



MITEI-IAP25 Modeling the path to net-zero energy Massachusetts Institute of Technology (MIT)

Medium-Term Stochastic Hydrothermal Coordination Model

Prof. Andres Ramos

https://pascua.iit.comillas.edu/aramos/Ramos_CV.htm

https://www.iit.comillas.edu/people/aramos

Andres.Ramos@comillas.edu

arght@mit.edu

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Learning objectives

- To understand
 - What is a medium-term hydrothermal coordination model
 - Purpose
 - How to use
 - How an optimization model is used to support hydropower plant operation
 - How stochasticity is modeled
 - Scenario tree
 - Effect of uncertainties in hydro scheduling decisions
 - What techniques are used for solving the stochastic problem
 - Stochastic optimization





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- 2. Modeling issues
- 3. Stochastic optimization
- 4. Prototype SHTCM. Mathematical formulation
- 5. Prototype SHTCM. Computer implementation



Medium term stochastic hydrothermal coordination model





Generation planning functions





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Hydro-power in Portugal

A huge hydroelectric power plant 250 km southeast of Lisbon in Portugal uses Alstom technology to combine and store wind and hydro energies. This plant has a capacity of 260 MW and supplies energy to 175,000 households. The reduction in CO2 emissions is the equivalent of removing 185,000 cars from the road. The biggest upper reservoir in Europe is 85 km long with a surface of 250 square kilometers.

During the day water falls into the lower reservoir, moving the turbines and producing electricity. But at night – when energy consumption falls – the turbine uses wind energy to pump water back into the upper reservoir so the cycle can continue the next day without significant water loss.

Alqueva reservoir







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Medium Term Stochastic Hydro



Hydrothermal operation

- Strong interaction between hydro and thermal plants. Must be scheduled simultaneously
- Possibility of storing water with time dependencies to represent water volume regulations
- Long-term storage capability allows better use of the water and, therefore, causes more extended optimization periods
- Existence of cascading and water dependencies between them
- Pumped-storage hydro plants introduce additional operational complexity
- The operational cost of hydro plants is negligible
- Hydro generation is very flexible but uncertain
 - Affordable way of storing energy at large scale
 - Inflows can have significant uncertainty





Opportunities for optimal decision making

- Optimization of hydro generation results in the replacement of expensive thermal generation
- Optimization of pumped-storage hydro plants' operation is based on pumping at cheap hours and turbining at the high-price ones
- High penetration of intermittent generation will stress the electric system operation. Storage hydro and pumped storage hydro plants are going to play a much more important role due to their flexibility and complementary use with intermittent generation
 - Besides, under a deregulated framework, electric companies manage their generation resources and need detailed operation planning tools







Uses of hydro scheduling models

- Determine the operation of complex basins
- Determine **re-powering** alternatives
- Determine the power capacity of new hydro investments
- Determine the risk (amount) of spillage
- Determine firm energy generation
- Determine the firm capacity





Medium term optimization model. Characteristics

- Hydroelectric vs. hydrothermal models
 - A hydroelectric model deals only with hydro plants
 - A hydrothermal model manages both hydro and thermal plants simultaneously
- Thermal units are considered individually. So rich marginal cost information for guiding hydro scheduling
- No aggregation or disaggregation process for hydro input and output is needed
- It isn't easy to obtain meaningful results for each hydro plant because:
 - It requires a considerable amount of data and
 - The complexity of hydro subsystems





2. Modeling issues

Modeling issues

- 3. Stochastic optimization
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Hydroelectric Dam



Ricobayo hydroelectric power plant





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Medium Term Stochastic



Variety of Spanish hydro subsystem

- Hydro reservoir volumes: 0.15 2433 hm³
- Hydro plant capacity: 1.5 934 MW
 - 375 units non UGH (small hydro)
 - 855 units UGH (large hydro), with 80 units > 50 MW



Almendra reservoir (2433 hm³) (April-2024) <u>https://youtu.be/5UA2DmJ6Zl0?si=-y7acE7tbeRqWVc7</u> https://www.lasexta.com/noticias/sociedad/las-desoladoras-imagenesaereas-del-embalse-de-la-almendra-en-salamanca-totalmenteseco_201711235a1728080cf2f56e3eb493b2.html

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Hydro subsystem modeling difficulties

- Topological complexities in waterways
- Nonlinearities in the production function. Head dependency: energy production depends on the water reserve at the reservoir and on the water inflows
 - Important when changes in reservoir levels are significant for the time scope of the model
- Stochasticity in natural hydro inflows
- Complex operation constraints by other uses of water (irrigation, minimum and maximum river flow, minimum and maximum reservoir levels, sporting activities)







Source: Iberdrola



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Alto Tâmega hydroelectric complex



(*) Does not include 4 MW of capacity installed in "Natural flow" circuit







Hydro plant Cortes II 290 MW

Cortes reservoir



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Stochastic hydro inflows

• Natural hydro inflows (clearly the most critical annual factor in the Spanish electric system)



- stochasticity in hydro inflows
- chronological pattern of inflows and
- capacity of the reservoir with respect to the inflows

	Year	Hydro energy	Index	% of being
		TWh		exceeded
	1990	20.3	0.98	98%
	1991	24.4	0.98	49%
annual	1992	18.5	0.74	83%
	1993	21.8	0.88	64%
	1994	23.9	0.96	52%
	1995	21.4	0.86	66%
	1996	39.1	1.57	5%
	1997	35.4	1.42	10%
	1998	26.7	1.07	37%
	1999	20.4	0.82	72%
	2000	26.6	1.07	38%
	2001	32.2	1.29	17%
	2002	21.6	0.87	65%
	2003	34.8	1.40	11%
	2004	23.0	0.92	58%
	2005	13.7	0.55	97%
	2006	24.4	0.98	49%
	2007	18.8	0.75	81%
	2008	19.6	0.78	77%
cause	2009	23.0	0.92	57%
	2010	38.2	1.53	6%
	2011	27.7	0.95	55%
)WS	2012	18.0	0.61	97%
	2013	41.0	1.41	9%
	2014	40.3	1.35	15%
	2015	25.1	0.82	79%
	2016	34.7	1.12	37%
	2017	16.0	0.53	99%
	2018	37.4	1.28	17%
	2019	26.0	0.88	64%
	2020	30.6	1.03	44%
Source: REE	2021	26.9	0.91	60%
al Coordination Mo	2022	19.5	0.67	89%
	2023	26.5	0.92	54%



How uncertain are annual hydro inflows in Spain?







