SEGRE
A Yearly Production Cost Model for Economic Planning

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I. Introduction

Economic planning is a major concern of medium term operations planning studies devoted to predict the future operation results of an electric utility. The remuneration of the Spanish electric utilities is determined, according to the Stable Legal Framework (SLF) [4], as a function of the results obtained from the operation of the system. Their economic planning functions typically include:

- calculation of the electricity tariff
- administration and periodic supervision of the revenues derived from the application of the SLF
- analysis and optimisation of the application of the SLF
- studies conducted to propose improvements and adjustments to the SLF

This production cost model addresses all the operating decisions in an integrated framework and establishes a compromise and balance among different modelling decisions. Its prime purpose is to predict the future system operation and determine their parameters (costs, fuel consumption, productions, etc.).

This model provides the minimum variable cost subject to operating constraints (generation and fuel constraints). Generation constraints include power reserve margin with respect to the system peak load, balance between generation and demand, hydro energy scheduling, maintenance scheduling, and generation limitations. Fuel constraints include minimum consumption quotas and fuel scheduling for domestic coal thermal plants. The relevant decision variables and the real operation of the power system are adequately represented, two types of decisions are addressed:

- *Interperiod* decisions are those regarding resources planning for multiple periods. In particular, maintenance scheduling for thermal units, yearly hydro energy scheduling, seasonal operation of pumped-hydro[1] units, and fuel scheduling are represented. The model determines the optimal hydrothermal coordination (i.e., the use of hydro against thermal generation resources).
- *Intraperiod* decisions correspond to a generation economic dispatch. In particular, those related to weekly/dairy operation of pumped-storage units and commitment decisions of thermal units.

This operations planning problem is formulated as a large-scale mixed integer optimisation problem. The model has been implemented in GAMS [1], a mathematical specification language specially indicated for the solution of optimisation problems, and solved by using CPLEX, a well-known MIP solver. The model is being used as a medium term tool for economic planning by IBERDROLA Generation Area [7] and integrated into the information system of the electric utility.

The medium term planning problem is stochastic by nature. Uncertainties arise in load, hydro inflows, thermal unit availability, etc. However, the model described is deterministic. Stochasticity in unit availability and load can be naturally implemented within this methodology via scenarios. Uncertainty in hydro inflows is modelled deterministically because medium term operation planning is performed under the assumption of average hydrology.

No model with this whole set of characteristics (i.e., fuel, maintenance and hydro scheduling on one hand and commitment decisions on the other hand) has been found in the literature. Models deciding seasonal hydro scheduling, usually based on stochastic dynamic programming or decomposition methods [3], represent in detail the spatial hydro dependencies but usually ignore the fuel and maintenance scheduling problems. Medium term fuel scheduling is decided using a large-scale linear programming approach in [6, 8]. Maintenance scheduling has been solved by many different techniques [5], decomposition techniques [9] and integer programming [2] among others. Combined seasonal and weekly/dairy operation of pumped units has not been addressed so far.

The paper is organised as follows. In section II it is presented the system description and modelling of each type of generation. Then, the model formulation is described although the mathematical expressions of the equations are relegated to the Appendix. The implementation of the model and some basic characteristics are discussed in section IV. Next, it is briefly described the regulatory and economic environment in which the Spanish electric utilities operate. In the next section it is described the application of the model to the Spanish electric power system. Finally, the conclusions are presented.

II. System Description

A production cost model determines the variables defining the system operation at minimum variable cost for the scope of the model. Let us define *horizon* as the point in time for which the system operation

[1] In the paper the following convention is used. A *pumped-hydro* unit is a pump-turbine having a large upper reservoir with seasonal storage capability that receives water from pumping and also from natural hydro inflows. By the contrary, a *pumped-storage* unit has a small upper reservoir filled only from pumped water allowing just a weekly or dairy cycle.

is to be modelled and *scope* as the duration of the time interval to be studied. In this medium term model, the horizon is two or three years ahead and the scope is usually one year. The scope is divided into *periods*, *subperiods* and *load levels*. Typically, periods will correspond to months, subperiods to weekdays and weekends of a month, and load levels to peak, plateau and off-peak hours.

