Stochastic Optimization as a Supporting Tool to Analyze the Performance of the Brazilian Hydrothermal Interconnect System under Critical Inflow Scenarios

Maria Elvira Piñeiro Maceira
DEA – Energy Optimization and Environment Department
Brazilian Interconnected System
Main Features

Gen. Cap. Mix
December/2013
124,796 MW

- Hydro 86 GW (69%)
- Nuclear 2 GW (2%)
- Thermal 19 GW (15%)
- Wind 2 GW (2%)
- Bio 10 GW (8%)
- Small hydro 5 GW (4%)

Gen. Cap. Mix
December/2023
195.883 MW

- Hydro 117 GW (60%)
- Nuclear 3 GW (2%)
- Thermal 28 GW (14%)
- Solar 4 GW (2%)
- Wind 22 GW (11%)
- Bio 14 GW (7%)
- Small hydro 7 GW (4%)

Note 1: Includes import
Note 2: Excludes self-production

Source: MME/EPE - PDE 2023

Hydropower Scheduling Workshop
Brazilian Interconnected System
Main Features

Continental Dimension
Large Scale Power System

4000 km

BRAZIL
EUROPE

Hydropower Scheduling Workshop
September/ 2015
Hydrothermal Coordination Problem

- Coupled in time and space
- Future water inflows have a stochastic behavior
- Inflows vary greatly in different seasons and even from year to year

Average Energy Inflows

Coefficient of Variation
The historical inflow records present multi-year dry periods.

Hydrothermal Coordination Problem

Southeast
Energy Optimization and Centralized Dispatch of Whole Power System

Several plants from different owners in the same riverbasin

Savings = ~ US$ 2.5 billions (source: ONS)
Brazilian Hydropower System

Energy Optimization and Centralized Dispatch of Whole Power System

Several plants from different owners in the same riverbasin

Four Energy Equivalent Reservoirs
Four Subsystems/Submarkets

Savings =~ US$ 2,5 billions
(source: ONS)
Energy Optimization and Centralized Dispatch of Whole Power System

Several plants from different owners in the same riverbasin

Savings = $2.5 billions (source: ONS)

Twelve Energy Equivalent Reservoirs
Four Subsystems/Submarkets

Brazilian Hydropower System
CEPEL’s Chain of Optimization Models for the Generation Expansion and Operational Planning of the Brazilian System

Energy Optimization and Centralized Dispatch of the Whole Interconnected Hydrothermal System:

20% More Energy Production

Need of capturing synergies in planning and operation stages

September/ 2015
Energy Optimization and Centralized Dispatch of the Whole Interconnected Hydrothermal System:

20% More Energy Production

Need of capturing synergies in planning and operation stages
CEPEL’s Chain of Optimization Models for the Generation Expansion and Operational Planning of the Brazilian System

**Stochastic Optimization Models**

- AAEXP: Strategic Environmental Assessment for the Generation Expansion Planning
- SINV: System for Hydropower River Basin Inventory
- AMBIENTRANS: Incorporation of the Environmental Dimension
- ANAFIN: Economic Financial Evaluation

**Simulation Models**

- MATRIZ: Brazilian Energy Matrix
- VENTO: Synthetic Wind, Generation, Hourly Wind Forecast
- GEVAZP: Synthetic Streamflow

**Synthetic Inflow Scenarios Generation Models**

- CONTROLE DE CHEIAS
- Weekly Streamflow Forecast

**Streamflow Forecasting Models**

- Short term Load forecast
- Daily Streamflow Forecast

**Investment and Commercialization Models**

- Hydrothermal Unit Commitment DC Network
- Corporate Sustainability Indicators

**Reliability Models**

- Hydrothermal Unit Commitment AC Network

**Energy Optimization and Centralized Dispatch of the Whole Interconnected Hydrothermal System:**

- **20% More Energy Production**
- Need of capturing synergies in planning and operation stages
CEPEL’s Chain of Optimization Models for the Generation Expansion and Operational Planning of the Brazilian System

