MPO: A tool for hydrothermal scheduling and pricing in a competitive framework

Andrés Ramos Michel Rivier Mariano Ventosa Manuel Rey Santiago Cerisola Luis Palacios
INSTITUTO DE INVESTIGACIÓN TECNOLÓGICA
Universidad Pontificia Comillas
Alberto Aguilera 23
28015 Madrid, SPAIN
andres.ramos@iit.upco.es

Ángel Chiarri Francisco Martínez-Córcoles Guadalupe de Cuadra
IBERDROLA
Hermosilla 3
28001 Madrid, SPAIN

KEYWORDS

Energy market, Competition, Hydro Energy Pricing, Stochastic Optimization, Equilibrium Constraints.

ABSTRACT

The paper describes a novel and unified approach to develop a fully detailed operations model under the new competitive framework among electric companies. The competitive behavior of the electric energy market is represented by the formulation of a set of equilibrium constraints that reproduce the optimality conditions for maximizing the profit of strategic firms. At the same time the system operation functions, such as probabilistic hydrothermal scheduling, thermal unit commitment, seasonal and daily operation of pumped units are considered. A scenario tree explicitly models stochastic natural inflows.

The model has been implemented in GAMS, an algebraic modeling language specially suited for optimization problems. This model has being applied to the Spanish electric energy system as a case study in the new competitive framework.

1 INTRODUCTION

A restructuring of the electric energy sector all around the world is underway. Spain is also currently immersed in deep changes with a completely new regulatory framework that begun in January 1998. The Law Act already approved establishes competition in generation based on a day-ahead wholesale trading pool for selling and buying energy. The Market Operator (MO) determines the actual operation of generating units, based on a simple hour by hour merit order of their simple bids. The market-clearing price is set for each hour by the highest accepted bid.

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 tactics and strategies in order to decide prices and quantities, i.e., bids that they will finally submit to the MO. The bids will determine the actual operation of their units and their incomes. Therefore, electric firms need to adapt the production cost models to the new competitive environment to fulfill new requirements.

The purpose and challenge of the current model has been the simultaneous implementation of a detailed hydrothermal coordination model and the market equilibrium resulting from competition among firms. State of the art stochastic optimization techniques have been used. Several references can be found dealing exclusively with stochastic hydrothermal coordination cost-based models, for example [Jacobs, 95] and [Pereira, 91]. Also several papers address the impact of competition in generation in hydrothermal systems, see for example [Scott, 96] and [Bushnell, 98]. However, the proposed approach is capable of including both characteristics and of being applied to a large-scale electric energy system.

On one hand, it considers in detail the technical operating constraints of the system. The model performs, for the time scope, scheduling of stochastic hydro inflows, seasonal operation of pumped-hydro units, weekly/daily operation of pumped-storage units, and thermal unit commitment for the generation system.

On the other hand, it represents the new competition framework with a new objective function, to maximize the firm’s profit (gross revenues minus operating variable costs). The approach proposed in this paper to model the competitive behavior of the electric energy market is based on the formulation of a set of constraints, namely the equilibrium constraints that reproduce the first order optimality conditions of the strategic firms objective function. Thus this approach achieves the profit maximization objective while keeping all the system operation details. The introduction of those constraints implies only some modifications to a production cost model. The market equilibrium is attained where each strategic firm achieves its maximum profit.

All these new characteristics that models must incorporate are especially challenging for hydro units. Currently, electric companies are facing the need of developing new hydro scheduling tools for these resources that previously were centrally dispatched by the System Operator (SO).

The paper is organized as follows. Firstly, the general objectives that guided the specification and development of this model are presented. Then, it is shown the system characterization for each element of the system and how they are modeled. In the following section, it is presented the schematic formulation of the optimization problem. Some computer implementation details are discussed afterwards. Next, it is described the Spanish electric system for which the model has been applied. Finally, some conclusions are extracted.

2 MODEL OBJECTIVES

Planning models are focused on obtaining the main decisions for the several operation stages of the generating units. Under the new regulatory framework new factors affect the operation of these units. For example, uncertainty in the behavior of other market agents, the capability of using contracts as hedging mechanisms against risk, or the different concatenated markets for energy and ancillary services with their clearing mechanisms. Besides classical operation results such as the expected production of each unit and its distribution along the time, see figure 1, other outcomes are now of interest. For example, the system pool prices estimation, the qualitative and quantitative evaluation of bidding strategies and tactics, the analysis of generation contracts, and the market share of the firms.

