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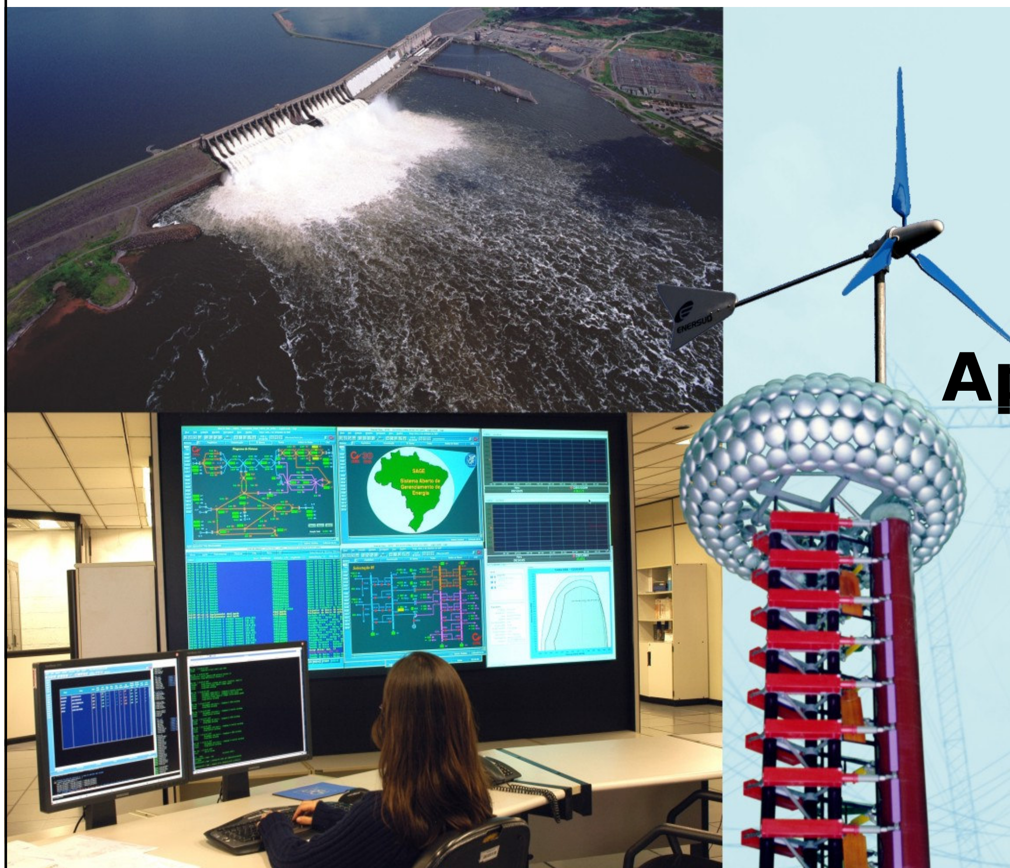

Risk-Averse Storage Level Surface (SAR) Applied to Hydrothermal Generation Planning within SDDP Solving Strategy"

A.L.Diniz, C.L.V. Vasconcellos, M.E.P. Maceira, D.D.J. Penna

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OUTLINE

- **LONG TERM HYDROTHERMAL PLANNING PROBLEM (LTHTP)**
  - Integration with other models
  - Problem Formulation and Solving Strategy – SDDP
- **RISK AVERSE APPROACHES**
  - Bibliographical Review
  - Use of Rule Curves
- **SAR – Risk Averse Surface (Multidimensional Rule Curves)**
  - Concept and overview

  Two-level SDDP/Benders Decomposition (BD) approach:
  - Upper level => SDDP for the multistage LTHTP problem
  - Lower level=> two-stage Benders Decomposition – SAR constraints
- **NUMERICAL RESULTS**
  - convergence & SAR construction statistics
  - Sensitivity analysis to parameters
  - Comparison results with previous approaches & System Operation
- **CONCLUSIONS**

LONG TERM HYDROTHERMAL PLANNING IN BRAZIL - OVERVIEW

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Horizon	Time step	Uncertainty	[Maceira et al,02] [Maceira et al,08]	System Representation	Solving Strategy
10 years	Monthly	Stochastic, Sampling	LONG-TERM (NEWAVE) ↓ Future cost function	Aggregated Reservoirs, System areas	SDDP
3 Months to 1 year	Weekly/ Monthly	Stochastic, Complete tree	MID-TERM (DECOMP) ↓ Future cost function	Hydro plants, System areas	DDP
1 week	Hourly/ Larger	Determi nistic	SHORT-TERM (DESSEM) ↓ Future cost function	Hydro Plants, DC power flow	Linear Program.
1 day	Hourly	Determi nistic	DAY AHEAD (DESS-UC)	Unit commitment DC Power Flow	Lagrangian Relaxation

LONG TERM HYDROTHERMAL PLANNING (LTHTP) – Traditional Formulation

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MULTI-STAGE STOCHASTIC LINEAR PROGRAMMING PROBLEM

[Birge,Louveaux,97]
[Kall,Mayer,10]

OBJECTIVE FUNCTION

$$\min \; E\left[\left(\sum_{t=1}^{T}\sum_{j=1}^{NT} c_j\left(GT_j^{t,\omega}\right)\right)+\alpha(v^T)\right]$$

Thermal generation + load schedding

CONSTRAINTS

Demand balance

$$\sum_{i\in H_j} gh_i^{t,\omega} + \sum_{i\in T_j} gt_i^{t,\omega} \pm \sum_{i\in Int_j} Int^{t,\omega} + Defc_j^t = D_j^t, \quad \forall t,\omega,j$$

Water conservation

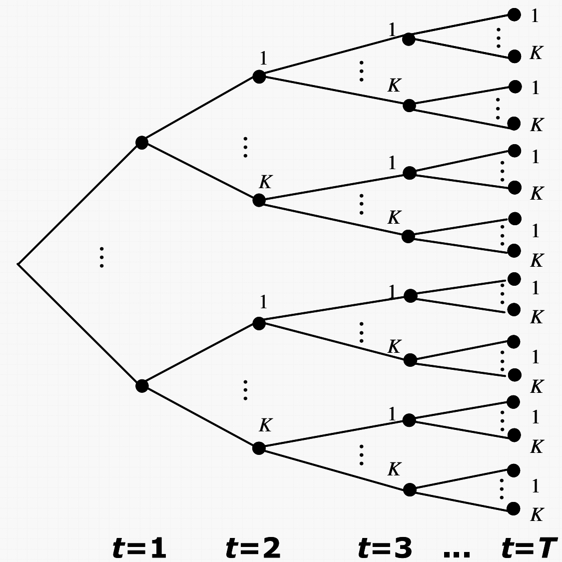
$$v_s^t = v_s^{t-1} - gh_s^{t,\omega} + \xi_s^{t,\omega}\Big|(\xi_{s,\;p-1,\dots P}^{t-p,\omega},\zeta), \;\forall t,\omega,j$$

Par-P model

[Maceira, Bezerra,97]

+ Many other operation constraints...