The load for each period is modelled as a staircase load duration curve, where an step is a load level. Hence, generation will be constant for each load level.

Each thermal, hydroelectric, pumped-hydro and pumped-storage unit is modelled individually. The size of the Spanish electric power system is briefly described in section VI.

Each thermal unit is divided into two blocks, being the minimum load block the first. Heat rate is specified by a straight line with independent and linear terms. Random outages are deterministically modelled by derating the unit's full capacity by its equivalent forced outage rate. A thermal plant consists of units in a physical plant. Fuel constraints affect the fuel consumption of domestic coal thermal plants.

Very small hydro units are aggregated. Spatial dependencies among hydro plants are considered irrelevant to the medium term thermal generation scheduling problem and ignored. Therefore, the variation in the hydro energy reserve of a reservoir due to the generation in a hydroelectric plant located upstream is not taken into account.

Only the economic utilisation of pumped units is considered. This economic function includes both the transference of energy from off-peak hours to peak hours and the alleviation of minimum load conditions in off-peak hours or maximum load conditions in peak hours. Additionally, these units may be operated for reliability purposes keeping their upper reservoirs full at the beginning of each week but this operation is not represented in the model.

III. Model Formulation

As mentioned previously this medium term production cost model performs hydro, maintenance and fuel scheduling, seasonal operation of pumped-hydro units, weekly/dairy operation of pumped-storage units, and thermal unit commitment for a generation system. The model is formulated as a large-scale mixed integer optimisation problem. The objective function to be minimised is the total variable cost for the scope of the model subject to operating constraints. These can be classified into inter and intraperiod, according to the periods that are involved in. The interperiod constraints are associated to the coordination in the use of limited resources (minimum quotas of fuel consumption, hydro inflows, seasonal pumping, storage and generation). The intraperiod constraints deal with the system operation in each period (thermal unit commitment, weekly/dairy pumping, storage and generation limits).

The detailed mathematical formulation of the objective function, the constraints and the variables involved in the problem is presented in the Appendix. Here, it is described their meaning.

A. Objective Function

The objective function represents the fuel costs (including independent and linear terms of the heat rate and O&M variable costs) plus startup costs plus storage costs of fuel stocks plus some penalties (due to non served power, interruptibility, and reserve margin defect) for all the load levels, subperiods and periods of the time scope.

B. Interperiod Constraints

These constraints tie all the periods considered in the model and correspond to maintenance, fuel and hydro scheduling.

1. Maintenance Scheduling

   The units will be an integer number of periods in maintenance according to the specified requirement. Also limits on the maximum number of thermal units simultaneously on maintenance on the same plant and on the maximum thermal capacity simultaneously on maintenance in any period with respect to the total installed thermal capacity are imposed. Contiguity among the periods in maintenance is required too if more than one is specified.

2. Fuel Scheduling

   For each thermal plant, the stock level at the beginning of each period is a function of the previous stock and the purchase and consumption done in the period. The initial and final storage levels are prespecified by the user. It represents the must-buy fuel purchase mandated by socioeconomic and political considerations for domestic coal plants, although their cost can be more expensive than other available fuels.

3. Hydro Scheduling

   For each hydro unit, the hydro reserve level at the beginning of each period is a function of the previous level, the hydro inflow, pumping and generation on that period. The initial and final hydro reserves are specified by the user.

C. Intraperiod Constraints

These constraints are internal to each period and represent the thermal unit commitment, the security constraint based on the reserve margin, generation-demand balance and the weekly/dairy operation of pumped-storage units.

1. Reserve Margin

   A power reserve margin for the peak load level of each subperiod must be met. This constraint represents the condition imposed to provide some amount of power available to account for increments in demand or failures of committed generation units.

2. Generation-Demand Balance

   Balance between generation and demand for any load level including non served power and interruptibility.