Spanish historical, max, and min reservoir levels



Máximo y mínimo estadístico: media de los valores máximos y mínimos de los últimos 20 años.



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At the end of the month



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How uncertain are hydro inflows in Brazil?



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Spot prices strongly driven by hydrology

-Spot prices (USD/MWh) — Yearly average – –



Average 2010-2017





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How uncertain are hydro inflows in Colombia?





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Stochastic hydro inflows

- Several measurement points in main different river basins
- Partial spatial correlation among them
- Positive temporal correlation in each one







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2. Modeling issues

Stochastic optimization

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Decision under uncertainty

DETERMINISTIC optimization

- Best decision when the future parameters are known with certainty (it can be the mean/mode values)
- Simulation. Scenario analysis
 - What could happen if ...?





• **STOCHASTIC** optimization

- Best decision when the future parameters are modeled as stochastic variables with known distributions
 - Discrete
 - Historical
 - Continuous \Rightarrow simulation

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Alternatives for modeling the uncertainty

- Wait and see, or scenario analysis, or what-if analysis, or sensitivity analysis
 - Decisions are taken once revealed the uncertainty
 - The problem is solved independently for each scenario
 - The scenario with mean value of the parameters is just a special case
 - A priori, decisions will be different for each deterministic scenario (anticipative, clairvoyant, not implementable)
 - Solution of a scenario can be infeasible in the others
- Here and now (stochastic) decisions
 - Decisions must be taken before revealing uncertainty
 - Non-anticipative decisions (only the available information so far can be used, no future information)
 - The only relevant decisions are those of the first stage, given that they are the only ones to be taken immediately
 - Stochastic solution considers the stochasticity distribution

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- Scenario analysis (deterministic)
 - Run the model supposing that the natural inflows will be the same as any of the previous historical inflows (i.e., the year 2015 or 2020, etc.) for the time scope
 - Run the model supposing that the natural inflows for each period will be precisely the mean of the historical values (i.e., average year) for the time scope
- Stochastic optimization
 - Run the model considering that the distribution of future natural inflows will be the same as it has been in the past







Stochastic hydro scheduling

- Determine the optimal operation of a hydro system subject to uncertainty in future hydro inflows
- Taking optimal decisions in different stages in the presence of random parameters with known distributions
- A decision tree represents uncertainty

High outflows (Spring 2010)



Minimum outflow



Aldeadávilla hydro plant



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Optimization-simulation combination

- Use the model in an open-loop control mechanism with a rolling horizon
 - 1. First, planning by stochastic optimization
 - 2. Second, simulation of the random parameters
- Repeat the process
- 1. Stochastic optimization
 - Determines optimal scheduling policies considering the uncertainty in a simplified way
- 2. Simulation (out-of-sample) (cross-validation)
 - Evaluates possible future outcomes of random parameters given the optimal policies obtained previously
- Focus on STOCHASTIC OPTIMIZATION MODELS






How to use of a medium term stochastic hydrothermal coordination model

- Run in a rolling mode (i.e., the model is run each week with a time scope of several months up to one year)
- Only decisions for the closest period are of interest (i.e., the next week). The remaining decisions are ignored









Probability tree or scenario tree

- Represents the evolution in the realization of uncertainty along time, different values of the random parameters along the time.
- Scenario: any path from the root to the leaves
- The scenarios that share information up to a certain time period share the same decisions in the tree (implementable decisions)
- The probability tree represents the dynamics of the random parameters and the non-anticipativity of the decisions and, therefore, is implicit in the constraint matrix







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Medium Term Stochastic Hydrothermal Coordination Model





Scenario tree trade-off

Big scenario tree and

simplified electric system operation problem

Where do we branch the tree?

Small scenario tree and

realistic electric system operation problem

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Where is it important to branch the tree?

- Where there is a huge variety of stochastic values
 - Winter and spring in hydro inflows
- Short-term future will affect more than long-term future
 - If the scope of the model is from January to December, branching in winter and spring will be more relevant than branching in autumn

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Scenario tree generation (ii)

- There is no established method to obtain a unique scenario tree
- A multivariate scenario tree is obtained by the neural gas clustering technique that simultaneously considers the main stochastic series and their spatial and temporal dependencies.
- Contamination: very extreme scenarios can be artificially introduced with a very low probability
- Number of scenarios generated enough for yearly operation
 planning
 ICAL ICADE







Scenario tree generation. Clustering in two dimensions



Centroids have the minimum distance to their corresponding points

Their probability is proportional to the number of points represented by the centroid







Natural hydro inflows (V)

Historical data series of hydro inflows in one reservoir

Aportaciones [m3/s]





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Natural hydro inflows (VI)

Initial scenario tree (15 scenarios) for hydro inflows in one reservoir





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Natural hydro inflows (VII)

Reduced scenario tree (8 scenarios) for hydro inflows in one reservoir





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Historical hydro inflows and scenario trees in Iceland



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Prototype SHTCM. Mathematical formulation





Prototype. Mathematical formulation

- Objective function
 - Minimize the total expected variable costs plus penalties for energy and power not served
- Variables
 - BINARY: Commitment, startup, and shutdown of thermal units
 - Thermal, storage hydro, and pumped-storage hydro output
 - Reservoir levels
- Operation constraints
 - Inter-period
 - Storage hydro and pumped-storage hydro scheduling *Water balance with stochastic inflows*
 - Intra-period
 - Load balance and operating reserve
 - Detailed hydro basin modeling
 - Thermal, storage hydro, and pumped-storage hydro operation constraints
- Mixed integer linear programming (MIP)