**Monthly Operation Planning - PMO**

**GEVAZP**
- Run at the beginning of each month
- Monthly Multivariate Energy Inflows Scenarios
- Weekly Streamflow Forecast for all the weeks of the present month

**PREVIVAZ**
- Run at the beginning of each week of the month
- Weekly Streamflow Forecasts for all the weeks of the first month

**NEWAVE**
- Hydrothermal Long Term Operation Planning
- Expected Cost to Go Function
  - (For each stage of the horizon, Multivariate State variables: energy equivalent reservoirs storages and past inflows)
- Run at the beginning of each month

**DECOMP**
- Hydrothermal Short Term Operation Planning
- Expected Cost to Go Function
  - (For each stage of the horizon, Multivariate State variables: hydroplant reservoir storages)
- Run at the beginning of each week of the month

**DESSEM**
- Hydrothermal Unit Commitment DC Network
- Supports ONS and agents unit commitment
- Run at the beginning of each week of the month

**CEPEL’s Chain of Optimization Models for the Generation Expansion and Operational Planning of the Brazilian System**

- Run at the beginning of each month
- Run at the beginning of each week of the month

**Weekly goal dispatch**
- Weekly Spot Price

**Hydropower Scheduling Workshop**

September/ 2015
First Module – Energy Equivalent Reservoir

The aggregation technique, known as equivalent reservoir representation, is based on the estimation of the energy produced by the complete depletion of the system reservoirs for a given set of initial storage.

The equivalent reservoir model is a composite representation for the multireservoir hydroelectric power system: one reservoir, which receives, stores and releases potential energy.

One equivalent reservoir can present hydraulic coupling with another equivalent reservoir downstream.

One or more energy equivalent reservoir attend the demand of a subsystem/submarket.

The Brazilian system is currently represented by 4 energy equivalent reservoirs in Operation Studies (9, in Jan/2016) and by 11 in Expansion Studies.
Third Module - Hydrothermal Operation Strategy

Stochastic dual dynamic programming (Benders decomposition) is used to solve the multi-stage stochastic linear programming problem (the operation dispatch problem)

**OBJECTIVE FUNCTION**

$$\min_{\omega} E \left[ \left( \sum_{t=1}^{T} \left( \sum_{i=1}^{NT} c(gt_i^{t,\omega}) + \sum_{s=1}^{NS} Defc_i^{t,\omega} \right) \right) \right]$$

Thermal generation and deficit costs until Aug/2013
**Third Module - Hydrothermal Operation Strategy**

Since Sep/2013 a risk averse approach is considered optimization.

The so called CVaR (Conditional Value at Risk)

A direct CVaR approach to SDDP was proposed and implemented in NEWAVE model.
**NEWAVE - Long Term Operation Planning Model**

**Third Module - Hydrothermal Operation Strategy**

**CONSTRAINTS**

\[
\sum_{i \in H_j} gh_{i,t}^{t,\omega} + \sum_{i \in T_j} gt_{i,t}^{t,\omega} \pm \sum_{i \in Int_j} \text{Int}_{t,\omega}^{t,\omega} + \text{Defc}_{j,t} = D_{j,t}, \quad \forall t, \omega, j
\]

- Demand supply - submarket

\[
earm_{s,t}^{t} = \text{earm}_{s,t}^{t-1} - gh_{s,t}^{t,\omega} + \xi_{s,t}^{t,\omega} \left( \xi_{s-t-p,\omega}^{t,\omega}, \zeta \right), \quad \forall t, \omega, j
\]

- Energy conservation – REE

\[
gh_{s,t}^{t,\omega} = f(\text{earm}_{j,t}^{t,\omega})
\]

- Par-P model

- Selective Sampling

- Energy interchanges limits among submarkets

- Lower bounds on total outflow – equivalent energy reservoir (REE)