3. Pumped-Storage Units

   Balance between pumped and generated energy by pumped-storage units in a period and a reservoir limit imposed to the pumped energy.

4. Thermal Generation Constraints

   For each thermal unit the maximum generation is less than the maximum available capacity and the minimum generation is greater than the minimum load. Thermal unit commitment related constraints state that the unit's output during higher load levels must be larger than its generation in lower load levels and that the commitment decision in a higher load subperiod (weekdays) must be greater than the commitment decision in a lower load subperiod (weekends).

   The above constraints enforce a minimum generation for each thermal unit committed at peak load level. Note that since the heat rate curves are represented as linear curves, during any load level all the committed units will be at their maximum output except one marginal unit.

D. Variables

All the variables involved in the previous formulation are: maintenance decisions, fuel stock levels, hydro productions, consumption of pumped-hydro units, hydro energy reserves, commitment decisions of thermal units, thermal generations, generation and consumption of weekly/dairy pumped-storage units, non served power, interruptible power and reserve margin defect.

The initial and final fuel stocks levels for each thermal plant and the initial and final energy reserves for each hydro unit are predefined by the user.

The variables regarding operation of the pumped-hydro and pumped-storage units are defined only for the periods, subperiods and load levels where they are meaningful according to the system operation.

The variables commitment and maintenance decisions for thermal units cause the problem to be mixed integer with the associated difficulty to be solved. Codes with such feature are needed, such as CPLEX or OSL for example.

IV. Implementation

The model has been implemented in GAMS version 2.25 [1], a mathematical specification language specially indicated for the solution of optimisation problems. It allows the creation of large and complex problems in a concise and reliable manner. This language lets the user to concentrate on the modelling problem by eliminating the writing details of special code in the preliminary stages of algorithmic development. GAMS is flexible and powerful. This flexibility is crucial in the development and test of new algorithms.

The problem as previously formulated is a large-scale mixed integer optimisation problem. Its size for the Spanish electric power system is about 10000 rows, 9000 variables, being 2500 discrete, and 38000 non zero elements in the constraints matrix. In particular recent developments in branch and bound and interior point methods are specially suited for the solution of these problems. Several MIP solvers can be used in conjunction with the GAMS language, CPLEX and OSL for example.

Careful attention when solving a large-scale optimisation problem should be paid to the scalation of constraints and variables. So GW is taken as the natural unit for power, TWh for energy, Tpta for monetary unit and kTcal for heat consumption.

The implementation of this model and its resolution using direct solution of the global problem using this compact and elegant algebraic language takes only 1400 lines of code. The model can be used in any hardware platform where GAMS and the solvers were available. Currently, a personal computer is being used.

The model is a very powerful and flexible tool that can easily be adapted to any electric power system. Several options have been provided to customise their use to different needs, such as the following:

- production cost model with a single node, demand and generation connected to the same node, with aggregation or deaggregation of the hydro units
- specification of the periods, subperiods and load levels when the pumped-hydro and pumped-storage units can be used for pumping or generation
- maintenance based exclusively on input data, optimisation with some input constraints and optimisation with no constraints
- demand increment with respect to a base case whose data are provided
- multiyear use for concatenated evaluation of an scope composed by several years
- sensitivities to a demand increment, different hydrologies, release of the minimum consumption quotas, and major overhaul of thermal units

The main results obtained from the model are: net and gross energy production for each generation unit; utilisation, commitment and shutdown hours for each unit; fuel consumption for thermal plant separated in guaranteed and spot market; fuel, startup, storage costs; maintenance schedule. These results can be presented for load level, for each period or grouped by electric utility.

V. Economic and operations environment

The economic environment in which the Spanish electric utilities develop their activity is the Stable Legal Framework. Their main objectives are to determine the average electric tariff for the least cost of service as well as the share corresponding to each utility, to assure the equitable distribution among the electric utilities of the incomes coming from the electric tariffs, and to encourage the efficiency in the operation of the units. The procedures to determine the incomes for each electric utility are regulated in there. The incomes are based on parameters obtained from the actual operation of the units (i.e., installed capacity, available capacity, minimum load, heat rate, energy production, utilisation hours, etc.). The model presented here produces the results to be used as input in the computation of future incomes for the electric utilities.

