MITEI-IAP24

Computational modeling for clean, reliable, and affordable electricity

Massachusetts Institute of Technology (MIT)

Medium-Term Stochastic Hydrothermal Coordination Model

Prof. Andres Ramos

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

Andres.Ramos@comillas.edu

arght@mit.edu

January 2024

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

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.

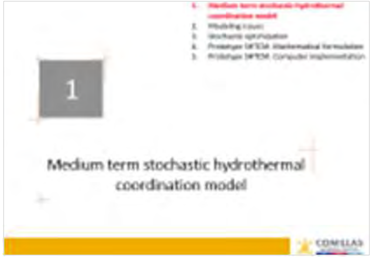
Alqueva reservoir

http://www.youtube.com/watch?v=82efZBKBXSg

References

- State-of-the-art in hydro scheduling
  - A. Rodrigo de Queiroz *Stochastic hydro-thermal scheduling optimization: An overview*. Renewable and Sustainable Energy Reviews 62 382–395. 2016 10.1016/j.rser.2016.04.065
  - J.W. Labadie *Optimal Operation of Multireservoir Systems: State-of-the-Art Review* JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT MARCH/APRIL 2004 pp. 93-111 10.1061/(ASCE)0733-9496(2004)130:2(93)
- Hierarchy of planning models
  - A. Ramos, S. Cerisola, J.M. Latorre *A Decision Support System for Generation Planning and Operation in Electricity Markets* in the book P.M. Pardalos, S. Rebennack, M.V.F. Pereira and N.A. Iliadis (eds.) *Handbook of Power Systems* pp. 797-817 Springer December 2009 ISBN 9783642024924
- Stochastic optimization
  - S. Cerisola, J.M. Latorre, A. Ramos *Stochastic Dual Dynamic Programming Applied to Nonconvex Hydrothermal Models* European Journal of Operational Research 218 (2012) 687–697 10.1016/j.ejor.2011.11.040
  - A. Ramos, S. Cerisola, J.M. Latorre, R. Bellido, A. Perea and E. Lopez *A decision support model for weekly operation of hydrothermal systems by stochastic nonlinear optimization* in the book G. Consiglio, M. Bertocchi (eds.) *Stochastic optimization methods in finance and energy* Springer 2011 ISBN 9781441995858
- Scenario tree generation
  - J.M. Latorre, S. Cerisola, A. Ramos *Clustering Algorithms for Scenario Tree Generation. Application to Natural Hydro Inflows* European Journal of Operational Research 181 (3): 1339-1353 Sep 2007 10.1016/j.ejor.2005.11.045
- Object-oriented simulation
  - J.M. Latorre, S. Cerisola, A. Ramos, R. Bellido, A. Perea *Creation of Hydroelectric System Scheduling by Simulation* in the book H. Qudrat-Ullah, J.M. Spector and P. Davidsen (eds.) *Complex Decision Making: Theory and Practice* pp. 83-96 Springer October 2007 ISBN 9783540736646
  - J.M. Latorre, S. Cerisola, A. Ramos, A. Perea , R. Bellido *Coordinated hydro power plant simulation for multi-reservoir systems* Journal of Water Resources Planning and Management 140 (2), 216-227, Feb 2014 10.1061/(ASCE)WR.1943-5452.0000306

Contents


1

Medium term stochastic hydrothermal coordination model


2

Modeling issues


3

Stochastic optimization


4

Prototype SHTCM. Mathematical formulation


5

Prototype SHTCM. Computer implementation

1

Medium term stochastic hydrothermal coordination model

Generation planning functions

Functions	Long term	**Medium term**	Short term
New liberalized market functions	• Capacity investments • Risk management • Long term contracts: - Fuel acquisition - Electricity selling	• Objectives: - Market share - Price • Budget planning • Future derivatives market bids	• Strategic bidding: - Energy - Power reserve - Other ancillary services
Traditional regulated operation functions	• Capacity investments - Installation - Repowering • Maintenance • Energy management - Nuclear cycle - Multiannual reservoirs	• Fuel management • Annual reservoir and seasonal pumped storage hydro management - Water value assessment	• Startup and shut-down of thermal units • Pumped storage hydro operation • Economic dispatch

Scope

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

Medium-term optimization model. Main modeling assumptions

- System characteristics and some data that are known with certainty (deterministic)
  - Technical characteristics of existing power plants
  - Multiple cascaded reservoirs
  - Net load demand (includes intermittent generation and imported/exported power)
  - Availability of generation units as a reduced-rated power
  - Fuel costs
- Uncertain or stochastic data
  - Unregulated (natural) hydro inflows
- Hydro plants are limited in both energy and power output
- Transmission network doesn't affect the optimal operation of the units (it is not represented)

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

Medium term optimization model. Results

- Operation planning
  - Fuel consumption, unit (thermal, storage hydro, and pumped storage hydro), and/or technology operation
  - CO2 Emissions
  - Reservoir management
  - Production targets for short-term models (water balance)

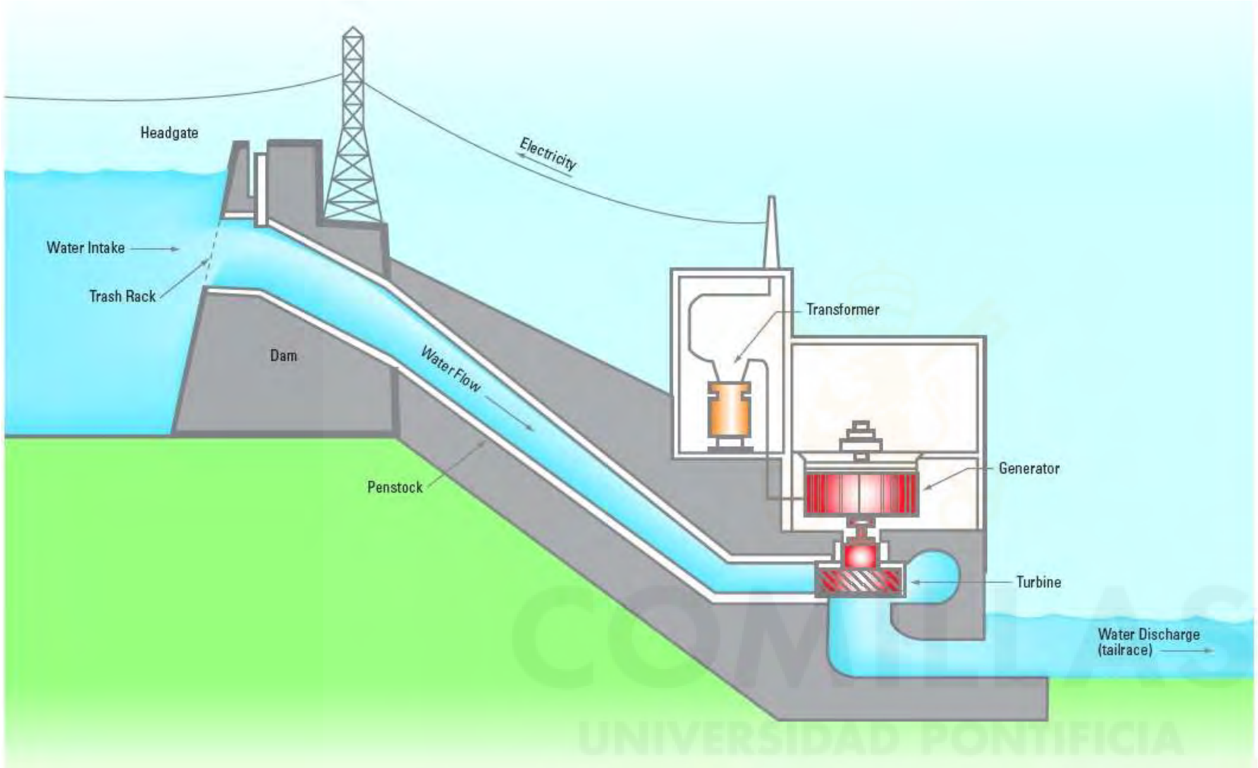
- Economic planning
  - Annual budget
  - Operational costs
  - System marginal costs
  - Economic targets for short-term models (water value)

1. Medium term stochastic hydrothermal coordination model
2. **Modeling issues**
3. Stochastic optimization
4. Prototype SHTCM. Mathematical formulation
5. Prototype SHTCM. Computer implementation

2

Modeling issues

Hydroelectric Dam



Source: http://etrical.wordpress.com/power-generation/

Ricobayo hydroelectric power plant

Variety of Spanish hydro subsystem

- Hydro reservoir volumes: 0.15 - 2433 hm^3
- 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 hm^3)

Almendra (Nov-2017)

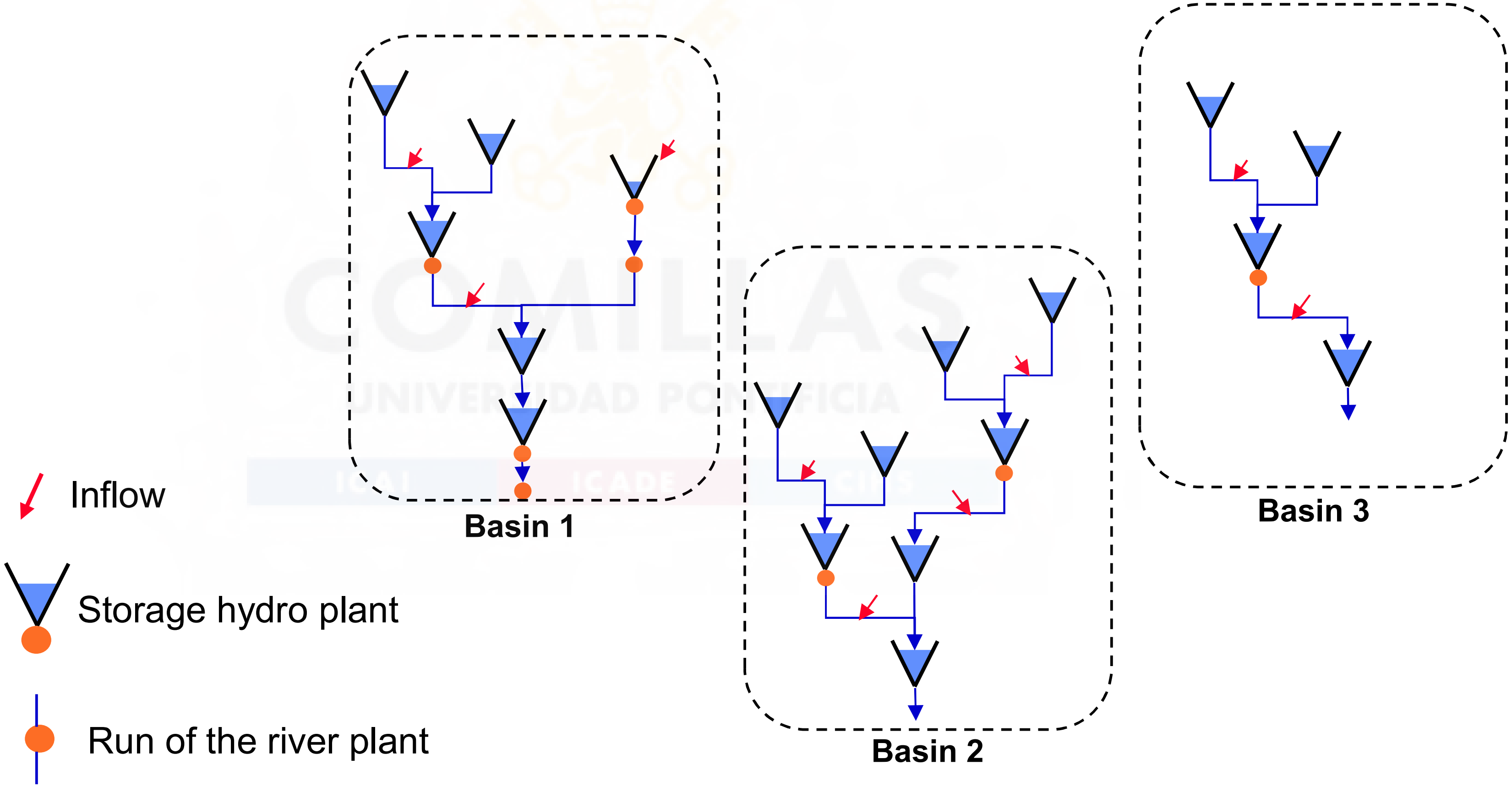
https://www.lasexta.com/noticias/sociedad/las-desoladoras-imagenes-aereas-del-embalse-de-la-almendra-en-salamanca-totalmente-seco_201711235a1728080cf2f56e3eb493b2.html

Hydro subsystem modeling difficulties

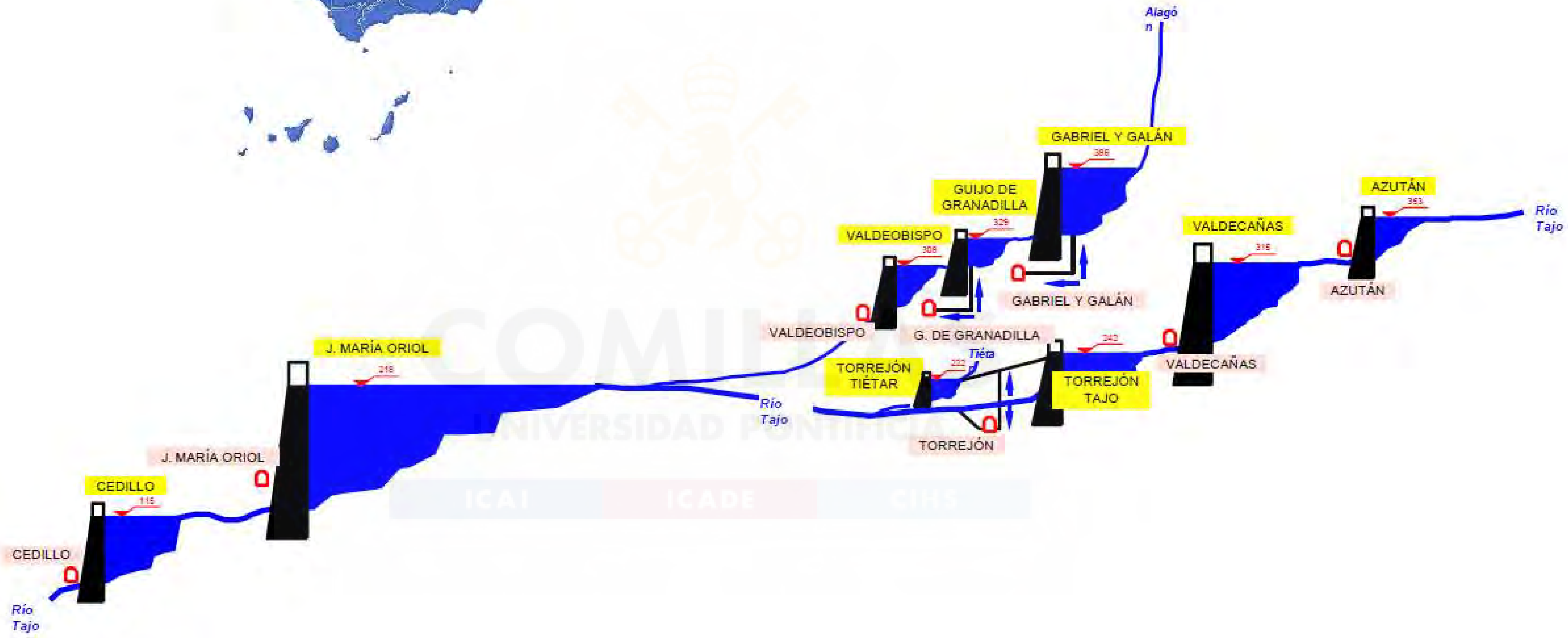
- Topological complexities in waterways
- Nonlinearities in the production function. Head dependency: energy production depends on the water reserve at the reservoir and on the water inflows
  - Important when changes in reservoir levels are significant for the time scope of the model
- Stochasticity 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)

Multiple basins

- The hydro subsystem is divided into a set of independent hydro basins:

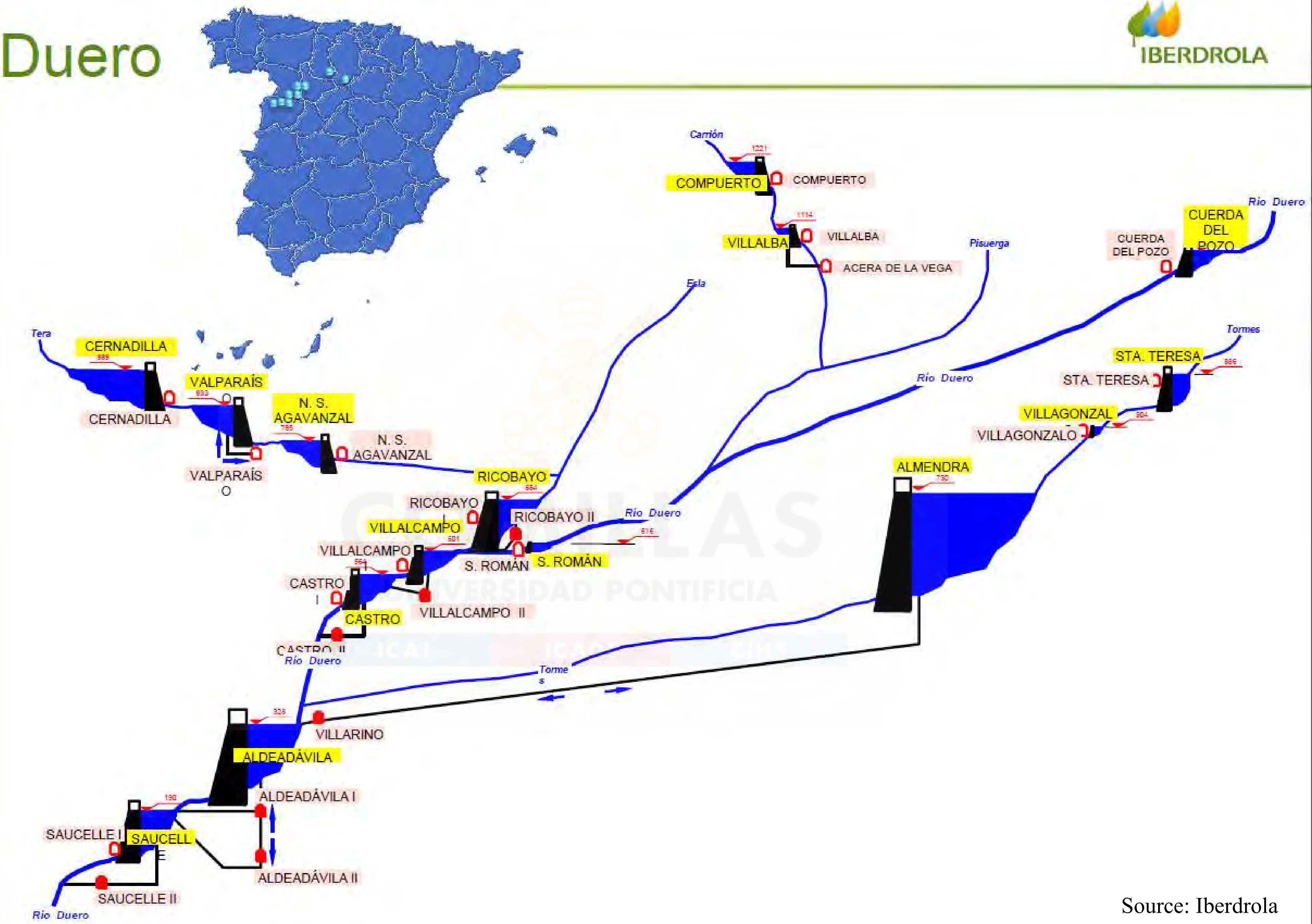


Tajo



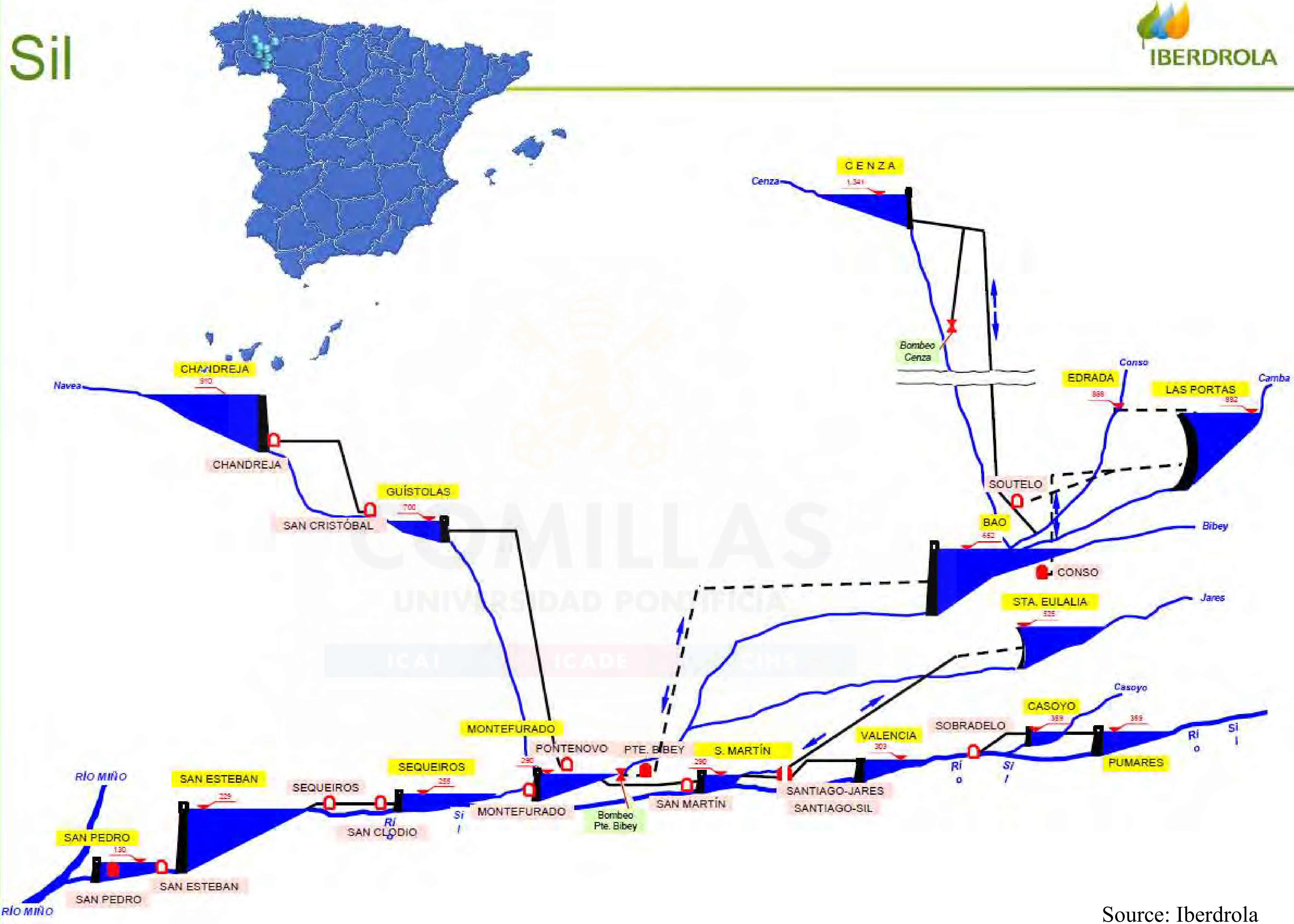
Source: Iberdrola

Duero



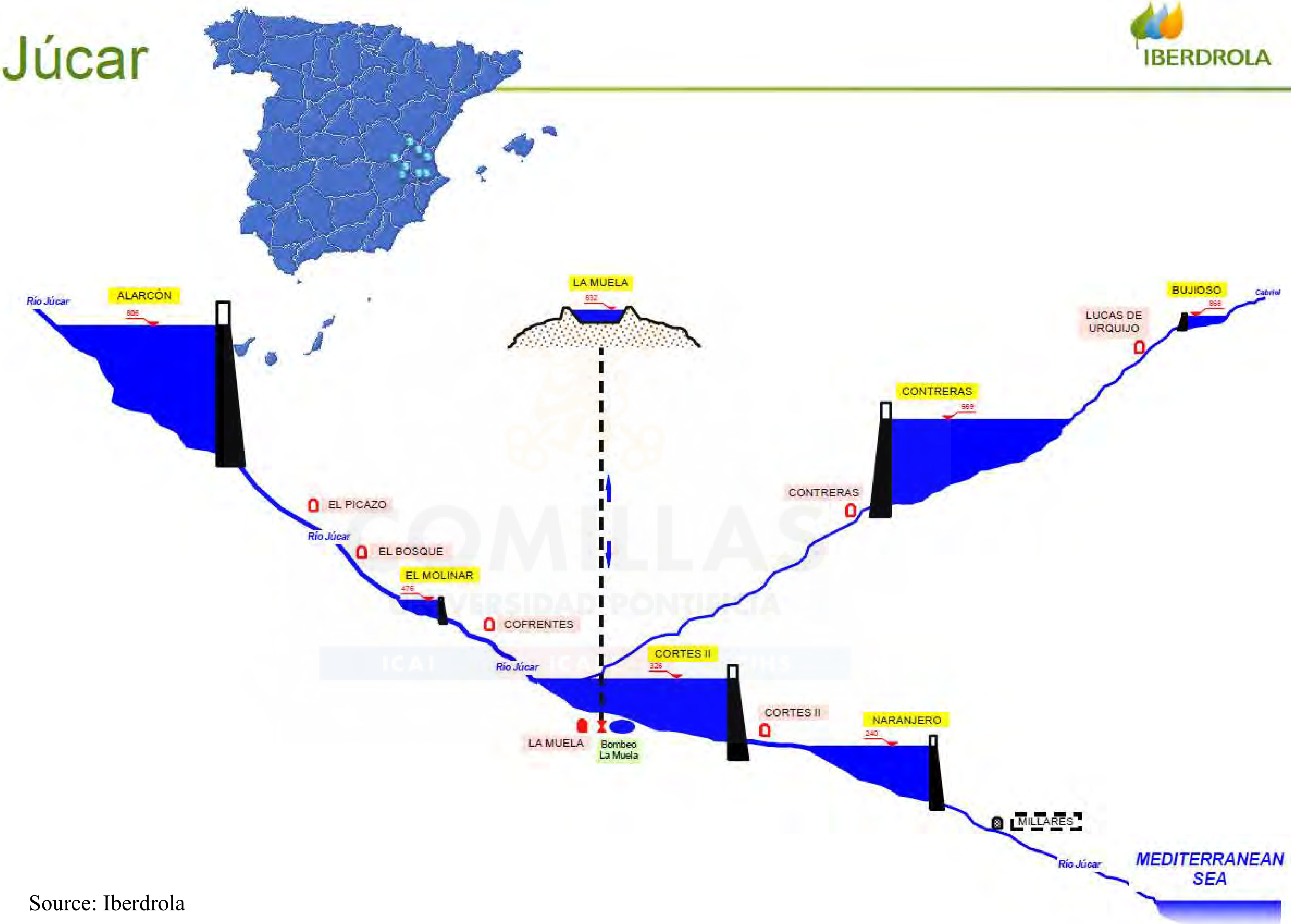
Source: Iberdrola

Sil



Source: Iberdrola

Júcar



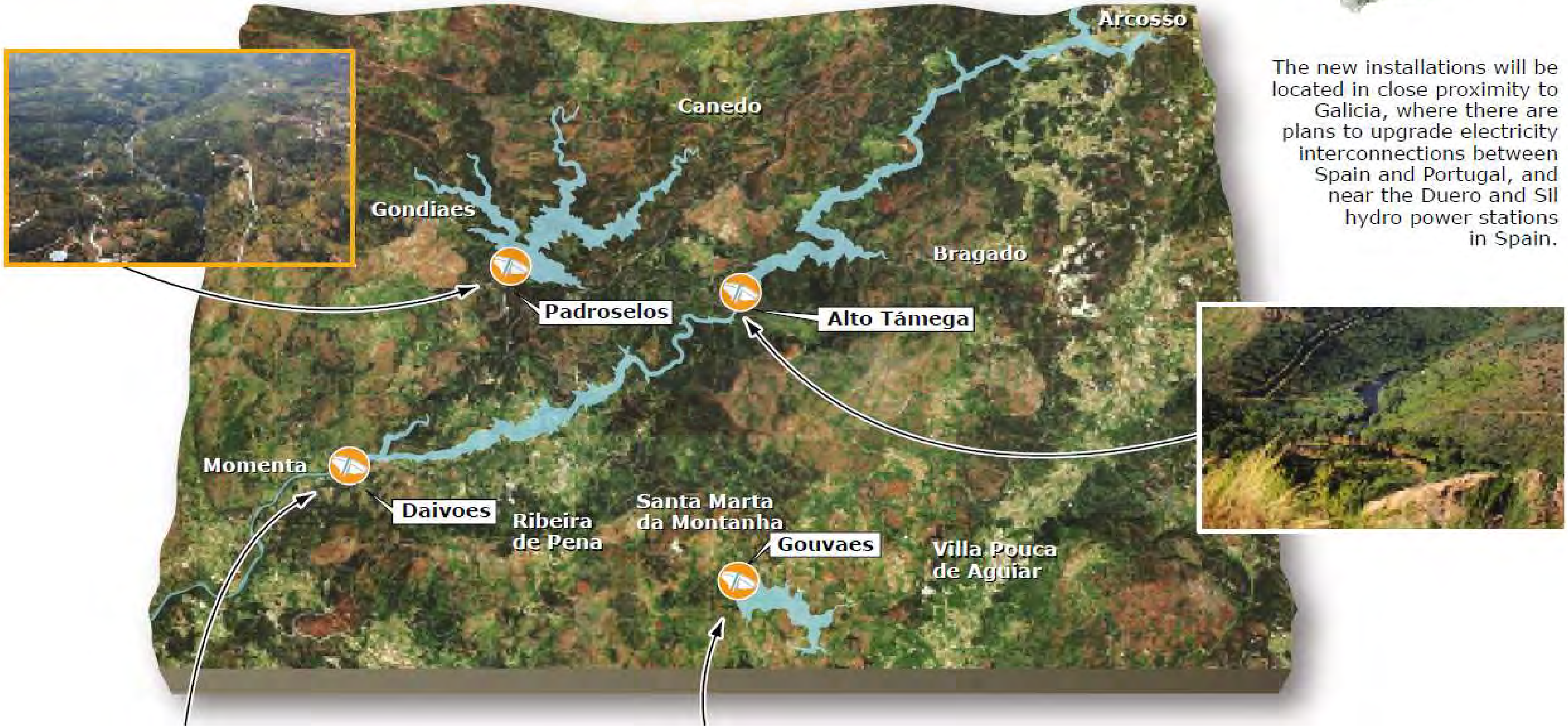
Source: Iberdrola

Alto Tâmega hydroelectric complex

IBERDROLA

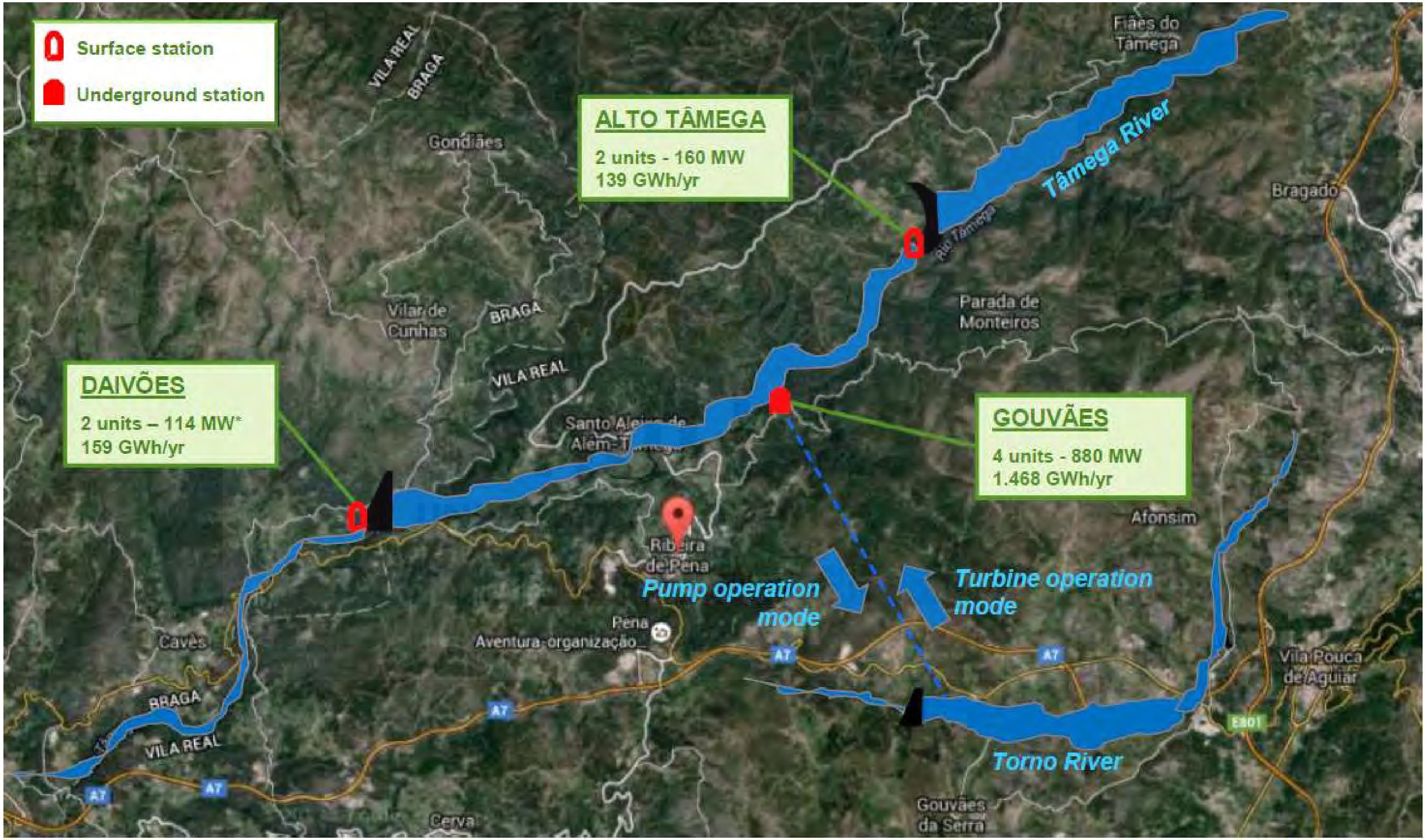
One of Europe's largest hydro projects over the last 25 years

Iberdrola will develop the Alto Támega hydroelectric complex in Portugal, one of the largest projects of its kind in Europe to have been carried out in the last 25 years. This initiative, which underlines the company's commitment to cleaner generation technology and to progress in Portugal, envisages exploiting hydroelectricity infrastructure at Gouvaes, Padroselos, Alto Támega and Daivoes for 65 years.



The new installations will be located in close proximity to Galicia, where there are plans to upgrade electricity interconnections between Spain and Portugal, and near the Duero and Sil hydro power stations in Spain.

Alto Tâmega hydroelectric complex



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

Alto Tâmega Project

https://www.iberdrola.com/about-us/lines-business/tamega

La Muela-Cortes hydroelectric complex (> 2000 MW)

La Muela upper reservoir

Pumped storage hydro La Muela
1722 MW

Hydro plant Cortes II
290 MW

Cortes reservoir

Stochastic hydro inflows

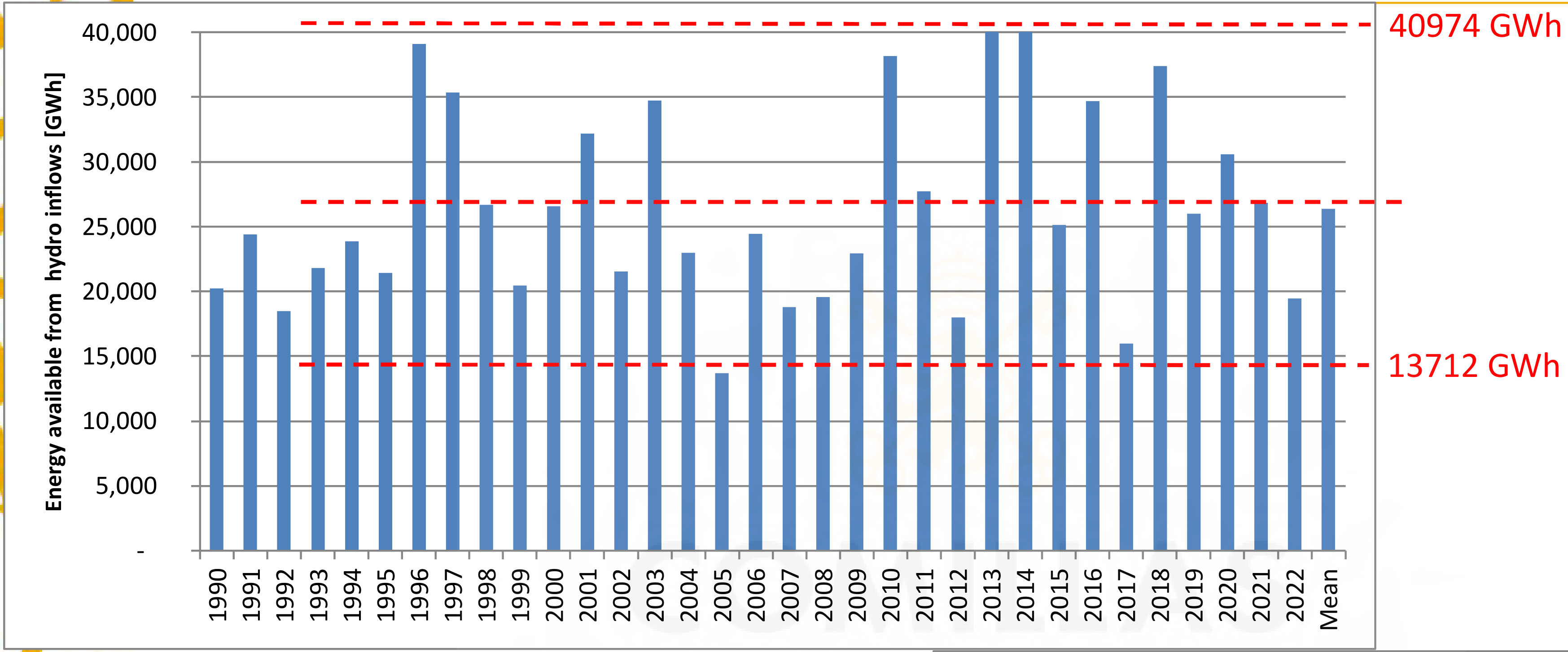
- Natural hydro inflows (clearly the most critical annual factor in the Spanish electric system)

- Changes in reservoir volumes are significant because of:
  - stochasticity in hydro inflows
  - chronological pattern of inflows and
  - capacity of the reservoir with respect to the inflows

Year	Hydro energy TWh	Index	% of being exceeded
1990	20.3	0.98	98%
1991	24.4	0.98	49%
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%
2009	23.0	0.92	57%
2010	38.2	1.53	6%
2011	27.7	0.95	55%
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%
2021	26.9	0.91	60%
2022	19.5	0.67	89%

Source: REE

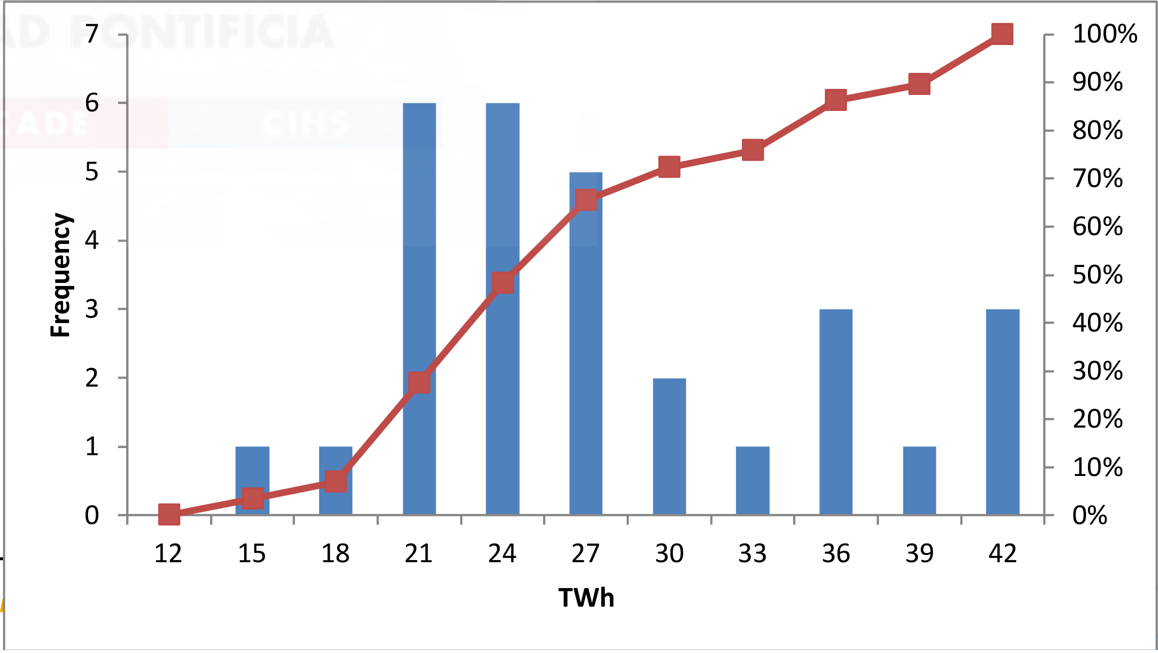
How uncertain are annual hydro inflows in Spain?



- Mean values

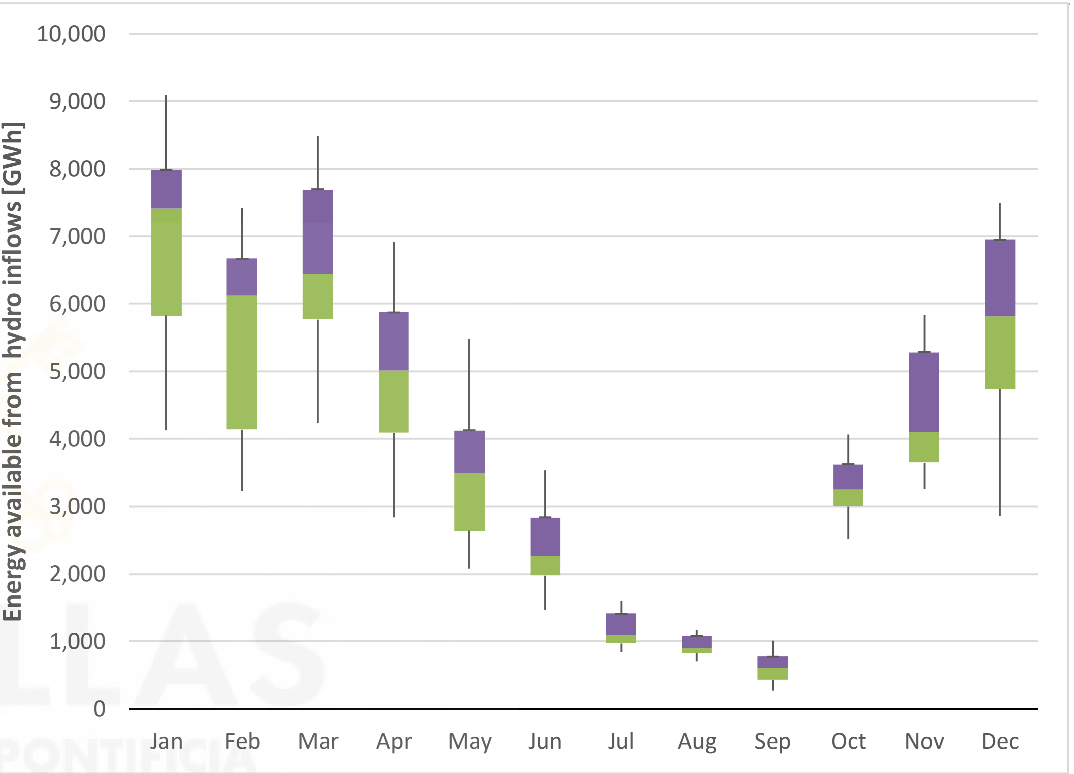
  26382 GWh

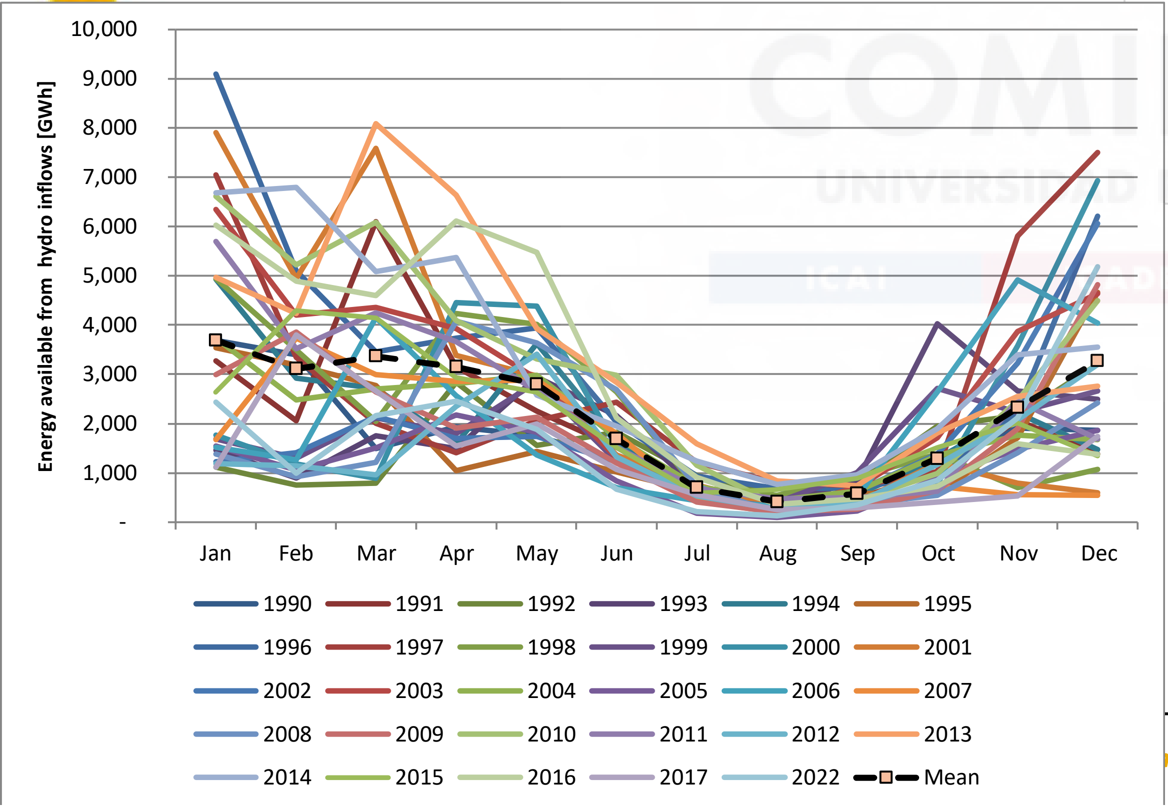
  3012 MW



Source: REE

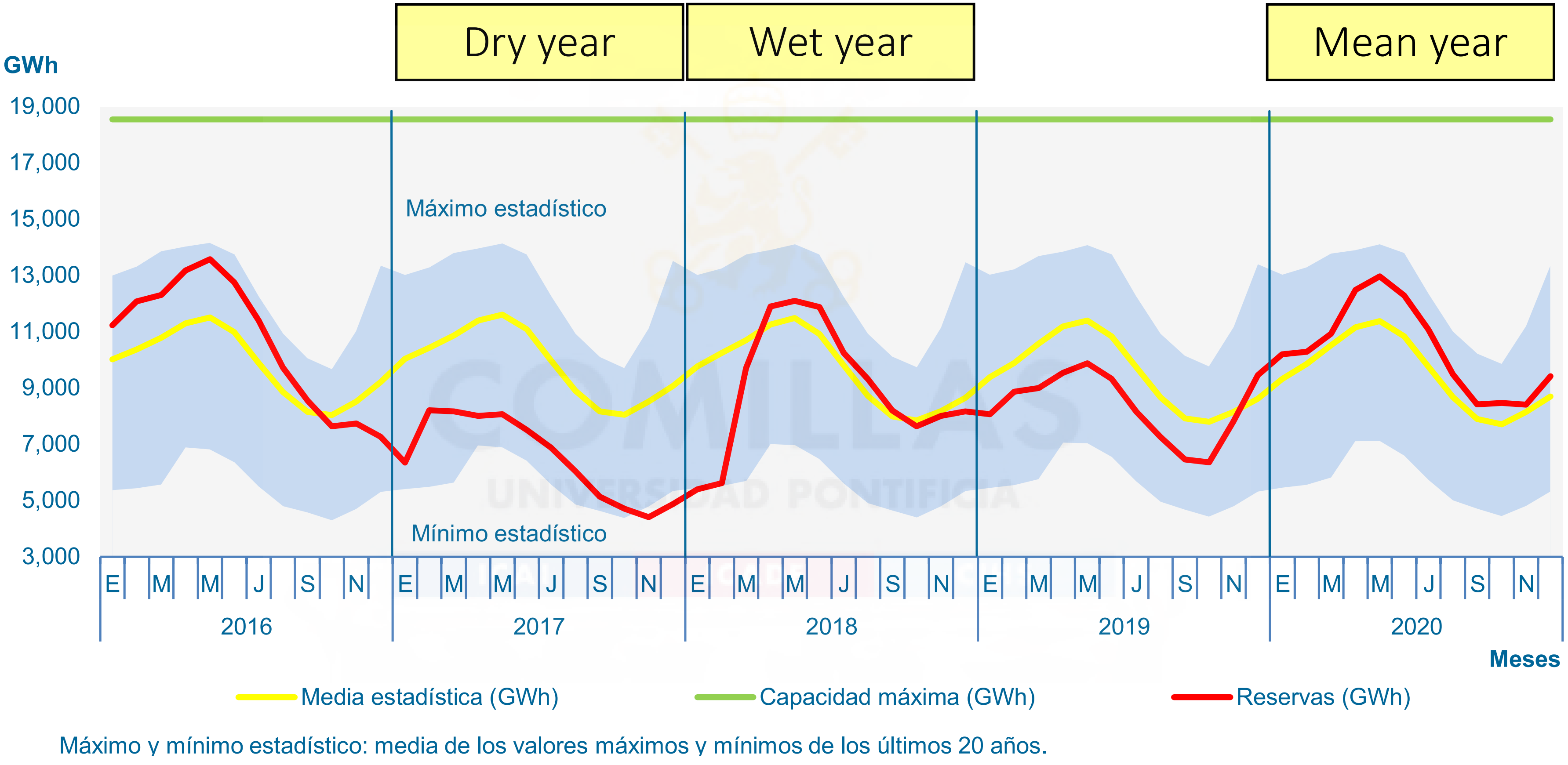
How uncertain are monthly hydro inflows in Spain?





Source: REE

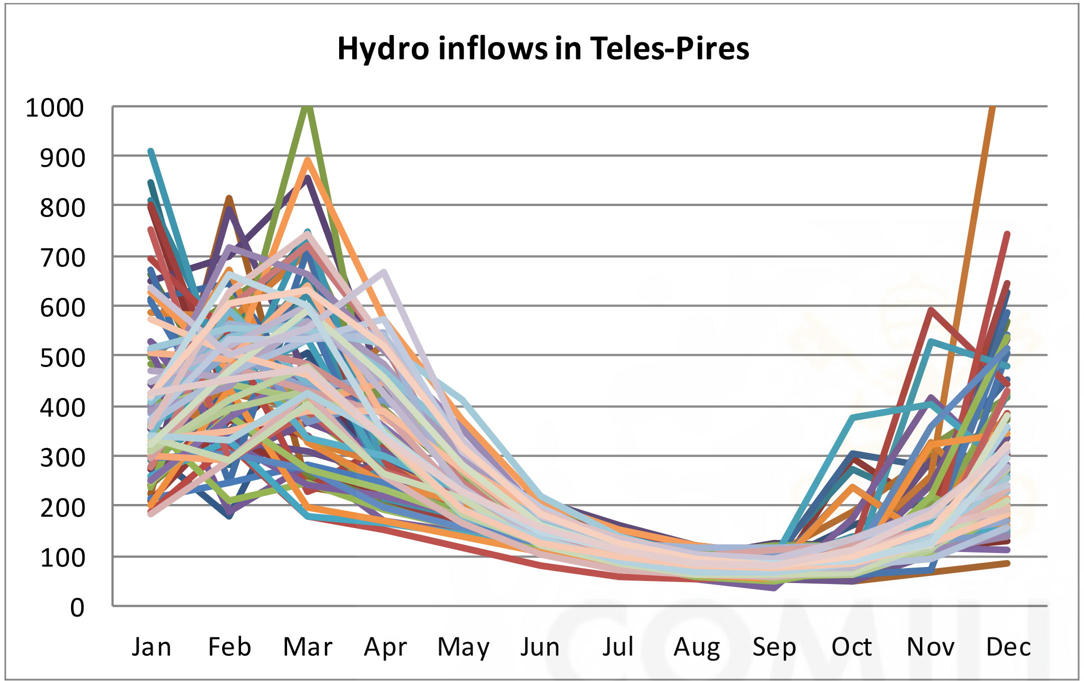
Historical, max and min reservoir levels

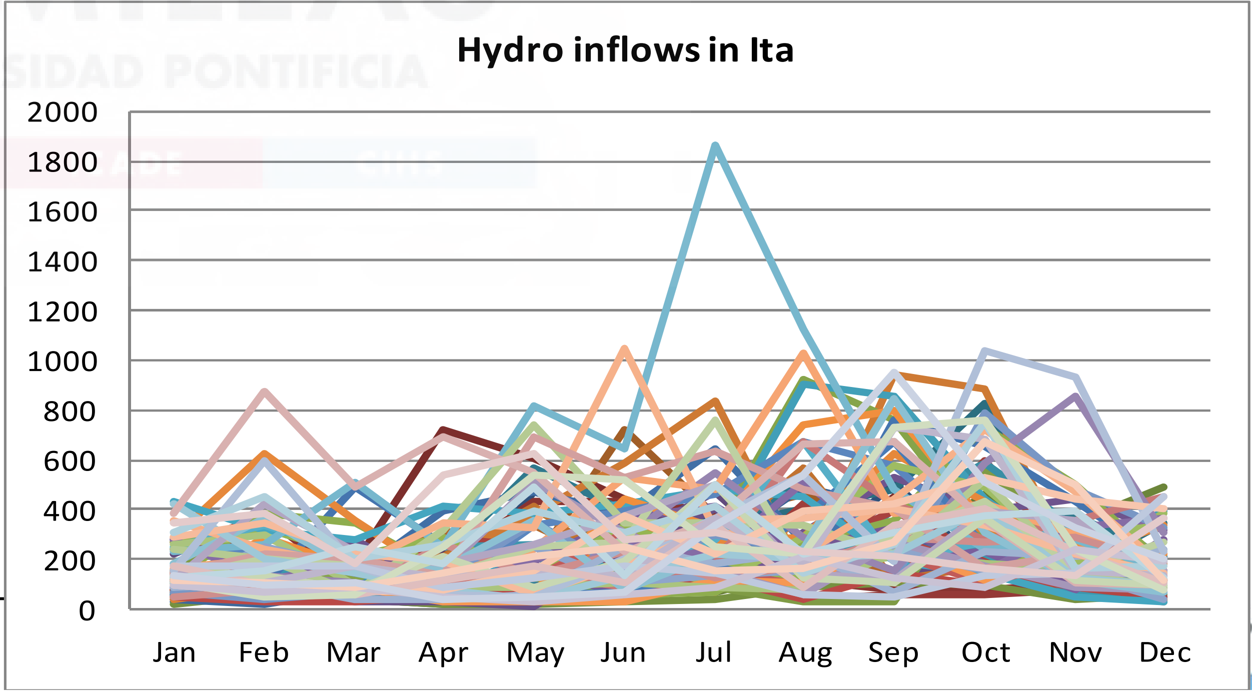


Máximo y mínimo estadístico: media de los valores máximos y mínimos de los últimos 20 años.

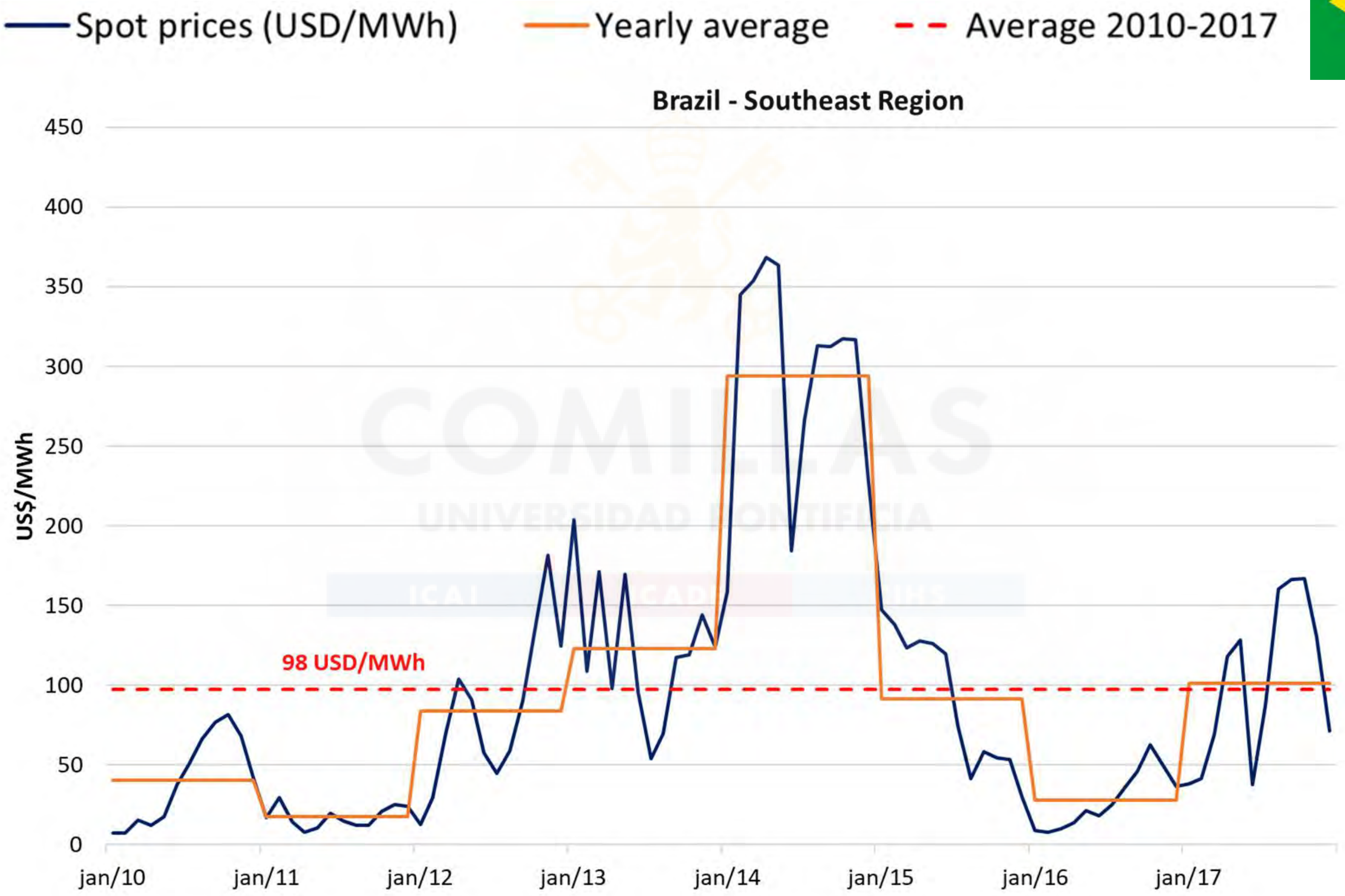
Source: REE

How uncertain are hydro inflows in Brazil?