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Time scope

- 1 month

Subperiod

Load level

- weekdays and weekends

peak, shoulder, and off-peak

1 year

Period

Period

Subperiod

Load level



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Demand (5 weekdays)



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Demand

- Monthly demand with several load levels
 - Peak, shoulder, and off-peak for weekdays and weekends
- All the weekdays of the same month are similar (same for weekends)





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Technical characteristics of thermal units (t)

- Maximum and minimum output
- Fuel cost
- Slope and intercept of the heat rate straight line
- Operation and maintenance (O&M) variable cost
 - No load cost = fuel cost x heat rate intercept
 - Variable cost = fuel cost x heat rate slope + O&M cost
- Cold startup and shutdown cost
- Up and down ramps

Max and min output[MW] $\overline{P}_t, \underline{P}_t$ No load cost $[\pounds/h]$ CF_t Variable cost $[\pounds/MWh]$ CV_t Startup cost $[\pounds]$ CSU_t Ration and a costShutdown cost $[\pounds]$ CSD_t Rational cost



€/*h*

 CF_{1}

 P_1

 RU_{\star}

 RD_{I}



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 \boldsymbol{P}

MW



Technical characteristics of hydro plants (h)

- Maximum and minimum output
- Production function (efficiency for conversion of water release in m³/s to electric power MW)
- Round-trip efficiency of pumped storage hydro plants
 - Only this ratio of the energy consumed to pump the water is recovered by turbining it

Max and min output	[MW]	$\overline{P}_{h}, \underline{P}_{h}$
Production function	$[kWh \ / m^3]$	$C_{_{h}}$
Efficiency called the teat	[p.u.]	$\eta_{_h}$







Technical characteristics of hydro reservoirs (r)

- Maximum and minimum water reserve
- Initial water reserve
 - Final reserve = initial reserve
- Natural hydro inflows

Max and min water reserve Initial and final water reserve $[hm^3]$ R'_{π} Stochastic natural hydro inflows











Scenario tree. Ancestor and descendant











Other system parameters

- Energy not served cost
- Operating power reserve not served cost
- Operating power reserve

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Variables

- Commitment, startup, and shutdown of thermal units (BINARY)
 - Commitment, startup and shutdown $\{0,1\}$ $uc_{pst}^{\omega}, su_{pst}^{\omega}, sd_{pst}^{\omega}$
- Production of thermal units and hydro plants
 - Production of a thermal or hydro unit $[MW] p_{psnt}^{\omega}, p_{psnh}^{\omega}$
- Consumption of pumped storage hydro plants



- Consumption of a hydro plant [MW] c_{psnh}^{ω}
- Reservoir levels (at the end of the period) Reservoir level $[hm^3]$ r_{pr}^{ω}
- Energy and power not served

Energy and power not served $[MW] ens_{psn}^{\omega}, pns_{ps}^{\omega}$







Constraints: Operating power reserve

Committed output of thermal units

- + Maximum output of hydro plants
- + Power not served
- ≥ Demand
- + Operating reserve

for peak load level, subperiod, period, and scenario [MW]

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$$\sum_{t} \bar{P}_{t} u c_{pst}^{\omega} + \sum_{h} \bar{P}_{h} + pn s_{ps}^{\omega} \ge D_{ps1} + O_{ps1}^{\mathsf{ICAL}} \forall \omega ps$$







Constraints: Generation and load balance

Generation of thermal units

- + Generation of storage hydro plants
- Consumption of pumped storage hydro plants
- + Energy not served
- = Demand for each load level, subperiod, period, and scenario [MW]

$$\sum_{t} p_{psnt}^{\omega} + \sum_{h} p_{psnh}^{\omega} - \sum_{h} c_{psnh}^{\omega} + ens_{psn}^{\omega} = D_{psn} \quad \forall \omega psn$$







Constraints: Commitment, startup, and shutdown

- All the weekdays of the same month are similar (same for weekends)
- Commitment decision of a thermal unit







Constraints: Commitment, startup, and shutdown

- Startup of thermal units can only be made in the transition between consecutive weekend and weekdays
 - Commitment of a thermal unit in a weekday
 - Commitment of a thermal unit in the weekend of previous period
 - = Startup of a thermal unit in this weekday
 - Startup of a thermal unit in this weekday

 $uc_{pst}^{\omega} - uc_{p-1s+}^{\omega'} = su_{pst}^{\omega} - sd_{pst}^{\omega} \quad \forall \omega pst \quad \omega' \in a(\omega)$

Shutdown only in the opposite transition

Commitment of a thermal unit in a weekend

- Commitment of a thermal unit in the previous weekday
- = Startup of a thermal unit in this weekend
- Shutdown of a thermal unit in this weekend [p.u.]

$$uc_{ps+1}^{\omega} - uc_{pst}^{\omega} = su_{ps+1t}^{\omega} - sd_{ps+1t}^{\omega} \quad \forall \omega pst$$

p.u.





Constraints: Commitment and production

Production of a thermal unit

Sector Commitment of a thermal unit x the maximum output reduced by availability rate [MW]

Production of a thermal unit

Example 2 Commitment of a thermal unit x the minimum output reduced by availability rate [MW]

 $uc_{pst}^{\omega}\underline{P}_t(1-Q_t) \le p_{psnt}^{\omega} \le uc_{pst}^{\omega}\overline{P}_t(1-Q_t) \quad \forall \omega psnt$

- If the thermal unit is committed ($uc_{pst}^{\omega} = 1$) it can produce between its minimum and maximum output
- If the thermal unit is not committed ($uc_{pst}^{\omega}=0$) it can't produce