SCENARIO TREE



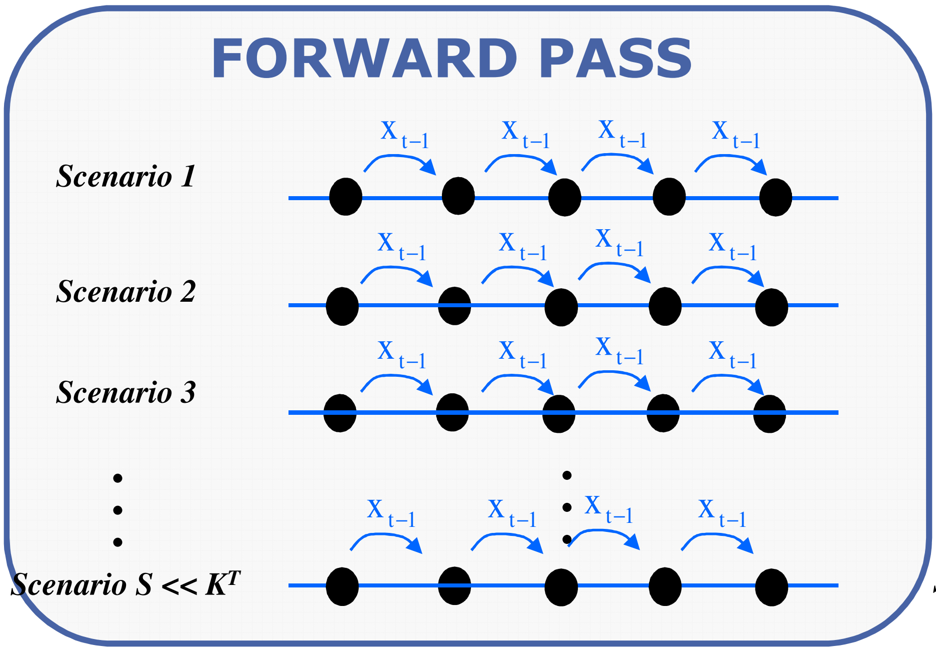
SELECTIVE SAMPLING

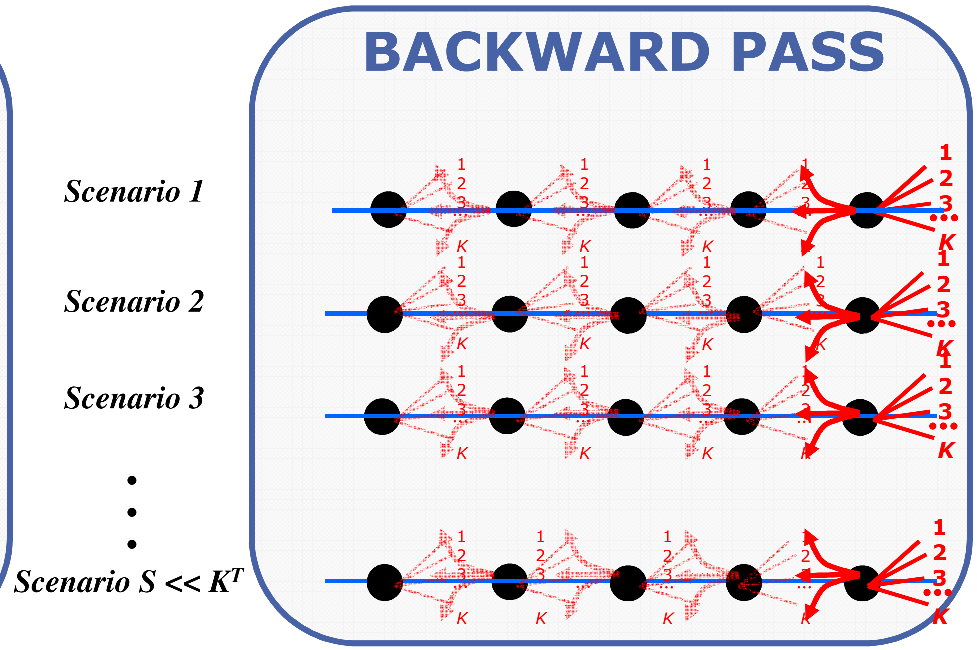
[Penna,Maceira,Damazio,11]

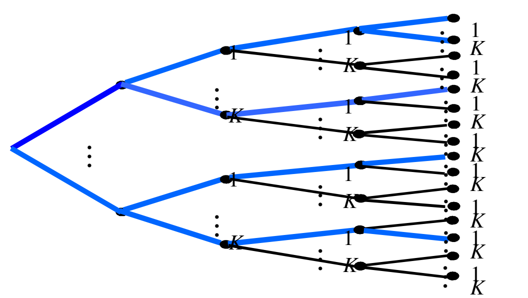
SOLVING STRATEGY

[Pereira,Pinto,91]

- **SDDP (Stochastic Dual Dynamic Programming) approach**



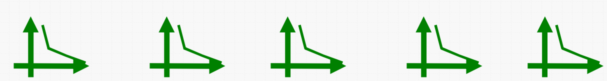




Benders cuts:

$$\varphi_t(x_{t-1}) \geq \sum_{\omega=1,\dots K} p_\omega \left[z_{t,\omega^*} + \left\langle \frac{\partial z_{t,\omega^*}}{\partial x_{t-1}}(\hat{x}_{t-1,s^*}), x_{t-1} - \hat{x}_{t-1,s^*} \right\rangle \right]$$

OUTPUT:



Optimal Operation Policy

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PREVIOUS EXPERIENCES

- **Managing the deficit risk (Traditional SDP)**
  - Calibration of unitary deficit costs
  - Indicator variable for shortage / risk constraints

[Askew,74], [GCOI,79]
[Sniedovich,79],
[Araripe Neto,Pereira, Kelman,85]

- **Profit Maximization in hydroelectric systems**
  - SDP/SDDP approach, Norwegian system **[Mo,Gjelsvik,Grundt,01]**
  - 2 stage SDDP problem for the real Brazilian system **[Marzano,04]**
  - 3 stage problem, single reservoir **[Iliadis,Pereira, et al,07]**

- **Probability of being below given reservoir levels**
  - Individual chance constraints **[Guigues,Sagastizabal,08]**
  - Joint chance constraints **[Andrieu,Henrion,Romisch,10]**

OFFICIALLY USED IN NEWAVE MODEL SINCE SEPT. 2013

- Nested Conditional Value-at-Risk (CVaR) in the objective function **[Shapiro,10]**
- Applicattion in the SDDP approach

[Philpott,Matos,10] [Shapiro et al,12] [Diniz et al,12]

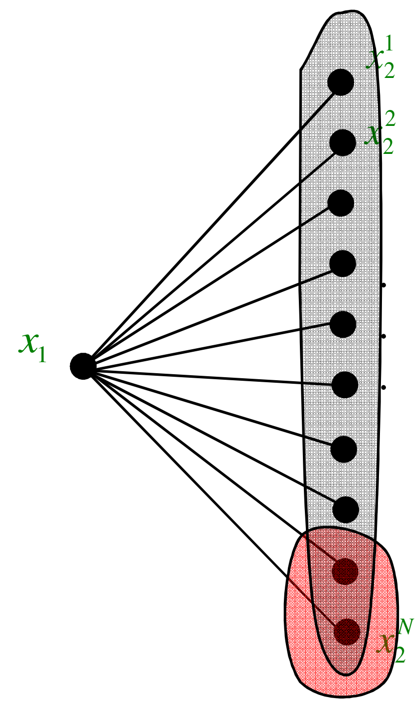
- Parameters: λ , α

Weight for Expected Value minimization

Weight for CVaR minimization

$$\min_{x_1}\left[c_1x_1 + (1-\lambda)E\left[\min_{x_2} c_2x_2\right] + \lambda\, CVaR_{\alpha}\left[\min_{x_2} c_2x_2\right]\right]$$

Risk level



OPTIMIZATION WITH CONDITIONED VALUE AT RISK (CVAR)

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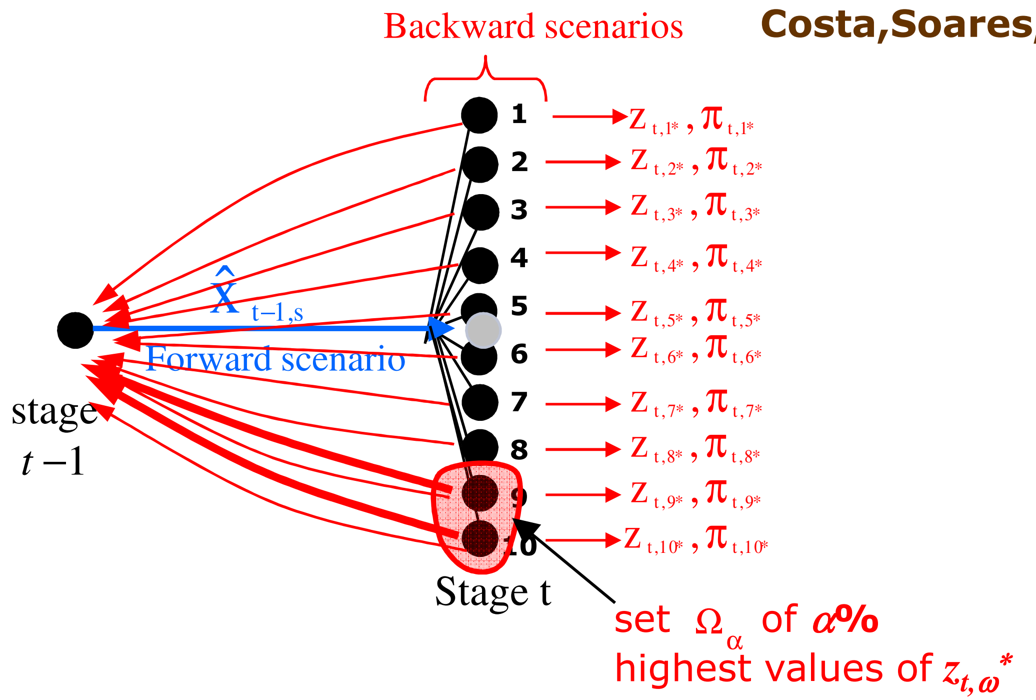
BACKWARD PASS