The electric tariff is determined based of the cost of service composed of the following items:

- fixed generation cost

  It includes the yearly standard cost assigned to cover depreciation and financial costs of the generation assets.

- O&M costs

  They are the costs required for the generation plants to be running once they have been committed. They are divided into fixed and variable. The first one depending on the installed capacity and the second one on the produced power.

- fuel cost

  This cost includes the net fuel cost plus the financial cost involved in maintaining a certain stock level.

- distribution cost

  This cost reflects all the costs related to the distribution process and concept.

- non-operating and working capital costs

  These are costs not directly related to the production or distribution functions.

Periods	P	12
Subperiods/period	S	2
Load Levels/subperiod	N	3
Thermal Units	T	71
Thermal Plants	C	39
Hydro / Pumped-Hydro Units	H	122
Pumped-Storage Units	B	8

	Constraints	Variables	Non-zeroes	Discrete	Time (s)
NUHA	9907	8635	37647	2556	1656
NUHB	15667	24355	77727	0	437

- other items

  The other items include revenues paid to Red Eléctrica de España (REE) (the owner of the high voltage transmission network and responsible of the control of the unified operation of the system) and several additional costs (externalities).

Besides the determination of the average price of the electricity the SLF also regulates and determines

- the methodology used in the correction of the tariff deviations from one year to the other,
- the transfer among utilities due to differences in generation structure and differences in market characteristics,
- the deferred revenues which account for the differences between accounting costs and revenues received from the tariff by the utilities for their generation plants.

The operation of the Spanish electric power system is done as follows. On one hand, thermal generation units, although owned and operated by public or private utilities, are centrally scheduled for production and dispatched by REE. On the other hand, hydroelectric units receive a weekly/dairy energy production target from REE and are operated to achieve this production goal by public or private utilities.

VI. Case Study

According to data extracted from 1994 statistical records, the Spanish power system met a maximum peak load of 25336 MW and a yearly energy demand of 145670 GWh. The installed generation capacity is 42096 MW (16110 MW are hydro, 10675 MW coal, 7910 MW oil/gas and 7401 MW nuclear). The share among energy produced by different utilities corresponds to IBERDROLA in a 40 %, ENDESA 40 %, UEFSA 15 % and other the remaining.

There are about 71 thermal generators (8 nuclear, 36 coal and the remaining oil/gas). Their production is about 80 % of the total generation.

There are 70 hydro units with capacity greater than 5 MW and annual energy production greater than 100 GWh, that can be grouped into about 10 basins. In the model they have been used units smaller than these. The maximum capacity at the same location is 915 MW. They produce as an average about 20 % of the total generation, ranging in between 13 % and 28 %, depending on the hydrology.

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

The model has been designed to represent the Spanish electric power system. The characteristics of the system regarding time division and number of elements are presented in the first table.

The time required to run this model depends on the option been solved. For the electric power system shown two options have been executed, the first one has a hydro units aggregation and discrete commitment and maintenance decisions and in second one the hydro units has been treated individually but there is a relaxation of the discrete decisions. The second table shows the sizes of the problem and the time consumption. Time is expressed in seconds, corresponding to a PC 486 at 33 MHz.

VII. Conclusions

The model presented in this paper is being used as a economic and operations planning tool representing the large-scale Spanish electric power system. The results provided by the model are used to supervise, evaluate, project and analyse the remuneration of the Spanish electric utilities according to the Stable Legal Framework (SLF). The SLF determines the electric tariff by a combination of cost of service plus yardstick competition method and calculates the economic transfers among utilities. In brief, the SLF establishes the methodology to determine the incomes of the electric utilities as a function of some standard parameters and some results from the operation of the system. In particular, the model is being used as a tool for medium term economic planning by IBERDROLA Generation Area.