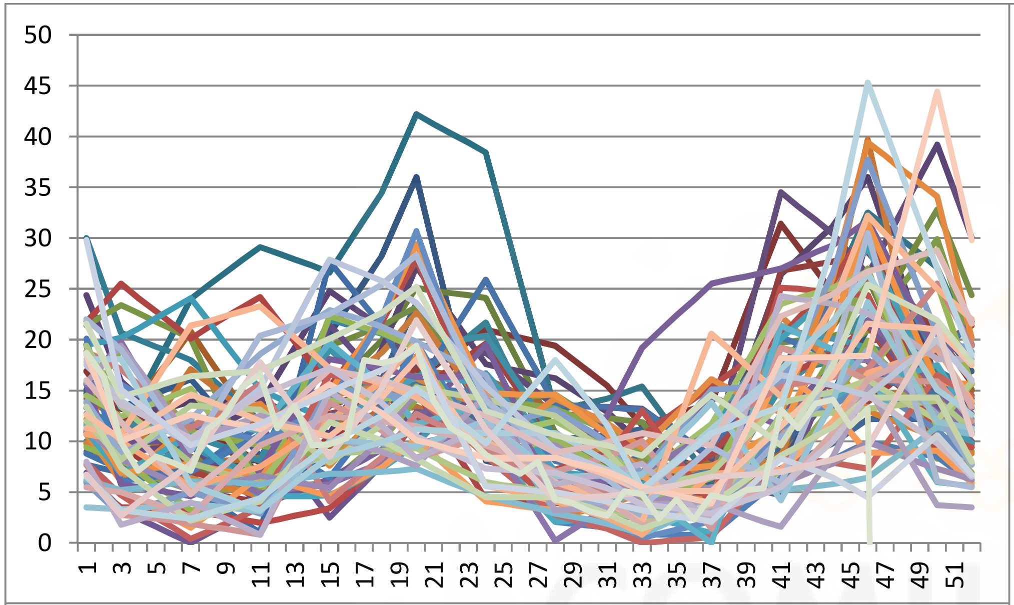


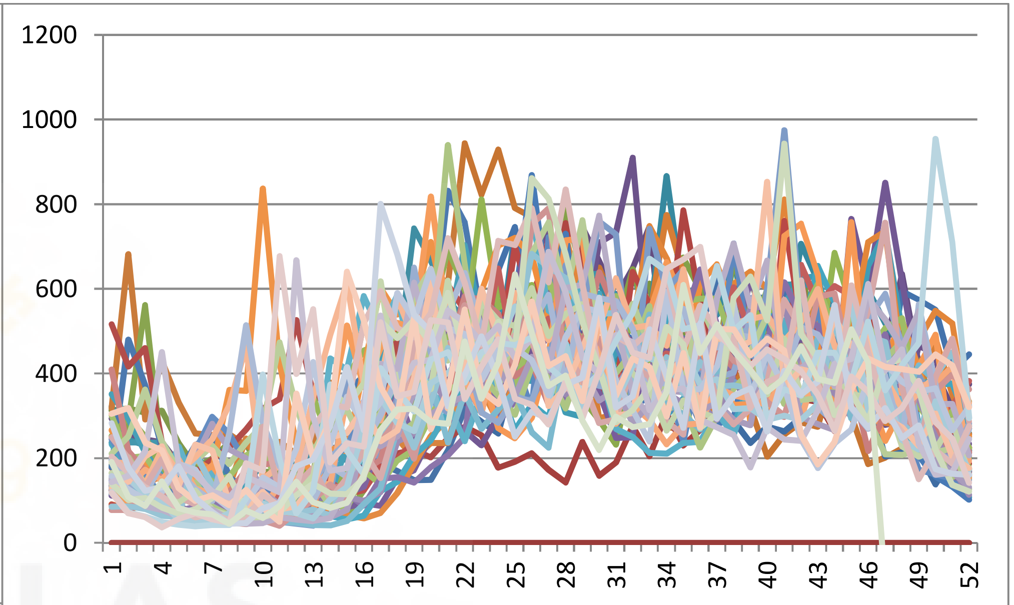
Spot prices strongly driven by hydrology

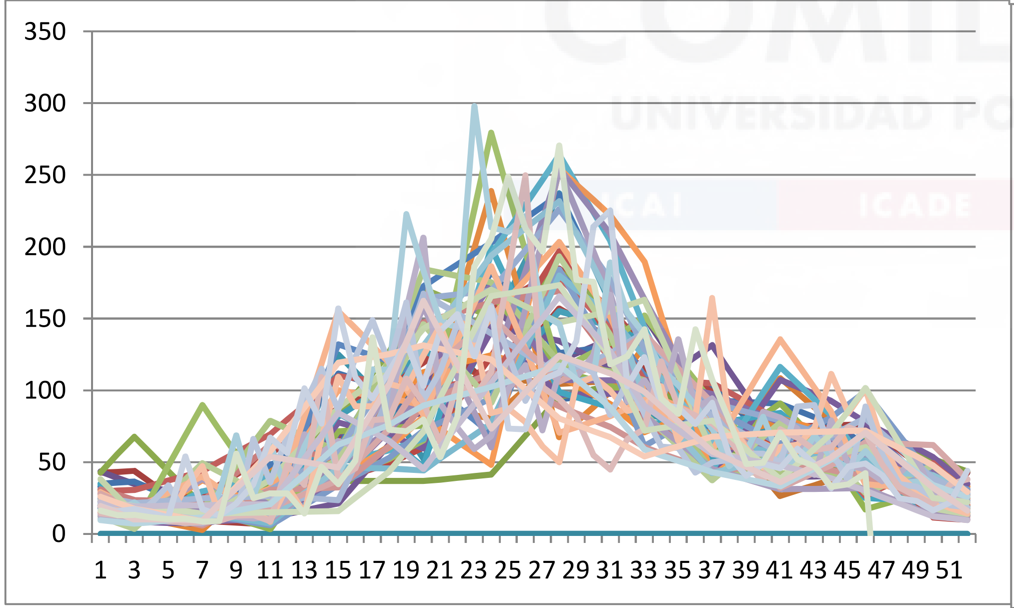


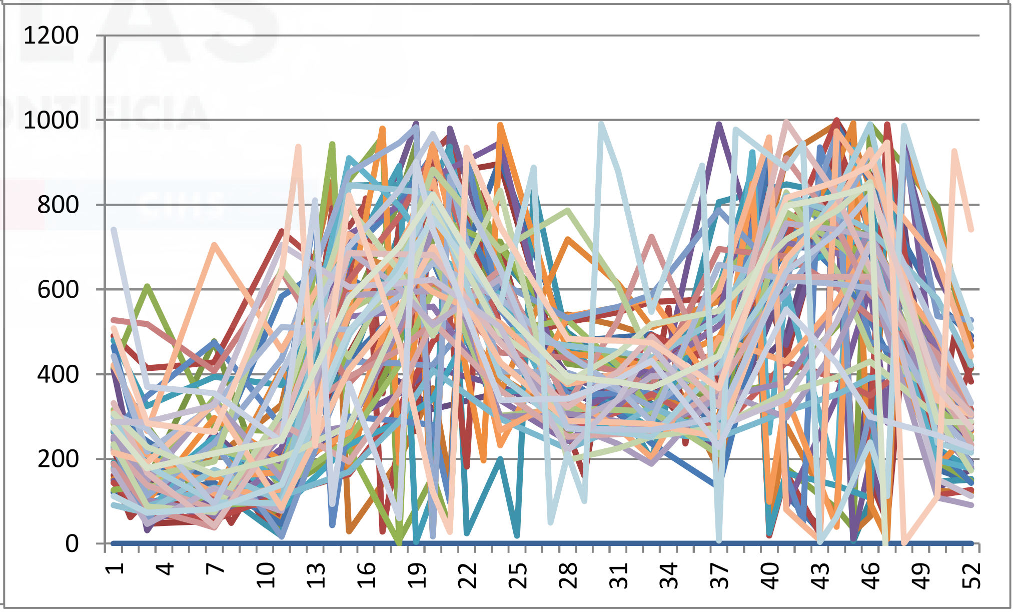
Source: L. Barroso. PSR

How uncertain are hydro inflows in Colombia?



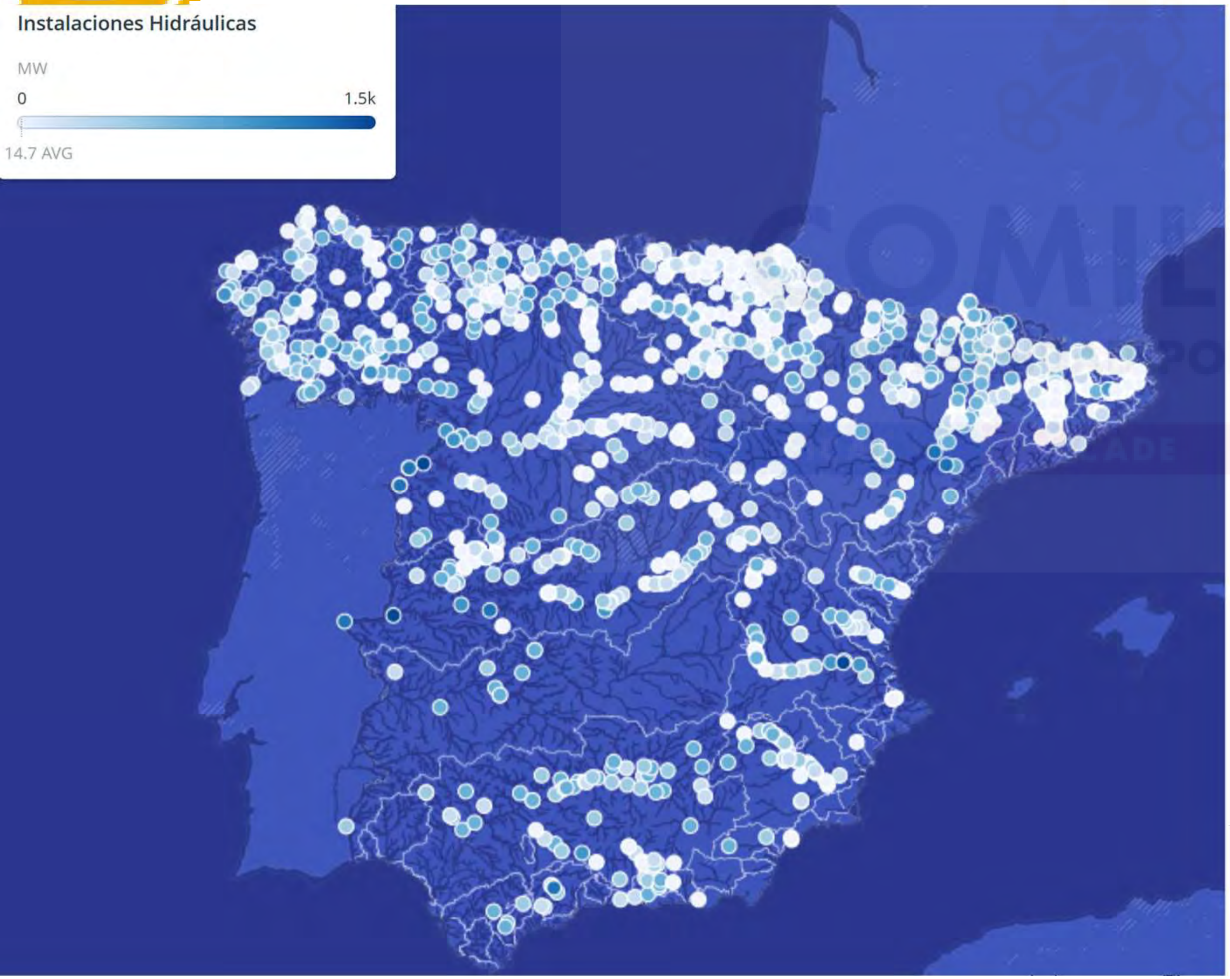






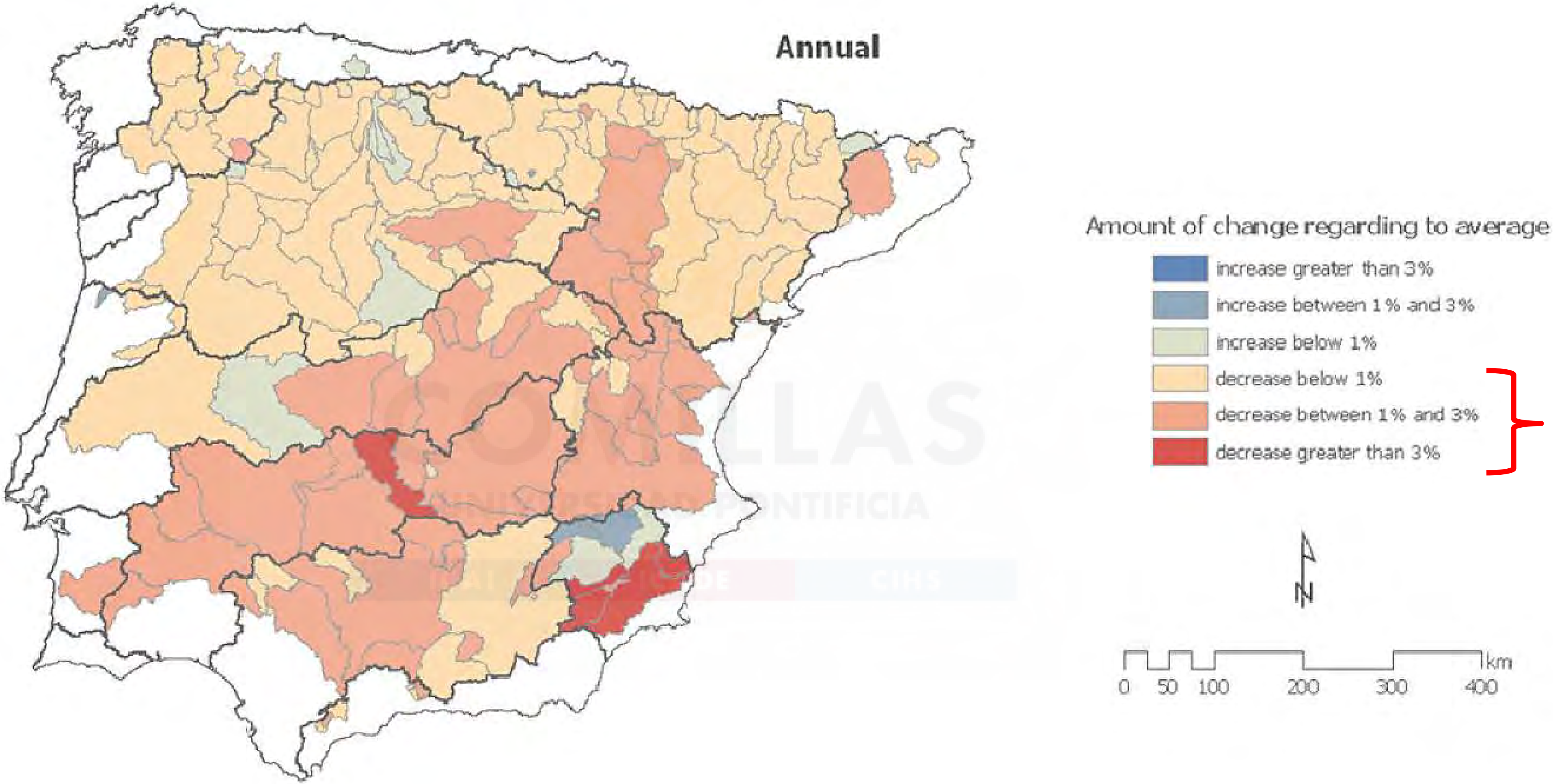
Stochastic hydro inflows

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



https://www.esios.ree.es/en/interesting-maps/hydraulic-installations-map

Inflows have decreased in Iberian rivers in the last 60 years



J. Lorenzo-Lacruz, S.M. Vicente-Serrano, J.I. López-Moreno, E. Morán-Tejeda, J. Zabalza. Recent trends in Iberian streamflows (1945–2005). *Journal of Hydrology*. Vol 414–415, Jan 2012, pp. 463-475

1. Medium term stochastic hydrothermal coordination model
2. Modeling issues
3. **Stochastic optimization**
4. Prototype SHTCM. Mathematical formulation
5. Prototype SHTCM. Computer implementation

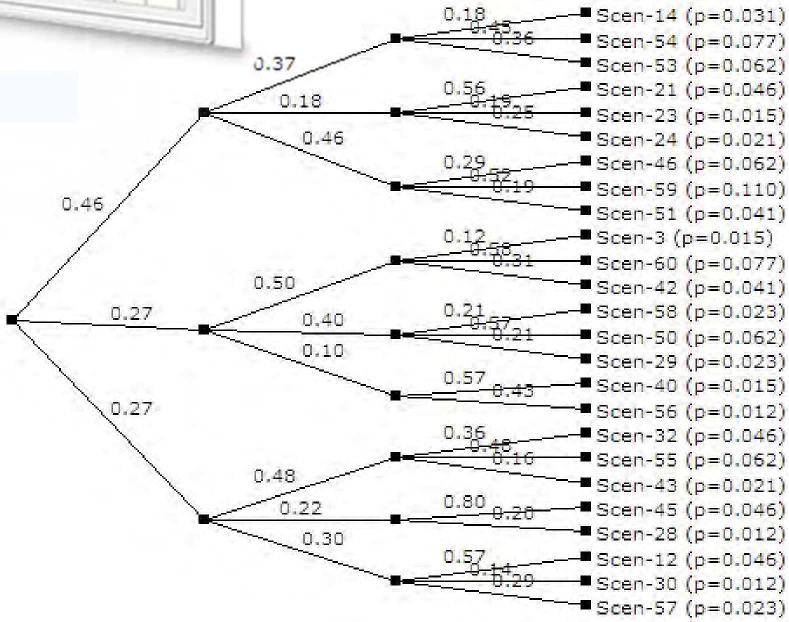
3

Stochastic optimization

Decision under uncertainty

- DETERMINISTIC optimization
  - Best decision when the future is known

- Simulation. Scenario analysis
  - What could happen if …?



- STOCHASTIC optimization
  - Best decision when the future is uncertain (with a known probability)

Alternatives for modeling the uncertainty (i)

- Wait and see or scenario analysis or what-if analysis
  - Decisions are taken once solved the uncertainty
  - The problem is solved independently for each scenario
  - The scenario with a mean value of the parameters is just a particular case
  - A priori, decisions will be different for each scenario (anticipative, clairvoyant, non-implementable)
  - Solution of a scenario can be infeasible in the others

Alternatives for modeling the uncertainty (iii)

- Here and now
  - Decisions must be taken before solving 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
  - It allows including risk-averse attitudes, penalizing the worst cases

  - STOCHASTIC OPTIMIZATION

Example: hydrothermal coordination problem

- Scenario analysis
  - Run the model supposing that the natural hydro inflows will be the same as any of the previous historical inflows (i.e., the year 1989 or 2004, etc.) for the time scope
  - Run the model supposing that the natural hydro inflows for each period will be exactly 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 hydro inflows will be the same as it has been in the past

What is a stochastic optimization model?

- If I knew the future (I am clairvoyant, anticipative, deterministic), I would run my system as cheapest as possible
  - I am not going to crash my car this year
  - It is going to rain enough in Brazil this year
  - No generating unit is going to fail in the next 24 hours
- If I don't know the future (it is uncertain, and I am not clairvoyant), I must hedge against it, and therefore I take a stochastic decision
  - I am going to buy a car insurance policy
  - I must sign some gas contracts for running CCGT units
  - N-1 dispatch criterion
- Stochastic decision will be cheaper than some of the (catastrophic) scenarios but more expensive than others

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

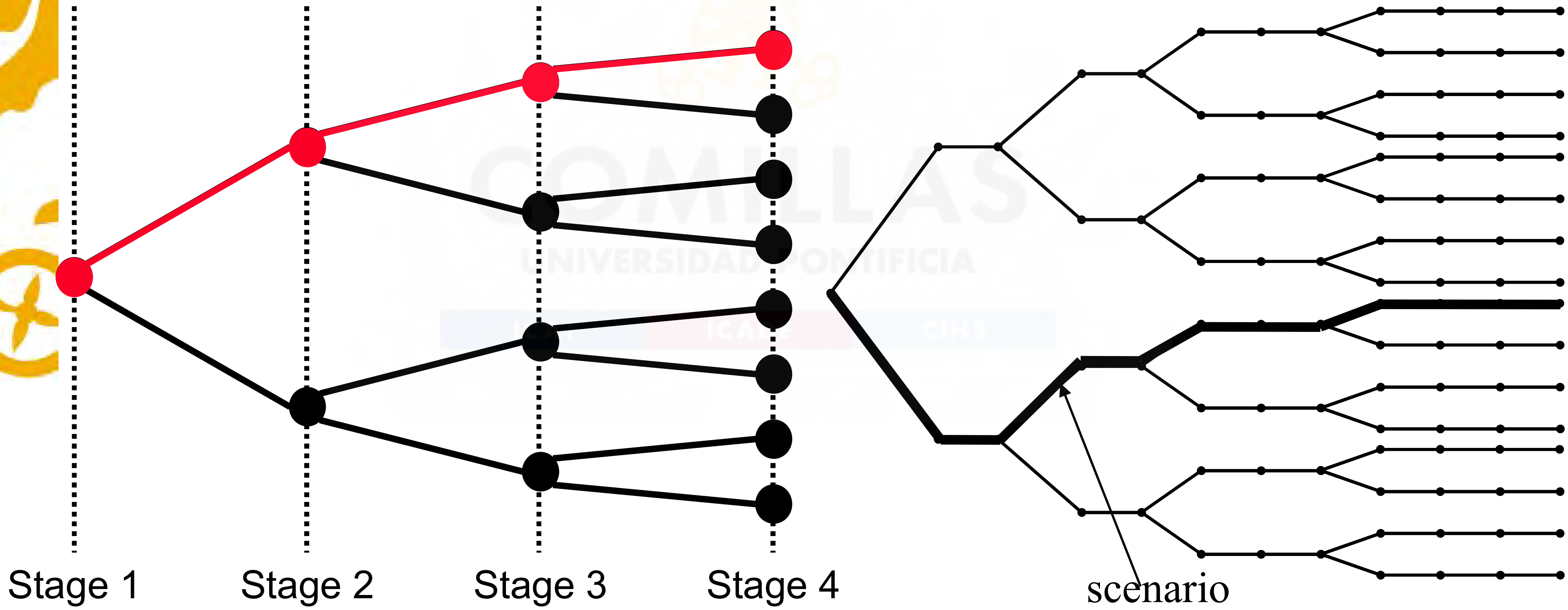
Aldeadávilla hydro plant

Probability tree or scenario tree

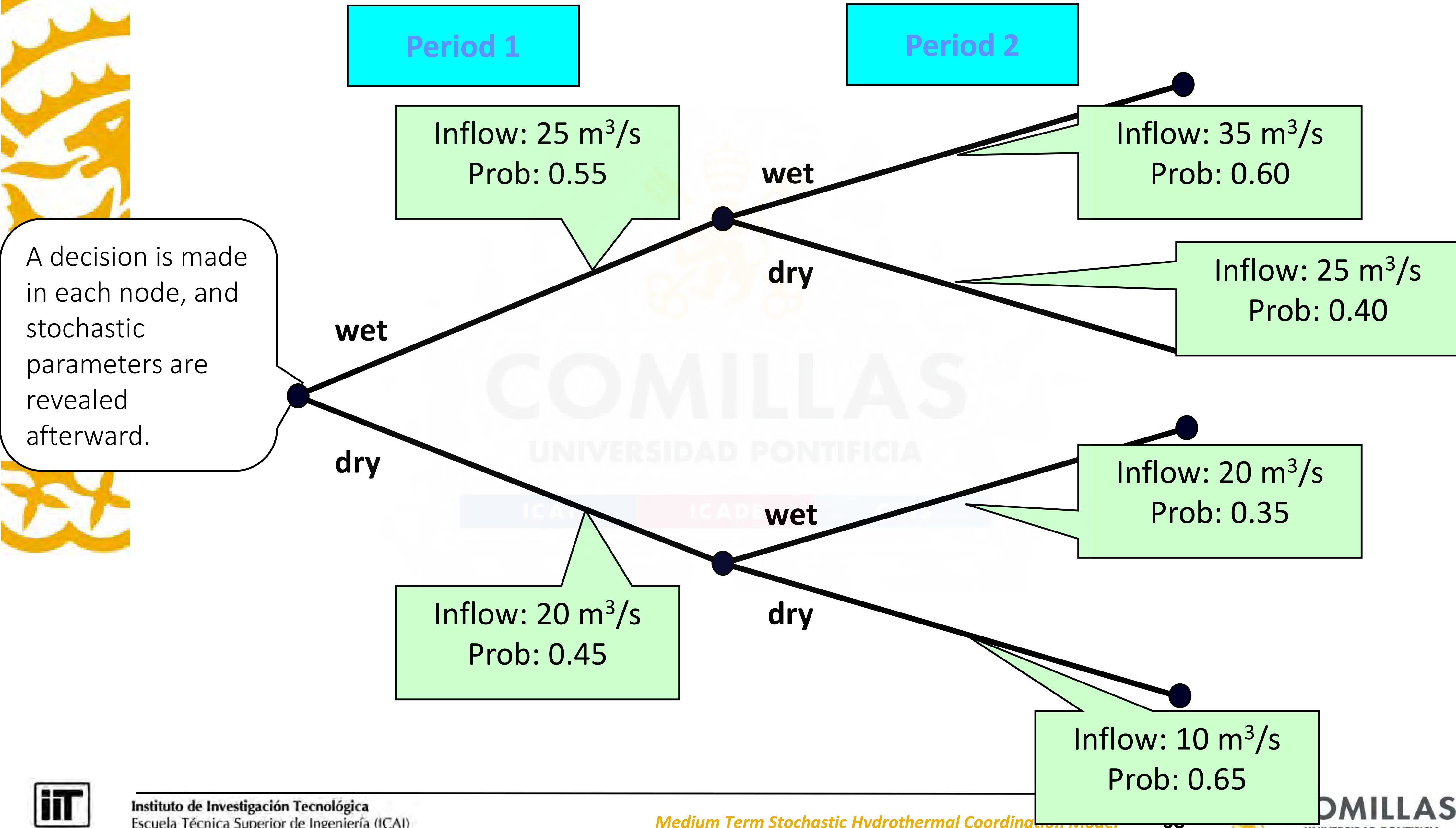
- Tree: represents how the stochasticity is revealed over time, i.e., the different states of the random parameters and simultaneously the non-anticipative decisions over time. Correlation among parameters should be considered
- Scenario: any path going from the root to the leaves
- The scenarios that share the information until a certain period do the same into the tree (non-anticipative decisions)

Scenario tree

- Nodes: where decisions are taken.
- Scenarios: instances of the random process.



Scenario tree example



A decision is made in each node, and stochastic parameters are revealed afterward.