[CEPEL,12a],

[Shapiro,Tekaya, Costa,Soares,12]

- solve subproblems for all bacward scenarios ω
- identify the scenarios related to the $\alpha\%$ highest values of $z_{t,\omega}$
- Build Benders cut with both expected value and risk averse terms



$$\varphi_t(x_{t-1}) \geq (1-\lambda)\sum_{\omega=1}^{K} p_\omega\left[z_{t,\omega^*} + \left\langle \pi_{t,\omega^*}, x_{t-1} - \hat{x}_{t-1,s}\right\rangle\right] + \left(\frac{\lambda}{\alpha}\right)\sum_{\omega\in\Omega_\alpha} p_\omega\left[z_{t,\omega^*} + \left\langle \pi_{t,\omega^*}, x_{t-1} - \hat{x}_{t-1,s}\right\rangle\right] = \overline{z}^* + \left\langle \overline{\pi}^*, x_{t-1} - \hat{x}_{t-1,s}\right\rangle$$

ALTERNATIVE RISK AVERSE APPROACH
Use of Rule Curve

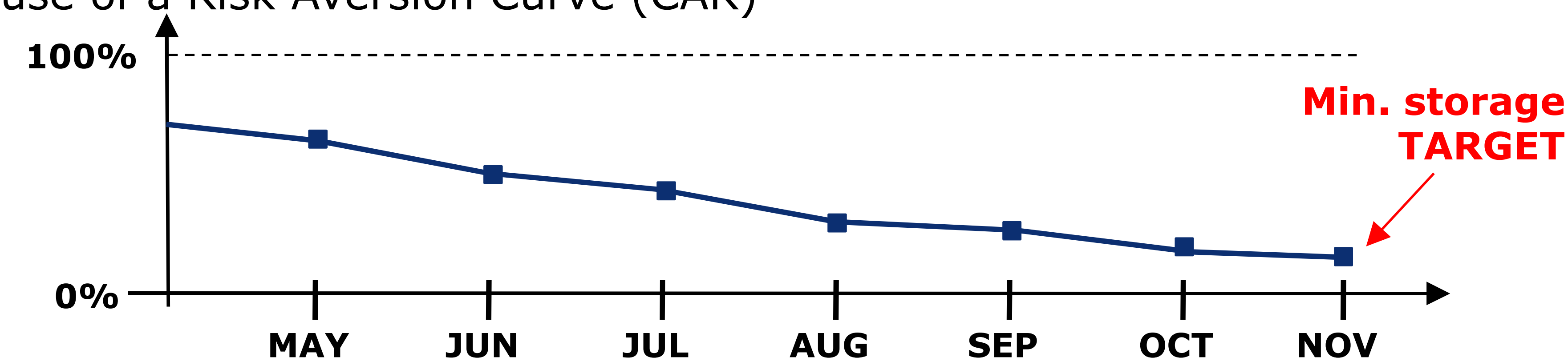
PURPOSE

- Minimum storage level curves to protect against the (first, second,...) worst scenario of historical record;
- Thermal generation is maximized whenever storage is below such curve

[Brudenell,Gilbreath,59] [Stage, Larsson,61] [Arvantidis,Rosing,70]

PREVIOUS OPERATION OF THE BRAZILIAN SYSTEM (unidimensional rule-curves)

- recursive calculations in time, based on a target level at the end of the dry season **[Carvalho, Rosenblatt,77]**
- use of a Risk Aversion Curve (CAR) **[Brasil,02]**



OBJECTIVES OF THIS WORK

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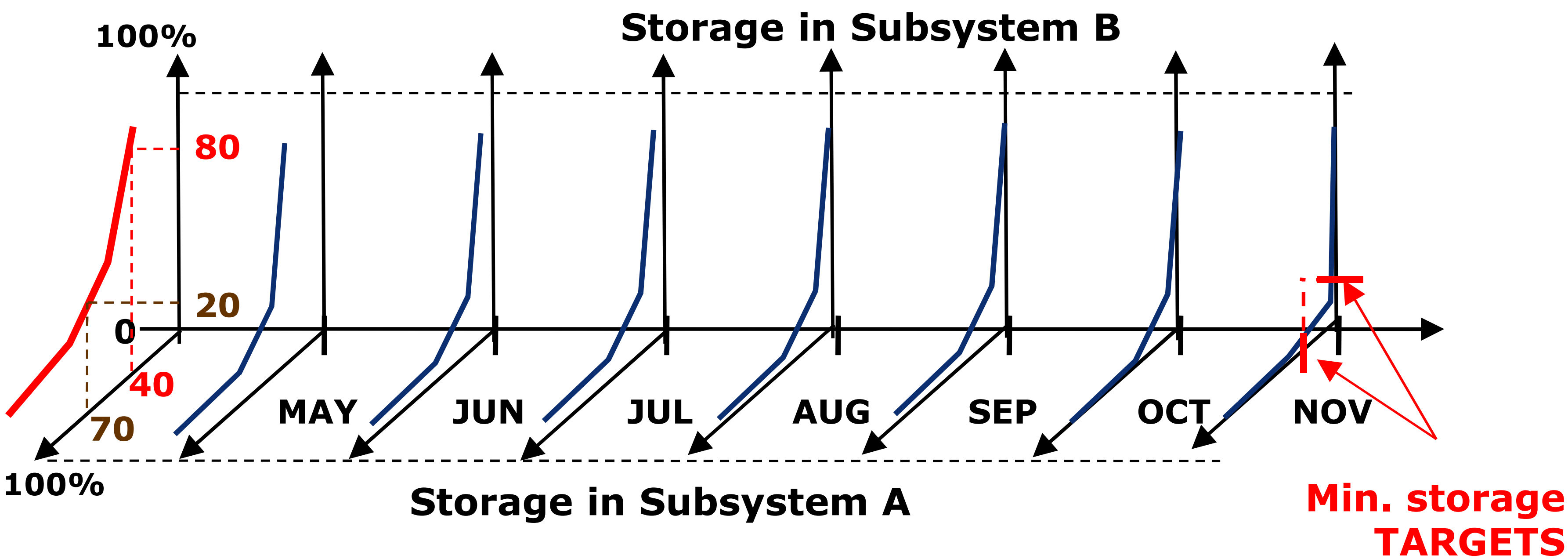
1) Extend the Rule Curve Approach to take into account energy interchange among subsystems

➡ Multidimensional Rule Curve – Risk Averse Surface (SAR)

[PSR,08]