Constraints: Water balance for each reservoir

- Reservoir volume at the beginning of the period
- Reservoir volume at the end of the period
- + Natural hydro inflows
- Spills from this reservoir
- + Spills from upstream reservoirs
- + Turbined water from upstream storage hydro plants
- Turbined and pumped water from this reservoir
- + Pumped water from upstream pumped hydro plants = 0

for each reservoir, period, and scenario [hm³]

$$r_{p-1r}^{\omega'} - r_{pr}^{\omega} + I_{pr}^{\omega} - s_{pr}^{\omega} + \sum_{\substack{r' \in up(r) \\ r' \in up(r)}} s_{pr'}^{\omega}} + \sum_{\substack{r' \in up(r) \\ r' \in up(r)}} d_{psn} p_{psnh}^{\omega} / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} p_{psnh}^{\omega} / C_h + \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} c_{psnh}^{\omega} \eta_h / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} c_{psnh}^{\omega} \eta_h / C_h = 0 \quad \forall \omega pr \quad \omega' \in a(\omega)$$



Constraints: Operation limits

Reservoir volumes between limits for each hydro reservoir [hm³]

$$\begin{split} R_r &\leq r_{pr}^{\omega} \leq \bar{R}_r \quad \forall \omega pr \\ R_{0r} &= R_{Pr}^{\omega} = R_r' \quad \forall \omega r \end{split}$$

Power output between limits for each unit

[MW]

[*p.u.*]

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$$uc_{pst}^{\omega}, su_{pst}^{\omega}, sd_{pst}^{\omega} \in \{0,1\} \quad \forall \omega pst$$

 $0 \le p_{psnt}^{\omega} \le \bar{P}_t (1 - Q_t) \quad \forall \omega psnt$

 $0 \le p_{psnh}^{\omega}, c_{psnh}^{\omega} \le \bar{P}_h \quad \forall \omega psnh$







Multiobjective function

- Minimize
 - Expected thermal variable costs [€]

$$\sum_{\omega pst} P_p^{\omega} SU_t su_{pst}^{\omega} + \sum_{\omega pst} P_p^{\omega} SD_t sd_{pst}^{\omega} + \sum_{\omega psnt} P_p^{\omega} d_{psn} CF_t uc_{pst}^{\omega} + \sum_{\omega psnt} P_p^{\omega} d_{psn} CV_t P_{psnt}^{\omega}$$

Expected penalties introduced in the objective function for energy and power not served
 [€]

$$\sum_{\omega psn} P_p^{\omega} d_{psn} CV' ens_{psn}^{\omega} + \sum_{\omega ps} P_p^{\omega} CV'' pns_{ps}^{\omega}$$







Short Run Marginal Cost (SRMC)

- Dual variable of generation and load balance $[\in/MW]$
 - Change in the objective function due to a marginal increment in the demand when binary variables (commitment, startup, and shutdown) are fixed

$$\sum_{t} p_{psnt}^{\omega} + \sum_{h} p_{psnh}^{\omega} - \sum_{h} c_{psnh}^{\omega} + ens_{psn}^{\omega} = D_{psn} : \sigma_{psn}^{\omega} \quad \forall \omega psn$$

Short Run Marginal Cost = dual variable / load level duration / scenario probability. Expressed in [€/MWh]

 $SRMC_{psn}^{\omega} = \sigma_{psn}^{\omega}/d_{psn}/P_p^{\omega} \quad \forall \omega psn$





Water value

- Dual variable of water balance for each reservoir [€/hm³]
 - Change in the objective function due to a marginal increment in the reservoir inflow

$$\begin{aligned} r_{p-1r}^{\omega'} - r_{pr}^{\omega} + I_{pr}^{\omega} - s_{pr}^{\omega} + \sum_{\substack{r' \in up(r) \\ r' \in up(r)}} s_{pr'}^{\omega}} \\ + \sum_{\substack{sn \\ h \in up(r)}} d_{psn} p_{psnh}^{\omega} / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} p_{psnh}^{\omega} / C_h \\ + \sum_{\substack{sn \\ h \in up(r)}} d_{psn} c_{psnh}^{\omega} \eta_h / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} c_{psnh}^{\omega} \eta_h / C_h = 0 \quad :\pi_{pr}^{\omega} \quad \forall \omega pr \quad \omega' \in a(\omega) \end{aligned}$$

 Turbining water has no variable cost. However, an additional hm³ turbined allows to substitute energy produced by thermal units with the corresponding variable cost (this is called water value)







- 2. Modeling issues
- 3. Stochastic optimization
- 4. Prototype SHTCM. Mathematical formulation
- 5. **Prototype SHTCM. Computer implementation**



Prototype SHTCM.

Computer implementation




StarGenLite SHTCM Medium Term Stochastic Hydrothermal Coordination Model (https://pascua.iit.comillas.edu/aramos/StarGenLite_SHTCM.zip)

- Files
 - Microsoft Excel interface for input data and output results StarGenLite SHTCM.xlsm
 - GAMS file StarGenLite_SHTCM.gms
- How to run it from Windows
 - Save the Excel workbook if data have changed
 - Run the model

Run



- The model creates
 - tmp_StarGenLite_SHTCM.xlsx with the output results
 - tmp_StarGenLite_SHTCM.gdx with the output results
 - StarGenLite_SHTCM.lst as the listing file of the GAMS execution
- Load the results into the Excel interface

Load results





StarGenLite_SHTCM Medium Term Stochastic Hydrothermal Coordination Model (<u>https://pascua.iit.comillas.edu/aramos/StarGenLite_SHTCM.zip</u>)

- Files
 - Text files for input data
 - GAMS file StarGenLite_SHTCM.gms
- How to run it from MacOS
 - Run the model from GAMS Studio with these parameters
 - u1=StarGenLite_SHTCM u2=1 u3=1
 - The model creates
 - tmp_StarGenLite_SHTCM.gdx with the output results
 - StarGenLite_SHTCM.lst as the listing file of the GAMS execution









* : × ~ Jx					
StarGen Lit	e Medium Term Stochas	tic Hydrothermal	Coordination M	odel	
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	Andrés l	Ramos			
	https://www.iit.com	<u>uillas.edu/aramo</u> comillas edu	<u>os/</u>		
	Run				
	Load res	sults			



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Input Data. Indices (i)