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

- *Long-term scope*

  The main functions within this time span (one or two years) are the annual budgeting and yearly production estimation for all the units and the subsequent monthly updates. Also it is determined the annual (or hyperannual) scheduling of hydro units, including also the value of water and the reservoir level profiles of each major reservoir.

- *Short-term scope*

  The aim of this time step (one up to several days) is to obtain the final prices and quantities to be offered taken explicitly into account the clearing mechanism of the MO. Different tactics can be experienced and explored (i.e., price differentiation between peak and off-peak hours). Hydro units play a very important role in implementing pricing tactics. The results obtained from the model can serve as a basis to establish hydro energy pricing.

  A medium-term scope of several months can be just thought as an extension of the short-term. All the information regarding inflow stochasticity is fully incorporated into the model at this time step because time dependencies of natural inflows usually span one or two weeks. Hydro scheduling at this level defines policies regarding the amount of water offered during the next months in weekly steps.

One of the main features of this model is the flexibility, which allows 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. Advantages of having only one model are, for example, coherence in the origin and elaboration of data, use of similar mathematical methods, and convenient presentation of the results.

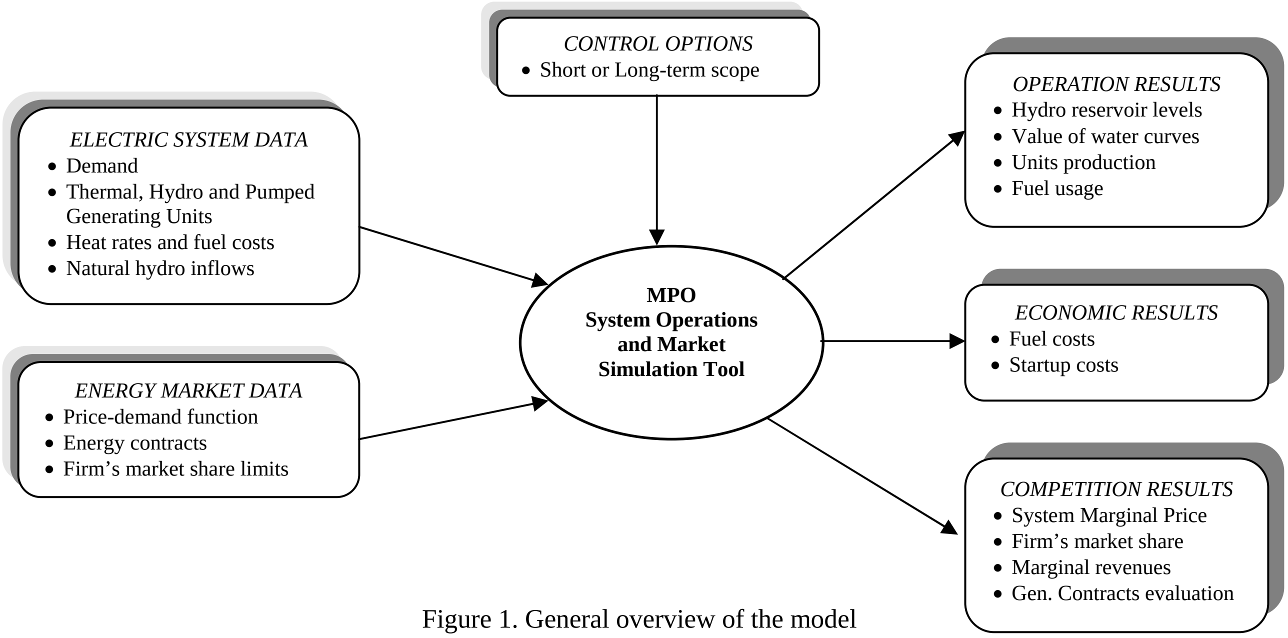

Figure 1. General overview of the model

3 SYSTEM CHARACTERIZATION

The representation of the electric system changes coherently with the different possible uses and scopes of the model. Below, the main elements that characterize an electric system are discussed.

Time steps

The time scope of the model is divided into *periods*, *subperiods* and *load levels*, which are the smallest time units. Although this time definition is flexible, for the short-term a period is typically a day and a load level is an hour. For the medium-term a period can be a week and a load level can last several similar hours. For the long-term a period corresponds to a month, a subperiod to all the working days or weekends and a load level to peak, shoulder and off-peak hours, for example.