OBJECTIVES OF THIS WORK

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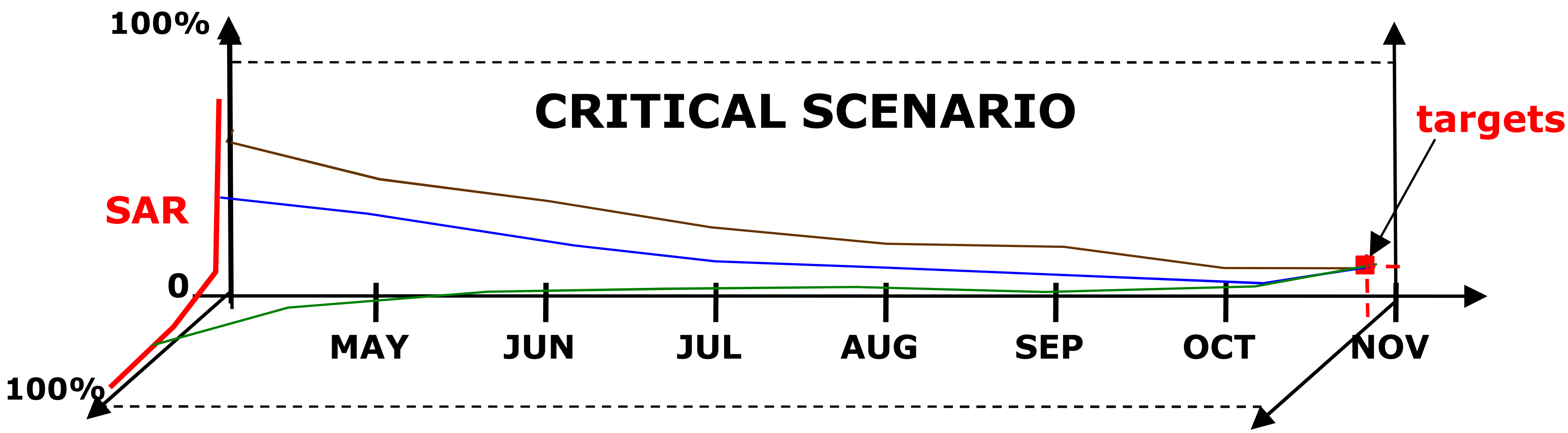
1) Extend the Rule Curve Approach to take into account energy interchange among subsystems

➡ Multidimensional Rule Curve – Risk Averse Surface (SAR)

DEFINITION: **[PSR,08]**

> **"Minimum values for the VECTOR of storages in the equivalent reservoirs, at the end of each time step, so that it is possible to meet storage targets at the end of the dry season, WITHOUT load curtailment, FOR A GIVEN CRITICAL SCENARIO"**



OBJECTIVES OF THIS WORK

2) Introduction of such risk aversion surface (SAR) into the SDDP solving strategy

- To compute / approximate the SAR iteratively during the course of the SDDP algorithm;
- It is only necessary to build the SAR for the regions / time steps where critical conditions are binding for the scenarios visited in the forward / backward passes

⬇

- **Outer level:** Standard SDDP algorithm;
- **Inner level:** two-stage Benders decomposition to solve the SAR subproblem for critical scenarios and build feasibility cuts for the outer level

CHOICE OF THE CRITICAL SCENARIO

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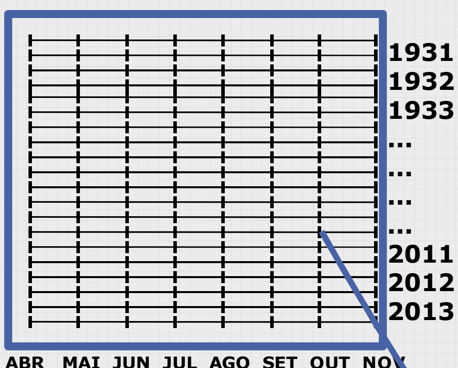
- **Two variants have been considered:**

UNCONDITIONED (HISTORICAL)

- **to pick one critical scenario from the historical record of past inflows**

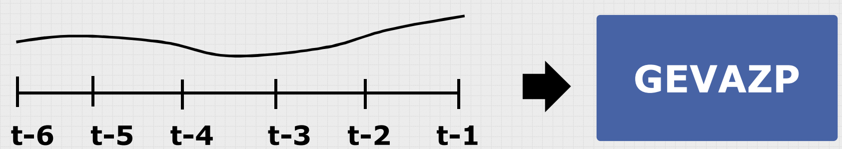


HISTORICAL RECORD

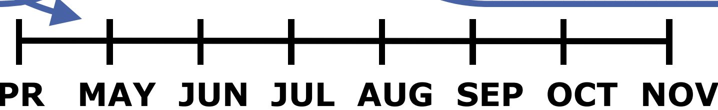
OR

CONDITIONED (SYNTHETIC)

- **to generate a forecast of future inflows by an auto-regressive model (par-P), given a set of previous inflows**



scenario generation model



CRITICAL SCENARIO

OVERALL SOLVING STRATEGY

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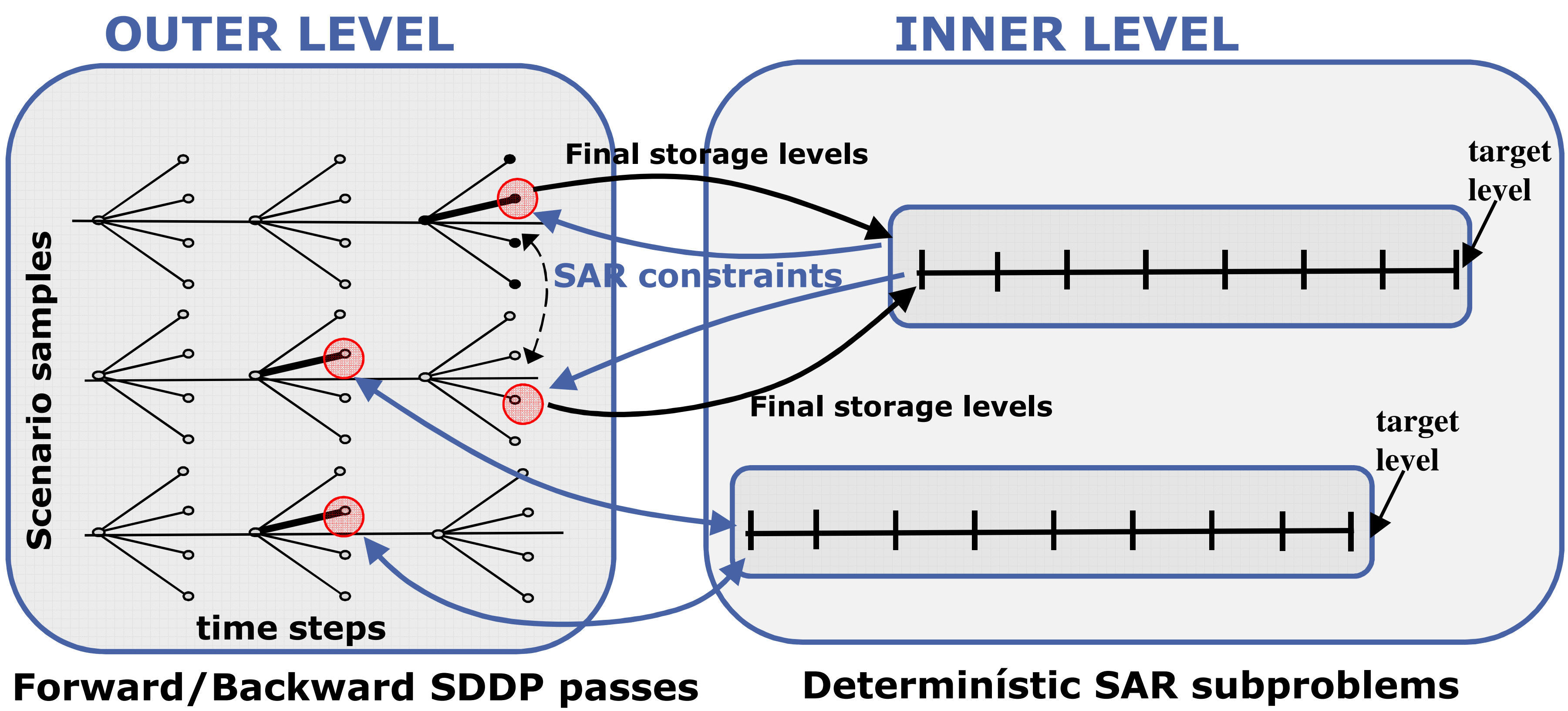

- initial conditions of the deterministic “SAR subproblem” are the final storages of the reservoirs in the main upper level (LTHTP) problem;
- SAR cuts will be built only if the system state (e.g. reservoir levels and past inflows) result in a violation of the target level of the SAR subproblem

INNER LEVEL SUBPROBLEMS (SAR subproblem)