	Inicio	Insertar Diseño de página	Fórmulas Datos Re	evisar Vista	♀ ¿Qué des	ea hacer?	targentite_s	SHTCM.XISH	- Excer							Andrés	Ramos Galá	n A	ŧ
	•	$X \sim f_X$																	
	B C	D	E	F	G	Н	I J	К	1	M	N	1	0	Р	Q	1	R	S	1222
	indices					Ē													
	р	periods	1	p01		p12	1												
	s	subperiods	1	WeekDay	,	WeekEnd	1	·											
	n	load levels	/	n01	*	n03	1												
	SC	scenarios	1	sc01	*	sc03	/												
	g	thermal units	1																
			Nuclear																
			Domestic	cCoal_Anthracite				M											
			BrownLig	gnite			· ·												
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			OCGT_2																
			OCGT_3) P(DNI											
			FuelOilGa	as															
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1		hydro plants	PO(P)																
			Storage	/er Judro1 Pacin1			1 D E												
			StorageH	Avdro2 Basin1															
			StorageH	lydro3 Basin1															
			Pumpeds	StorageHvdro															
							1												
	r	reservoirs																	
							/												
			RunOfRiv	/er															
			Reservoir	r1_Basin1															
			Reservoir	r2_Basin1															
			Peceruoi	r2 Pacin1															





Input Data. Indices (ii)

Fuh(r,g) re	D D eservoir upstream of hydro plant	E F RunOfRiver Reservoir1_Basin1 Reservoir3_Basin1 PumpedStorageHydro RunOfRiver Reservoir1_Basin1	G H I / / . RunOfRiver . StorageHydro1 Rasin1	J K	i L	М	<u> </u>	N	0	Ρ	Q	R	£ [S
B C ruh(r,g) n	D eservoir upstream of hydro plant	E F RunOfRiver Reservoir1_Basin1 Reservoir3_Basin1 PumpedStorageHydro RunOfRiver Reservoir1_Basin1	G H I	J K	L	М		N	0	Р	Q	R		S
ruh(r,g) n	eservoir upstream of hydro plant	RunOfRiver Reservoir1_Basin1 Reservoir3_Basin1 PumpedStorageHydro RunOfRiver Reservoir1_Basin1	/ / . RunOfRiver . StorageHydro1_Rasin1	6										
ruh(r,g) n	eservoir upstream of hydro plant	RunOfRiver Reservoir1_Basin1	/ / . RunOfRiver . StorageHydro1_Basin1											
		RunOfRiver Reservoir1_Basin1	/ . RunOfRiver . StorageHydro1 Basin1											
		Reservoir2_Basin1 Reservoir3_Basin1	 StorageHydro2_Basin1 StorageHydro3_Basin1 	8										
rph(r,g) n	eservoir upstream of pumped hydro plant		1											
		PumpedStorageHydro	• PumpedStorageHydro /											
nur(g,r) n	ydro plant upstream of reservoir		1	D.B.D										
		StorageHydro1_Basin1 StorageHydro2_Basin1	Reservoir3_Basin1Reservoir3_Basin1											
hpr(g,r) p	umped hydro plant upstream of reservoir		ICAD											
		PumpedStorageHydro	PumpedStorageHydro											
rur(r,r) r	eservoir 1 upstream of reservoir 2		1											
		Reservoir1_Basin1 Reservoir2_Basin1	Reservoir3_Basin1Reservoir3_Basin1											
			1											
Menu	Indices Parameters DemandDu	ration Generation I Infl		GrOutput	Energy	SrEpprov V	NtrRc	<u>.</u>						





Input Data. Cost of energy and power not served





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Input Data. Demand, operating reserve and duration







Input Data. Hydro and thermal parameters

\bullet : $\times \checkmark f_x$																		
B C	D	E	F	G	Н	1	J	K	LM	N	0	Р	- E	Q	R	S	Т	
* thermal generation																		
		Mr. D. J.	r 10 i			0.00		FFOR										
*	[MW]	[MW]	FueiCost [€/Mcal]	[Mcal/MWh]	[Mcal/h]	[€/MWh]	[Mcal]	[p.u.]	Aux									
Nuclear	771.6	771.6	1.00	15				0.00	15.00									
DomesticCoal_Anthracite	588.0	235.2	0.02	2400	50000	6	2000000	0.00	49.70									
BrownLignite	203.1	81.2	0.02	2300	50000	6	2000000	0.00	50.92									
ImportedCoal_SubBituminous	150.4	60.2	0.02	2300	50000	6	2000000	0.00	52.65									
ImportedCoal_Bituminous	194.4	100.0	0.02	2200	20000	6	2000000	0.00	49.14									
CCGT 2	500.0	100.0	0.03	900	300000	4	1000000	0.00	45.00									
CCGT 3	500.0	100.0	0.03	1000	300000	4	1000000	0.00	48.00									
CCGT_4	667.5	133.5	0.03	800	300000	4	1000000	0.00	37.48									
OCGT_1	400.0		0.03	2000	100000	4		0.00	67.50									
OCGT_2	400.0		0.03	2100	100000	4		0.00	70.50									
OCGT_3	400.0		0.03	2200	100000	4	4000000	0.00	73.50									
FuelOliGas	441.8		0.06	2000	300000	3	1000000	0.00	160.74									
			- U	NIVI	:KSI	DAD	PO			IA								
* hydro generation																		
	MaxProd	MinProd	ProdFunct	Efficiency	MaxCons													
*	[MW]	[MW]	[kWh/m ³]	[p.u.]	[MW]													
RunOfRiver	150.0																	
StorageHydro1_Basin1	200.0		0.30															
StorageHydro2_Basin1	200.0		0.30															
StorageHydro3_Basin1	200.0		0.30	0.70	200.0													
PumpedStorageHydro	200.0			0.70	200.0													
-																		
										7								