Period 1

Period 2

wet

Inflow: 25 m³/s
Prob: 0.55

dry

Inflow: 20 m³/s
Prob: 0.45

wet

Inflow: 35 m³/s
Prob: 0.60

dry

Inflow: 25 m³/s
Prob: 0.40

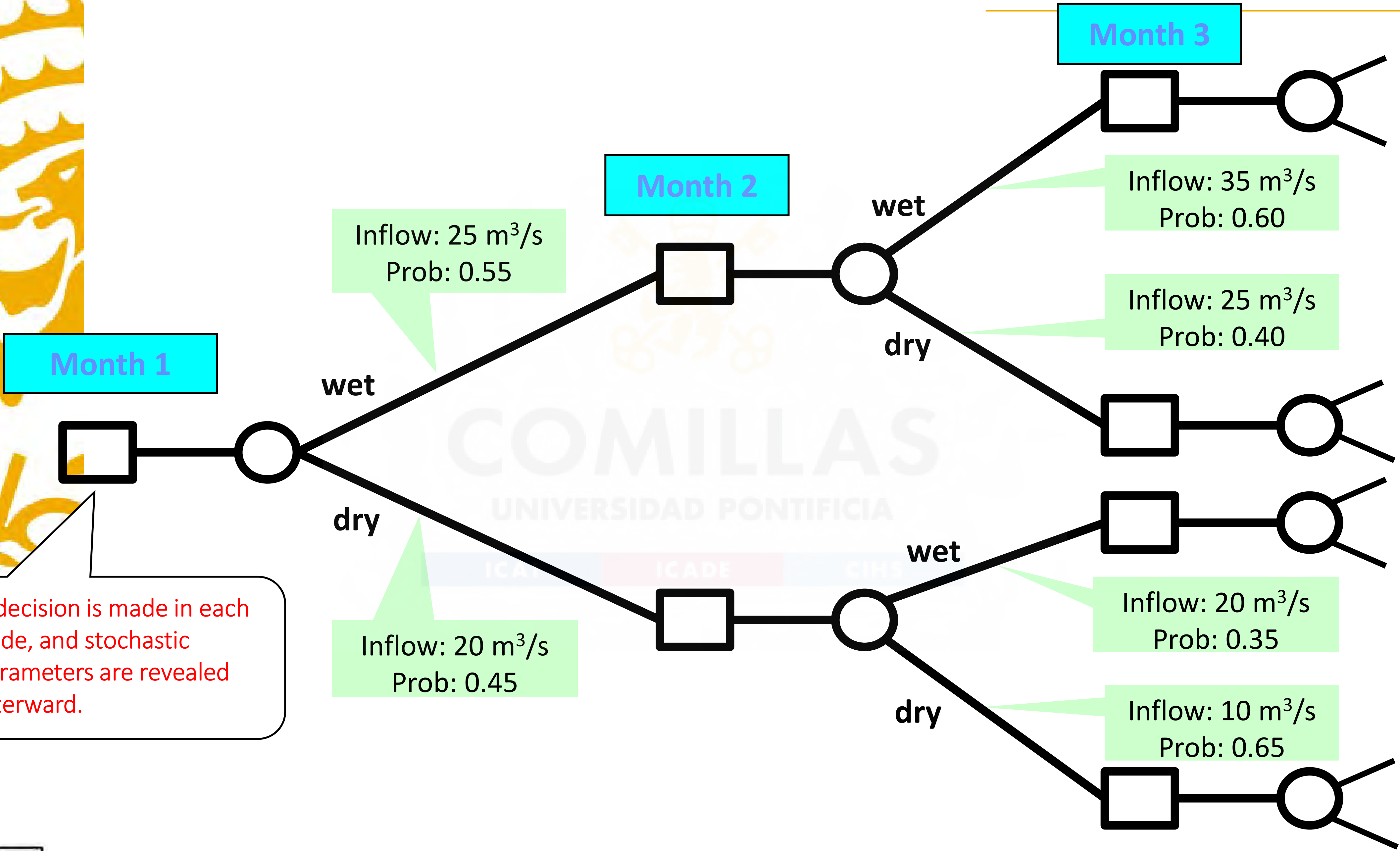
wet

Inflow: 20 m³/s
Prob: 0.35

dry

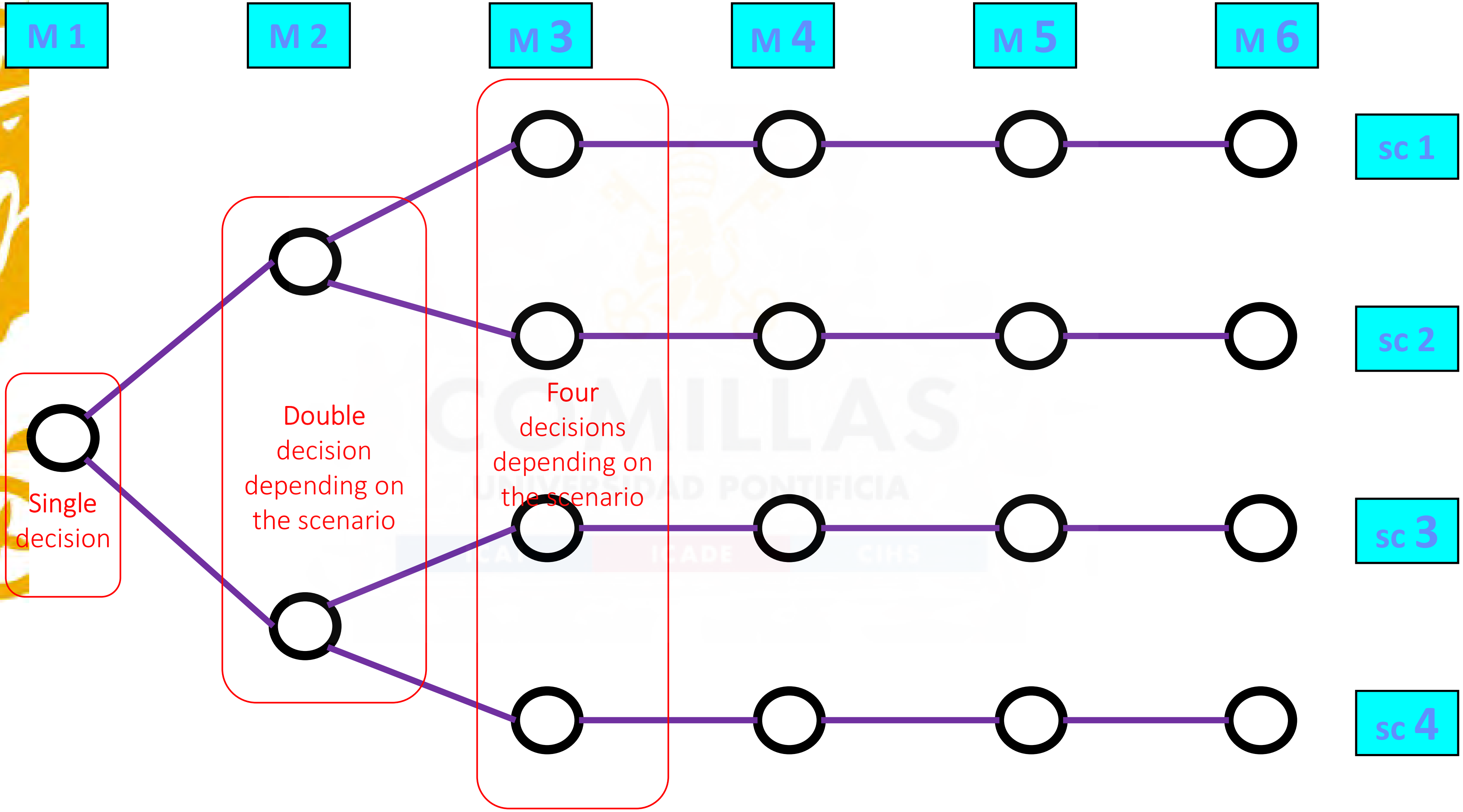
Inflow: 10 m³/s
Prob: 0.65

Decision tree for stochastic hydro scheduling



A decision is made in each node, and stochastic parameters are revealed afterward.

Scenario tree for 6 months



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

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

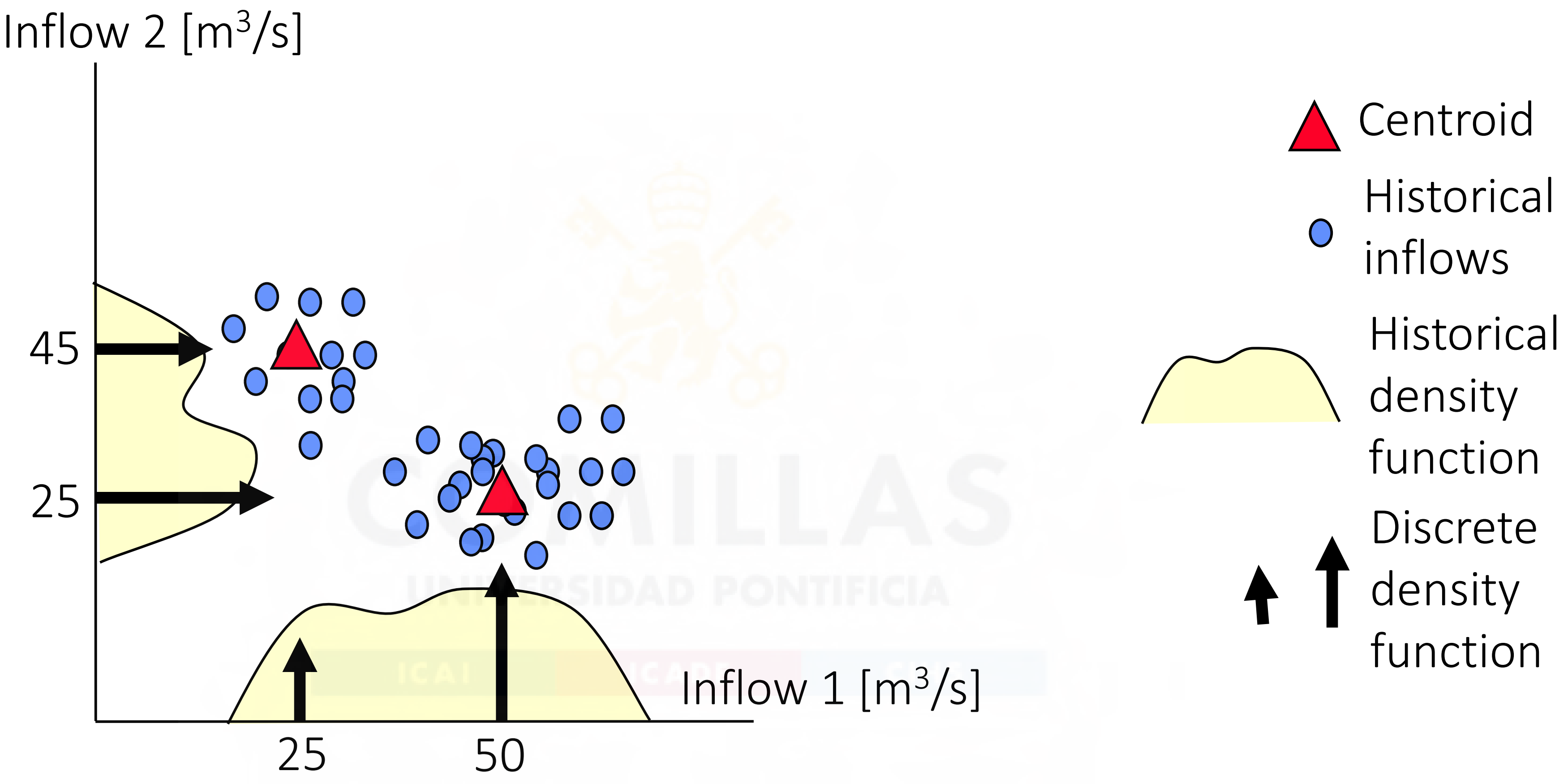
Scenario tree generation (i)

- Univariate series (one hydro inflow/reservoir)
  - Distance from the cluster centroid to each series from a period to the last one
- Multivariate series (several hydro inflows/reservoirs)
  - Distance from the multidimensional cluster centroid to each series of each variable from a period to the last one

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

Clustering in two dimensions



Centroids have the minimum distance to their corresponding points

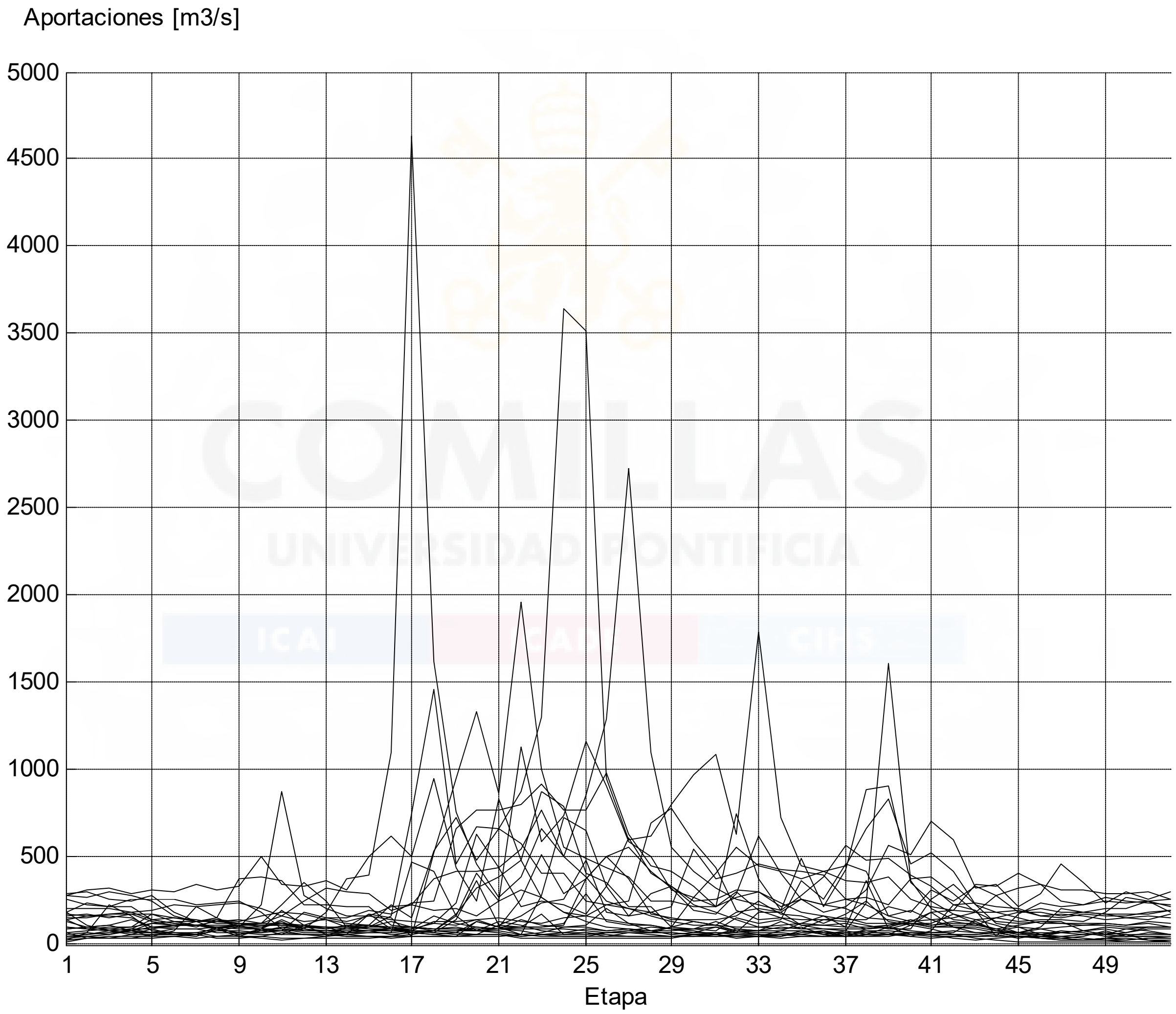
Their probability is proportional to the number of points represented by the centroid

Common approach for tree generation

- Process divided into two phases:
  - Generation of a scenario tree.
    Neural gas method.
  - Reduction of a scenario tree.
    Using probabilistic distances.

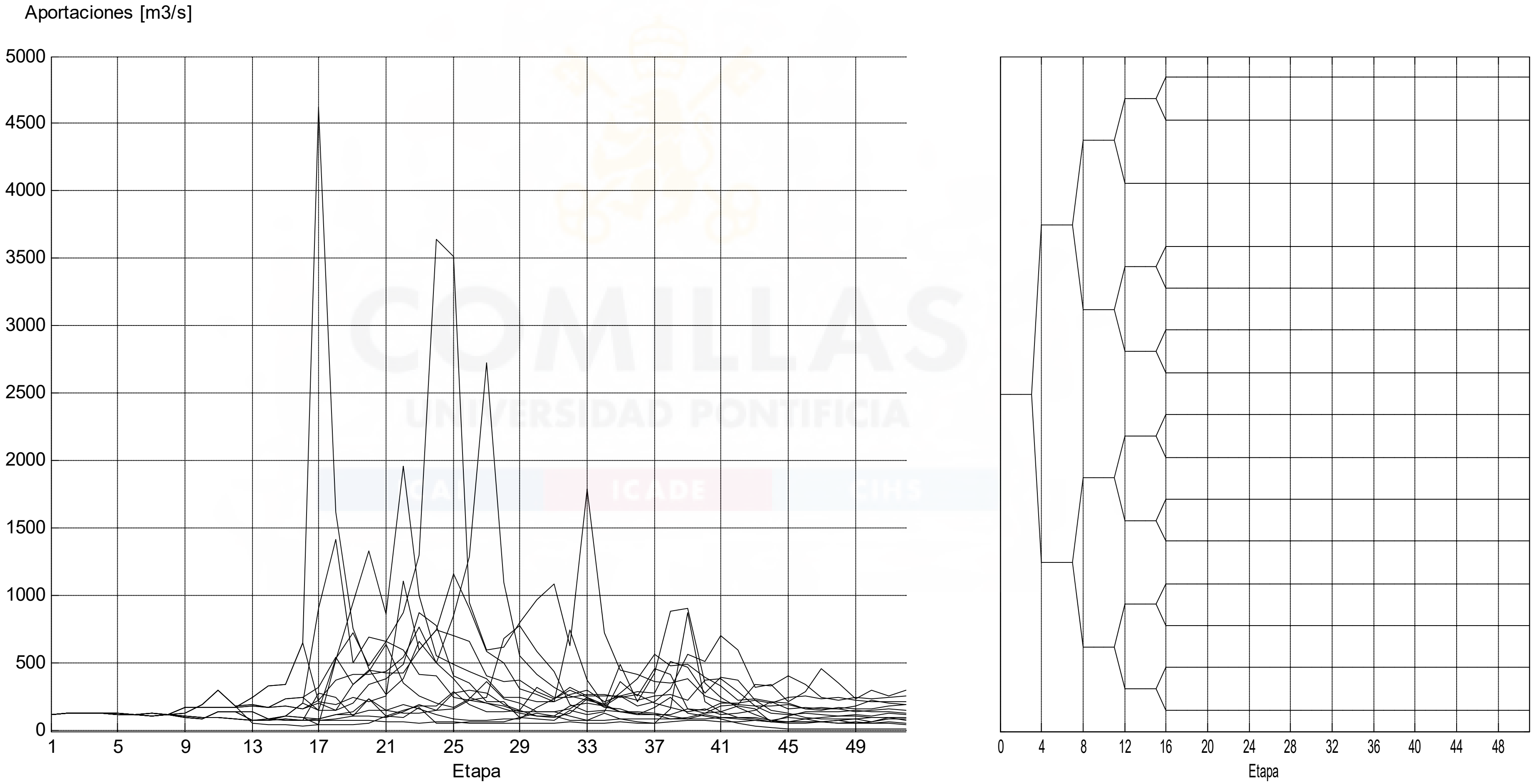
Natural hydro inflows (V)

- Data series for one hydro inflow:



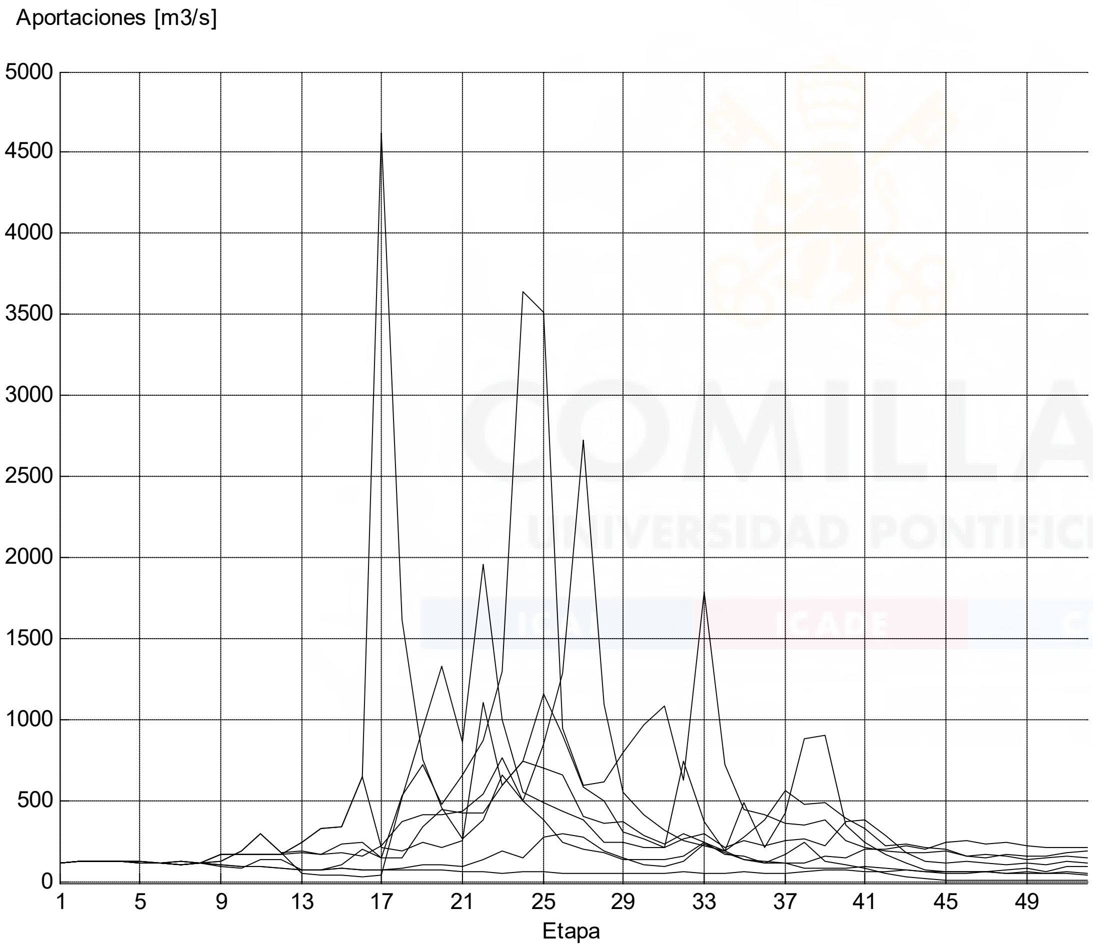
Natural hydro inflows (VI)

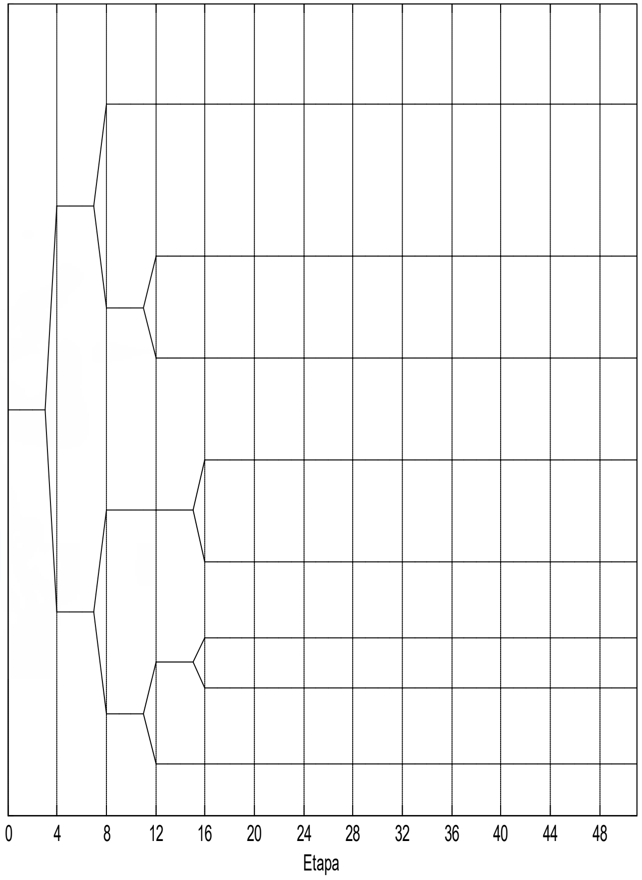
- Initial scenario tree (15 scenarios) for one hydro inflow



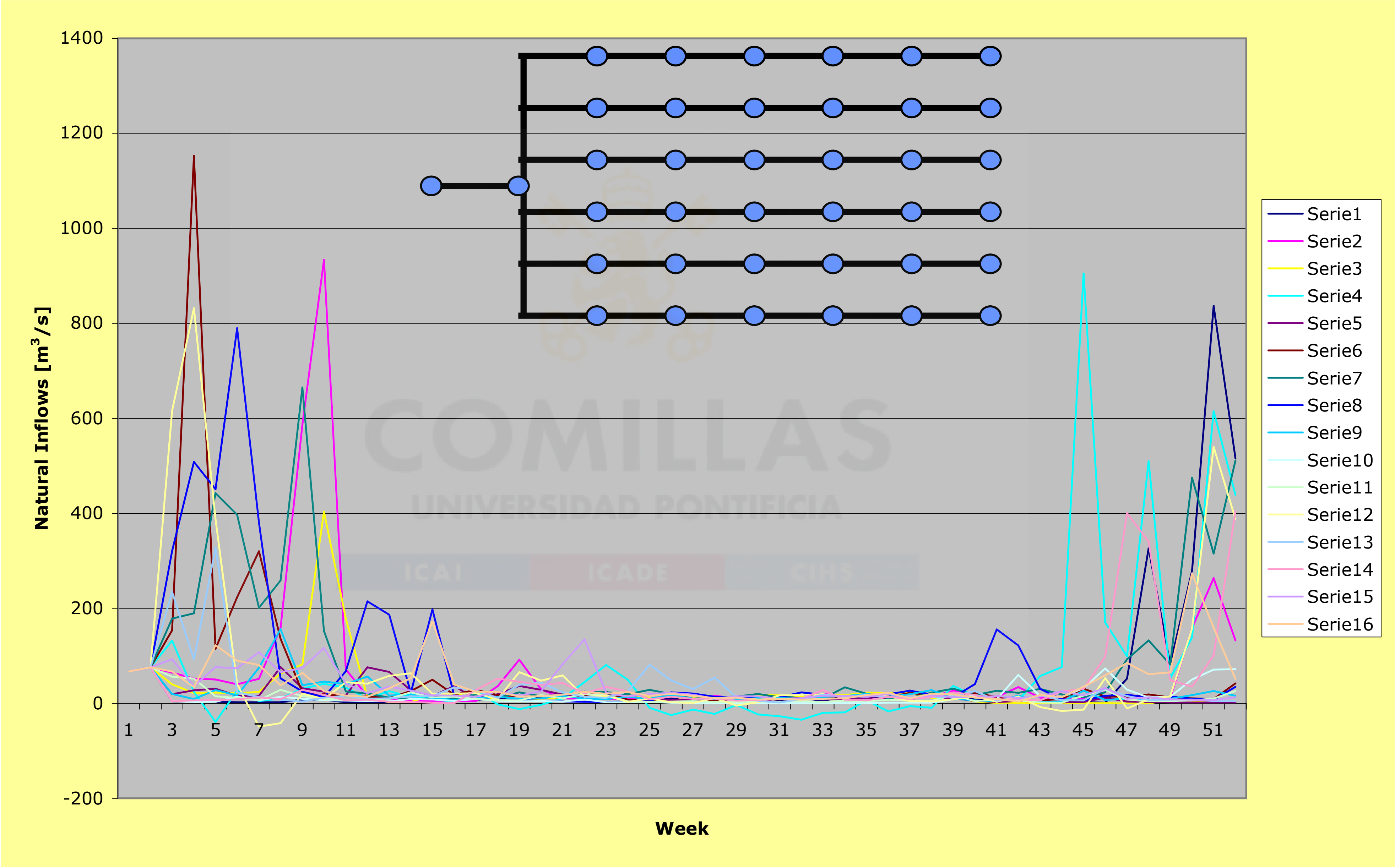
Natural hydro inflows (VII)