Demand

Demand is considered constant in the load levels. For the short-term scope the demand is *chronological*, i.e., load levels keep the temporal sequence of hours. For the long-term the demand is *monotonic*, i.e., a stepwise *load duration curve* where a load level represent the same type of hours (peak, for example) of all days of the same period.

In classical production cost models the demand is inelastic and has to be met. In the market approach the demand is elastic with respect to the price. In the model, the demand response to the system marginal price (SMP) is represented by a linear function.

Thermal subsystem

Thermal units are individually represented. Each unit is divided into two blocks, being the minimum load block the first. A straight line with no load and linear terms specifies the heat rate. Random outages are deterministically modeled by derating the unit's full capacity by its equivalent forced outage rate (EFOR). Each unit can be either in preventive maintenance, available but disconnected or in operation. Ramp rates are only considered in the short-term scope.

Startup, fuel and fungible costs represent the variable costs of a thermal unit.

For the short-term scope, startup and commitment decisions are determined for each load level. However, for long-term scope thermal units can only be committed for each subperiod (working days or weekends).

Hydro subsystem

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. For the future, the assumed hypothesis is that only data regarding hydro plants of the own company will be available. Those of the competitors will only be known approximately and they will require a different modeling approach.

For the short-term scope hydro units of the own firm are represented in detail, i.e., it is denominated *water modeling*. The approach considers the topological relations among hydro units of the same basin, the output of the unit as a function of the flow of water and the reservoir level. A water balance for each hydro reservoir is stated for each load level.

For each hydro unit in the long-term scope or just for the hydro units of the competitors in the short-term scope, hydro inflows are represented in energy and similarly the balance equation for each reservoir, i.e., it is denominated *energy modeling*. In this approach the units of the same basin (or subbasin) are aggregated and the spatial dependencies ignored.

At the end of the time scope reservoir levels can be prespecified or decided by the model given a value of water (or hydro energy) function.

In both short and long-term scopes natural inflows (measured in water or energy units) can be stochastic. The scenarios of stochastic inflows can be organized in a scenario tree, where each node represents a scenario given by an inflow and an associated probability. For example, a scenario tree for a time scope of eight periods is depicted in figure 2. The second period has two different inflows and the third and the fourth have only one value. In the example, the total number of scenarios is 43.

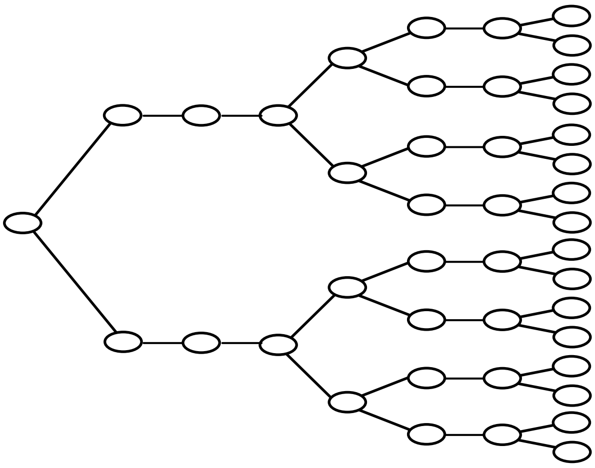

Figure 2. Scenario tree.

Traditionally, hydro plants have been scheduled to minimize the generation variable costs of thermal units. Hydro units were used to equalize the system marginal costs over the time scope considered. When maximizing the profit of the company an important result achieved is that hydro units equalize the firm's marginal cost. The value of water does not represent costs anymore. It is calculated as a function of the future profit of any thermal unit.

Pumped subsystem

Pumped-hydro, with seasonal reservoir capability, and pumped-storage units, with just weekly/daily capacity, are considered. Their representation is similar to the hydro units except that they have a pumping capacity with a total performance coefficient for the operation.

4 PROBLEM FORMULATION

The hydrothermal coordination problem under competition is an *stochastic programming* problem formulated as a very large-scale mixed integer optimization problem with scenarios representing stochasticity in hydro inflows.

Objective function

The *objective function* consists of maximizing the direct utility function, i.e., the demand and generation surplus as in any market equilibrium, (1) and (2) respectively in figure 3. However, this can be expressed as the minimization of total variable costs for the scope of the model subject to all the operating constraints, that resembles a classical production cost model. Variable costs are divided into generation costs (startup, fuel and fungible costs) and non-served demand costs, (3) and (4) respectively in figure 3.