Input Data. Inflows and scenario tree

Archivo	ے ۔ رہ Inicio	- 🗔 🕼	Diseño de	🗊 🔻	Fórmulas	Dato	s Revis	ar Vista	0 :	Oué des	ea haceri	Sta	arGenLi	te_SHTCM	1.xlsm - I	Excel												Andrés	团 Ramos i	— Galán		X
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A	В	С	DE	F	G	Н	I J	KI	M	N	0 P	Q	R	S	ĺ	т	- K	U		v		w	1	х	1	Y		z		AA	f	AE
1 2	<u> </u>												-																			
3	* natur	al hydro inflow	s [m³/s]																													
5				p01	p02	p03	p04 p0	5 p06 p0	07 p08	p09 j	p10 p11	1 p12																				
6	Ru	nOfRiver	. sc01	40.0	40.0	40.0	35.0 30	.0 20.0 20	0.0 20.0	30.0	35.0 40.	0 40.0)																			
	Ru	nOfRiver	. sc02	40.0	38.0	38.0	33.3 28	.5 19.0 19	.0 19.0	28.5	33.3 38.	0 38.0)																			
3	Ru	nOfRiver	. sc03	40.0	42.0	42.0	36.8 31	.5 21.0 21	.0 21.0) 31.5 3	36.8 42.	0 42.0)																			
	* Ru	nOfRiver	. sc01	40.0	39.4	39.4	34.5 29	.6 19.7 19	0.7 19.7	29.6 3	34.5 39.	4 39.4																				
8	Re	servoir1 Basin	1 sc01	34.5	48 7	66.2	76 1 33	6 10 4	4 15 3	146	16 1 62	7 157 1																				
	Re	servoir1_Basin	1 . sc02	34.5	34.1	46.3	53.3 23	.5 7.3	.8 10.7	7 10.2	11.3 43.	9 110.0	5																			
	Re	servoir1 Basin	1 . sc03	34.5	65.7	89.4	102.7 45	.4 14.0 7	.3 20.7	7 19.7	21.7 84.	6 212.1																				
	* Re	servoir1_Basin	1 . sc01	34.5	44.6	60.6	69.6 30	.7 9.5 4	.9 14.0) 13.4	14.7 57.	4 143.7	,																			
	Re	servoir2_Basin	1 . sc01	28.8	6.9	11.9	4.4 16	.6 4.6 5	.3 8.8	3 6.1	10.7 36.	3 60.0)																			
	Re	servoir2_Basin	1 . sc02	28.8	5.2	8.9	3.3 12	.5 3.5 4	.0 6.6	5 4.6	8.0 27.	2 45.0)																			
	Re	servoir2_Basin	1 . sc03	28.8	9.7	16.7	6.2 23	.2 6.4 7	.4 12.3	3 8.5	15.0 50.	8 84.0)																			
	* Re	servoir2_Basin	1 . sc01	28.8	6.5	11.2	4.1 15	.6 4.3 5	.0 8.3	3 5.7 :	10.1 34.	1 56.4																				
	De	convoir? Dooin	1	112.0	E4 0	101.0	21.2.20	6 540 25	2 16 0	2 21 2 2	11 2 22	7 160 4	2																			
	Re	servoir3_Basin	1 . SCO1	113.0	34.9	60.6	12 7 17	8 22 0 15	2 10.0	1 12 7	12 7 20	2 101 0																				
	Re	servoir3 Basin	1 . sc03	113.8	76.8	141.4	29.7 41	.5 76.8 35	.4 23.6	5 29.7	29.7 47.	1 235.7	,																			
	* Re	servoir3 Basin	1 . sc01	113.8	48.3	88.9	18.7 26	.1 48.3 22	.2 14.8	3 18.7	18.7 29.	6 148.1																				
		100						~																								
	<u> </u>						1																									
	* scena	irio tree																														
				Ancestor	FirstPeriod	Prob																										
			sc01	, -1	1	0.500																										
			sc02	1	2	0.400																										
			sc03	1	2	0.100																										
				/																												
	L																															
		terminal termina		1	0	Dunit	- 1.0		1		Call		1	C-0.1			Cat	10	14/4-0			6										-
9 F		vienu Indic	es Para	ameters	Demand	Duratic	on Gen	eration	Inflow		Grue	C Ou	tput	Grout	put	Energy	GrEn	hergy	WTR	€ (+) : [•				1110000	1990					•
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StarGenLite SHTCM (i)



Medium Term Stochastic Hydrothermal Coordination Model



StarGenLite_SHTCM (ii)

* definitions

sets

р		period				
p1(p)	first	period				
pn(p)	last	period				
S		subperiod				Set definition
s1(s)	first	subperiod				Set definition
n		load level				
n1(n)	first	load level				
SC	scena	rio				
sca	(sc) scena	rio				
scp	(sc,p) tree	defined as sc	enario and pe	eriod		
scscp	(sc,p,sc) ances	tor sc	2 of node	(sc1 p)		
scsch	(sc,sc,p) desce	ndant (sc	2 p) of node	sc1		
scscr	(sc,p,sc) repre	sentative sc	2 of node	(sc1 p)		
spsn(s	sc,p,s,n) <mark>activ</mark>	e load levels	for each sce	enario		
psn (p,s,n) <mark>activ</mark>	e load levels				
g	gener	ating unit				
t (g)	therm	al unit				
h (g)	hydro	plant				
r		reservo	ir			
rs(r)	stora	ge reservo	ir			
ruh(r	,g)	reservoir	upstream of	hydro	plant	
rph(r	,g)	reservoir	upstream of	pumped hydro	plant	
hur(g	,r)	hydro plant	upstream of	reservoir		
hpr(g	,r) pumpe	d hydro plant	upstream of	reservoir		
rur(r	,r)	reservoir 1	upstream of	reservoir 2		





parameters

StarGenLite_SHTCM (iii)