- Thermal generation limits - submarket

- Storage limits - REE

**Benders cuts**

\[
\phi_l(x_{i-1}) \geq \sum_{\omega=1}^{K} p_\omega \left[ z_{i,\omega}^{t,\omega} + \frac{\partial z_{i,\omega}}{\partial x_{i-1}} (\hat{x}_{i-1,\omega} - x_{i-1}) \right]
\]

**OUTPUT:**

- Operation Policy
Forth Module - system operation simulation by using multivariate inflows scenarios

- Calculation of system performance probabilistic indices
  - energy deficit risks
  - expected energy not supplied
  - expected operation marginal costs
  - Probability distributions of operating costs, marginal costs, flow interchanges, hydro generation, thermal generation etc

- Energy inflows scenarios
  - multivariate
    - spatial and time correlation
  - synthetic streamflows generation
    - 2,000 scenarios
  - PAR(p) model
    - Conditioned or not to the recent trend
  - historical record sequences
**Second Module – Energy Inflows Scenarios Generation**  
**GEVAZP model**

**Forward pass**

- Scenario 1
- Scenario 2
- Scenario 3
- Scenario S << K^T

**Backward pass**

- Scenario 1
- Scenario 2
- Scenario 3
- Scenario S << K^T

**Optimal policy construction (200 scenarios)**

**Final simulation operation policy (2000 scenarios)**

**Conditioned or not to recent past inflows**

---

*Hydropower Scheduling Workshop*  
*September/ 2015*
Choose a stochastic time series model that ensures resemblance between the historical and synthetic inflow sequences (streamflows or energy inflows)

**Stochastic time series model:** PAR(p)  
- the inflow at period \( t \) is a function of the past inflows \( (t-1), (t-2), \ldots \)  
- the time dependence structure is seasonal  
- preserves temporal and spatial correlation and considers selective sampling

Scenarios can be conditioned to recent past inflow or each scenario can be conditioned to a different past inflow
Demand Supply Evaluation

2014
Energy Inflows - Historical Records
1931 to 2015

Southeast

South

monthly average
2014

Northeast

North

2015
Energy Inflows – Historical Record for February/14 and January/15

(% of Monthly Mean)

% MLT Histórica - Fevereiro - (1931 a 2014)

% MLT Histórica - FEV - (1931 a 2014)

% MLT Histórica - mês Janeiro - (1931 a 2015)

% MLT Histórica - mês Janeiro - (1931 a 2015)
- Recognize relevant uncertainties, such as inflows to reservoirs
- Select a set of indicators
- Choose an appropriate methodology to estimate the indices associated to these indicators
  - Synthetic and historical inflow scenarios
  - Conditioned and “unconditioned” synthetic inflow scenarios
- If the trend is extreme, as occurred in February 2014 or January 2015, the synthetic scenarios could present very low representation in historical record
  - It is recommended that the evaluation of system performance periods ahead is made from “unconditioned” synthetic inflow scenarios and historical scenarios
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs - 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)

<table>
<thead>
<tr>
<th>Month</th>
<th>S.S. with TH</th>
<th>S.S. without TH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar</td>
<td>39.5%</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>29.3%</td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>12.8%</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>5.4%</td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>0.1%</td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>0.0%</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>0.0%</td>
<td></td>
</tr>
</tbody>
</table>

Feb/14

- E inflow: 39.00%
- Storage: 35.40%

S.S. conditioned to past inflow
S.S.
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs - 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)

March 2014
April 2014

Indices calculated by PMOs - 2014

<table>
<thead>
<tr>
<th>Month</th>
<th>E inflow</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb/14</td>
<td>39.00%</td>
<td>35.40%</td>
</tr>
<tr>
<td>mar/14</td>
<td>64%</td>
<td>36.90%</td>
</tr>
</tbody>
</table>
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs - 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs of 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)