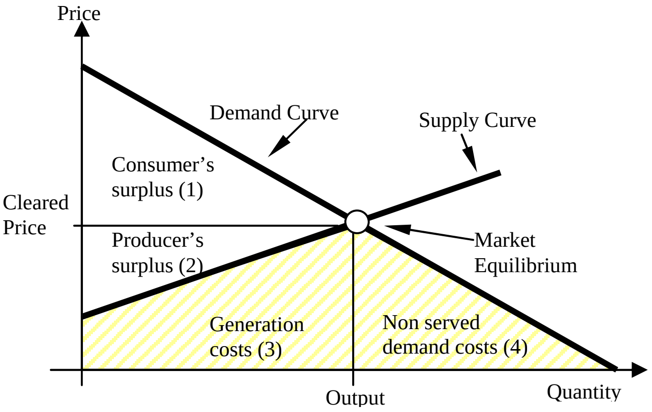

Figure 3. Direct utility function.

Interperiod constraints

Interperiod constraints are those regarding the use of limited resources for multiple periods. In particular, hydro and fuel scheduling, and seasonal pumped-storage units are considered.

Hydro scheduling constraints deal with the optimal scheduling of stochastic natural inflows. As previously commented, an alternative water or energy modeling can be used to represent hydro units.

Fuel scheduling constraints may represent take-or-pay contracts or must-buy purchase of domestic coal for socio-economic reasons.

Intraperiod constraints

Intraperiod constraints deal with the system operation in each period. For example, balance between generation and demand, unit commitment constraints like reserve margin or ramp rates, weekly/daily balance of pumped-storage units and all the generation limits of the units.

Equilibrium constraints

These constraints are formulated for each period and represent the competition among firms and the resulting market equilibrium. The following constraints are considered. First, SMP as a linear function of the electricity demand for each load level. Second, firm's marginal cost greater than the variable cost of any of its committed units. Third, upper and lower limits in firm's market share. And finally, lower limit to the output of strategic firms.

Strategic companies are those with some market power, i.e., capability to influence the price considering their long-term contracts. Their profit maximization equation is formulated by the first order condition that establishes a lower limit to their output below a certain value dependent on the system marginal price, the firm's marginal cost and the slope of the price equation. That can be expressed equivalently by the point where firm's marginal cost equals marginal revenue. *Fringe* firms are those bidding prices equal to their marginal cost.

Variables

The variables of the problem are quantities, as in a Cournot equilibrium. Regarding the operating decisions, they are commitment decision of thermal units, output levels of generating units, power consumption of pumped units, and hydro reservoir levels. Regarding the market decisions, the non-served demand of demand bids and the SMP at the equilibrium point.

Solution algorithm

Due to the integer nature of some decisions and the huge size, the solution of the previous problem requires some decomposition algorithm, namely the *stochastic nested Benders decomposition* technique, see [Morton, 96]. This method avoids the curse of dimensionality of stochastic dynamic programming by iteratively centering the evaluation of future costs around the states of interest.

The nested decomposition algorithm is a natural extension of Benders algorithm for multistage stochastic problems. It breaks the interperiod constraints and solves iteratively each subproblem that corresponds to the system operation in one period. In any algorithm iteration it is done one pass from the first to the last period and vice versa solving each subproblem. In the forward pass it is decided the final state of each hydro reservoir for each subproblem (ancestor) and passed to the following subproblems (descendant). In the backward pass it is sent the dual information required for building a Benders cut. These cuts are just linear approximations of future costs with respect to the final reservoir levels.

Implementation

The model has been coded in the GAMS 2.50 algebraic modeling language [Brooke, 96]. This high level language allows a powerful, fast and compact implementation of optimization problems. CPLEX 6.0 has been the optimizer chosen for the solution of the MIP subproblem.

The size of the optimization problems changes depending on the modeling scope. For example, a long-term case has a size of approximately 2000 constraints by 2000 variables for each of the twelve periods (months) in the deterministic case. A medium-term case reaches 7000 constraints by 7000 variables in each period (week). So a tree of 100 scenarios will have 700000 equations by 700000 variables, a problem size that can not be solved directly with current solvers.

A very careful attention has been paid to the implementation of the model in order to decrease the solution time. In particular, several techniques have been used such as mathematical reformulation of the problem to decrease the number of constraints and/or elements, natural scalation of variables and constraints around 1 and algorithmic variable bounding.