pDemand p,s,n) hourly load [GW] pOperReserve(p,s,n) hourly operating reserve [GW] pDuration p,s,n) duration [h] pCommitt) commitment of the unit [0-1] (sc,g,p,s (sc,g,p,s,n) production of the unit pProduct [GW] of the unit pEnergy (sc,g,p,s,n) energy [GWh]) reservoir level pReserve (sc,r,p [hm3] (sc, p,s,n) short run marginal cost pSRMC [M€ per GWh] pWValue (sc,r,p) water value [M€ per hm3] pEFOR **EFOR** (g) [p.u.] pMaxProd maximum output [GW](g) pMinProd minimum output [GW] (g) maximum consumption [GW] pMaxCons (g) variable cost slope [M€ per GWh] Parameter pSlopeVarCost(g) pInterVarCost(g) intercept variable cost [M€ per h] definition pStartupCost (g) startup [M€] cost pMaxReserve (r) maximum reserve [km3] pMinReserve (r) minimum reserve [km3] pIniReserve (r) initial reserve [km3] pProdFunct (g) production function [GWh per km3] pEffic (g) pumping efficiency [p.u.] pInflows (r,sc,p)inflows [km3] inflows original pInfl0rg (r, sc, p)[km3] pENSCost energy non-served cost [M€ per GWh] pPNSCost power non-served cost [M€ per GW] pProbsc (sc,p) probability of a given node lag(p)backward counting of period scenario number scaux



StarGenLite_SHTCM (iv)

<pre>variables vTotalVCost</pre>	total system variable cost	[M€]
<pre>binary variables vCommitt (sc,p,s, g) vStartup (sc,p,s, g) vShutdown (sc,p,s, g)</pre>	commitment of the unit startup of the unit shutdown of the unit	[0-1] [0-1] [0-1]
<pre>positive variables vProduct (sc,p,s,n,g) vConsump (sc,p,s,n,g) vENS (sc,p,s,n) vPNS (sc,p,s) vWtReserve(sc,p, r) vSpillage (sc,p, r)</pre>	production of the unit consumption of the unit energy non served power non served water reserve at end of period spillage	[GW] [GW] [GW] [km3] [km3]
<pre>equations eTotalVCost eOpReserve(sc,p,s,n) eBalance (sc,p,s,n) eMaxOutput(sc,p,s,n,g) eMinOutput(sc,p,s,n,g) eProdctPer(sc,p,s,n,g) eStrtUpPer(sc,p,s, g) eStrtUpNxt(sc,p,s, g) eWtReserve(sc,p, r)</pre>	1C All and a system variable cost operating reserve load generation balance max output of a committed unit min output of a committed unit unit production in same period unit startup in same period unit startup in next period water reserve	[M€] [GW] [GW] [GW] [GW] [GW] [GW]





StarGenLite_SHTCM (vi)

* read input data from Excel and include into the model











iT

StarGenLite_SHTCM (viii)

* scaling of parameters

pDemand (p pOperReserve(p),s,n)),s,n)	<pre>= pDemand = pOperResery</pre>	(p,s,n) /e(p,s,n)	*	1e-3 1e-3	, ,		Parameter scaling
pENSCost) = y	= pENSCost		*	1e-3	;		
pPNSCost		= pPNSCost		*	1e-3			
pEFOR ((t)	= pThermalGer	n(t,'EFOR');				
pMaxProd ((t)	= pThermalGer	n(t,'MaxProd') *	1e-3	* [1-pEFOR(t)];		
pMinProd ((t)	= pThermalGer	n(t,'MinProd') *	1e-3	* [1-pEFOR(t)];		
pSlopeVarCost((t)	= pThermalGer	n(t,'OMVarCost') *	1e-3	+		
		pThermalGer	n(t, SlopeVarCost) *	1e-3	* pihermalGen(t,	'FuelCost');	
pInterVarCost((t)	= plhermalGer	n(t, InterVarCost) *	1e-6	<pre>* pIhermalGen(t,</pre>	<pre>FuelCost');</pre>	
pStartupCost ((t)	= pThermalGer	n(t,'StartupCost')*	1e-6	* pThermalGen(t,	'FuelCost');	
pMaxProd ((h)	= pHydroGen	(h, 'MaxProd')*	1e-3	;		
pminprod (n)	= pHyaroGen	(n, Minprod) *	1e-3			
priaxcons ((II) (b)	= pHydroGen	(n, Maxcons) ↑ \ *	1e-3	;		
perourunct ((II) (b)	= pHydroGen	(n, ProuFunct)) *	1e+3	TIFICIA		
p = 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1 + 1	(II) (n)	- provincio	(II, ETTICIENCY (n. 'MaxPosonyo') \ *	10-2	ر •		
nMinRosonvo ((') ('r)	- preservoir	(n 'MinReserve') *	10-2			
nTniReserve ((r) (r)	= nReservoir	(r 'IniReserve') *	10-3	, GUIG		
	('))	1C-J	و		
<pre>pInflows(r,sc, pInflOrg(r,sc,</pre>	p) p)	= pInflows = pInflows	(r,sc,p (r,sc,p) *)	1e-6	* 3.6* sum [(s,n),	pDuration(p,s	;,n)]; ;
<pre>* if the produ * if the effic</pre>	uction ciency	function of a of a	a hydro plant is 0 a hydro plant is 0	9, i 9, i	t is d t is d	changed to 1 and s changed to 1	scaled to 1000)
pProdFunct(h) pEffic (h)	\$[pPro \$[pEff	dFunct(h) = @ ic (h) = @	0] = 1e3 ; 0] = 1 ;					
	Tecnológica							
Escuela Técnica Superior de	e Ingeniería	(ICAI)	Mediu	ım Te	rm Stoc	hastic Hydrothermal Coo	ordination Model	137





StarGenLite_SHTCM (ix)

* bounds on variables

vProduct.up vConsump.up	(sc,p,s,n,g) (sc,p,s,n,h)	<pre>= pMaxProd(g) = pMaxCons(h)</pre>	• • •	Bounds on v	<i>v</i> ariables
vENS.up	(sc,p,s,n)	= pDemand(p,s,n)	;		
vWtReserve.u	p(sc,p,r)	= pMaxReserve(r)	;		

vWtReserve.lo(sc,p,r) = pMinReserve(r) ; vWtReserve.fx(sc,p,r) \$pn(p) = pIniReserve(r) ;