- Reduced scenario tree (8 scenarios) for one hydro inflow

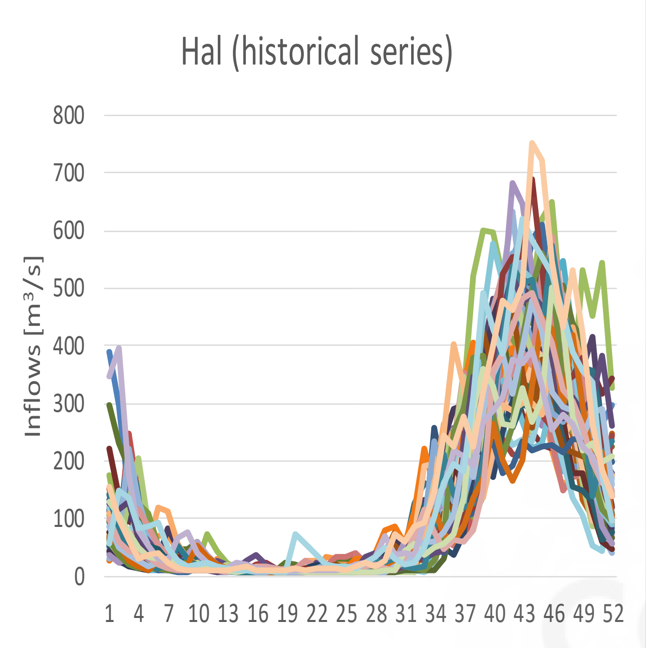


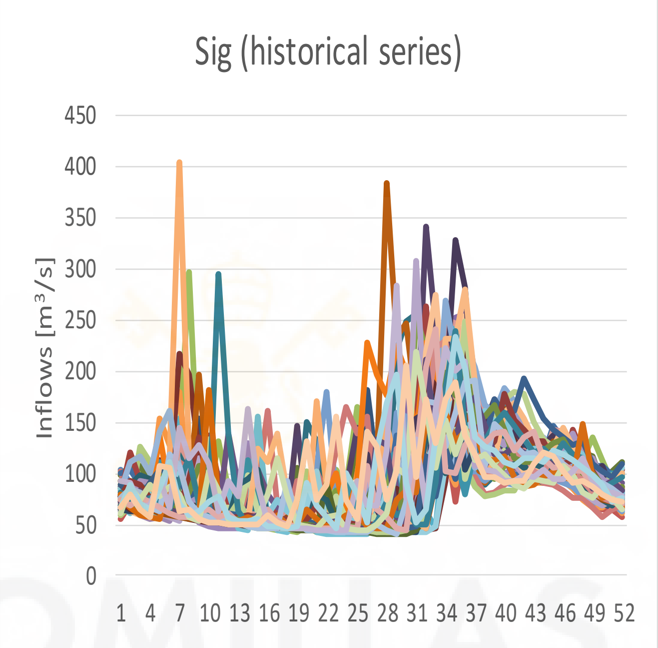


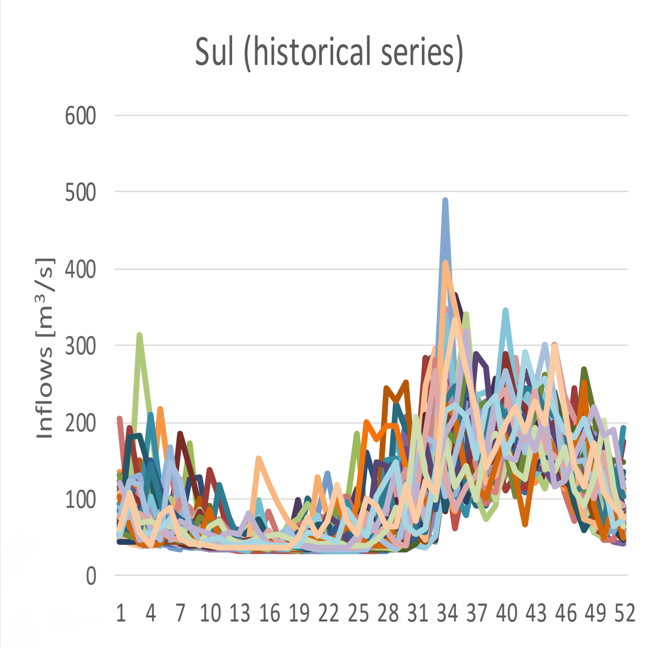
Natural hydro inflows: scenario tree

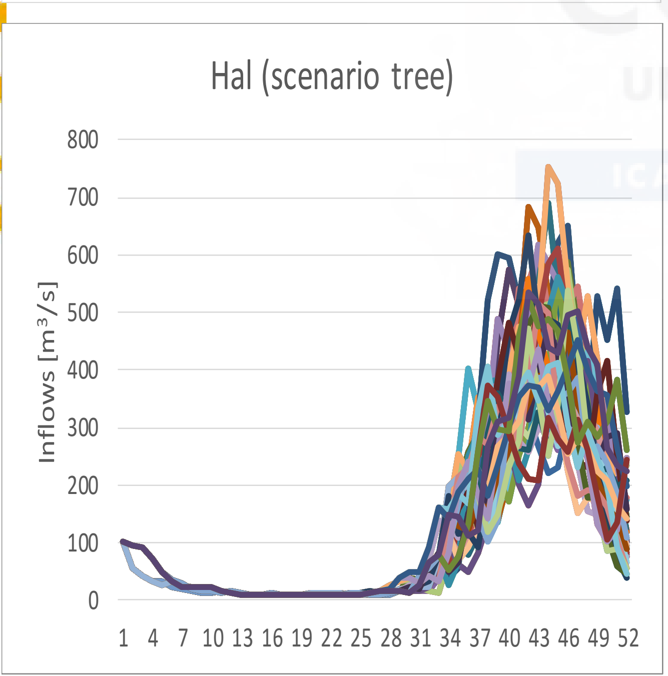


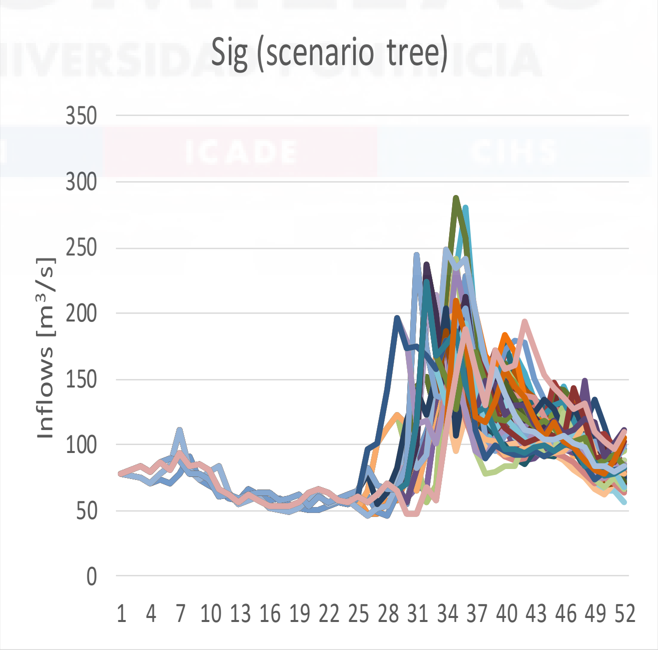
Historical hydro inflows and scenario trees in Iceland

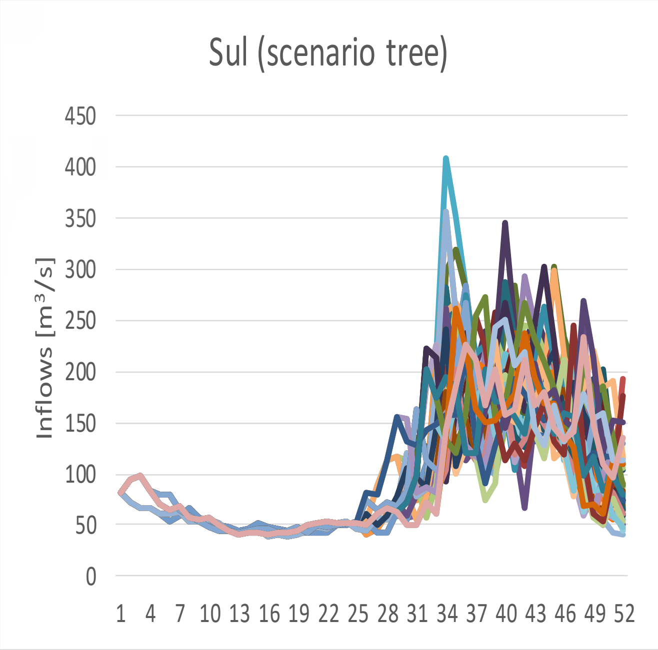

Hal (historical series)


Sig (historical series)


Sul (historical series)


Hal (scenario tree)


Sig (scenario tree)


Sul (scenario tree)

1. Medium term stochastic hydrothermal coordination model
2. Modeling issues
3. Stochastic optimization
4. **Prototype SHTCM. Mathematical formulation**
5. Prototype SHTCM. Computer implementation

4

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)

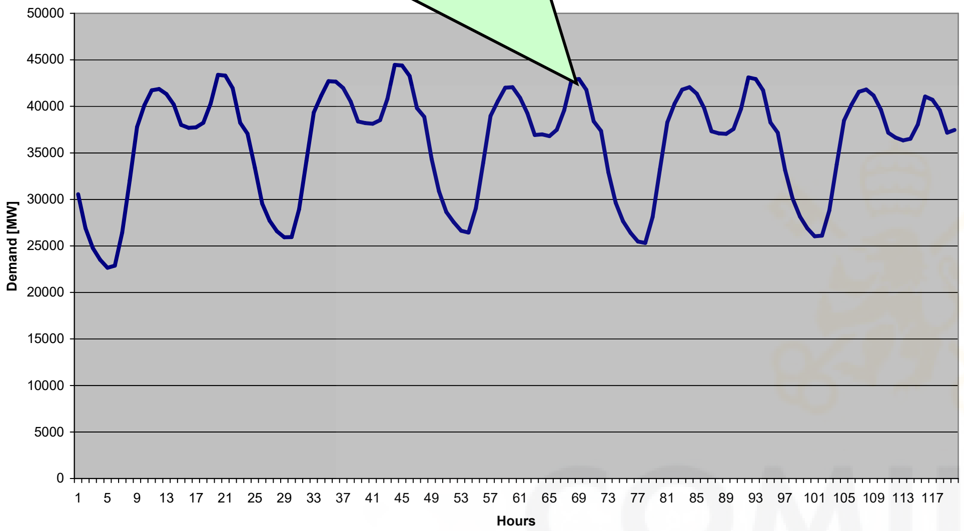
Indices

- Time scope
  - 1 year
- Period
  - 1 month
- Subperiod
  - weekdays and weekends
- Load level
  - peak, shoulder, and off-peak

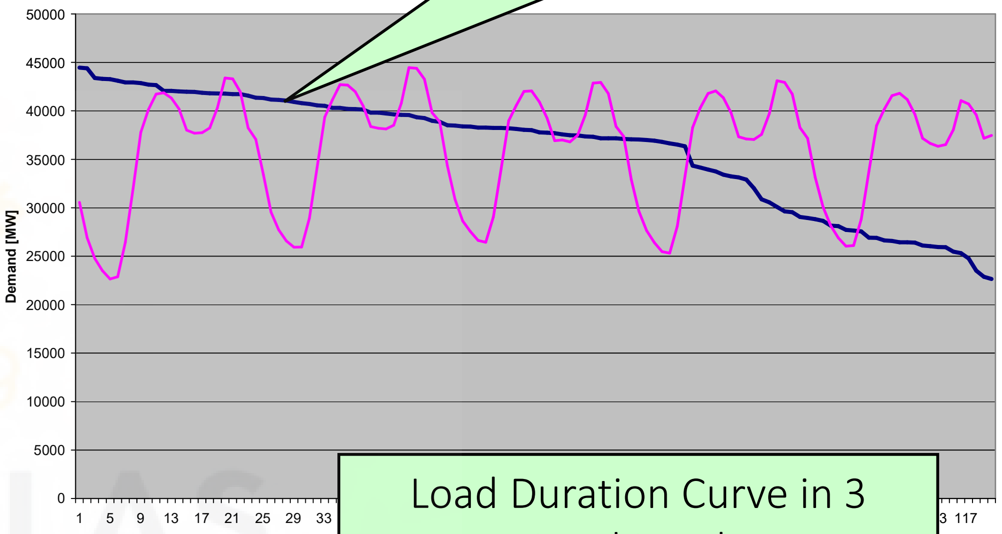
$Period$	p
$Subperiod$	s
$Load\ level$	n

Demand (5 weekdays)

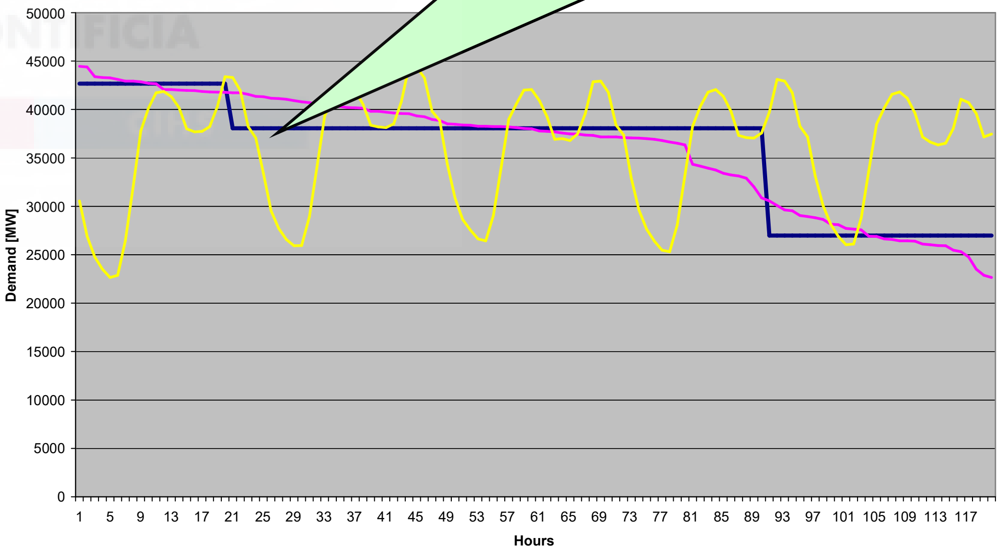
Chronological Load Curve



Load Duration Curve



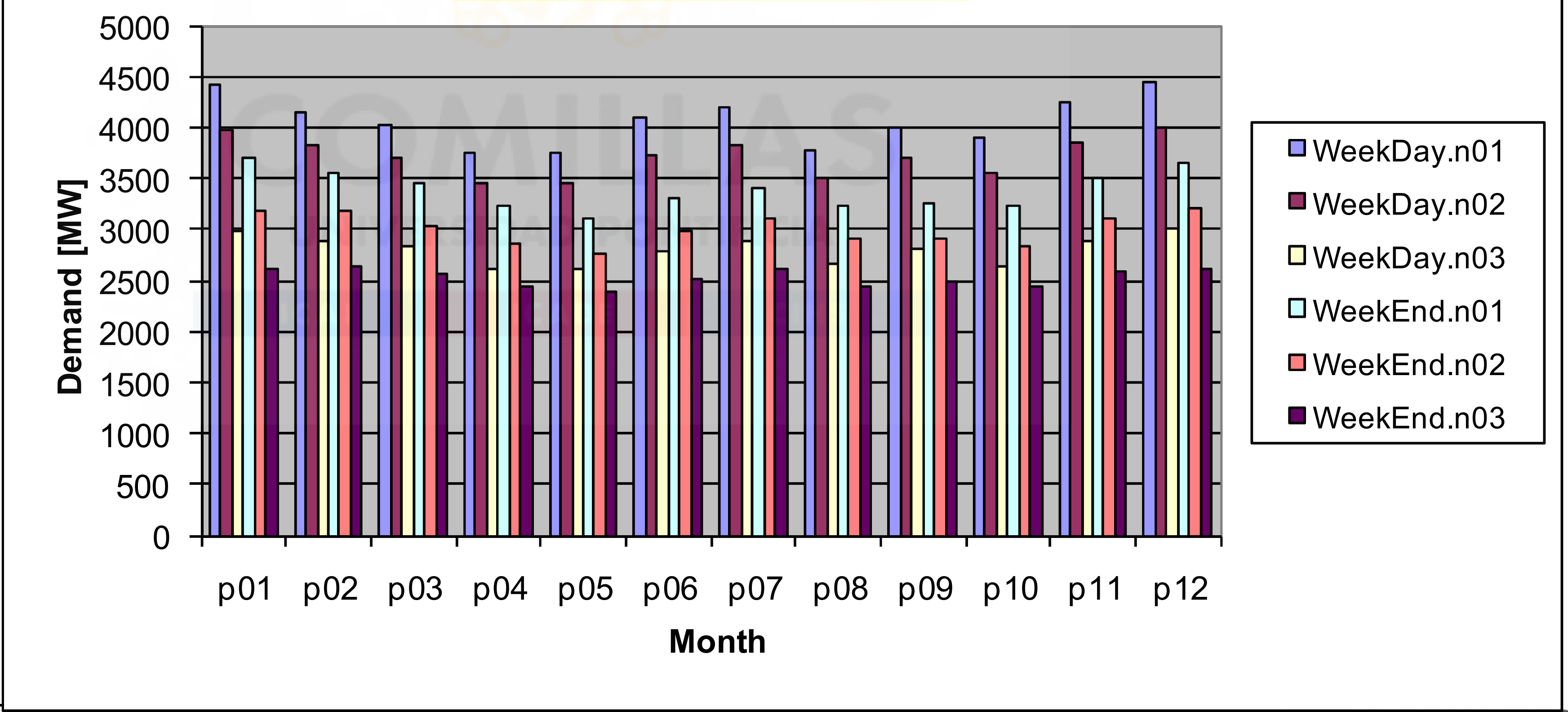
Load Duration Curve in 3 Load Levels



Demand

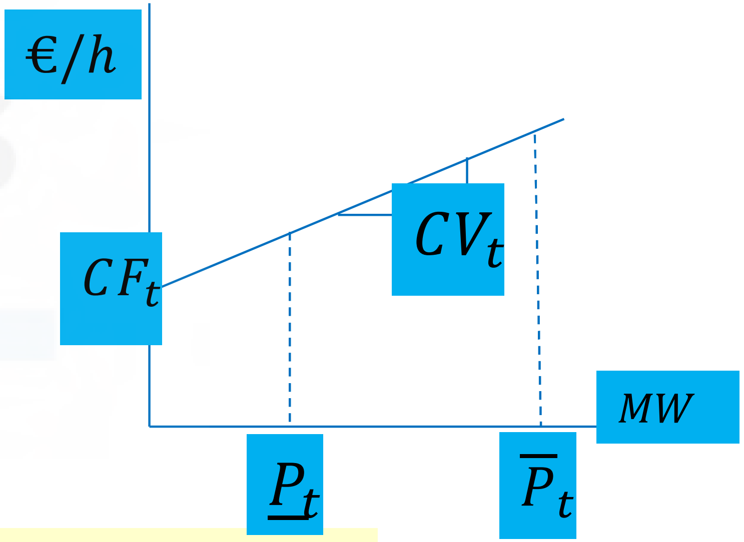
- Monthly demand with several load levels
  - Peak, shoulder, and off-peak for weekdays and weekends
- All the weekdays of the same month are similar (same for weekends)

$$\begin{array}{lll} \textit{Demand} & [MW] & D_{psn} \\ \textit{Duration} & [h] & d_{psn} \end{array}$$



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	[€/h]	CF_t
Variable cost	[€/MWh]	CV_t
Startup cost	[€]	CSU_t
Shutdown cost	[€]	CSD_t

Ramp up	[MW/h]	RU_t
Ramp down	[MW/h]	RD_t

Technical characteristics of hydro plants (h)

- Maximum and minimum output
- Production function (efficiency for conversion of water release in m^3/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

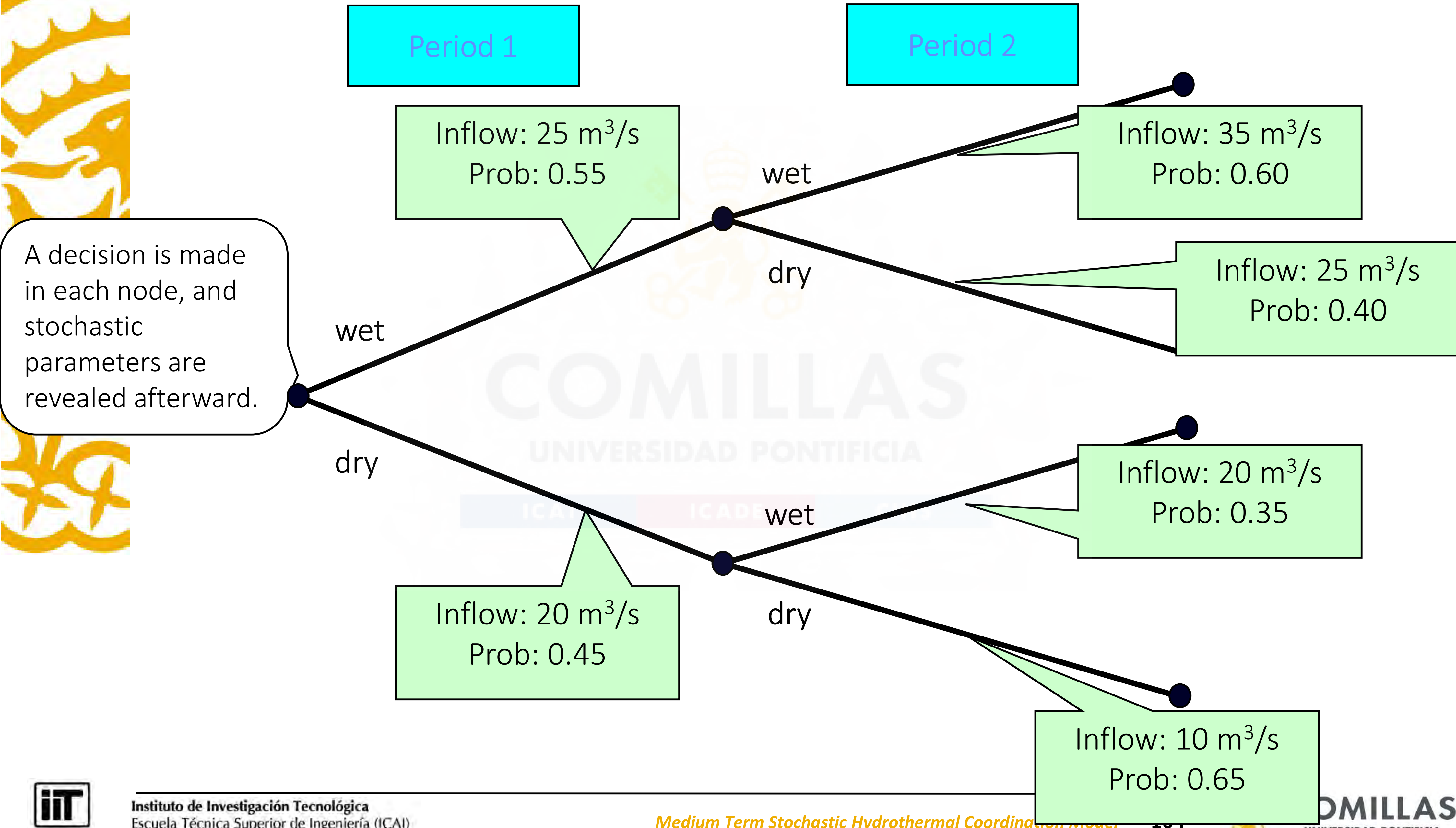
Max and min output	[MW]	$\overline{P}_h, \underline{P}_h$
Production function	[kWh/m^3]	C_h
Efficiency	[p.u.]	η_h

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	$[hm^3]$	$\overline{R}_r, \underline{R}_r$
Initial and final water reserve	$[hm^3]$	R'_r
Stochastic natural hydro inflows	$[m^3/s]$	I^{ω}_{pr}

Scenario tree example



Period 1

Period 2

A decision is made in each node, and stochastic parameters are revealed afterward.

wet

Inflow: 25 m^3/s
Prob: 0.55

dry

Inflow: 20 m^3/s
Prob: 0.45

wet

Inflow: 35 m^3/s
Prob: 0.60

dry

Inflow: 25 m^3/s
Prob: 0.40

wet

Inflow: 20 m^3/s
Prob: 0.35

dry

Inflow: 10 m^3/s
Prob: 0.65

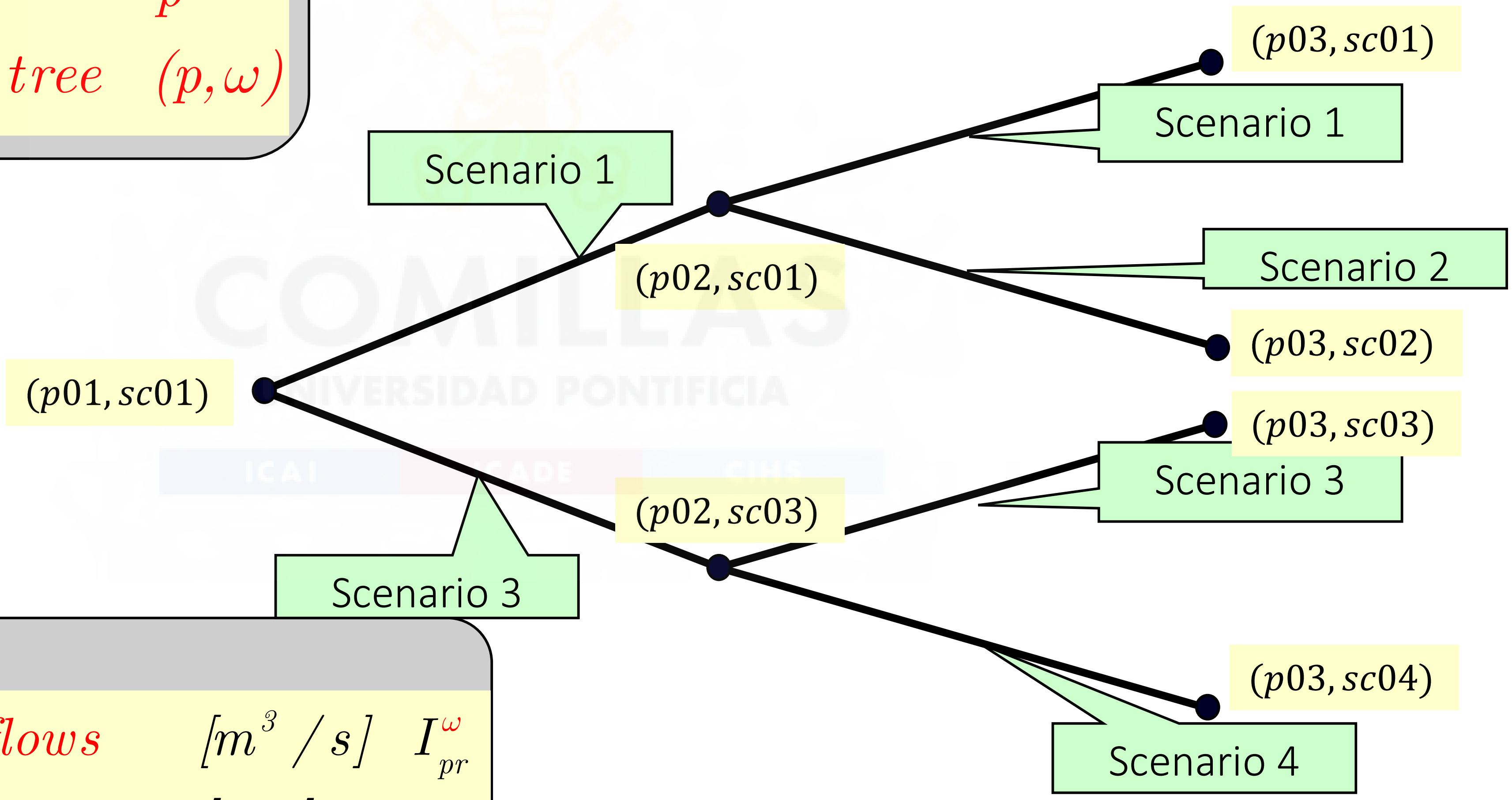
Scenario tree. Ancestor and descendant

Tree structure

Scenario	ω
Period	p
Scenario tree	(p,ω)

Tree relations

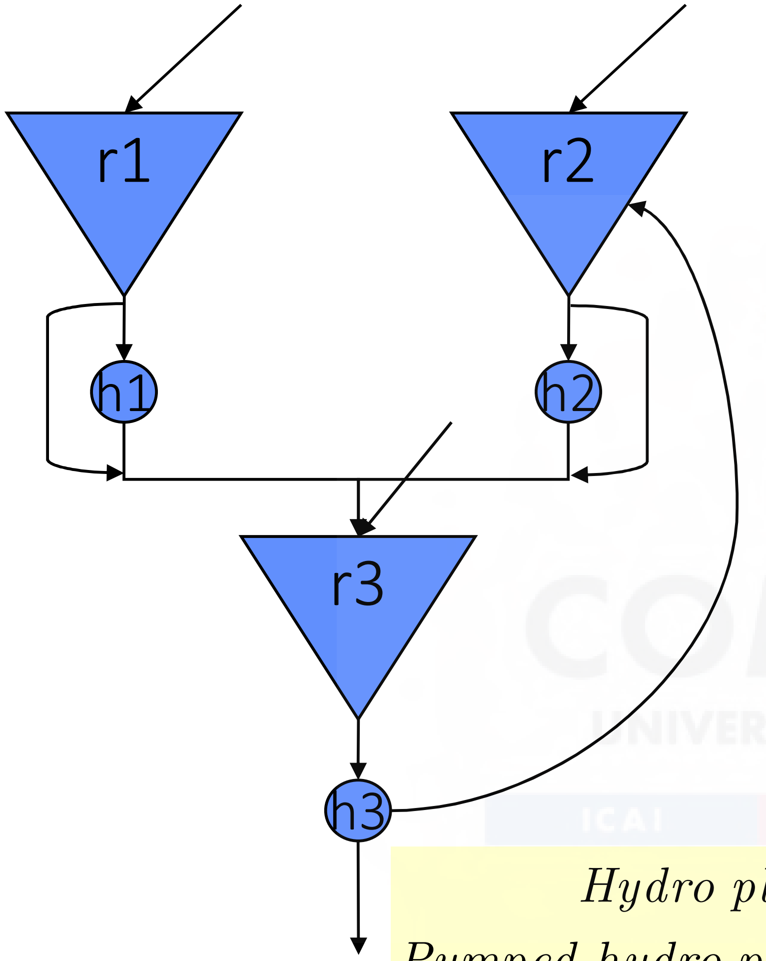
$\omega' \in a(\omega)$ $\quad (p02, sc03) \in a[(p03, sc03)]$