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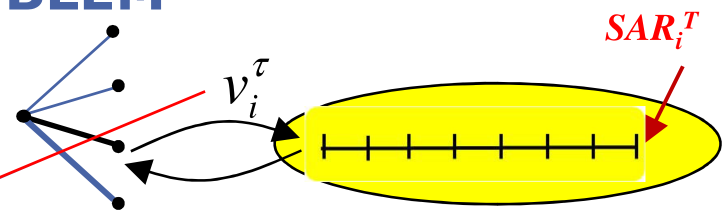
MULTISTAGE DETERMINISTIC SUBPROBLEM



$$\beta(v_i^\tau) = \min_{z,ea,gh,gt,f} \sum_{\tau=t+1}^{T} \sum_{i=1}^{NSIS} z_i^\tau$$

load schedding

s.t.

$$v_i^{\tau+1} + gh_i^\tau = v_i^\tau + I_i^\tau, \quad i = 1,\ldots,NSIS, \quad \tau = t+1,\ldots,T$$

$$gh_i^\tau + \sum_{j\in\Omega_i}\left(f_{j,i}^\tau - f_{i,j}^\tau\right) + z_i^\tau = D_i^\tau - \sum_{i=1}^{NT} gt_{\max i}^\tau, \quad i = 1,\ldots,NSIS, \quad \tau = t+1,\ldots,T$$

$$v_i^T \geq SAR_i^T \quad i = 1,\ldots,NSIS$$

$$z_i^\tau, ea_i^\tau, gh_i^\tau, gt_i^\tau, f_{i,j}^\tau \geq 0 \quad \tau = t+1,\ldots,T, \quad i = 1,\ldots,NSIS$$

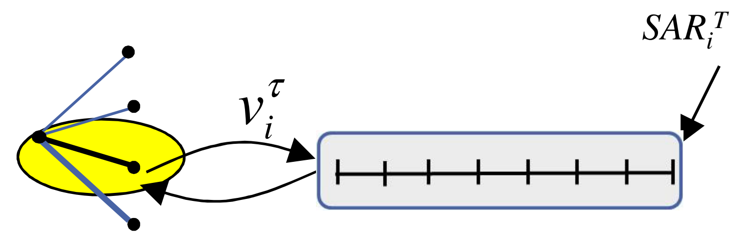
1st parameter:

Target level in EACH subsystem, at the end of the dry season;

To check system conditions and build SAR constraints if necessary (Benders feasibility cuts)

OUTER LEVEL SUBPROBLEMS (LTHTP subproblem for each scenario)

LTHTP subproblem



2nd parameter: penalty for SAR violation

$$\min_{x^t,\alpha_{t+1}} \quad c\,x^t + p_{SAR}\Delta_{SAR} + \alpha_{t+1}$$

→ **present + future costs**

$$s.a. \quad \begin{cases} A_t x^t = b^t - Ex^{t-1} \\ \alpha_{t+1} \geq \varpi_\ell + (\pi^\ell)^{\mathrm{T}} x^t, \quad \ell = 1,\ldots,\Lambda \\ h(ea^{t+1}) + \Delta_{SAR} \geq 0 \\ x^t \geq 0, \end{cases}$$

→ **Demand balance**
Water balance
Variables limits
etc.

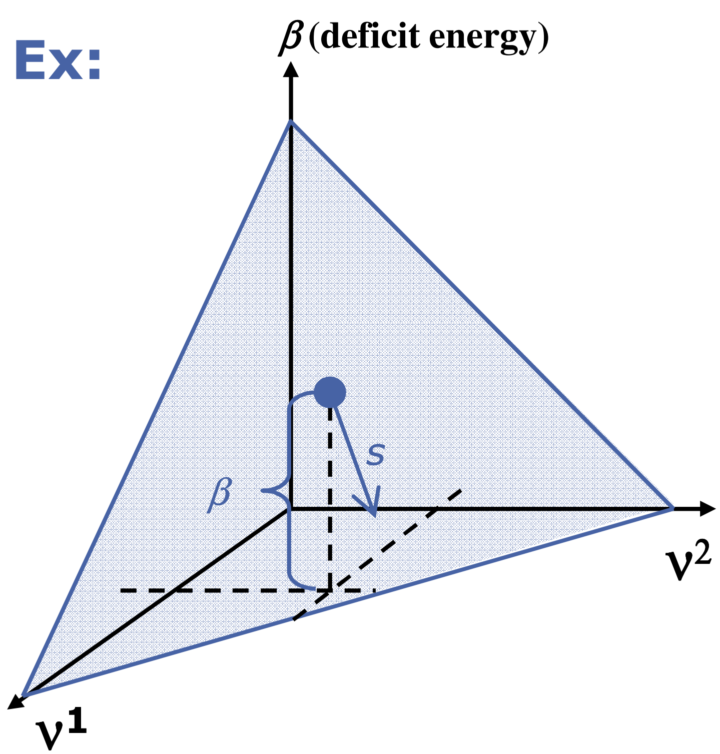
SAR constraint is a multivariate expression on energy storages and past energy inflows

$$\sum_{i=1}^{nsis} \pi_{VS,t+1}^{i,k} v_{t+1}^{i} + \Delta_{SAR,t+1}^{k} \geq RHS_{t+1}^{k} + \sum_{i=1}^{i} \sum_{j=1}^{p} \pi_{ASj,t+1}^{i,k} I_{t+1-j}^{i}$$

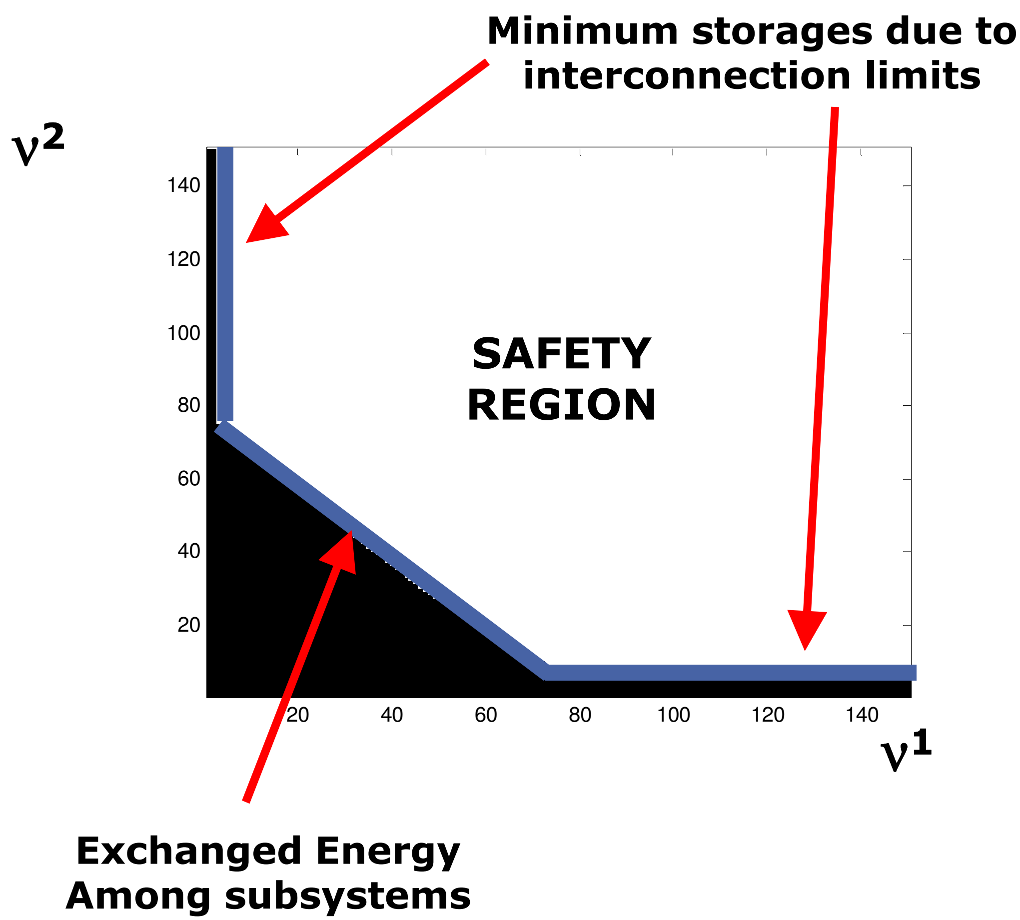
SAR - RISK AVERSE SURFACE
Shape of the Feasibility Cuts