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StarGenLite_SHTCM (x)

```
* define the nodes of the scenario tree and determine ancestor sc2 of node (sc1 p) and descendant (sc2 p) of node sc1
                  ) $[ord(p) >= pScnTree(sc, 'FirstPeriod')
         sc,p
scp (
                                                                                                  ] = yes ;
scscp(scp(sc,p),scc)  (ord(p) > pScnTree(sc, 'FirstPeriod') and ord(scc) = ord(sc)
                                                                                                  ] = ves ;
scscp(scp(sc,p),scc) $[ord(p) = pScnTree(sc, 'FirstPeriod') and ord(scc) = pScnTree(sc, 'Ancestor')] = yes ;
scsch(sc,scp(scc,p)) $scscp(scc,p,sc)
                                                                                                    = yes ;
pProbSc(sc,pn(p)) = pScnTree(sc, 'Prob')/sum[scc, pScnTree(scc, 'Prob')];
loop (p $[not p1(p)],
  pProbSc(scp(sc,p+lag(p))) = sum[scsch(sc,scc,p+(lag(p)+1)), pProbSc(scc,p+(lag(p)+1))];
);
* delete branches with probability 0 and define the active load levels
                  ) pProbSc(sc,p) = 0
scp (
         sc,p
                                                                 = no ;
         sc,p,scc) probSc(sc,p) = 0 or pProbSc(scc,p-1) = 0] = no;
scscp(
scsch(sc,scc,p
                                                                  = yes $scscp(scc,p,sc);
spsn (scp(sc,p),s,n) $psn
                              (p,s,n)
                                                                  = yes ;
* determine the representative sc2 of node (sc1 p) for non-existing scenarios in the tree
loop (sc $sum[p, pProbSc(sc,p)],
  scaux = ord(sc) ;
  loop (p,
      scscr(sc,p+lag(p),scc) $[ord(scc) = scaux] = yes ;
                            $[ord(scc) = scaux] = yes ;
     SCA(scc)
     scaux = sum[scscp(sca,p+lag(p),scc), ord(scc)];
      SCA(scc)
                                                 = no;
                                                                                            Building the scenario tree
   );
);
SCA(sc) $sum[p, pProbSc(sc,p)] = yes ;
```





StarGenLite_SHTCM (xi)









Medium term optimization model. Results

- Operation planning
 - Unit (thermal, storage hydro, and pumped-storage hydro) operation
 - Reservoir management
 - Targets for short-term models (water balance)

• Economic planning

- System marginal costs
- Targets for short-term models (water value)









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Output Data. Thermal unit commitment



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Output Data. Production





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Output Data. Energy



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Reservoir level at the end of each period



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Medium Term Stochastic Hydrothermal Coordination Model





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Water value



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Output Data. Short Run Marginal Cost (SRMC)





If the SHTCM model is solved with binary UC decisions, no marginal impact of those decisions is considered



Stochastic measures

- Expected value with perfect information (EVWPI) o Wait and See (WS)
 - Weighted mean of the objective function of each scenario knowing what is going to happen (for minimization problems always ≤ the objective function for the stochastic problem)
- Value of the stochastic solution (VSS)
 - Difference between the objective function of the expected value for the mean value solution of the stochastic parameters EEV and that of the stochastic problem RP
- *Expected value of perfect information (EVPI)* or mean regret
 - Weighted average of the difference between the stochastic solution for each scenario and the perfect information solution in this scenario (always positive for minimization)
 - How much are you willing to pay to have perfect information.

$WS \le RP \le EEV$

EVPI = RP - WSVSS = EEV - RP $EVPI \ge 0 \qquad VSS \ge 0$







Stochastic measures

				sc01	sc02	sc03	Expected	Stochastic
Generation	RunOfRiver	in p01	MWh	107136	107136	107136	107136	107136
Generation	StorageHydro_Basin1	in p01	MWh	79200	67356	82629	79200	78741
Generation	StorageHydro_Basin2	in p01	MWh	37466	17600	44903	37466	12602
Generation	StorageHydro_Basin3	in p01	MWh	124281	86400	148800	118110	92787
Reserve	StorageHydro_Basin1	end p01	hm ³	328	368	317	328	330
Reserve	StorageHydro_Basin2	end p01	hm ³	452	518	427	452	535
Reserve	StorageHydro_Basin3	end p01	hm ³	779	800	734	800	800
Total	Hydro Generation	in p01	<mark>MWh</mark>	348083	278492	383467	341912	291265
Total	Reserve	end p01	hm ³	1560	1686	1478	1581	1665
Total	System Variable Cost		M€	1 <mark>123</mark> .997	1144.447	1103.624	1129.624	1130.284

1	EWPI or WS	EEV	VSS	EVPI
ľ,	1130.140	1130.360	0.077	0.144

In this case study, stochasticity in hydro inflows is not relevant from the point of view of total variable cost

... but it is essential for defining the operation of the first period







Task assignment

- Compute the water value numerically for a particular period and reservoir by running twice the hydrothermal model and comparing this water value with the dual variable of the water balance constraint. Apply it to one reservoir in period 1 scenario 1 and another in period 7 scenario 3.
 - Note that you need to take care of the change from m³/s to km³ and of the scenario probability
- Introduce intermittent power (with curtailment) into the model
 - Play with this generation to observe the complementarity between hydro and intermittent generation
 - Evaluate all the stochastic measures of considering the stochasticity of hydro inflows
 - Introduce a take or pay gas contract into the model





Takeaways

- Purpose of a medium-term stochastic hydrothermal coordination model
 - Characteristics
 - Overview
 - Results for operation planning and economic planning
 - Main modeling assumptions
- Prototype mathematical formulation
 - General structure
 - Parameters, variables, equations, objective function
 - Short-run marginal cost, water value
- Case study with *StarGenLite_SHTCM*
 - Input data
 - Output data













Prof. Andres Ramos https://pascua.iit.comillas.edu/aramos/Ramos_CV.htm https://www.iit.comillas.edu/people/aramos

Andres.Ramos@comillas.edu

arght@mit.edu



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