Medium-term Hydro Operation in a Competitive Electricity Market

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Abstract – This paper presents a model to represent medium-term hydro operation in a deregulated power market. The objective of the model is to maximise the profit for a firm. The system is represented in two different levels: weekly and yearly. Weekly module computes profit as a function of total hydro production of the firm in each week. The yearly module uses this function to obtain the optimal operation that maximises profit.

Keywords: Power Systems Operation, Profit Maximisation, Medium-term Hydrothermal Scheduling.

I. INTRODUCTION

The traditional electrical power systems operation models represent how these system work during a period of time, including their technical constraints. These models operate in a centralised way, minimising total operation cost [1]. Progressive introduction of competitive schemes for unit commitment in Spain [2] as in many other countries, leads to different model that perform operation from a firm viewpoint. These models intend to maximise firm's profit [3].

This focus generates different decision and changes the classic concept of *water value*. It must be compute not as a total cost decrease but as one firm's profit increase. Market representation is more complicated than centralised operation representation because it is not an optimisation problem but an equilibrium problem [4].

We introduce VALORE model developed by ENDESA, the Spanish main electrical utility. This model represents a simplified model of electrical market, maximises profit from one firm viewpoint, determines optimal use of hydro resources and obtains water value.

II. MODEL STRUCTURE

The model consists of two modules, the first one studies weekly operation. It computes a function that determines the relationship between profit of our firm and hydro production for the utility for each week. The second one, that studies yearly operation, optimises profit for a year time.

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These two modules operate in a single execution way. They don't use a iterative method to find the optimal solution. This problem doesn't fit a linear programming or dynamic programming structure because functions obtained by weekly module are not lineal or convex. A solution based on dynamic programming combined with games theory can be seen in [5] and [6]. Market equilibrium can be also been represented with additional constraint to a centralised model [7], [8]. Other alternative models maximise profit but don't represent market equilibrium [9].

III. SYSTEM REPRESENTATION

A. Indices

j	Thermal unit.
h	Hydro unit.
hn	Our firm's hydro unit.
hc	Competence's hydro unit.
p	Yearly operation period (one week).
k	Weekly operation period (one hour).
t	Segment of a linear piecewise profit function.

B. Thermal subsystem

Thermal subsystem is only represented in the weekly operation module.

α_j	Heat rate of *j* thermal unit (independent term).
β_j	Start-up cost of *j* thermal unit.
χ_j	Shutdown cost of *j* thermal unit.
δ_j	Heat rate of *j* thermal unit (linear term).
$\overline{P}_j$, $\underline{P}_j$	Maximum and minimum power of *j* thermal unit.
r_j,s_j	Increase and decrease rate of *j* thermal group.

C. Hydro subsystem

Hydro subsystem consists of a set of hydro groups. They are also considered as hydro bid units. Each hydro group has an associated reservoir with its storage expressed in energy. Inflows are also expressed in energy.

The maximum power of each hydro generator linearly depends on reservoir storage. It is assumed than run-of-the-river production is known and equally distributed all week along. Run-off-the-river production is separately considered, it is subtracted from hydro productions.

Each hydro generator h is characterised by the following parameters:

$\overline{P}_h$, $\underline{P}_h$	Maximum and minimum power of h hydro generator.
$\overline{b}_h$	Maximum pumping power of h hydro generator.
ρh	Pumping performance.
w	Water bid price.
f_k	Run-of-the-river power in k hour. It is assumed it is known.
E	Total hydro energy produced by the competence. It is assumed it is known.

Yearly operation module parameters:

Uh, Vh	Coefficients of linear relationship between maximum power and storage.
$\overline{R}_h$, $\underline{R}_h$	Maximum and minimum reservoir storage.
Evh	Hydro groups immediately over h.
βh	Inflows performance to groups below.
Aph	Inflows (except run-off-the-river) for a hydro generator h in a period p. (It is expressed in energy).
$r0h$	Initial storage for a hydro generator.
w_{tp}	Water bid price.
f_{kp}	Run-off-the-river power in hour k and period p.
E_p	Total hydro energy produced by competence in p period.

D. Demand

d_k	Demand in k hour.

In yearly module:

d_{kp}	Demand in k hour and p period.
l_p	Duration of p period.

IV. WEEKLY OPERATION

Weekly operation module determines the relationship between profit and hydro energy produced by our firm in each week. It is computed independently for each week.

