Quantity represents a natural and familiar unit for trading and operation people. It is the way they use to understand the operation of the system. So quantities are coherently passed down from the yearly predictions to the hourly bids for the next day.

The model has been coded in the GAMS algebraic modeling language [Brooke, 96]. This high level language allows a powerful, fast and compact implementation of optimization problems.

The model is being used to represent the Spanish electric energy system. In order to present the size and complexities of the system some data extracted from 1996 statistical records are given next. The system met a maximum peak load of 25357 MW and a yearly energy demand of 140936 GWh. The installed generation capacity is 42859 MW (13879 MW are storage hydro, 2670 MW of pumping hydro, 10674 MW of coal, 8214 MW of oil/gas and 7422 MW of nuclear).

There are about 81 thermal generating units (9 nuclear, 36 coal and remaining oil/gas). Their production is about 80 % of the total generation.

There are 86 hydro units with capacity greater than 5 MW and annual energy production greater than 100 GWh, which can be grouped into about 9 basins. There are many other smaller hydro units. The maximum capacity at the same hydro plant is 915 MW. All they produce about a 20 % of the total production as an average, ranging from 15 to 25 % depending on the hydrology.

There are 8 pumped-storage units, but their impact on the annual energy production is minimum (about 1 %).

HYDRO MODELING

On one hand, hydro subsystems can play a significant role in the new competitive framework due to their flexibility. On the other hand, storage hydro modeling is the most challenging because of two main reasons. One is the intrinsic complexity of hydroelectric chains and the other is the availability of data regarding plant characteristics and reservoir inflows of the competitors. In the former regime all the data about hydro plants were publicly known or at least were known by the SO. In the new regime only the data regarding the hydro plants of the own company will be available. Those of the competitors will be known only approximately in the future.

Because of these reasons two modeling approaches are used for storage hydro plants:

- Inflows and reservoir volumes of hydro subsystems of the competitors are scheduled in energy units (GWh). Even the scheduling can be avoided and energy productions can be directly extrapolated from the past operation by using probabilistic distribution functions.

- Own hydro subsystems are modeled at the maximum level of detail. That is, with the hydro physical network including reservoirs, river beds, canals, spillways, etc and representing inflows and reservoir volumes in natural units (for example in m^3/s and Hm^3 respectively).

By using this representation the most detailed results are obtained for the own hydro subsystems and only approximated and aggregated results are determined for hydro subsystems of the competitors.

HYDRO SCHEDULING

The previous model performs hydro scheduling, seasonal operation of pumped-hydro units, weekly/daily operation of pumped-storage units, and thermal unit commitment for the generation system. It is formulated as a large-scale linear optimization problem where many scenarios represent the stochasticity in water inflows. This medium-term hydro scheduling algorithm is solved by stochastic nested Benders decomposition techniques, as in references [Jacobs, 95], [Morton, 96], [Pereira, 91].

The *objective function* to be minimized is the total variable costs for the scope of the model subject to operating constraints. These can be classified into inter and intraperiod constraints, according to the periods that are involved in. *Interperiod constraints* are associated to the coordination in the use of limited resources (hydro inflows, and seasonal pumping, storage and generation). *Intraperiod constraints* deal with the system operation in each period (balance between generation and demand, thermal unit commitment, weekly/daily pumping, storage and all the generation limits). This stochastic scheduling capability has been an extension to a previously production cost model, see [Ramos, 95] and [Martínez-Córcoles, 95].

The nested decomposition algorithm breaks the interperiod constraints. It solves iteratively each subproblem, which corresponds to the system operation in one period. For any iteration it is done one pass from the first to the last period and vice versa. In the forward pass the state of each hydro reservoir is decided in each subproblem (father) and passed to the following ones (children). In the backward pass it is sent the dual information required for building a Benders cut. Stochastic water inflows imply that each father may have several children with different associated probabilities.

Schematically, this classical production model is stated in Figure 1, considering only the white areas. The introduction of market equilibrium constraints implies only some minor modifications to the previous intraperiod constraints of the optimization problem. Their purpose is to incorporate the maximization of the contribution margin of each firm into the classical minimization problem while keeping all the system operation details. The shaded areas correspond to the constraints introduced. Therefore, the same decomposition algorithm is used.

Traditionally, hydro plants have been scheduled to minimize the generation costs of the thermal units. Hydro units were used to equalize the system marginal costs over the time span considered. When maximizing the contribution margin of the company an important result achieved is that hydro units equalize the firm’s marginal costs.

Minimization of

Sum for each period, subperiod and load level[2] of total variable costs
+ non served demand costs

Subject to

Interperiod operating constraints
• Hydro scheduling including seasonal pumping

Intraperiod operating constraints
• Balance between generation and served demand
• Weekly pumping
• Generation limits
• Other operating constraints
• Equilibrium constraints
• Marginal revenues equal marginal cost for each firm
• Variable cost of each firm as a function of the committed units
• System marginal price (SMP) as a function of the demand

Figure 1. Schematic representation of a production model.

An important change is the introduction of the elasticity of the demand, i.e., the response of the demand to the energy price. In classic production cost models the demand was inelastic and had to be met. Now the equilibrium quantity is obtained by maximizing the total surplus defined as the sum of consumer's and producer's surplus. In fact, maximizing the total surplus is exactly equal to minimizing the area below the supply curve on the left of the equilibrium quantity (accepted generation) and below the demand curve on the right of this quantity (i.e., non served demand), see Figure 2.