The SEGRE model provides the minimum variable cost subject to operating constraints (generation and fuel constraints). Generation constraints include power reserve margin with respect to the system peak load, generation-demand balance, maintenance scheduling, hydro energy scheduling, and generation limitations. Fuel constraints include minimum consumption quotas and fuel scheduling for domestic coal thermal plants. The relevant decision variables and the real operation of the power system are adequately represented. Two types of decisions are addressed: interperiod decisions are those regarding resources planning for multiple periods, (i.e., maintenance scheduling, yearly hydro energy scheduling, seasonal operation of pumped-hydro units, and fuel scheduling) and intraperiod decisions correspond to a generation optimal economic dispatch (i.e., weekly/daily operation of pumped-storage units and commitment decisions of thermal units).

The operations planning problem is formulated as a large-scale mixed integer optimisation problem. The model has been formulated in GAMS, a modelling language specially indicated for the solution of optimisation problems, and solved by using a simplex or interior point method with different well-known solvers.

The model is a very powerful and flexible tool easily adaptable to any electric power system.

References

[1] Brooke, A., Kendrick, D. and Meeraus, A. *RELEASE 2.25 GAMS A Users Guide*. The Scientific Press. South San Francisco, USA. 1992.

[2] Edwin, K.W. and Curtius, F. "New Maintenance Scheduling Method with Production Cost Minimization via Integer Linear Programming" *International Journal of Electric Power and Energy Systems*. Vol. 12, pp. 165-170. 1990.

[3] Gorenstin, B.G., Campodonico, N.M., Costa, J.P. and Pereira, M.V.F. "Stochastic Optimization of a Hydro-Thermal System Including Network Constraints" *IEEE Transactions on Power Systems*. Vol. 7, No. 2, pp. 791-797. May 1992.

[4] IBERDROLA "El Marco Legal Estable" Febrero 1990.

[5] Kralj, B.L. and Petrovic, R. "Optimal Preventive Maintenance Scheduling of Thermal Generating Units in Power Systems. A Survey of Problem Formulations and Solution Methods". *European Journal of Operational Research*. Vol 35, No 1, pp 1-15. April 1988.

[6] Moslehi, K., Sherkat, V.R. and Cacho, F. "Optimal Scheduling of Long-Term Fuel Purchase, Distribution, Storage and Consumption" *1991 Power Industry Computer Application Conference*. pp. 98-104. May 1991.

[7] Ramos, A. and Mu'noz, L. "Especificaci'on matem'atica detallada y elaboraci'on de una maqueta de un modelo de simulaci'on del sistema el'ectrico peninsular" Technical Report prepared by IIT for IBERDROLA. October 1993.

[8] Sherkat, V.R. and Ikura, Y. "Experience with Interior Point Optimization Software for a Fuel Planning Application" *IEEE Transactions on Power Systems*. Vol. 9, No. 2, pp. 833-840. May 1994.

[9] Yellen, J., Al-Khamis, T.M., Vemuri, S. and Lemonidis, L. "A Decomposition Approach to Unit Maintenance Scheduling" *IEEE Transactions on Power Systems*. Vol. 7, No. 2, pp. 726-733. May 1992.

APPENDIX

I. Notation

In this section all the symbols used along the paper are identified and classified according to their use into auxiliary, input and output variables.

A. Indexes and Auxiliary Variables

B number of pumped-storage units.
C number of thermal plants.
H number of hydro and/or pumped-hydro units.
N number of load levels.
P number of periods.
S number of subperiods.
T number of thermal units.
$t \in c$ thermal units t belonging to plant c.