<table>
<thead>
<tr>
<th>Month</th>
<th>Feb/14</th>
<th>mar/14</th>
<th>Apr/14</th>
<th>May/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>E inflow</td>
<td>39.00%</td>
<td>64%</td>
<td>80%</td>
<td>76%</td>
</tr>
<tr>
<td>Storage</td>
<td>35.40%</td>
<td>36.90%</td>
<td>38.5%</td>
<td>37.4%</td>
</tr>
</tbody>
</table>
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs of 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)

Mar 6,4 Apr 7,4 May 6,7 Jun 5,4 4,8 Jul 0,1, 1,7 August

S.S. conditioned to past inflow S.S.
Probability of Annual Energy Deficit in 2014 at each Time of Evaluation

Indices calculated by PMOs of 2014

SOUTHEAST - 2014
Annual Risk of Deficit (%)

March to December 2014

Similar analysis with historical energy inflows record were performed

Analysis with DECOMP model were performed considering similar historical scenarios

<table>
<thead>
<tr>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4</td>
<td>7.4</td>
<td>12.8</td>
<td>5.4</td>
<td>1.7</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7.4</td>
<td>12.8</td>
<td>5.4</td>
<td>1.7</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Energy Deficit Risks
Comparison between Years
2001 and 2014/2015
## Energy Inflows (ena) and Initial Reservoir Storages (earm)

### 2014 and 2001

<table>
<thead>
<tr>
<th></th>
<th>SE</th>
<th>S</th>
<th>NE</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Em Fev 2014</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ena</td>
<td>39,0%</td>
<td>59,0%</td>
<td>27,0%</td>
<td>100,0%</td>
</tr>
<tr>
<td>earm</td>
<td>35,4%</td>
<td>37,6%</td>
<td>42,2%</td>
<td>80,0%</td>
</tr>
<tr>
<td><strong>Em Fev 2001</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ena</td>
<td>72,7%</td>
<td>241,4%</td>
<td>36,9%</td>
<td>82,2%</td>
</tr>
<tr>
<td>earm</td>
<td>35,1%</td>
<td>98,3%</td>
<td>38,4%</td>
<td>85,1%</td>
</tr>
<tr>
<td><strong>Em Mar 2014</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ena</td>
<td>64,0%</td>
<td>166,0%</td>
<td>26,0%</td>
<td>116,0%</td>
</tr>
<tr>
<td>earm</td>
<td>36,9%</td>
<td>46,2%</td>
<td>41,7%</td>
<td>83,8%</td>
</tr>
<tr>
<td><strong>Em Mar 2001</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ena</td>
<td>70,8%</td>
<td>178,9%</td>
<td>31,7%</td>
<td>78,7%</td>
</tr>
<tr>
<td>earm</td>
<td>34,9%</td>
<td>96,2%</td>
<td>37,6%</td>
<td>85,8%</td>
</tr>
</tbody>
</table>
Monthly Operational Planning Results for March to June – 2014 and 2001

Energy Deficit Risks

June 2001: in case energy rationing had not been adopted
Monthly Operational Planning Results for March to June – 2014 and 2001

NORDESTE
Risco de Qualquer Deficit

Northeast Region

<table>
<thead>
<tr>
<th>mês</th>
<th>S.Sint. 2014</th>
<th>S.Sint. 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Março</td>
<td>0,9</td>
<td>20,6</td>
</tr>
<tr>
<td>Abril</td>
<td>1,3</td>
<td>27,5</td>
</tr>
<tr>
<td>Maio</td>
<td>1,9</td>
<td>44,3</td>
</tr>
<tr>
<td>Junho</td>
<td>1,3</td>
<td>60,2</td>
</tr>
</tbody>
</table>

June 2001: in case energy rationing had not been adopted.
Conclusion Remarks

One key parameter to support the decision of implementing or not an energy rationing in Brazil, in 2014 and 2015, was the stochastic optimization studies based on Cepel’s chain of optimization models

Therefore, the decision of not implementing energy rationing was taken based on technical evaluation
Thank you!

elvira@cepel.br