GENERAL STRUCTURE OF SAR CONSTRAINTS

Ex:



$$\beta(\hat{v}_i^{\tau}) + \frac{\partial \beta}{\partial v_i^{\tau}}(\hat{v}_i^{\tau})\left(v_i^{\tau} - \hat{v}_i^{\tau}\right) \leq 0$$



NUMERICAL RESULTS
Real Large-Scale Brazilian System

GENERAL SETTING

- 149 hydro plants (91 GW) => **4 equivalent energy reservoirs**
- 127 thermal plants (24 GW)
- **120 time steps** (5 year horizon, monthly steps)
- **20 scenarios per stage** (20^120 multistage scenarios)
- forward sampling - 200 scenarios

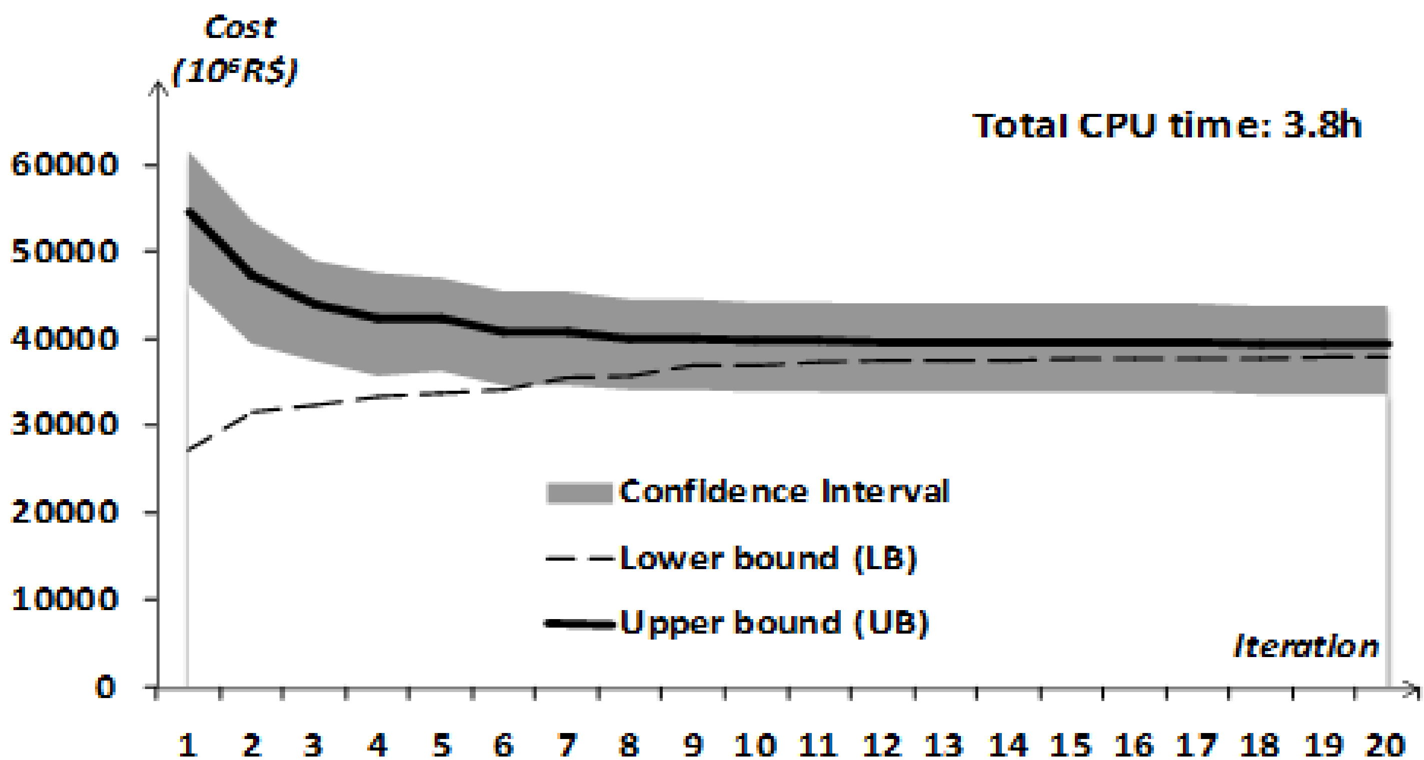
SAR CONFIGURATION

- **conditioned scenario** => forecast based on past inflows
- SAR level at the end of november:
  - ✓ SE = NE = 30%
  - ✓ SE = NE = 40%
  - ✓ SE = 47%, NE = 35%
- Penalty for violation of SAR : 940, 150, 100, 50 R$/MWh

NUMERICAL RESULTS
Real Large-Scale Brazilian System

CONVERGENCE

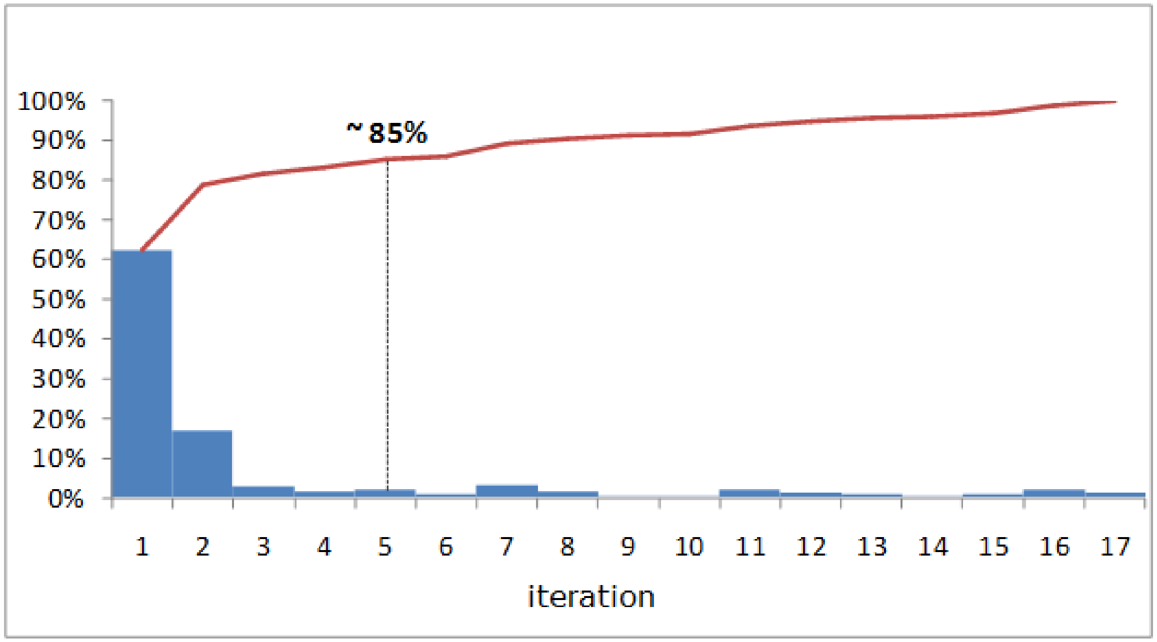
- **Similar behavior to risk-neutral and CVaR cases for SDDP**



NUMERICAL RESULTS
Real Large-Scale Brazilian System

SAR CONSTRUCTION STATISTICS

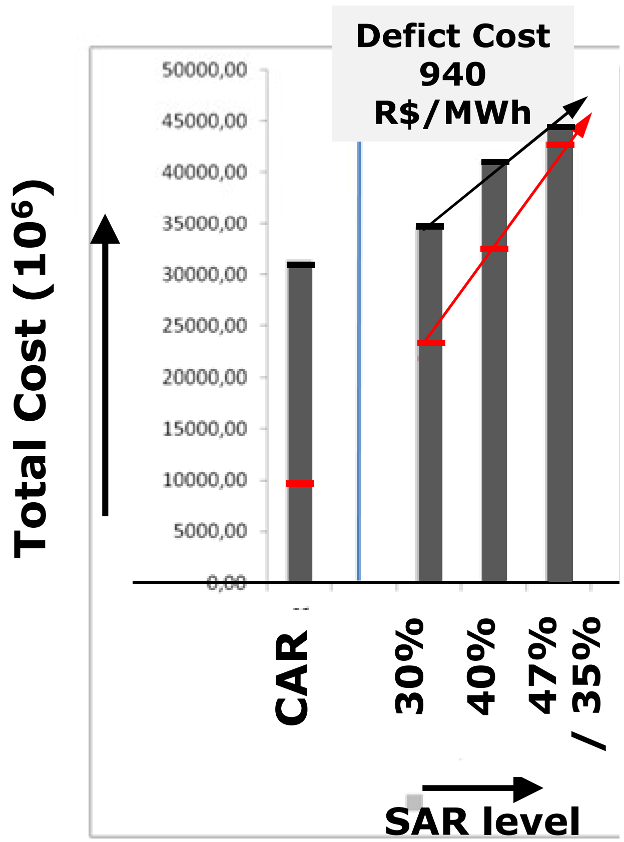
- **Most of the SAR cuts are built until de 5th SDDP iteration**