B. Input Variables

A_{hp} hydro inflows expressed in energy for hydro unit h in period p.
$\overline{b}_b, \underline{b}_b$ maximum and minimum capacity of pumped-storage unit b when pumping.
C_{cp} minimum quota of fuel consumption in thermal plant c at the beginning of period p.
c_c fuel storage cost in thermal plant c per unit of time.
d_{nsp} power demand in load level n of subperiod s of period p.
d'_{nsp} interruptible power demand in load level n of subperiod s of period p.
D_{nsp} duration of the load level n of subperiod s of period p.
g maximum number of thermal units simultaneously in maintenance on the same plant.
$\overline{e}_h, \underline{e}_h$ maximum and minimum capacity of pumped-hydro unit h when pumping.
$\overline{h}_{hp}, \underline{h}_{hp}$ maximum and minimum capacity of hydro unit h in period p.
k_t auxiliary services consumption coefficient of thermal unit t.
m coefficient of the thermal installed capacity simultaneously in maintenance in any period.
M_t number of periods in scheduled maintenance for the thermal unit t.
o_t heat rate (independent term) of thermal unit t.
o'_t heat rate (linear term) of thermal unit t.
$\overline{p}_t, \underline{p}_t$ maximum and minimum rated capacity of thermal unit t.
q_t EFOR of thermal unit t.
R power reserve margin.
$\overline{R}_h, \underline{R}_h$ maximum and minimum hydro energy reserve of hydro unit h.
r_t startup cost of thermal unit t.
$\overline{S}_c, \underline{S}_c$ maximum and minimum fuel storage capacity of thermal plant c.
$\overline{t}_b, \underline{t}_b$ maximum and minimum capacity of pumped-storage unit b when generating.
u_t O&M variable cost of thermal unit t.
V_b upper reservoir limit of pumped-storage unit b.
v_t fuel cost of thermal unit t.
W penalty cost by power reserve defect.
w unserved energy cost.
w' interruptible energy cost.
η_b performance of pumped-storage unit b.
η_h performance of pumped-hydro unit h.

C. Output Variables

a_{tsp} commitment decision of thermal unit t in subperiod s of period p [0/1].
b_{bnsp} power consumption by pumped-storage unit b in load level n of subperiod s of period p.
e_{hnsp} power consumption by pumped-hydro unit h in load level n of subperiod s of period p.
f_{sp} defect of power reserve in subperiod s of period p.
h_{hnsp} generation of hydro unit h in load level n of subperiod s of period p.
i_{tp} unavailability by scheduled maintenance for thermal unit t during period p [0/1].
n_{nsp} non served power in load level n of subperiod s of period p.
n'_{nsp} interruptible power in load level n of subperiod s of period p.
p_{tnsp} generation of thermal unit t in load level n of subperiod s of period p.

R_{hp} hydro energy reserve of hydro unit h at the beginning of period p.
S_{cp} fuel storage capacity of thermal plant c at the beginning of period p.
t_{bnsp} generation of pumped-storage unit b in load level n of subperiod s of period p.
ξ_{tp} auxiliary variable in the equation of contiguity among the periods on maintenance.

II. Model Formulation

It follows the mathematical formulation of the objective function, the constraints and the variables involved in the problem.

A. Objective Function

$$
\begin{aligned}
\text{Min} \quad & \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{n=1}^{N} D_{nsp} \sum_{t=1}^{T} \left[v_t(o_t a_{tsp} + o'_t p_{tnsp}) + u_t p_{tnsp} \right] \\
+ \quad & \sum_{p=1}^{P}\sum_{s=2}^{S}\sum_{t=1}^{T} r_t (a_{ts-1p} - a_{tsp}) \\
+ \quad & \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{n=1}^{N}\sum_{c=1}^{C} c_c D_{nsp} S_{cp} \\
+ \quad & \sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{n=1}^{N} D_{nsp}(w n_{nsp} + w' n'_{nsp}) \\
+ \quad & W \sum_{p=1}^{P}\sum_{s=1}^{S} f_{sp}
\end{aligned} \tag{1}
$$

B. Interperiod Constraints

1. Maintenance Scheduling

   Maintenance requirement for each thermal unit

$$\sum_{p=1}^{P} i_{tp} = M_t \tag{2}$$

   Limit on the maximum number of thermal units simultaneously on maintenance on the same plant

$$\sum_{t \in c} i_{tp} \leq g \tag{3}$$

   Limit on the maximum thermal capacity simultaneously on maintenance in any period with respect to the total installed thermal capacity

$$\sum_{t=1}^{T} i_{tp} \overline{p}_t \leq m \sum_{t=1}^{T} \overline{p}_t \tag{4}$$