Tree data

Stochastic inflows	$[m^3/s]$	I_{pr}^{ω}
Scenario probability	$[p.u.]$	P_p^{ω}

Hydro topology



Only one spillage per reservoir can be considered

	Written in Math	Written in GAMS	Example
Hydro plant upstream of reservoir	$h \in up(r)$	$hur(h,r)$	$(h1,r3)$
Pumped hydro plant upstream of reservoir	$h \in up(r)$	$hpr(h,r)$	$(h3,r2)$
Reservoir upstream of hydro plant	$h \in dw(r)$	$ruh(r,h)$	$(r2,h2)$
Reservoir upstream of pumped hydro plant	$h \in dw(r)$	$rph(r,h)$	$(r3,h3)$
Reservoir upstream of reservoir	$r' \in up(r)$	$rur(r,r)$	$(r1,r3)$

Other system parameters

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

Energy not served cost	[€/MWh]	CV'
Operating power reserve not served cost	[€/MW]	CV''
Operating reserve	[MW]	O_{ps1}

Variables

- Commitment, startup, and shutdown of thermal units (BINARY)

$$Commitment,\ startup\ and\ shutdown\quad \{0,1\}\quad uc_{pst}^{\omega}, su_{pst}^{\omega}, sd_{pst}^{\omega}$$

- Production of thermal units and hydro plants

$$Production\ of\ a\ thermal\ or\ hydro\ unit\quad [MW]\quad p_{psnt}^{\omega}, p_{psnh}^{\omega}$$

- Consumption of pumped storage hydro plants

$$Consumption\ of\ a\ hydro\ plant\quad [MW]\quad c_{psnh}^{\omega}$$

- Reservoir levels (at the beginning of the period)

$$Reservoir\ level\quad [hm^{3}]\quad r_{pr}^{\omega}$$

- Energy and power not served

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

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]*

$$\sum_t \bar{P}_t uc^{\omega}_{pst} + \sum_h \bar{P}_h + pns^{\omega}_{ps} \geq D_{ps1} + O_{ps1} \quad \forall \omega ps$$

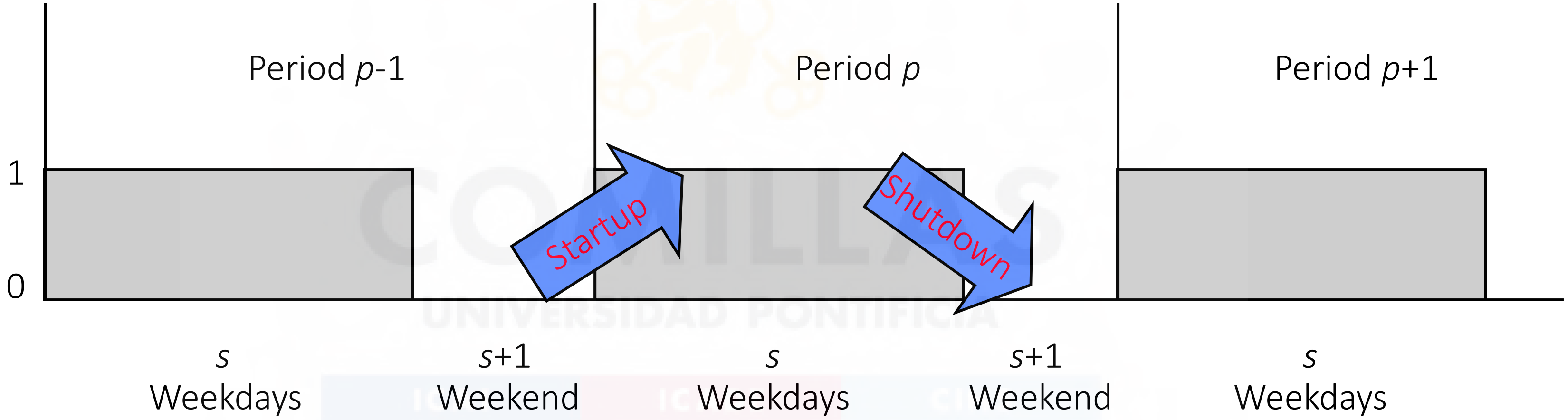
Constraints: Generation and load balance

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*]

$$\sum_t p^{\omega}_{psnt} + \sum_h p^{\omega}_{psnh} - \sum_h c^{\omega}_{psnh} + ens^{\omega}_{psn} = D_{psn} \quad \forall \omega psn$$

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 [p.u.]

$$uc^{\omega}_{pst} - uc^{\omega'}_{p-1s+} = su^{\omega}_{pst} - sd^{\omega}_{pst} \quad \forall \omega pst \quad \omega' \in a(\omega)$$

- 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.]

$$uc^{\omega}_{ps+1t} - uc^{\omega}_{pst} = su^{\omega}_{ps+1} - sd^{\omega}_{ps+1} \quad \forall \omega pst$$

Constraints: Commitment and production

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

Production of a thermal unit
≥ *Commitment of a thermal unit* x *the minimum output*
reduced by availability rate [*MW*]

$$uc^{\omega}_{pst}\underline{P}_t(1-Q_t) \le p^{\omega}_{psnt} \le uc^{\omega}_{pst}\bar{P}_t(1-Q_t) \quad \forall \omega psnt$$

- If the thermal unit is committed ($uc^{\omega}_{pst} = 1$) it can produce between its minimum and maximum output
- If the thermal unit is not committed ($uc^{\omega}_{pst} = 0$) 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* [*hm*^{3}]

$$r_{p-1r}^{\omega'} - r_{pr}^{\omega} + I_{pr}^{\omega} - s_{pr}^{\omega} + \sum_{r'\in up(r)} s_{pr'}^{\omega}$$

$$+ \sum_{\substack{sn \\ h\in up(r)}} d_{psn} p_{psnh}^{\omega} / C_h - \sum_{\substack{sn \\ h\in dw(r)}} d_{psn} p_{psnh}^{\omega} / C_h$$

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

Constraints: Operation limits

Reservoir volumes between limits for each hydro reservoir [*hm*³]

$$\underline{R}_r \le r^{\omega}_{pr} \le \bar{R}_r \qquad \forall \omega pr$$

$$R_{0r} = R^{\omega}_{Pr} = R'_r \qquad \forall \omega r$$

Power output between limits for each unit [*MW*]

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

$$0 \le p^{\omega}_{psnh}, c^{\omega}_{psnh} \le \bar{P}_h \quad \forall \omega psnh$$

Commitment, startup, and shutdown for each unit [*p.u.*]

$$uc^{\omega}_{pst}, su^{\omega}_{pst}, sd^{\omega}_{pst} \in \{0,1\} \quad \forall \omega pst$$

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 [*€/MW*]
  - Change in the objective function due to a marginal increment in the demand when binary variables (commitment, startup, and shutdown) are fixed

$$\sum_t p^{\omega}_{psnt} + \sum_h p^{\omega}_{psnh} - \sum_h c^{\omega}_{psnh} + ens^{\omega}_{psn} = D_{psn} \quad : \sigma^{\omega}_{psn} \quad \forall \omega psn$$

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

$$SRMC^{\omega}_{psn} = \sigma^{\omega}_{psn} / d_{psn} / P^{\omega}_{p} \quad \forall \omega psn$$

Water value

- Dual variable of water balance for each reservoir [*€/hm*^{3}]
  - Change in the objective function due to a marginal increment in the reservoir inflow

$$
\begin{aligned}
&r^{\omega'}_{p-1r} - r^{\omega}_{pr} + I^{\omega}_{pr} - s^{\omega}_{pr} + \sum_{r' \in up(r)} s^{\omega}_{pr'} \\
&+ \sum_{\substack{sn \\ h \in up(r)}} d_{psn} p^{\omega}_{psnh} / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} p^{\omega}_{psnh} / C_h \\
&+ \sum_{\substack{sn \\ h \in up(r)}} d_{psn} c^{\omega}_{psnh} \eta_h / C_h - \sum_{\substack{sn \\ h \in dw(r)}} d_{psn} c^{\omega}_{psnh} \eta_h / C_h = 0 \quad : \pi^{\omega}_{pr} \quad \forall \omega pr \quad \omega' \in a(\omega)
\end{aligned}
$$

- Turbining water has no variable cost. However, an additional hm^3 turbined allows to substitute energy produced by thermal units with the corresponding variable cost (this is called water value)

1. Medium term stochastic hydrothermal coordination model
2. Modeling issues
3. Stochastic optimization
4. Prototype SHTCM. Mathematical formulation
5. **Prototype SHTCM. Computer implementation**

5

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
  - 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

Run

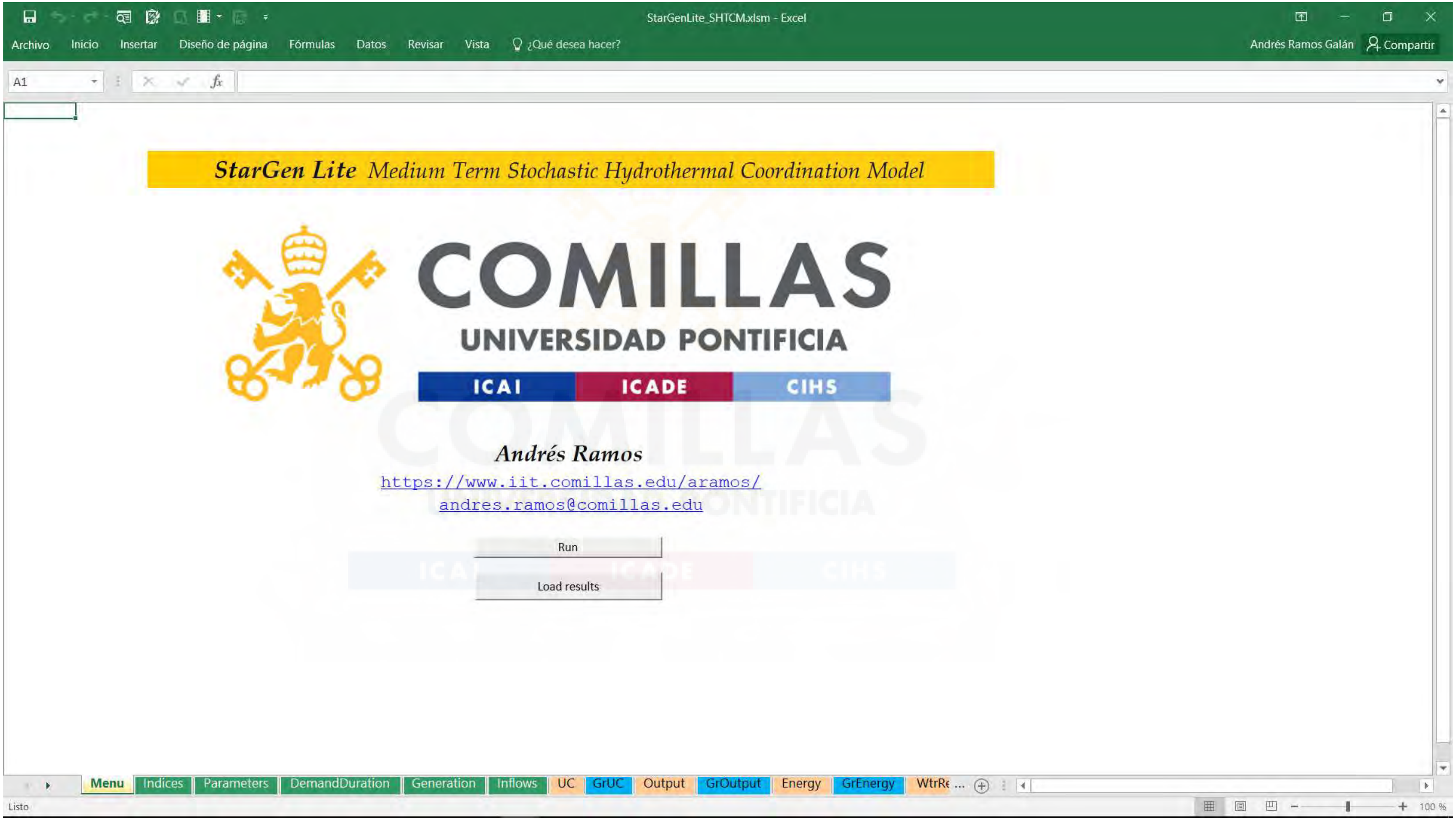
Load results

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

- 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

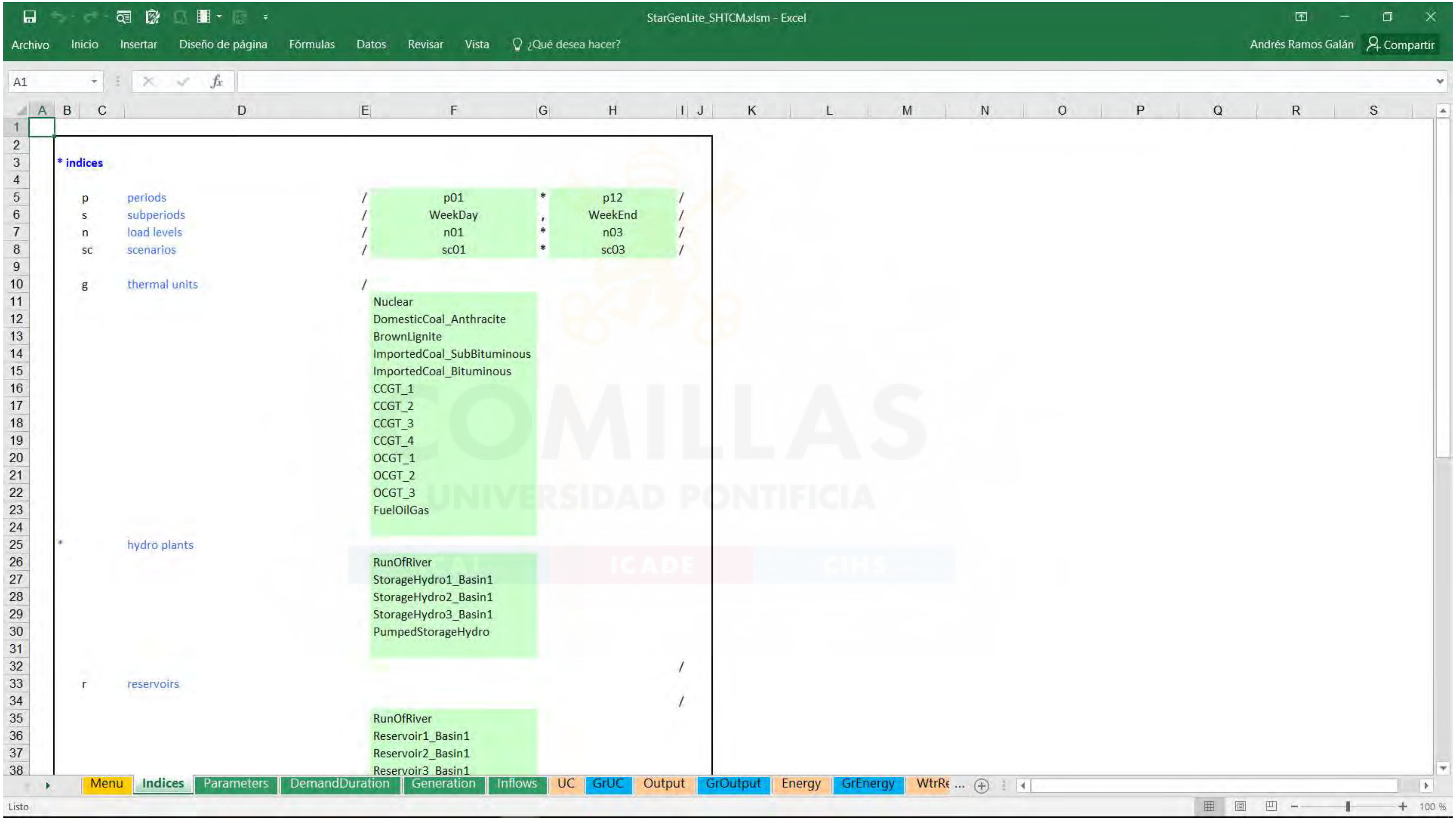
Menu



StarGen Lite *Medium Term Stochastic Hydrothermal Coordination Model*

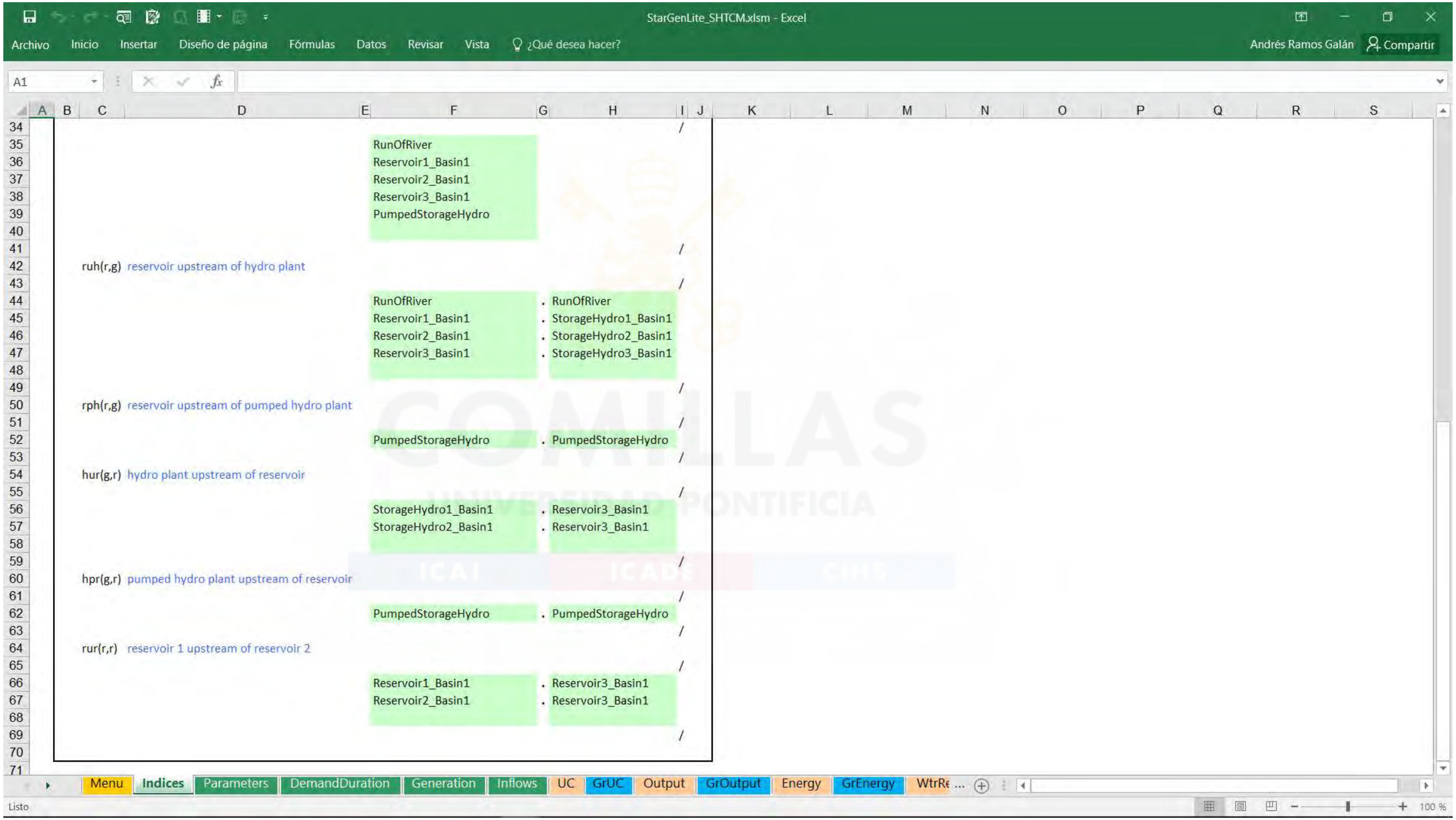
Andrés Ramos
https://www.iit.comillas.edu/aramos/
andres.ramos@comillas.edu

Input Data. Indices (i)



* indices						
p	periods	/	p01	*	p12	/
s	subperiods	/	WeekDay	,	WeekEnd	/
n	load levels	/	n01	*	n03	/
sc	scenarios	/	sc01	*	sc03	/
g	thermal units	/				
			Nuclear			
			DomesticCoal_Anthracite			
			BrownLignite			
			ImportedCoal_SubBituminous			
			ImportedCoal_Bituminous			
			CCGT_1			
			CCGT_2			
			CCGT_3			
			CCGT_4			
			OCGT_1			
			OCGT_2			
			OCGT_3			
			FuelOilGas			
*	hydro plants					
			RunOfRiver			
			StorageHydro1_Basin1			
			StorageHydro2_Basin1			
			StorageHydro3_Basin1			
			PumpedStorageHydro			
						/
r	reservoirs					
						/
			RunOfRiver			
			Reservoir1_Basin1			
			Reservoir2_Basin1			
			Reservoir3_Basin1			

Input Data. Indices (ii)



/

RunOfRiver
Reservoir1_Basin1
Reservoir2_Basin1
Reservoir3_Basin1
PumpedStorageHydro

/

ruh(r,g) reservoir upstream of hydro plant

/

RunOfRiver . RunOfRiver
Reservoir1_Basin1 . StorageHydro1_Basin1
Reservoir2_Basin1 . StorageHydro2_Basin1
Reservoir3_Basin1 . StorageHydro3_Basin1

/

rph(r,g) reservoir upstream of pumped hydro plant

/

PumpedStorageHydro . PumpedStorageHydro

/

hur(g,r) hydro plant upstream of reservoir

/

StorageHydro1_Basin1 . Reservoir3_Basin1
StorageHydro2_Basin1 . Reservoir3_Basin1

/

hpr(g,r) pumped hydro plant upstream of reservoir

/

PumpedStorageHydro . PumpedStorageHydro

/

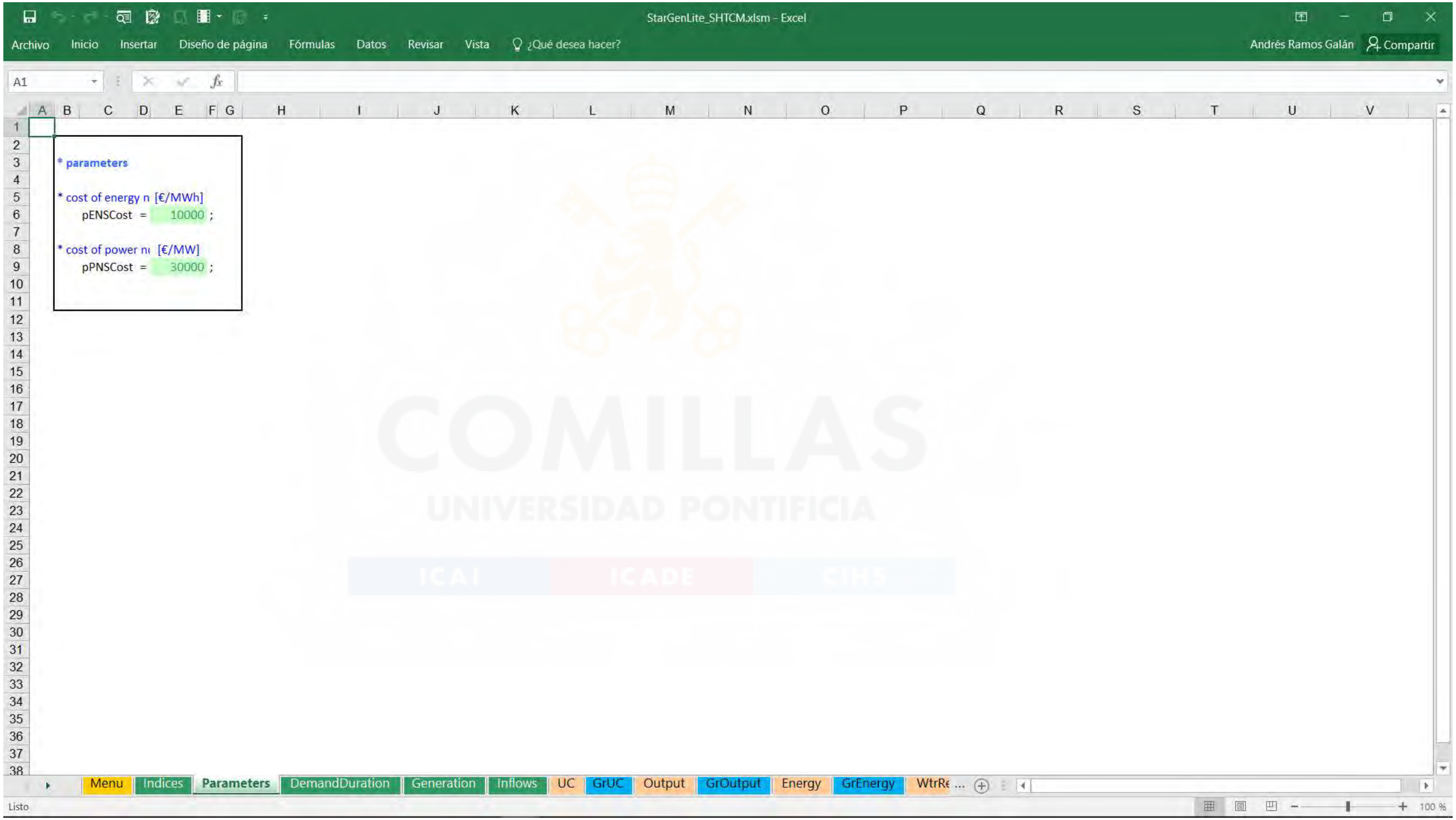
rur(r,r) reservoir 1 upstream of reservoir 2

/

Reservoir1_Basin1 . Reservoir3_Basin1
Reservoir2_Basin1 . Reservoir3_Basin1

/

Input Data. Cost of energy and power not served

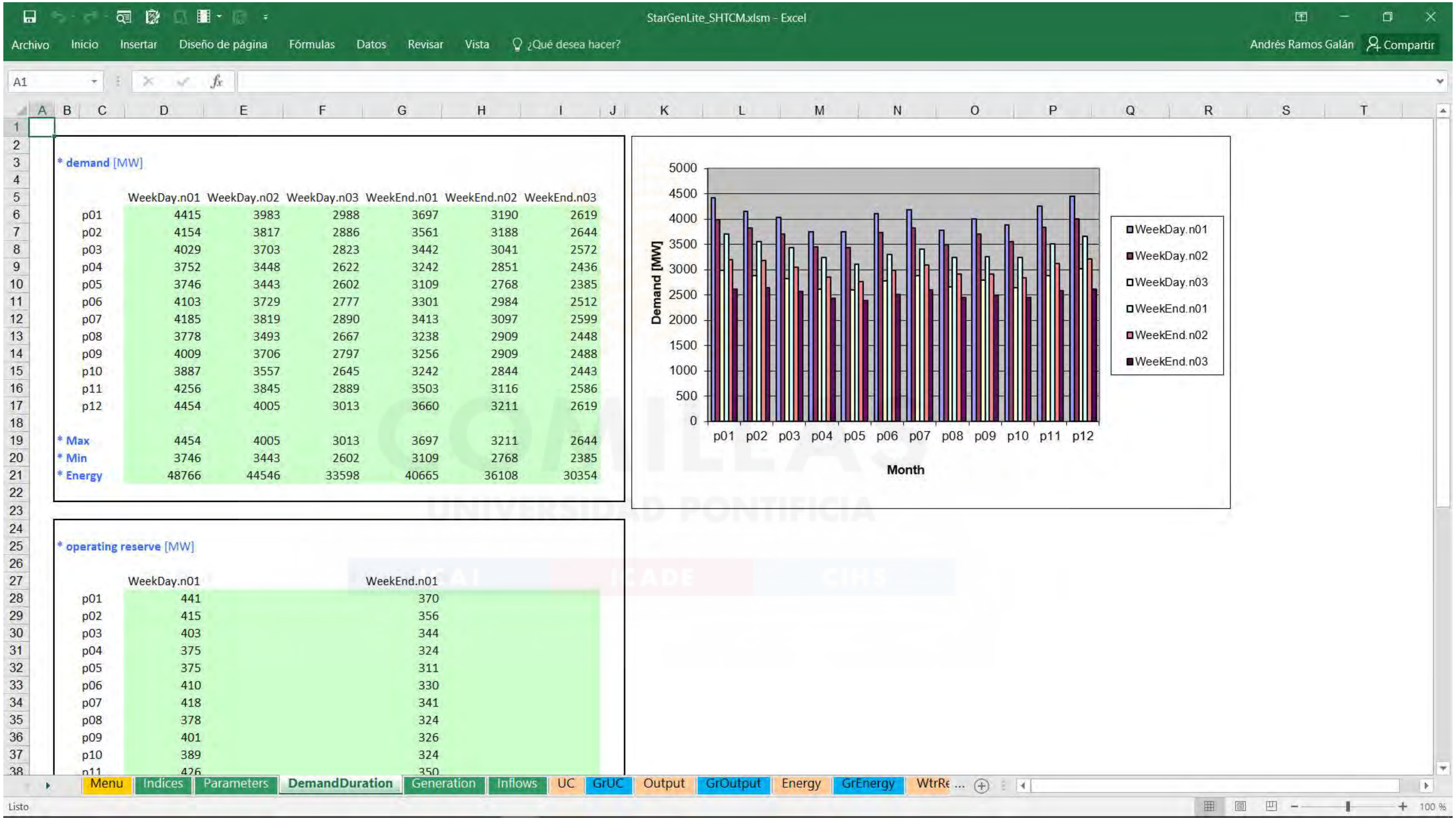


* parameters

* cost of energy n [€/MWh]
pENSCost = 10000 ;