The contribution margin for a certain load level is calculated as the difference between revenues and costs. Revenues are calculated as the SMP times the energy produced by the firm minus its variable costs. The profit maximization problem for each company is formulated as the objective function of the firm contribution margin subject to all the operating constraints. This problem can be solved by constructing the Lagrangian and then formulating the Karush-Kuhn-Tucker first order optimality conditions. However, we can neglect the Lagrangian terms associated to the operating constraints (because they

[2] The model scope is divided into different time intervals denominated periods, subperiods and load levels.

will also be met by the production cost problem) and then the equal sign of the optimality conditions is replaced by a greater or equal than.

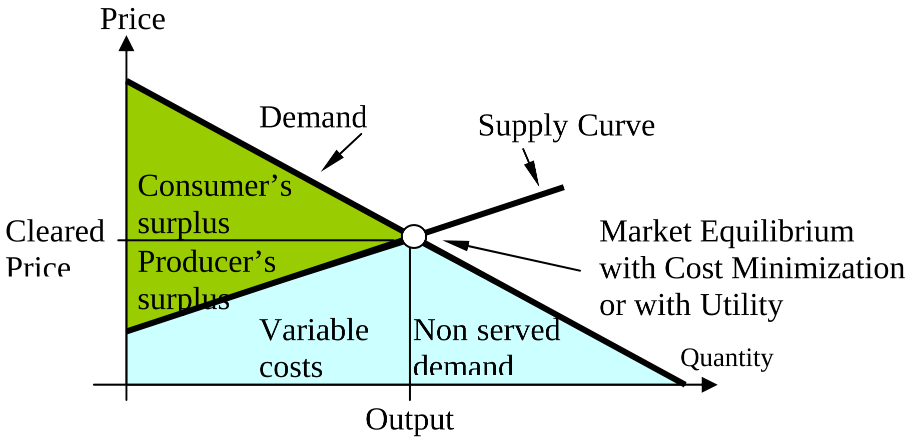

Figure 2. Direct utility function.

Therefore, for each firm in each load level the derivative of the contribution margin with respect to the power generated by the firm is

$$SMP + P_i \frac{\partial SMP}{\partial P} - MC(P_i) \geq 0$$

Where P_i is the generation of the firm i, $MC(P_i)$ is the marginal cost as a function of P_i, $\partial SMP / \partial P$ is the change in the SMP due to a change in the capacity of the firm, corresponds to the slope of the demand curve, that is negative.

The two first terms of the constraints are the marginal revenues of the firm and the last term corresponds to the marginal cost. So the equation meaning is,

$$\textit{marginal revenue} \geq \textit{marginal cost}$$

Also this equation can express the maximum generation of each firm is willing to make to maximize their profits as a function of the SMP, its marginal cost and the slope of the demand curve

$$P_i \leq \frac{SMP - MC(P_i)}{-\partial SMP / \partial P}$$

An ascending stepped function represents the firm's marginal cost as a function of its own generation. The steps represent the variable (fuel, consumables and operation and maintenance) costs of the different committed generating units. Then marginal cost of each firm is greater than any variable cost of a committed unit, and can be expressed as a function of the commitment binary variables:

$$MC_i \geq v_g a_g \quad \forall g \in i$$

Where MC_i is the marginal cost of firm i, v_g is the variable cost of unit i and a_g is the commitment state of unit g.

The market-clearing price, system marginal price, is represented by a linear function of the electricity demand, but simultaneously in the objective function is transformed into a descending stepping function (with the slope of the linear function) where each step is a fictitious demand bid.

$$SMP = SMP_0 + \frac{\partial SMP}{\partial P} \sum_i P_i$$

The above model should be used to predict the medium-term behavior of the companies as strategic or marginal, to understand how these strategies can affect the own results and what protection mechanisms can be incorporated in the own strategy. In that context, the model must take into account other components of the revenues that can influence the companies behavior, such as medium and long-term contracts, transition costs, capacity payments, etc.

HYDRO BIDDING

The results obtained by this model are the quantities that each firm has to produce at different time steps to maximize its contribution margin. From that results a postprocessor module derives the bidding prices needed to achieve the former quantities. Those prices will have the costs as a lower bound. Also detailed tactics should be implemented to adapt the desired productions to the clearing mechanism. Hydro units play another very important role in providing ancillary services such as secondary and tertiary reserve, but they are outside the scope of the current model.

Regarding hydro energy bids energy quality plays an important role. Run-of-the-river plants offer their energy at zero prices to completely avoid spillage. However, to maximize revenues reservoir hydro units must bid their energy at the estimated SMP for each hour. Because the estimation of the SMP is difficult some conservative approach can be used. A great percentage of the energy is offered at some price below the estimated SMP and the remaining energy is bided with a stepwise function around that value. This approximate tactic detects the true value of the SMP.

CONCLUSION

The paper has described a unified approach for maximizing the contribution margin of each company and simultaneously determining the scheduling of hydro units by using a stochastic nested decomposition method. This approach keeps all the system operation details while defining the strategic or marginal behavior of the companies. Modeling characteristics of hydro units depends on the generator ownership. The internal hydroelectric reservoir chains are represented in fully detail while external hydro plants are aggregated into subsystems. The main results of the model are hydro energy quantities for the different time steps from long to short term. At the closer step this quantity is transformed by a postprocessor module into energy and price offered by each generator for each hour of the next day to be sent to the market operator.

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