Besides, several algorithmic improvements have been made to the standard nested decomposition method that greatly increase the performance.

- For example, the deterministic case is firstly directly solved to obtain an initial point for the stochastic problem.
- Also, the use of previous bases taken from solves of the same or similar problems reduces the solution time in successive solves to just a 10 % of the first one.
- An automatic selection of the most suited optimization method has been implemented. The interior point method is used for large-scale optimization problems (above 10000 constraints by 10000 variables). The simplex method is convenient for smaller problem sizes or when a very good starting point can be used. Therefore, each problem is firstly solved by the interior point method while in successive solves the simplex method is used.
- An aggregation of nodes with single descendant in the scenario tree is made to avoid the time consumed by the modeling language when interfacing with the optimizer. For example, in the tree of figure 2 subproblems of periods 2, 3 and 4 of the same branch are simultaneously solved.

These improvements are automatically selected according to some heuristic criteria adapted to the current cases.

5 CASE STUDY

The model has been applied to the Spanish electric energy system. The maximum peak load is 27219 MW and the yearly energy demand is 162204 GWh. The installed generation capacity is 43374 MW (16132 MW of them are hydro, 11209 MW coal, 4597 MW oil, 3814 MW gas, and 7622 MW nuclear).

There are 73 thermal generators that produce about 80 % of the total generation. The hydro subsystem is composed by more than 70 units with capacity greater than 5 MW and annual energy production greater than 100 GWh. They produce as an average about 20 % of the total generation, ranging between 13 and 28 % depending on the hydrology. There are 8 pumped-storage units but their impact on the annual production is minimum (about 1 %).

Regarding the electric market, four main holdings are responsible of producing the electric demand of the system. Their approximate market shares are 45, 35, 15 and 5 %. The first holding is more oriented to thermal energy generation while the second is more hydro based.

The cases studied so far have presented good converging properties, reaching the optimal solution in around six iterations of the decomposition algorithm.

6 CONCLUSIONS

The paper has described a novel and unified approach to develop a fully detailed probabilistic operation model under the new competitive framework. The competitive behavior of the electric energy market is represented by the formulation of a set of equilibrium constraints that reproduce the optimality conditions for maximizing the firm’s profit. At the same time the system operation functions, such as thermal unit commitment, hydrothermal scheduling, seasonal and daily operation of the pumped units are considered. Especial emphasis has been paid to the stochasticity of natural inflows that is modeled by a scenario tree.

The model is flexible and may be used to represent several hierarchical time scopes from short to long-term. The electric system representation is adequately adapted to them.

This model has been implemented in GAMS, a powerful algebraic modeling language, and has being applied to the Spanish electric energy system as a case study in the new competitive framework.

AKNOWLEDGEMENTS

This research has been supported by IBERDROLA through different research projects and additional support has being received from the Comisión Interministerial de Ciencia y Tecnología by a research grant.

REFERENCES

[Brooke, 96] Brooke, A., Kendrick, D. and Meeraus, A. *GAMS Release 2.25 A User's Guide*. GAMS Development Corporation, 1996.

[Bushnell, 98] Bushnell, J. “Water and Power: Hydroelectric Resources in the Era of Competition in the Western US” *3rd Electric Industry Restructuring Conference*. University of California at Berkeley. March 1998.

[Jacobs, 95] Jacobs, J, Freeman, G., Grygier, J., Morton, D. P., Schultz, G., Staschus, K. and Stedinger, J. “SOCRATES: A System for Scheduling Hydroelectric Generation under Uncertainty” *Annals of Operations Research*. Vol 59, pp 99-133. 1995.

[Morton, 96] Morton, D. P “An Enhanced Decomposition Algorithm for Multistage Stochastic Hydroelectric Scheduling” *Annals of Operations Research*. Vol 64, pp 211-235. 1996.

[Pereira, 91] Pereira, M.V.F. and Pinto, L.M.V.G. “Multi-Stage Stochastic Optimization Applied to Energy Planning” *Mathematical Programming*. Vol 52, pp 359-375. August 1991.

[Ramos, 95] Ramos, A. et al. “A Medium Term Bulk Production Cost Model Based on Decomposition Techniques” *Stockholm Power Tech*. 1995.

[Scott, 96] Scott, T.J. and Read, E.G. “Modelling Hydro Reservoir Operation in a Deregulated Electricity Market” *International Transactions in Operational Research*. Vol 3, pp 243-253. 1996.