* cost of power n [€/MW]
pPNSCost = 30000 ;

Input Data. Demand, operating reserve and duration



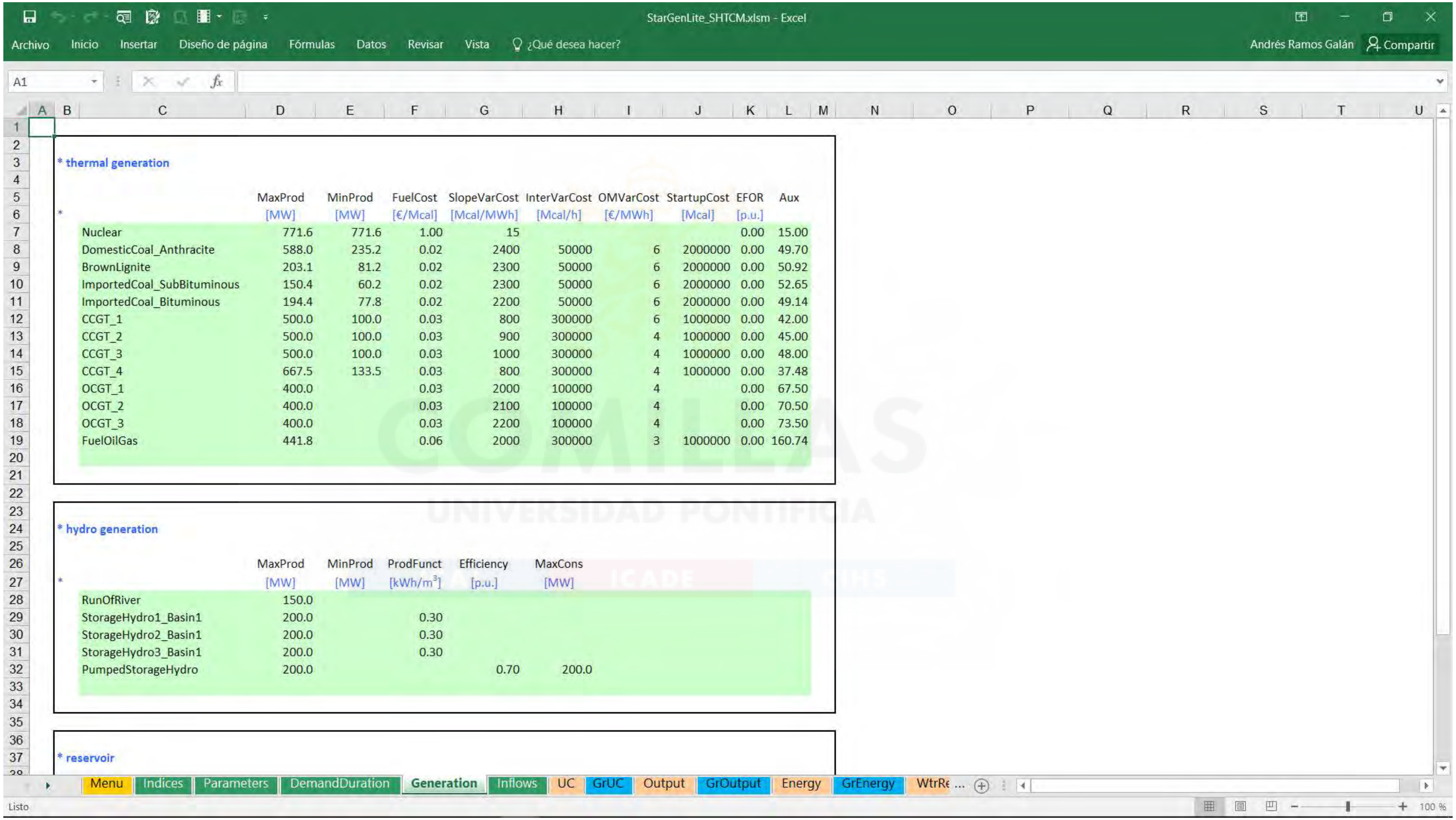
* **demand** [MW]

	WeekDay.n01	WeekDay.n02	WeekDay.n03	WeekEnd.n01	WeekEnd.n02	WeekEnd.n03
p01	4415	3983	2988	3697	3190	2619
p02	4154	3817	2886	3561	3188	2644
p03	4029	3703	2823	3442	3041	2572
p04	3752	3448	2622	3242	2851	2436
p05	3746	3443	2602	3109	2768	2385
p06	4103	3729	2777	3301	2984	2512
p07	4185	3819	2890	3413	3097	2599
p08	3778	3493	2667	3238	2909	2448
p09	4009	3706	2797	3256	2909	2488
p10	3887	3557	2645	3242	2844	2443
p11	4256	3845	2889	3503	3116	2586
p12	4454	4005	3013	3660	3211	2619
* **Max**	4454	4005	3013	3697	3211	2644
* **Min**	3746	3443	2602	3109	2768	2385
* **Energy**	48766	44546	33598	40665	36108	30354

* **operating reserve** [MW]

	WeekDay.n01	WeekEnd.n01
p01	441	370
p02	415	356
p03	403	344
p04	375	324
p05	375	311
p06	410	330
p07	418	341
p08	378	324
p09	401	326
p10	389	324
p11	426	350

Input Data. Hydro and thermal parameters



* thermal generation

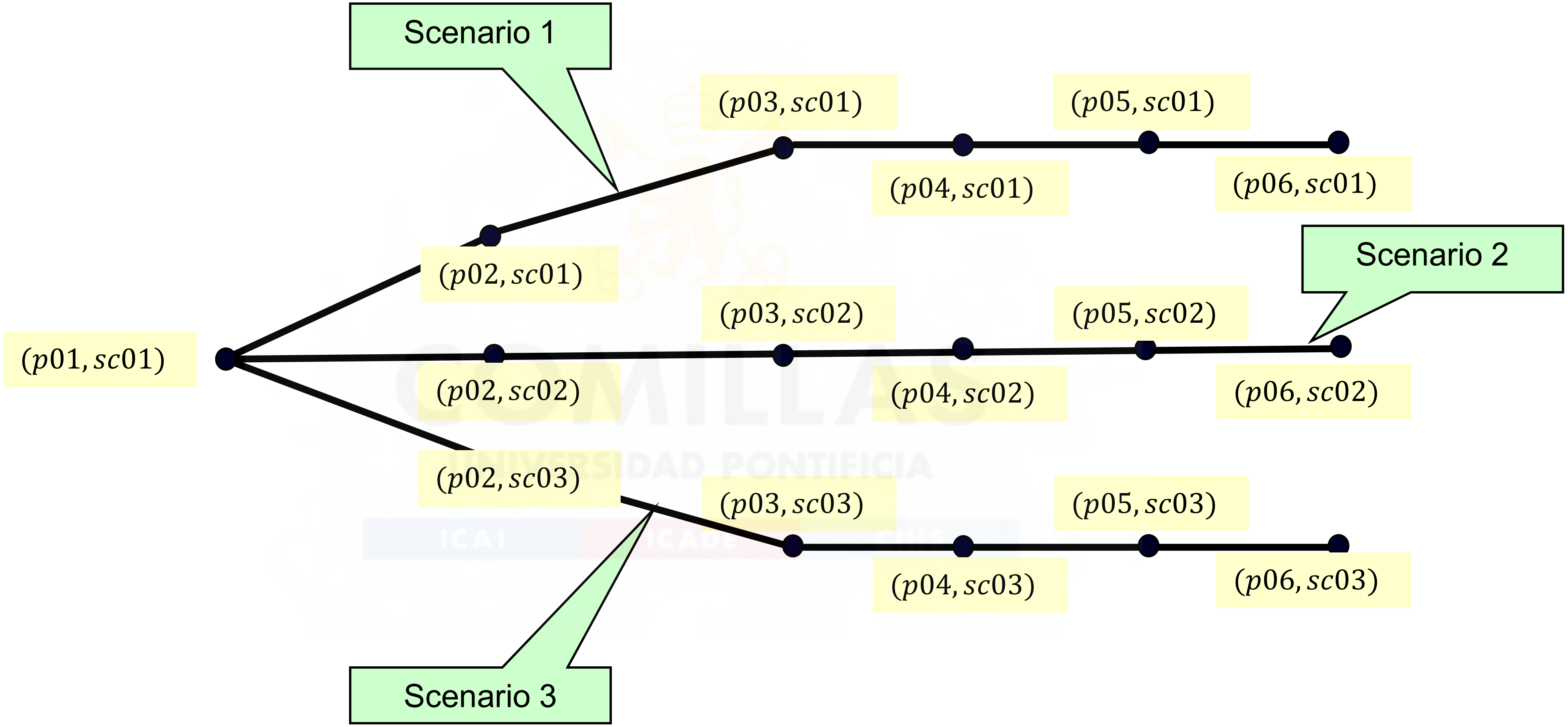
*	MaxProd [MW]	MinProd [MW]	FuelCost [€/Mcal]	SlopeVarCost [Mcal/MWh]	InterVarCost [Mcal/h]	OMVarCost [€/MWh]	StartupCost [Mcal]	EFOR [p.u.]	Aux
Nuclear	771.6	771.6	1.00	15				0.00	15.00
DomesticCoal_Anthracite	588.0	235.2	0.02	2400	50000	6	2000000	0.00	49.70
BrownLignite	203.1	81.2	0.02	2300	50000	6	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	77.8	0.02	2200	50000	6	2000000	0.00	49.14
CCGT_1	500.0	100.0	0.03	800	300000	6	1000000	0.00	42.00
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		0.00	73.50
FuelOilGas	441.8		0.06	2000	300000	3	1000000	0.00	160.74

* hydro generation

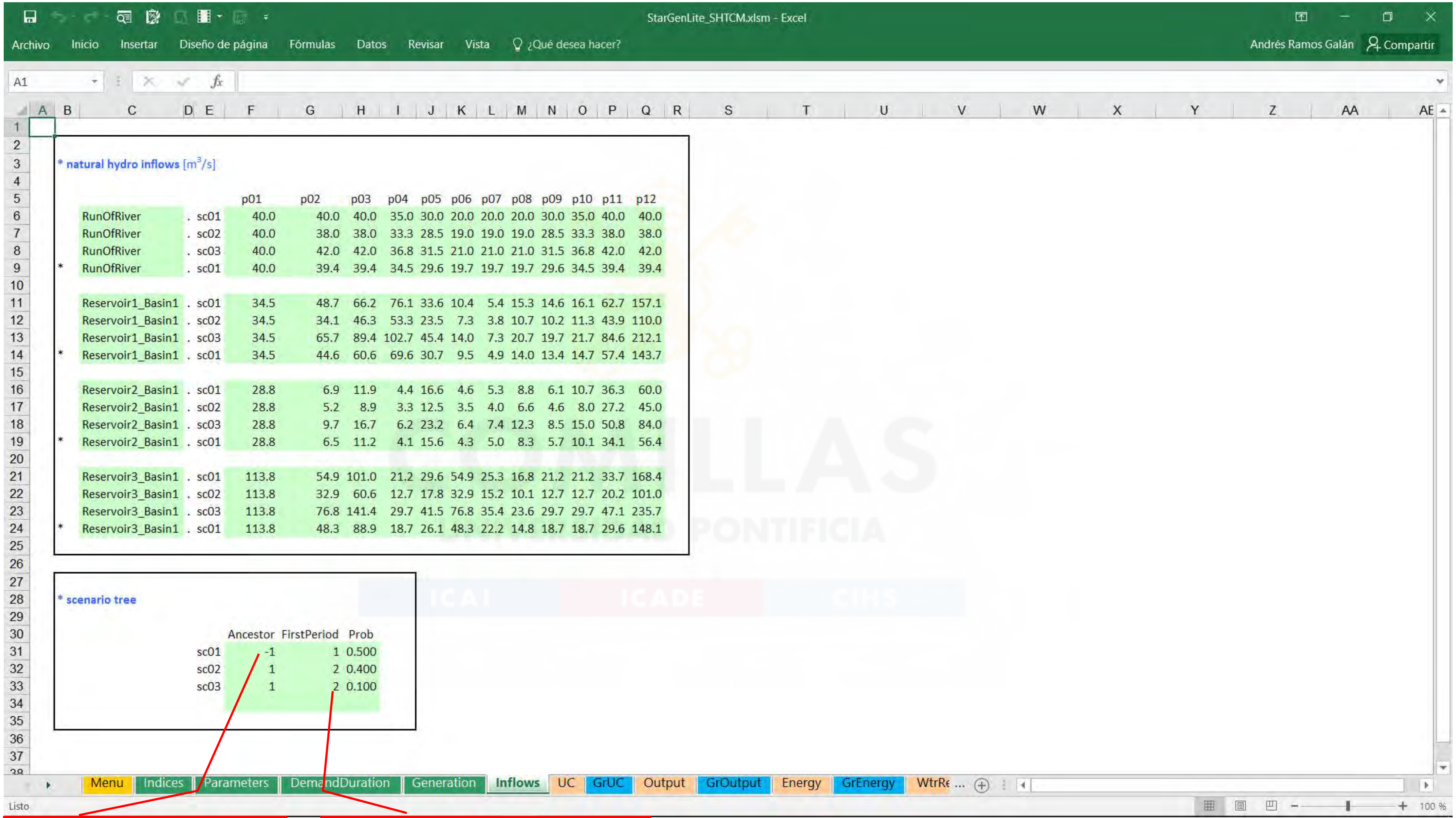
*	MaxProd [MW]	MinProd [MW]	ProdFunct [kWh/m³]	Efficiency [p.u.]	MaxCons [MW]
RunOfRiver	150.0				
StorageHydro1_Basin1	200.0		0.30		
StorageHydro2_Basin1	200.0		0.30		
StorageHydro3_Basin1	200.0		0.30		
PumpedStorageHydro	200.0			0.70	200.0

* reservoir

Scenario tree



Input Data. Inflows and scenario tree



* natural hydro inflows [m³/s]

				p01	p02	p03	p04	p05	p06	p07	p08	p09	p10	p11	p12
	RunOfRiver	.	sc01	40.0	40.0	40.0	35.0	30.0	20.0	20.0	20.0	30.0	35.0	40.0	40.0
	RunOfRiver	.	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
	RunOfRiver	.	sc03	40.0	42.0	42.0	36.8	31.5	21.0	21.0	21.0	31.5	36.8	42.0	42.0
*	RunOfRiver	.	sc01	40.0	39.4	39.4	34.5	29.6	19.7	19.7	19.7	29.6	34.5	39.4	39.4
	Reservoir1_Basin1	.	sc01	34.5	48.7	66.2	76.1	33.6	10.4	5.4	15.3	14.6	16.1	62.7	157.1
	Reservoir1_Basin1	.	sc02	34.5	34.1	46.3	53.3	23.5	7.3	3.8	10.7	10.2	11.3	43.9	110.0
	Reservoir1_Basin1	.	sc03	34.5	65.7	89.4	102.7	45.4	14.0	7.3	20.7	19.7	21.7	84.6	212.1
*	Reservoir1_Basin1	.	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
	Reservoir2_Basin1	.	sc01	28.8	6.9	11.9	4.4	16.6	4.6	5.3	8.8	6.1	10.7	36.3	60.0
	Reservoir2_Basin1	.	sc02	28.8	5.2	8.9	3.3	12.5	3.5	4.0	6.6	4.6	8.0	27.2	45.0
	Reservoir2_Basin1	.	sc03	28.8	9.7	16.7	6.2	23.2	6.4	7.4	12.3	8.5	15.0	50.8	84.0
*	Reservoir2_Basin1	.	sc01	28.8	6.5	11.2	4.1	15.6	4.3	5.0	8.3	5.7	10.1	34.1	56.4
	Reservoir3_Basin1	.	sc01	113.8	54.9	101.0	21.2	29.6	54.9	25.3	16.8	21.2	21.2	33.7	168.4
	Reservoir3_Basin1	.	sc02	113.8	32.9	60.6	12.7	17.8	32.9	15.2	10.1	12.7	12.7	20.2	101.0
	Reservoir3_Basin1	.	sc03	113.8	76.8	141.4	29.7	41.5	76.8	35.4	23.6	29.7	29.7	47.1	235.7
*	Reservoir3_Basin1	.	sc01	113.8	48.3	88.9	18.7	26.1	48.3	22.2	14.8	18.7	18.7	29.6	148.1

* scenario tree

	Ancestor	FirstPeriod	Prob
sc01	-1	1	0.500
sc02	1	2	0.400
sc03	1	2	0.100

Ancestor scenario
-1 means root node

First period where this
scenario branches

StarGenLite_SHTCM (i)

```
$Title StarGen Lite Medium Term Stochastic Hydrothermal Coordination Model (SHTCM)

$OnText

Developed by

   Andrés Ramos
   Instituto de Investigacion Tecnologica
   Escuela Tecnica Superior de Ingenieria - ICAI
   UNIVERSIDAD PONTIFICIA COMILLAS
   Alberto Aguilera 23
   28015 Madrid, Spain
   Andres.Ramos@comillas.edu
   https://pascua.iit.comillas.edu/aramos/Ramos_CV.htm

   October 23, 2017

$OffText

$OnEmpty OnMulti OffListing

* options to skip or not the Excel input/output
* if you want to skip it put these values to 1
* in such a case input files must be already in the directory created by any other means
* output file will be the tmp.gdx that can be exported to Excel manually
$ifthen.OptSkipExcelInput      %gams.user2% == ""
$  setglobal OptSkipExcelInput  0
$else.OptSkipExcelInput
$  setglobal OptSkipExcelInput  %gams.user2%
$endif.OptSkipExcelInput

$ifthen.OptSkipExcelOutput      %gams.user3% == ""
$  setglobal OptSkipExcelOutput 0
$else.OptSkipExcelOutput
$  setglobal OptSkipExcelOutput %gams.user3%
$endif.OptSkipExcelOutput

* solve the optimization problems until optimality
option OptcR = 0
```

Model name

Authorship and version

Allow declaration of empty sets and multiple declaration. Suppress listing

Obtain the optimal solution

StarGenLite_SHTCM (ii)

```
* definitions

sets
   p                         period
   p1(p)          first      period
   pn(p)          last       period
   s                      subperiod
   s1(s)          first   subperiod
   n                     load level
   n1(n)          first load level
   sc             scenario
   sca  (sc      ) scenario
   scp  (sc,p    ) tree defined as scenario and period
   scscp(sc,p,sc) ancestor         sc2    of node (sc1 p)
   scsch(sc,sc,p) descendant      (sc2 p) of node  sc1
   scscr(sc,p,sc) representative   sc2    of node (sc1 p)
   spsn(sc,p,s,n) active load levels for each scenario
   psn (   p,s,n) active load levels

   g              generating unit
   t (g)          thermal    unit
   h (g)          hydro      plant
   r                         reservoir
   rs(r)          storage    reservoir
   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)       pumped hydro plant upstream of reservoir
   rur(r,r)              reservoir 1 upstream of reservoir 2

alias (sc,scc,sccc), (r,rr)
```

Set definition

StarGenLite_SHTCM (iii)

```
parameters
   pDemand     (     p,s,n) hourly load                    [GW]
   pOperReserve(     p,s,n) hourly operating reserve       [GW]
   pDuration   (     p,s,n) duration                       [h]
   pCommitt    (sc,g,p,s  ) commitment of the unit         [0-1]
   pProduct    (sc,g,p,s,n) production of the unit         [GW]
   pEnergy     (sc,g,p,s,n) energy     of the unit         [GWh]
   pReserve    (sc,r,p    ) reservoir level                [hm3]
   pSRMC       (sc,  p,s,n) short run marginal cost        [M€ per GWh]
   pWValue     (sc,r,p    ) water value                    [M€ per hm3]

   pEFOR        (g)         EFOR                           [p.u.]
   pMaxProd     (g)         maximum output                 [GW]
   pMinProd     (g)         minimum output                 [GW]
   pMaxCons     (g)         maximum consumption            [GW]
   pSlopeVarCost(g)         slope     variable cost        [M€ per GWh]
   pInterVarCost(g)         intercept variable cost        [M€ per   h]
   pStartupCost (g)         startup            cost        [M€]
   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]
   pInflOrg     (r,sc,p)    inflows original               [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
   scaux                    scenario number
```

Parameter definition

StarGenLite_SHTCM (iv)

```
variables
   vTotalVCost              total system variable cost     [M€]

binary   variables
   vCommitt  (sc,p,s,  g)   commitment of the unit         [0-1]
   vStartup  (sc,p,s,  g)   startup     of the unit        [0-1]
   vShutdown (sc,p,s,  g)   shutdown    of the unit        [0-1]

positive variables
   vProduct  (sc,p,s,n,g)   production  of the unit        [GW]
   vConsump  (sc,p,s,n,g)   consumption of the unit        [GW]
   vENS      (sc,p,s,n  )   energy non served              [GW]
   vPNS      (sc,p,s    )   power  non served              [GW]
   vWtReserve(sc,p,    r)   water reserve at end of period [km3]
   vSpillage (sc,p,    r)   spillage                       [km3]

equations
   eTotalVCost              total system variable cost     [M€]
   eOpReserve(sc,p,s,n  )   operating reserve              [GW]
   eBalance  (sc,p,s,n  )   load generation balance        [GW]
   eMaxOutput(sc,p,s,n,g)   max output of a committed unit [GW]
   eMinOutput(sc,p,s,n,g)   min output of a committed unit [GW]
   eProdctPer(sc,p,s,n,g)   unit production in same period [GW]
   eStrtUpPer(sc,p,s,  g)   unit startup     in same period
   eStrtUpNxt(sc,p,s,  g)   unit startup     in next period
   eWtReserve(sc,p,    r)   water reserve                  [km3] ;
```

Variables

Equation definition

StarGenLite_SHTCM (v)

```
* mathematical formulation

eTotalVCost    .. vTotalVCost =e= sum[(spsn(sc,p ,s,n)  ), pProbSc(sc,p)*pDuration(p,s,n)*pENSCost        *vENS    (sc,p,s,n  )] +
                                  sum[(scp (sc,p),s     ), pProbSc(sc,p)                 *pPNSCost        *vPNS    (sc,p,s    )] +
                                  sum[(scp (sc,p),s,   t), pProbSc(sc,p)                 *pStartupCost (t)*vStartup(sc,p,s,   t)] +
                                  sum[(spsn(sc,p ,s,n),t), pProbSc(sc,p)*pDuration(p,s,n)*pInterVarCost(t)*vCommitt(sc,p,s,   t)] +
                                  sum[(spsn(sc,p ,s,n),t), pProbSc(sc,p)*pDuration(p,s,n)*pSlopeVarCost(t)*vProduct(sc,p,s,n,t)] ;

eOpReserve(spsn(sc,p,s,n1(n))) .. sum[t, pMaxProd(t)*vCommitt(sc,p,s,   t)] + sum[h, pMaxProd(         h)] + vPNS(sc,p,s  ) =g= pDemand(p,s,n) + pOperReserve(p,s,n) ;
eBalance  (spsn(sc,p,s,   n )) .. sum[g,             vProduct(sc,p,s,n,g)] - sum[h, vConsump(sc,p,s,n,h)] + vENS(sc,p,s,n) =e= pDemand(p,s,n)                       ;

eMaxOutput(spsn(sc,p,s,n),t) $pMaxProd(t) .. vProduct(sc,p,s,n,t) / pMaxProd(t) =l= vCommitt(sc,p,s,t) ;
eMinOutput(spsn(sc,p,s,n),t) $pMinProd(t) .. vProduct(sc,p,s,n,t) / pMinProd(t) =g= vCommitt(sc,p,s,t) ;

eProdctPer(spsn(sc,p,s1(s),n),g) .. vProduct(sc,p,s+1,n,g) =l= vProduct(sc,p,s,n,g) ;

eStrtUpPer(scp(sc,p),s1(s),t) $[card(s) > 1              ] .. vCommitt(sc,p,s+1,t) =e=                      vCommitt(sc ,p  ,s  ,t)  + vStartup(sc,p,s+1,t) -
vShutdown(sc,p,s+1,t) ;
eStrtUpNxt(scp(sc,p),s1(s),t) $[card(s) > 1 and not p1(p)] .. vCommitt(sc,p,s  ,t) =e= sum[scscp(sc,p,scc), vCommitt(scc,p-1,s+1,t)] + vStartup(sc,p,s  ,t) - vShutdown(sc,p,s
,t) ;

eWtReserve(scp(sc,p),  r) .. sum[scscp(sc,p,scc), vWtReserve(scc,p-1,r)] + pIniReserve(r) $p1(p) - vWtReserve(sc,p,r) +
                             pInflows(r,sc,p) - vSpillage(sc,p,r) + sum[rur(rr,r), vSpillage(sc,p,rr)]  +
                             sum{(s,n), pDuration(p,s,n)*sum[hur(h,r), vProduct(sc,p,s,n,h)/pProdFunct(h)]} -
                             sum{(s,n), pDuration(p,s,n)*sum[ruh(r,h), vProduct(sc,p,s,n,h)/pProdFunct(h)]} +
                             sum{(s,n), pDuration(p,s,n)*sum[hpr(h,r), vConsump(sc,p,s,n,h)/pProdFunct(h)*pEffic(h)]} -
                             sum{(s,n), pDuration(p,s,n)*sum[rph(r,h), vConsump(sc,p,s,n,h)/pProdFunct(h)*pEffic(h)]} =e= 0 ;

model mSHTCM / all / ;
mSHTCM.SolPrint = 1 ; mSHTCM.HoldFixed = 1 ;
```

Reduced solution output

Model includes all the equations

Eliminate fixed variables

Mathematical formulation of equations

StarGenLite_SHTCM (vi)

```
 * read input data from Excel and include into the model

file TMP / tmp_%gams.user1%.txt /
$OnEcho  > tmp_%gams.user1%.txt
   r1=    indices
   o1=tmp_indices.txt
   r2=    param
   o2=tmp_param.txt
   r3=    demand
   o3=tmp_demand.txt
   r4=    oprres
   o4=tmp_oprres.txt
   r5=    duration
   o5=tmp_duration.txt
   r6=    thermalgen
   o6=tmp_thermalgen.txt
   r7=    hydrogen
   o7=tmp_hydrogen.txt
   r8=    reservoir
   o8=tmp_reservoir.txt
   r9=    inflows
   o9=tmp_inflows.txt
   r10=    tree
   o10=tmp_tree.txt
$OffEcho
* Mac OS X and Linux users must comment the following call and copy and paste the named ranges of the Excel interface into the txt files
$ifthen.OptSkipExcelInput '%OptSkipExcelInput%' == '0'
$call xls2gms m i="%gams.user1%.xlsm" @"tmp_%gams.user1%.txt"
$else.OptSkipExcelInput
$  log Excel input skipped
$endif.OptSkipExcelInput

sets
$include tmp_indices.txt
;
$include tmp_param.txt
table     pDemand(p,s,n)
$include tmp_demand.txt
table     pOperReserve(p,s,n)
$include tmp_oprres.txt
table     pDuration(p,s,n)
$include tmp_duration.txt
table     pThermalGen(g,*)
$include tmp_thermalgen.txt
table     pHydroGen(g,*)
$include tmp_hydrogen.txt
table     pReservoir(r,*)
$include tmp_reservoir.txt
table     pInflows(r,sc,p)
$include tmp_inflows.txt
table     pScnTree(sc,*)
$include tmp_tree.txt
;

* Mac OS X and Linux users must comment the following execute
execute 'del tmp_"%gams.user1%".txt tmp_indices.txt tmp_param.txt tmp_demand.txt tmp_oprres.txt tmp_duration.txt tmp_thermalgen.txt tmp_hydrogen.txt tmp_reservoir.txt tmp_inflows.txt
tmp_tree.txt' ;
```

Read input from Excel named ranges and write into text files

Input from text files into GAMS

Delete read text files

StarGenLite_SHTCM (vii)

```
* determine the first and last period and the first subperiod

p1(p)      $[ord(p) =       1] = yes ;
s1(s)      $[ord(s) =       1] = yes ;
n1(n)      $[ord(n) =       1] = yes ;
pn(p)      $[ord(p) = card(p)] = yes ;
psn(p,s,n) $pDuration(p,s,n)   = yes ;
lag(p) = card(p) - 2*ord(p) + 1 ;

* assignment of thermal units, storage hydro and pumped storage hydro plants

t (g) $[pThermalGen(g,'MaxProd'   ) and pThermalGen(g,'FuelCost')] = yes ;
h (g) $[pHydroGen  (g,'MaxProd'   )                              ] = yes ;
rs(r) $[pReservoir (r,'MaxReserve') > 0                          ] = yes ;
```