A classic unit-commitment model based on mixed-integer programming, similar to that described in [10] is used to compute minimum cost centralised operation. Computing is repeated for each period p and for different hydro energy prices t. Demand is considered deterministic and known. It is also assumed than run-off-the-river production and hydro competence production is known.

Weekly operation is represented with a one-hour period including demand supply constraints, maximum and minimum power, start-up and shutdown costs and increase and decrease rates. Each thermal generator works with its real estimated cost. So, it is assumed (only for the weekly module) that every generator bids its real cost.

E. Decision variables in weekly module

t_{jk}	Thermal production of j thermal generator in k hour.
y_{jk}	Start-up of j thermal unit in k hour. (Binary variable.)
z_{jk}	Shutdown of j thermal unit in k hour. (Binary variable.)
v_{jk}	Commitment status of j thermal unit in k hour. (Binary variable.)
p_{jk}	Power generation over minimum power of j thermal unit in k hour. (Binary variable.)
h_{hk}	Power generation of h hydro generator h in k hour.
b_{hk}	Power consumption for pumping by h hydro generator in k hour.

F. Weekly operation constraints

Weekly operation is subject to the following constraints:

Generated power:

$$t_{jk} = \underline{P}_j v_{jk} + p_{jk} \quad \forall j,k \tag{1}$$

Generated power must be greater than minimum power.

$$p_{jk} \le \left(\overline{P}_j - \underline{P}_j\right) v_{jk} \quad \forall j,k \tag{2}$$

Power balance.

$$\sum_j t_{jk} + \sum_h h_{hk} + f_k = d_k + \sum_h b_{hk} \quad \forall k \tag{3}$$

Starts-up and shutdowns.

$$y_{jk} - z_{jk} - v_{jk} = -v_{j,k-1} \quad \forall j,k \tag{4}$$

Increase and decrease rates.

$$-r_j \le p_{jk} - p_{j,k-1} \le s_{jk} \quad \forall j,k \tag{5}$$

Competence energy balance.

$$\sum_{k,hc} h_{hc,k} - \rho_{hc} b_{hc,k} \le E \quad \forall j,k \tag{6}$$

Upper and lower decision variables bounds are also included as operation constraints.

G. Objective function for weekly module

The objective function to minimise represents total system operation costs. It will be referred as C.

$$C = min(\sum_{jk}(\beta_j y_{jk} + \alpha_j v_{jk} + \delta_j \underline{P}_j v_{jk} + \\ + \delta_j p_{jk} + \chi_j z_{jk}) + w_t \sum_{hn,k}(h_{hn,k} - \rho_{hn} b_{hn,k})) \quad (7)$$

Cost depends on some of the input data:

$$C = F(f_k, E, d_k, w) \quad (8)$$

H. Weekly module usage

Profit is computed as a function on hydro energy produced in a week by our firm with weekly operation module. The yearly module uses this function as an input data. The weekly model is executed several times for each period p using the corresponding value of run-off-the-river production, competence hydro production and demand. For each period the module is also executed repeatedly to obtain several segments (t) to construct profit as a linear piecewise function.

$$C_{pt} = F(f_{kp}, E_p, d_{kp}, w_t) \quad (9)$$

Profit is computed por each period p and each water value t with the following expression. (Note that t+1 executions are needed to obtain t segments.):

$$MCY_{pt} = I_{pt} + \sum_k (P_{kpt} * \lambda_{kpt} - c_{kpt}) \quad (10)$$

Where:

MCY_{pt} Profit in period p and segment t.

I_{pt} Contract incomes in period p and segment t. These income include long-term contracts and competence transition costs. They are computed using weekly operation results.

P_{kpt} Firm production in k hour, p period and t segment. It is the sum of all generators belonging to our firm.

λ_{kpt} System marginal price in k hour, p period and t segment. See next section.

c_{ktp} Operation costs for our firm in k hour, p period and t segment.

Finally, profit functions are a set of $t+1$ points for each period p: (MCX_{pt}, MCY_{pt}). MCX_{pt} represents hydro energy produced by our firm.

$$MCX_{pt} = \sum_{k,hn} h_{hn,k} - \rho_{hn} b_{hn,k} \quad (11)$$

I. System marginal price estimation

The value of system marginal price can be computed in two different ways. It can be approximated directly as marginal cost in k hour, p period and t segment. This estimation produces lower values than real market values but it allows performing sensibility studies.