   Contiguity among the periods on maintenance

$$i_{tp} \leq \sum_{p' \leq M_t} (\xi_{tp+p'-1} + \ldots + \xi_{tp+M_t-1}) \tag{5}$$

   having the variable ξ_{tp} to satisfy the convexity equation

$$\sum_{p=1}^{P} \xi_{tp} = 1 \tag{6}$$

2. Fuel Scheduling

$$\sum_{s=1}^{S}\sum_{n=1}^{N}\sum_{t\in c} D_{nsp}\left(o_t a_{tsp} + o_t' \frac{p_{tnsp}}{k_t}\right) \geq C_{cp} + S_{cp} - S_{cp+1} \tag{7}$$

3. Hydro Scheduling

$$\sum_{s=1}^{S}\sum_{n=1}^{N} D_{nsp}(h_{hnsp} - \eta_h e_{hnsp}) \leq A_{hp} + R_{hp} - R_{hp+1} \tag{8}$$

C. Intraperiod Constraints

1. Reserve Margin

$$\sum_{t=1}^{T} \overline{p}_t k_t (1-q_t) a_{tsp} + \sum_{h=1}^{H} \overline{h}_{hp} + \sum_{b=1}^{B} \overline{t}_b + f_{sp} \geq d_{1sp}(1+R) \tag{9}$$

2. Balance between generation and demand.

$$\sum_{t=1}^{T} p_{tnsp} + \sum_{h=1}^{H}(h_{hnsp} - e_{hnsp}) + \sum_{b=1}^{B}(t_{bnsp} - b_{bnsp}) + n_{nsp} + n'_{nsp} = d_{nsp} \tag{10}$$

3. Pumped-Storage Units

$$\sum_{s=1}^{S}\sum_{n=1}^{N} D_{nsp}(\eta_b b_{bnsp} - t_{bnsp}) = 0 \tag{11}$$

$$\sum_{s=1}^{S}\sum_{n=1}^{N} D_{nsp} b_{bnsp} \leq V_b \tag{12}$$

4. Thermal Generation Constraints

$$\underline{p}_t k_t a_{tsp} \leq p_{tNsp} \tag{13}$$

$$p_{t1sp} \leq \overline{p}_t k_t (1-q_t) a_{tsp} \tag{14}$$

$$p_{tn+1sp} \leq p_{tnsp} \tag{15}$$

$$a_{ts+1p} \leq a_{tsp} \tag{16}$$

D. Variables

All the variables involved in the previous formulation are subject to the following bounds: maintenance decisions for thermal units

$$i_{tp} = \{0,1\}$$

$$0 \leq \xi_{tp} \leq 1$$

fuel stock levels

$$\underline{S}_c \leq S_{cp} \leq \overline{S}_c$$

hydro productions and consumption of seasonal pumped-hydro units

$$\underline{h}_{hp} \le h_{hnsp} \le \overline{h}_{hp} \qquad \underline{e}_h \le e_{hnsp} \le \overline{e}_h$$

hydro energy reserves

$$\underline{R}_h \le R_{hp} \le \overline{R}_h$$

commitment decisions of thermal units

$$a_{tsp} = \{0, 1\}$$

thermal generations

$$p_{tnsp} \le \overline{p}_t k_t (1 - q_t)$$

generation and consumption of weekly/dairy pumped-storage units

$$\underline{t}_b \le t_{bnsp} \le \bar{t}_b \qquad \underline{b}_b \le b_{bnsp} \le \bar{b}_b$$

non served power and interruptible power

$$n_{nsp} \le d_{nsp} \qquad n'_{nsp} \le d'_{nsp}$$

reserve margin defect

$$f_{sp} \le d_{1sp}(1 + R)$$