SENSITIVITY ANALYSIS

- Large costs AND load schedding for high penalties of SAR violation
- Penalty value should be calibrated to yield reasonable results

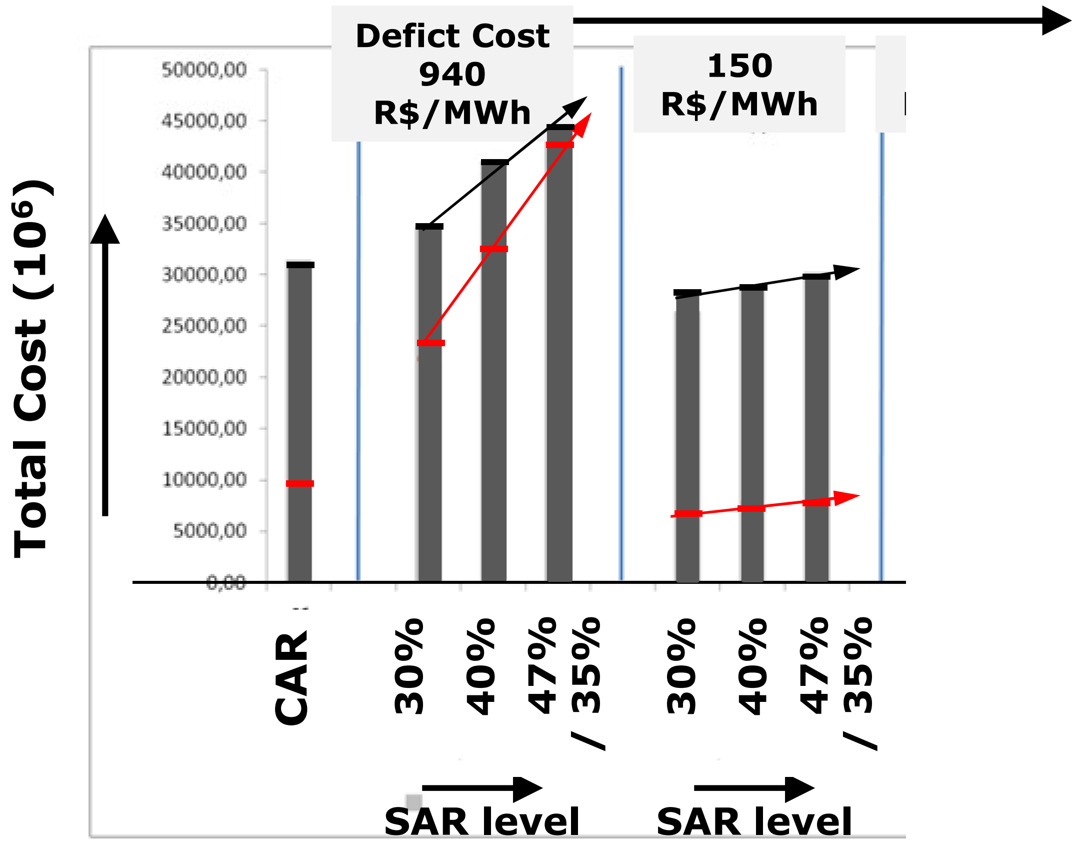
Penalty for SAR violation (LTHTP subproblem)



SENSITIVITY ANALYSIS

- Large costs AND load schedding for high penalties of SAR violation
- Penalty value should be calibrated to yield reasonable results

Decreasing penalty for SAR violation (LTHTP subproblem)



SENSITIVITY ANALYSIS

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- Large costs AND load schedding for high penalties of SAR violation
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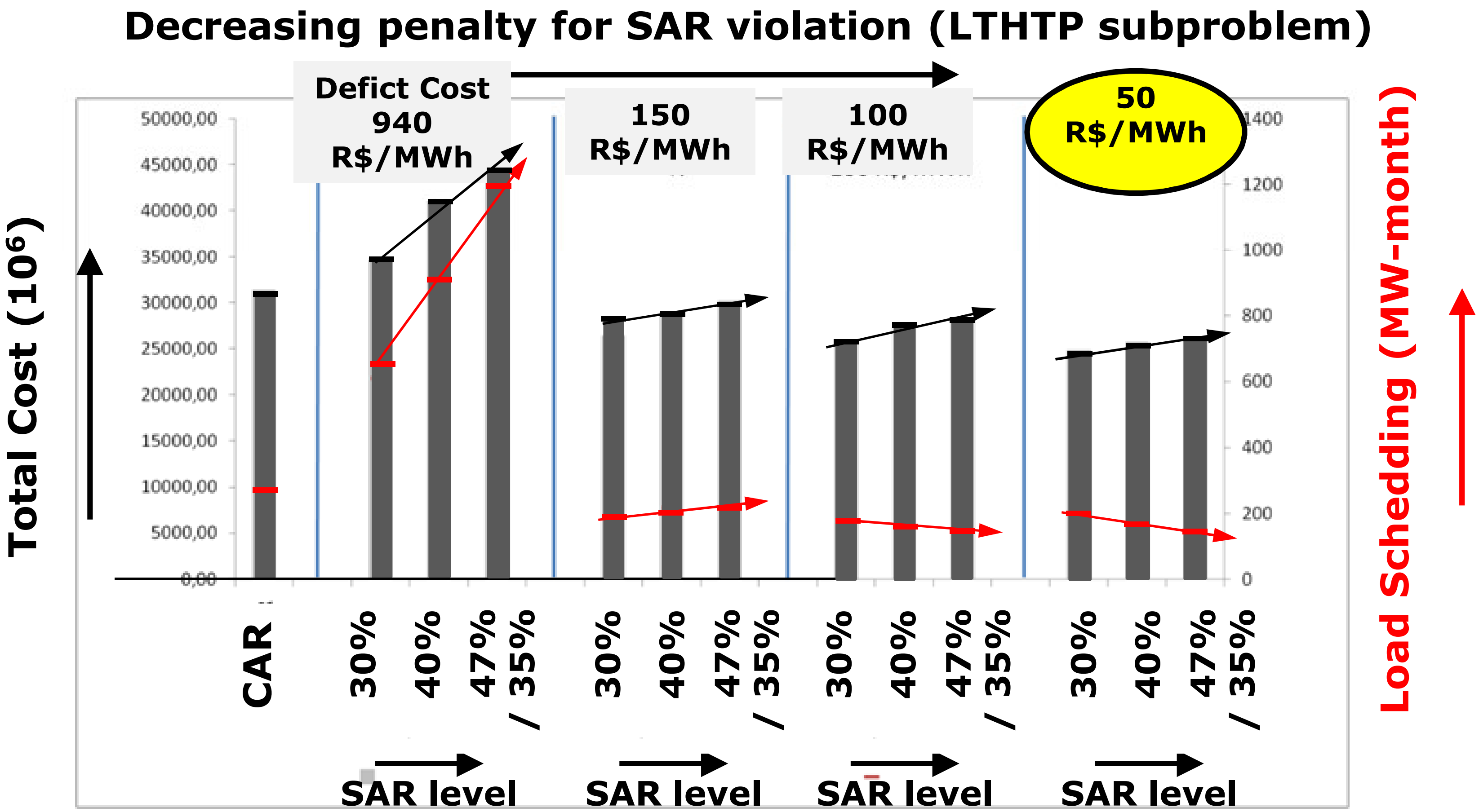
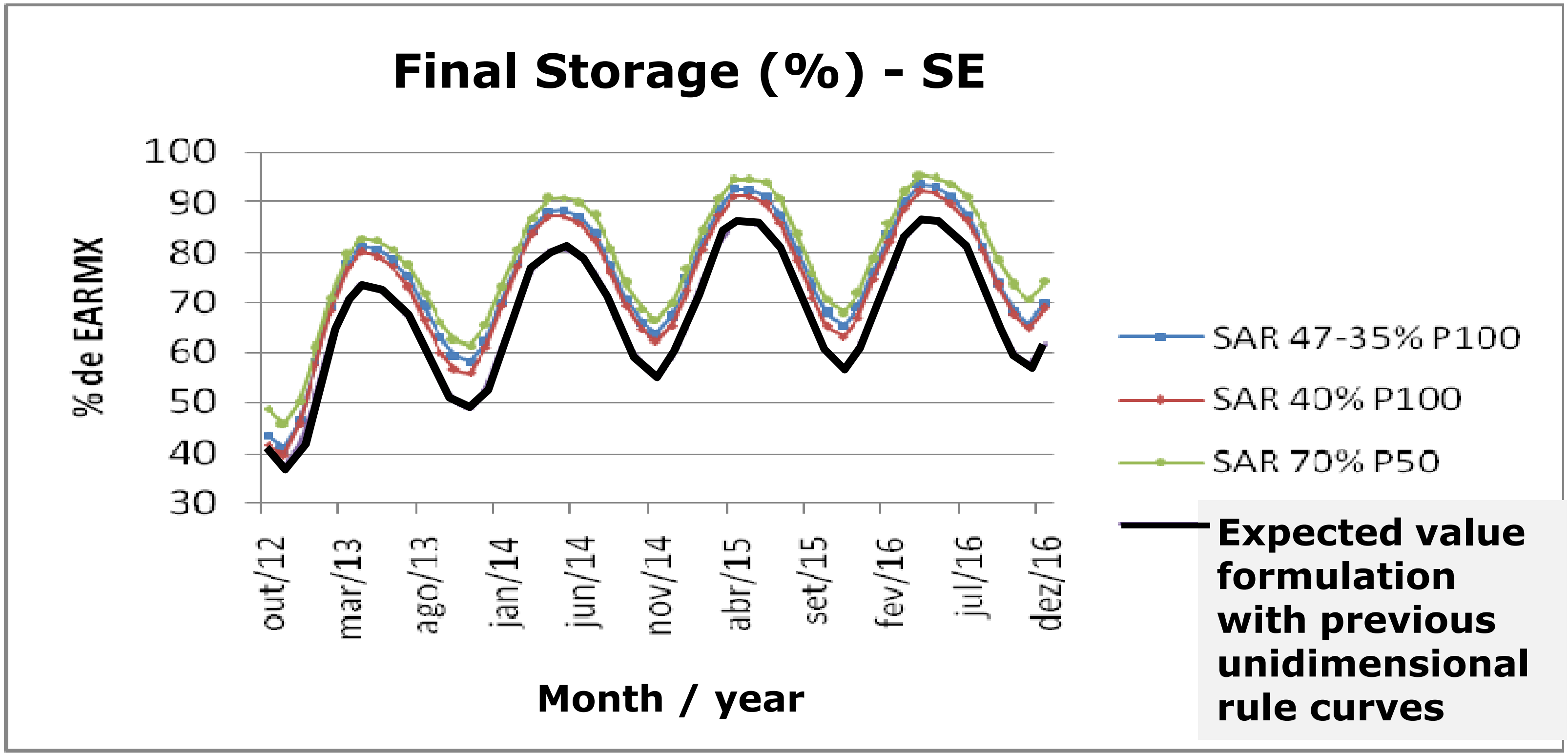