The second method determines marginal price from equilibrium condition. We have defined profit for our firm MCY_1 in (10). If we derive this expression with respect to total production of our firm P_1 and we assume that I=0, we obtain for each period p and segment t:

$$\frac{\partial MCY_1}{\partial P_1} = P_1 \frac{\partial \lambda}{\partial P_1} + \lambda - \frac{\partial C_1}{\partial P} \quad (12)$$

As we are at equilibrium point this expression is equal to zero and we express marginal price as:

$$\lambda = \frac{\partial C_1}{\partial P_1} - P_1 \frac{\partial \lambda}{\partial P_1} \quad (13)$$

The first term is our firm's marginal cost and we can compute it as system marginal cost. This term correspond to the first approximation, previously described. Second term represents the capability of our firm to change marginal cost. The derivative of marginal price with respect to our firm's production can be statistically obtained from competence past biding.

V. YEARLY OPERATION

The yearly operation model maximises profit for our firm. It includes hydro operation constraints: energy balance for each reservoir and operation bounds for power and energy. The objective of this module is to distribute available hydro energy in the year periods. This energy is considered in a deterministic way, it is assumed it is known as an input data.

Profit functions are represented as linear piecewise functions. These functions are not linear nor convex so they are included in the model using binary functions to point which segment is active in the function.

J. Decision variables in yearly module

Operation variables:

eph Energy production for h hydro unit in p period.

$phph$ Power production for h hydro unit in p period (it includes pumping consumption).

$veph$ Spillage (in energy) for h hydro unit in p period.

rph Reservoir storage (in energy) for h hydro unit in p period.

mcp Obtained profit in p period.

Variables to represent profit functions:

φ_{pt} Activity variable. Its value is 1 from the active segment to the last one. It is zero in the rest of segments.

α_{pt} Filling variable. It indicates the percentage of a segment that is active.

K. Yearly operation constraints

Total energy for each hydro unit:

$$e_{ph} = d_p * ph_{ph} \quad \forall p,h \tag{14}$$

Total competence energy production:

$$\sum_{hc} e_{p,hc} = E_p \quad \forall p \tag{15}$$

Maximum power as a linear function of energy storage:

$$ph_{ph} \le U_h + V_h * r_{p-1,h} \quad \forall p,h \tag{16}$$

Hydro energy balance. It includes inflows, pumping and spillage:

$$r_{ph} - r_{p-1h} = -l_p * ph_{ph} + A_{ph} - ve_{ph} \quad \forall p,h \tag{17}$$

Reservoir storage is equal at the beginning and at the end of the year:

$$r_{p*h} = r0_h \quad \forall h \tag{18}$$

Profit function definition through activity and filling variables:

Activity variable is increasing:

$$\varphi_{p(t+1)} \ge \varphi_{pt} \quad \forall p,t \tag{19}$$

Only active segment has a value different from zero for filling variable:

$$\alpha_{pt} \le \varphi_{pt} - \varphi_{p(t-1)} \quad \forall p,t \tag{20}$$

Filling variables determine total hydro energy production for our firm:

$$\sum_{hn} e_{p,hn} = \sum_t \left[MCX_{pt} \left(\varphi_{pt} - \varphi_{p,t-1} \right) \right] + \sum_t \left[\alpha_{pt} \left(MCX_{p,t-1} - MCX_{pt} \right) \right] \quad \forall p \tag{21}$$

Total hydro energy production of our firm depends on the active segment and its filling variable. There is only an active segment an it allows to obtain the value of profit variable for each period.

$$mc_p \le MCY_{pt} + \frac{MCY_{p,t+1} - MCY_{pt}}{MCX_{p,t+1} - MCX_{pt}} \left(\sum_{hn} e_{p,hn} - MCX_{pt} \right) + T * (1 - (\varphi_{pt} - \varphi_{p(t-1)})) \quad \forall p,t \tag{22}$$

T An upper bound for profit in any period.

L. Objective function for yearly module

It represents yearly profit for our firm. It is a function to maximise.

$$MC = \sum_p mc_p \tag{23}$$

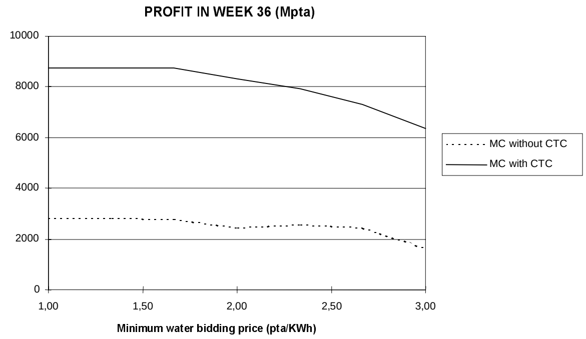

Fig. 1. Relationship between profit and hydro production in a week.