RESERVOIR LEVELS

- ⬆ Targel level for SAR subproblem
- ⬆ Penalty for SAR violation

=> ⬆ **Storage Levels**



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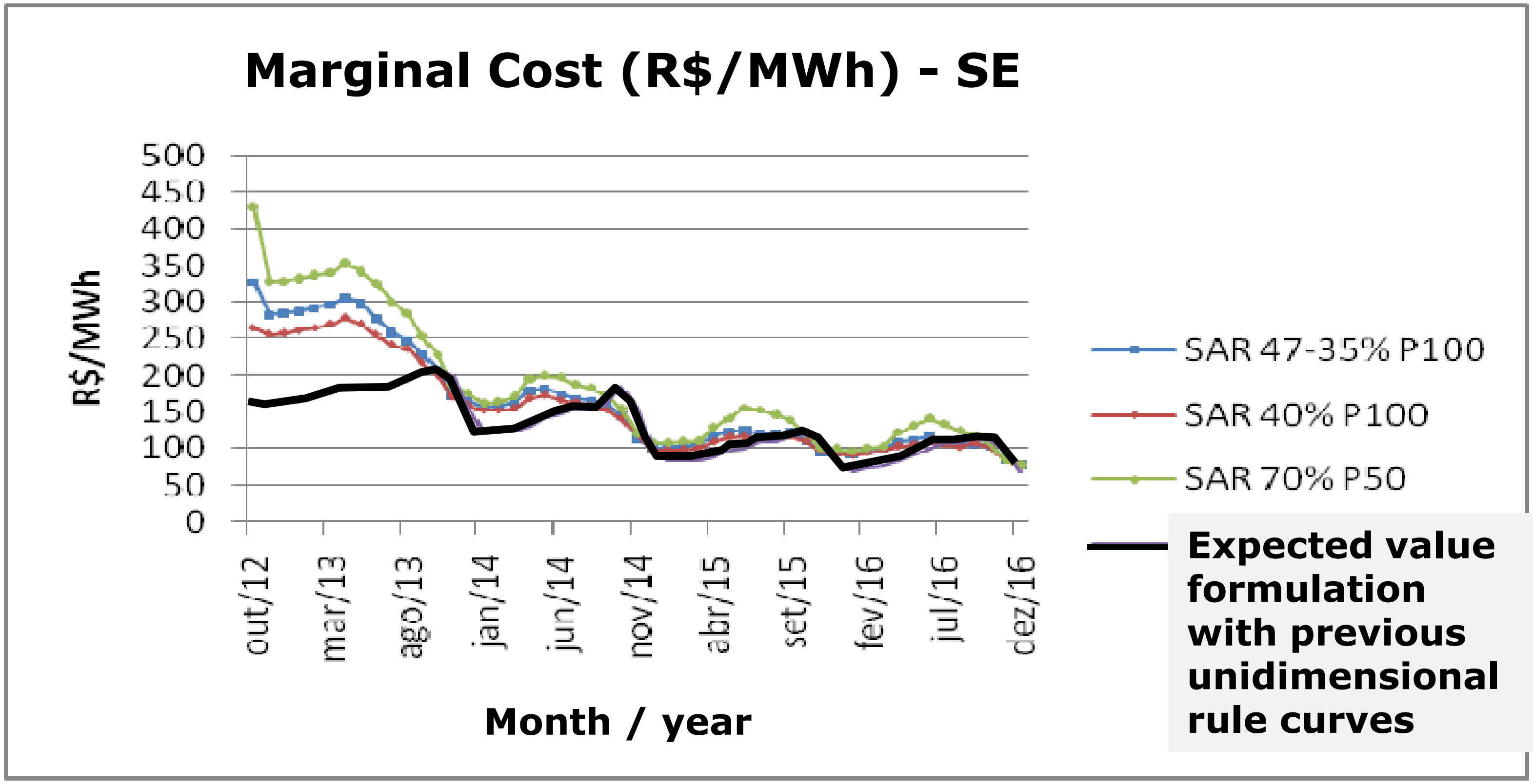
SYSTEM MARGINAL COSTS

- ⬆ Targel level for SAR subproblem
- ⬆ Penalty for SAR violation

=> ⬆ **System Marginal Costs**



CONCLUSIONS

- **Consideration of Risk Aversion Surfaces of Energy Storage in the reservoirs for power generation planning**:
  Alternative approach as compared to other risk-averse approaches (unidimensional rule curves , CVaR)

- **Development of a two-level SDDP algorithm:**
  Usual forward / backward passes in the upper level and deterministic “worst-case” subproblems in the lower level

- **Advantages over unidimensional rule curves:**
  Yields higher storage levels and lower risks as compared to previous uni-dimensional rule curves
  (with higher costs, higher system marginal costs, higher spillage)

- **Aplicability:**
  Practical Results for the real large-scale Brazilian system

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