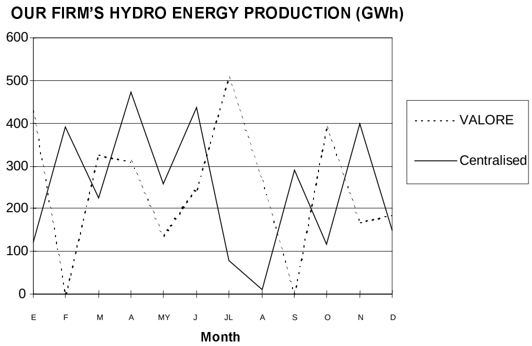

Fig. 2. Monthly energy production in VALORE compared to a centralised model.

M. Water value

Water value for each period is represented by dual variable of hydro energy balance constraint (17).

VI. CASE STUDY

The model has been implemented using GAMS language. It has been applied to Spanish electricity market. There are 89 thermal units, 29 hydro units in the system. ENDESA has 36 thermal units and 10 hydro units. ENDESA is the main Spanish electric firm with a market share of 51%. The study is extended to 52 weeks considering 168 operation hours for each one. Profit functions have been represented with 7 segments. Marginal price has been approximated as marginal cost.

The results are compared to results obtained with a cost minimisation classic model with the same technical constraints.

Fig. 1 presents a profit function generated by weekly module. There are two different versions, one includes a representation o costs of transition to competence (CTC) in term I of equation (10), the other considers this term equal to zero. These functions are non-linear and non-convex. Term I makes these functions smoother and easier to optimise. Next results consider I=0.

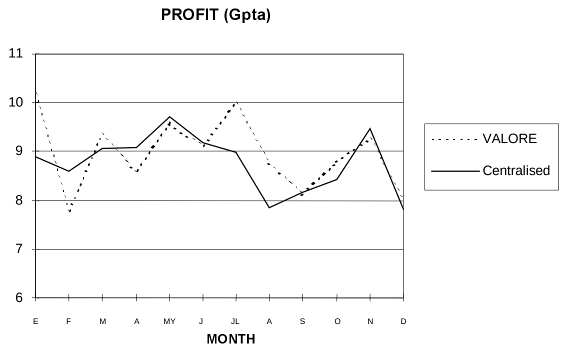

Fig. 3 Monthly profit in VALORE compared to a centralised model.

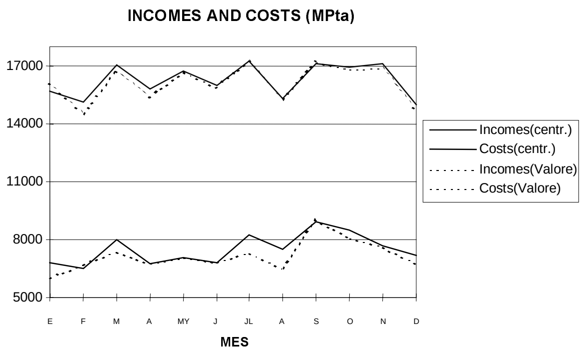

Fig. 4 Incomes and costs in VALORE compared to a centralised model.

Monthly hydro production is shown in Fig. 2. There is a different energy distribution compared with centralised model. Production increases in summer months. Fig. 3 shows monthly profit computed both with VALORE and with a centralised model. Profit obtained with VALORE is greater, specially in summer months. This profit is explained in Fig. 4, firm costs decrease during summer weeks. Incomes are very similar in both models because system marginal price is considered equal to system marginal system.

VII. CONCLUSIONS

We have presented a model that represents medium-term hydro operation in a large electric market from the viewpoint of a firm intending to maximise its yearly profit. Energy distribution is different from that suggested by a centralised model when we use this focus. This different operation implies a different water value. Water value in VALORE model is computed as the increase of our firm's profit when there is an additional MWh available in a reservoir. This value is obtained from the dual variable of energy balance constraint.

This profit representation allows including long-term contracts or costs of transition to competence (CTC) as considered in Spanish electrical market. It is possible to estimate system marginal price from operation values or is possible to approximate then equal to marginal cost. The second approximation is better for sensibility or comparison studies than for absolute variable estimation.

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X. BIOGRAPHIES

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