First period, first subperiod
first load level, …

Defining thermal and hydro
units and reservoirs

StarGenLite_SHTCM (viii)

```
* scaling of parameters

pDemand     (p,s,n) = pDemand     (p,s,n)           * 1e-3 ;
pOperReserve(p,s,n) = pOperReserve(p,s,n)           * 1e-3 ;
pENSCost            = pENSCost                      * 1e-3 ;
pPNSCost            = pPNSCost                      * 1e-3 ;

pEFOR        (t)    = pThermalGen(t,'EFOR'        ) ;
pMaxProd     (t)    = pThermalGen(t,'MaxProd'     ) * 1e-3 * [1-pEFOR(t)] ;
pMinProd     (t)    = pThermalGen(t,'MinProd'     ) * 1e-3 * [1-pEFOR(t)] ;
pSlopeVarCost(t)    = pThermalGen(t,'OMVarCost'   ) * 1e-3 +
                      pThermalGen(t,'SlopeVarCost') * 1e-3 * pThermalGen(t,'FuelCost') ;
pInterVarCost(t)    = pThermalGen(t,'InterVarCost') * 1e-6 * pThermalGen(t,'FuelCost') ;
pStartupCost (t)    = pThermalGen(t,'StartupCost' ) * 1e-6 * pThermalGen(t,'FuelCost') ;

pMaxProd     (h)    = pHydroGen  (h,'MaxProd'     ) * 1e-3 ;
pMinProd     (h)    = pHydroGen  (h,'MinProd'     ) * 1e-3 ;
pMaxCons     (h)    = pHydroGen  (h,'MaxCons'     ) * 1e-3 ;
pProdFunct   (h)    = pHydroGen  (h,'ProdFunct'   ) * 1e+3 ;
pEffic       (h)    = pHydroGen  (h,'Efficiency'  )        ;
pMaxReserve  (r)    = pReservoir (r,'MaxReserve'  ) * 1e-3 ;
pMinReserve  (r)    = pReservoir (r,'MinReserve'  ) * 1e-3 ;
pIniReserve  (r)    = pReservoir (r,'IniReserve'  ) * 1e-3 ;

pInflows(r,sc,p)    = pInflows   (r,sc,p          ) * 1e-6 * 3.6*sum[(s,n), pDuration(p,s,n)] ;
pInflOrg(r,sc,p)    = pInflows   (r,sc,p          )                                           ;

* if the production function of a hydro plant is 0, it is changed to 1 and scaled to 1000
* if the efficiency          of a hydro plant is 0, it is changed to 1

pProdFunct(h) $[pProdFunct(h) = 0] = 1e3 ;
pEffic    (h) $[pEffic    (h) = 0] =   1 ;
```

Parameter scaling

StarGenLite_SHTCM (ix)

```
* bounds on variables

vProduct.up  (sc,p,s,n,g)    = pMaxProd(g)    ;
vConsump.up  (sc,p,s,n,h)    = pMaxCons(h)    ;

vENS.up      (sc,p,s,n  )    = pDemand(p,s,n) ;

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

Bounds on variables

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

scp  (    sc,p     ) $[ord(p) >= pScnTree(sc,'FirstPeriod')                                       ] = yes ;
scscp(scp(sc,p),scc) $[ord(p) >  pScnTree(sc,'FirstPeriod') and ord(scc) = ord(sc)                ] = yes ;
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

scp  (    sc,p     ) $[pProbSc(sc,p) = 0                        ] =  no ;
scscp(    sc,p ,scc) $[pProbSc(sc,p) = 0 or pProbSc(scc,p-1) = 0] =  no ;
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 ;
      SCA(scc)               $[ord(scc) = scaux] = yes ;
      scaux = sum[scscp(sca,p+lag(p),scc), ord(scc)] ;
      SCA(scc)                                   =  no ;
   ) ;
) ;
SCA(sc) $sum[p, pProbSc(sc,p)] = yes ;
```

Building the scenario tree

StarGenLite_SHTCM (xi)

```
* solve stochastic hydrothermal coordination model

solve mSHTCM using MIP minimizing vTotalVCost ;

* scaling of the results

pCommitt(sca,t,    p,s   ) = sum[scscr(sca,p,scc)                , vCommitt.l  (scc,p,s,  t)                                                  ]     + eps ;
pProduct(sca,g,psn(p,s,n)) = sum[scscr(sca,p,scc)                , vProduct.l  (scc,p,s,n,g)                                                ]*1e3 + eps ;
pEnergy (sca,g,psn(p,s,n)) = sum[scscr(sca,p,scc)                , vProduct.l  (scc,p,s,n,g)                *pDuration(p,s,n)                ]*1e3 + eps ;
pReserve(sca,rs(r),p     ) = sum[scscr(sca,p,scc)                , vWtReserve.l(scc,p,    r)                                                ]*1e3 + eps ;
pWValue (sca,rs(r),p     ) = sum[scscr(sca,p,scc) $pProbSc(scc,p), eWtReserve.m(scc,p,    r)/sum[psn(p,s,n), pDuration(p,s,n)]/pProbSc(scc,p)]*1e3 + eps ;
pSRMC   (sca,  psn(p,s,n)) = sum[scscr(sca,p,scc) $pProbSc(scc,p), eBalance.m  (scc,p,s,n  )                /pDuration(p,s,n) /pProbSc(scc,p)]*1e3 + eps ;

* data output to xls file

put TMP putclose 'par=pProduct rdim=2 rng=Output!a1' / 'par=pEnergy rdim=2 rng=Energy!a1' / 'par=pReserve rdim=2 rng=WtrReserve!a1' / 'par=pWValue rdim=2
rng=WtrValue!a1' / 'par=pSRMC rdim=1 rng=SRMC!a1' / 'par=pCommitt rdim=2 rng=UC!a1' /
                 'text="Scen"         rng=Output!a1' / 'text="Scen"        rng=Energy!a1' / 'text="Scen"         rng=WtrReserve!a1' / 'text="Scen"
rng=WtrValue!a1' / 'text="Scen"      rng=SRMC!a1' / 'text="Scen"         rng=UC!a1' /
                 'text="Unit"         rng=Output!b1' / 'text="Unit"        rng=Energy!b1' / 'text="Reservoir"     rng=WtrReserve!b1' / 'text="Reservoir"
rng=WtrValue!b1' /                                  'text="Unit"         rng=UC!b1' /
execute_unload   'tmp_%gams.user1%.gdx' pProduct pEnergy pReserve pWValue pSRMC pCommitt
*$ifthen.OptSkipExcelOutput '%OptSkipExcelOutput%' == '0'
execute          'gdxxrw tmp_"%gams.user1%".gdx SQ=n EpsOut=0 O=tmp_"%gams.user1%".xlsx @tmp_"%gams.user1%".txt'
execute          'del    tmp_"%gams.user1%".gdx
*$else.OptSkipExcelOutput
*$  log Excel output skipped
*$endif.OptSkipExcelOutput
execute          'del                                                                    tmp_"%gams.user1%".txt'

$OnListing
```

Solve the optimization problem

Scaling the results

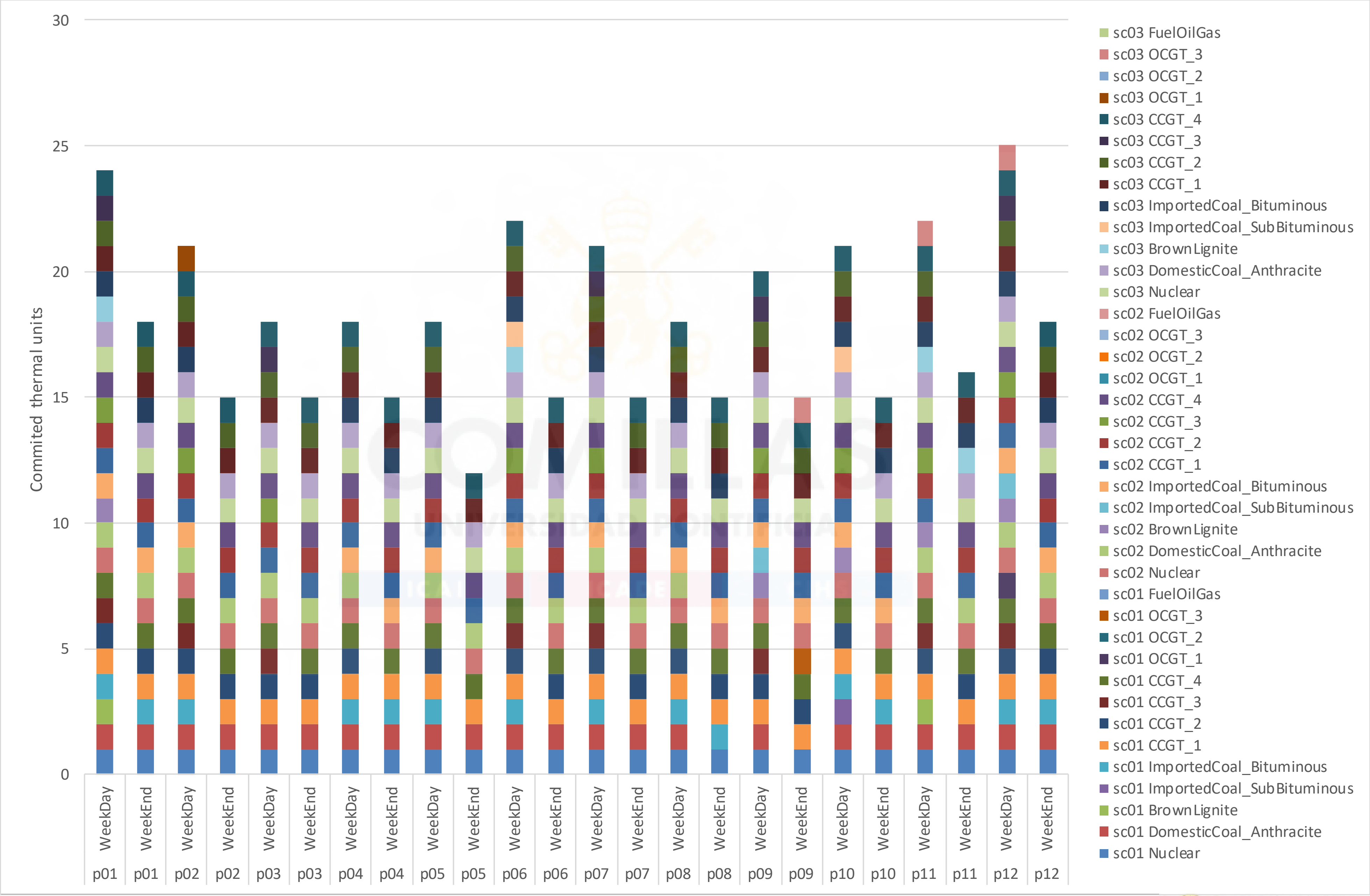
Write output to Excel

Medium term optimization model. Results

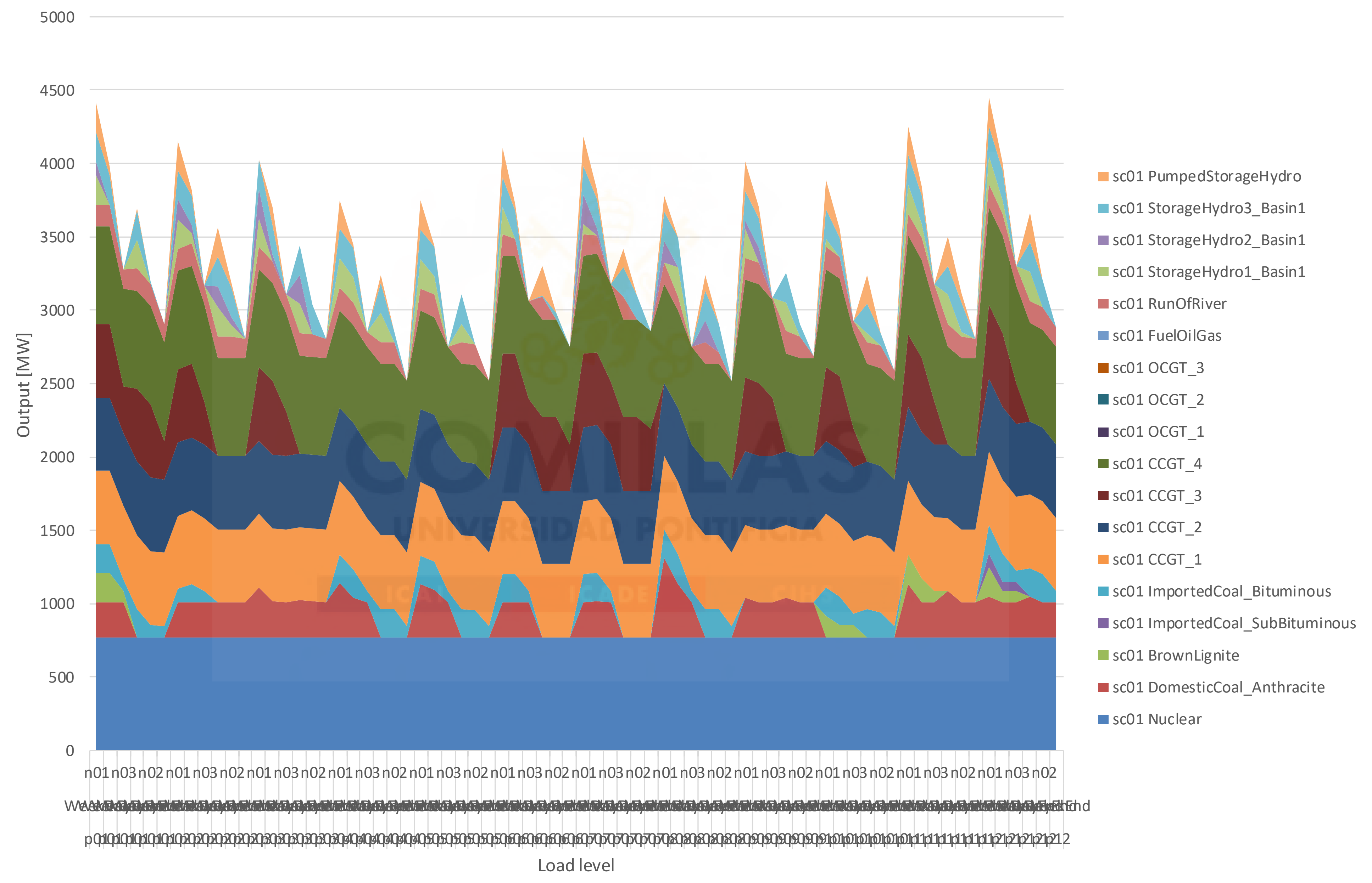
- Operation planning
  - Unit (thermal, storage hydro, and pumped-storage hydro) operation
  - Reservoir management
  - Targets for short-term models (water balance)

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

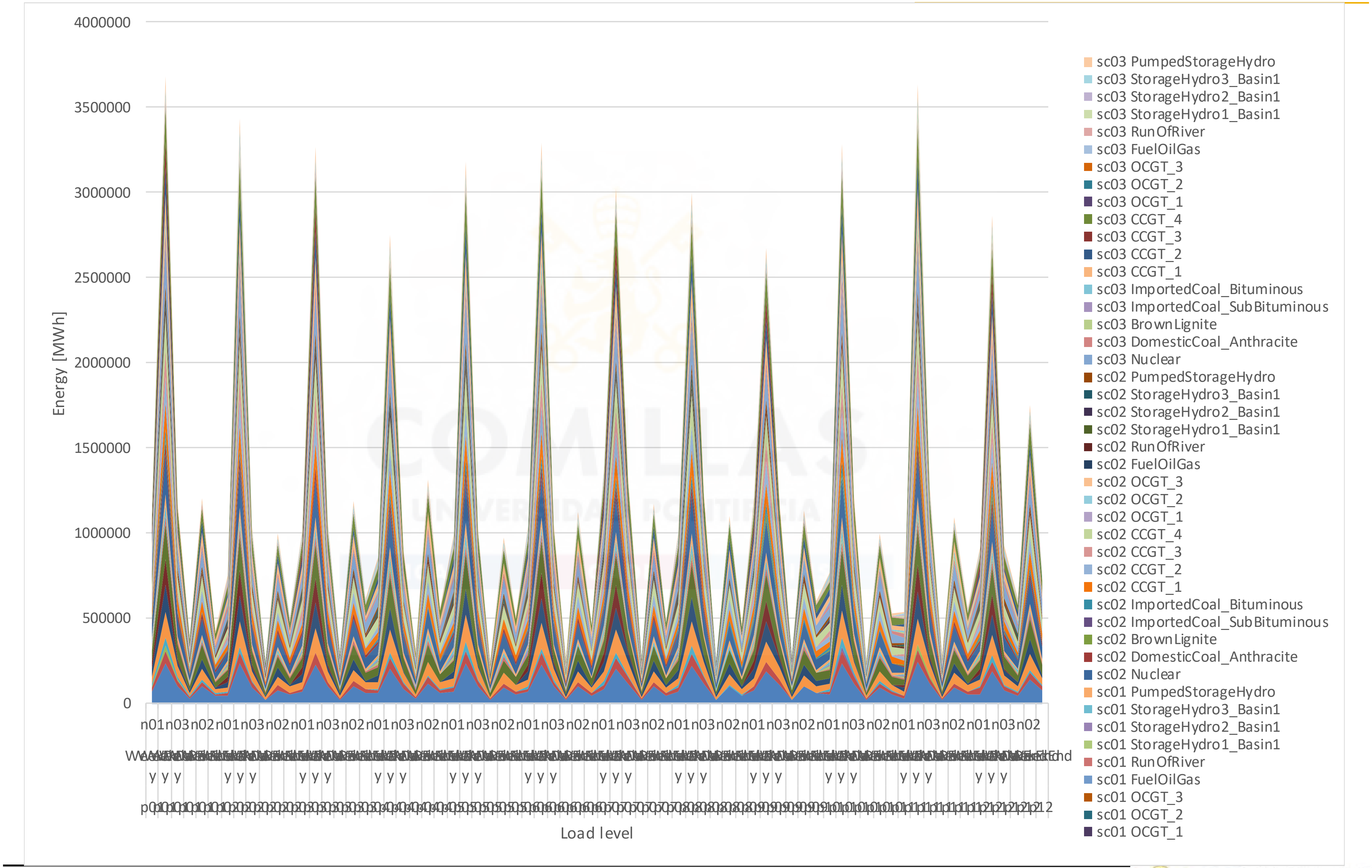
Output Data. Thermal unit commitment



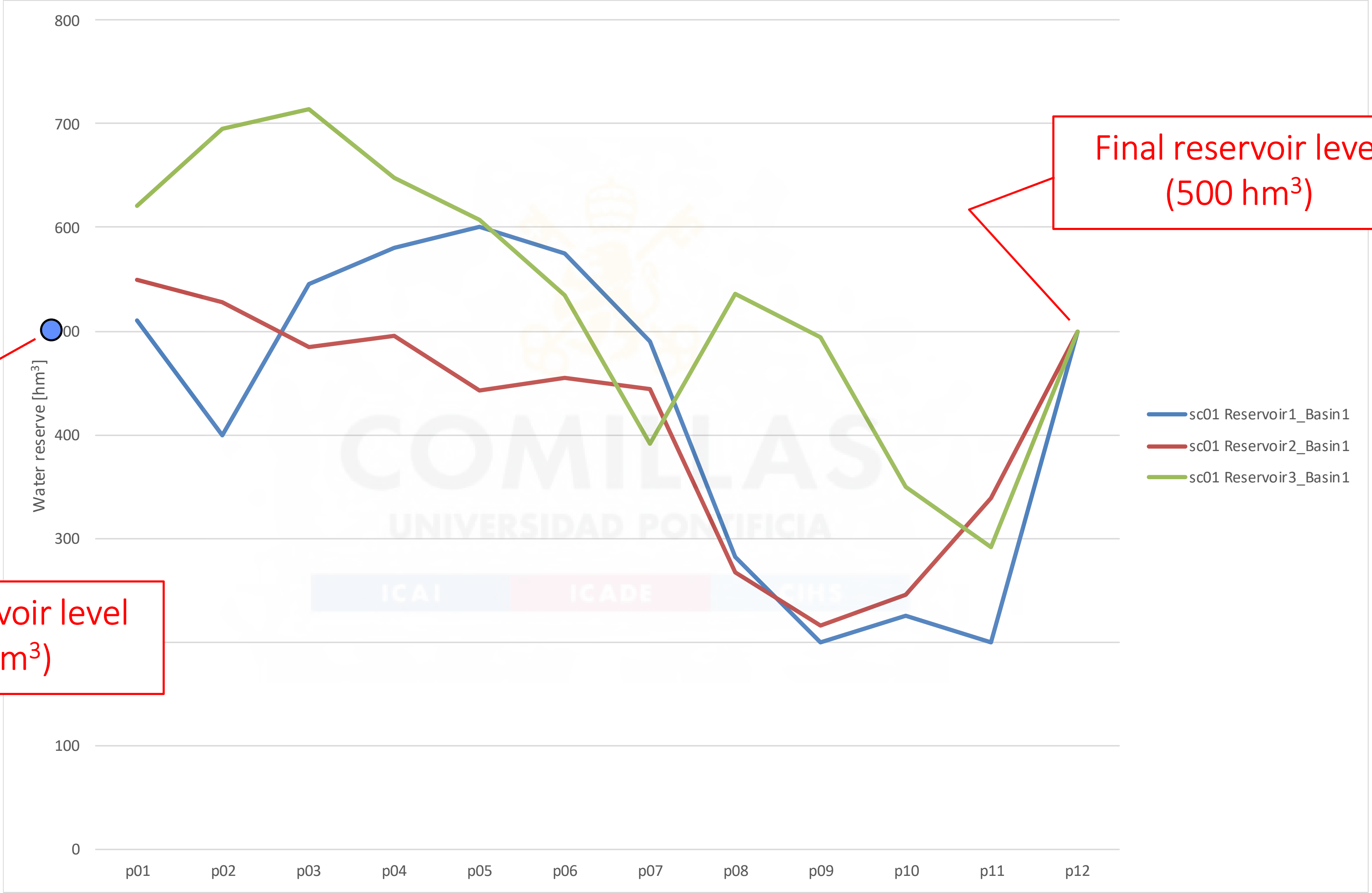
Output Data. Production



Output Data. Energy



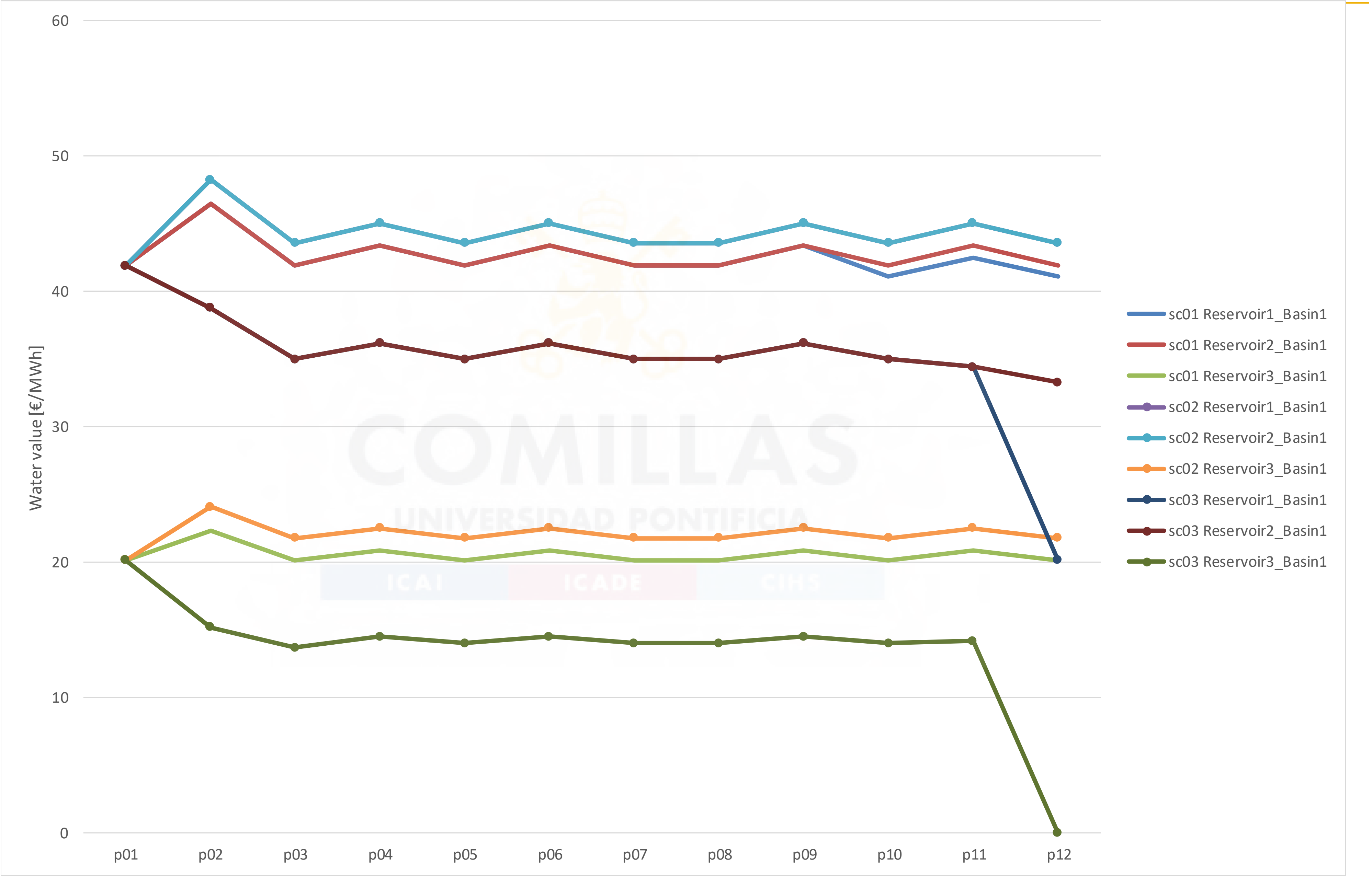
Reservoir level at the end of each period



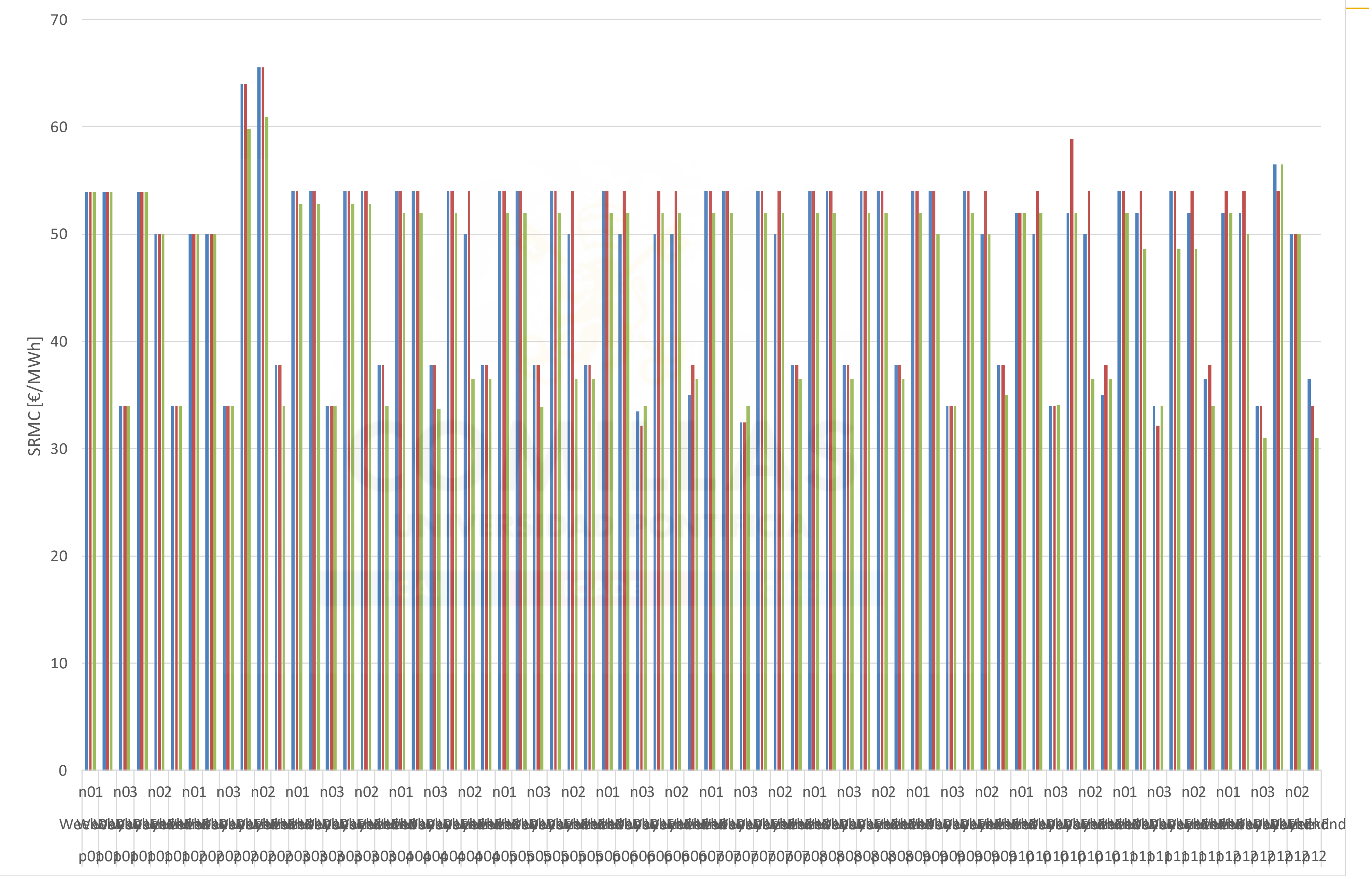
Final reservoir level ($500\ hm^3$)

Initial reservoir level ($500\ hm^3$)

Water value


60
50
40
30
20
10
0
Water value [€/MWh]
p01
p02
p03
p04
p05
p06
p07
p08
p09
p10
p11
p12
sc01 Reservoir1_Basin1
sc01 Reservoir2_Basin1
sc01 Reservoir3_Basin1
sc02 Reservoir1_Basin1
sc02 Reservoir2_Basin1
sc02 Reservoir3_Basin1
sc03 Reservoir1_Basin1
sc03 Reservoir2_Basin1
sc03 Reservoir3_Basin1

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

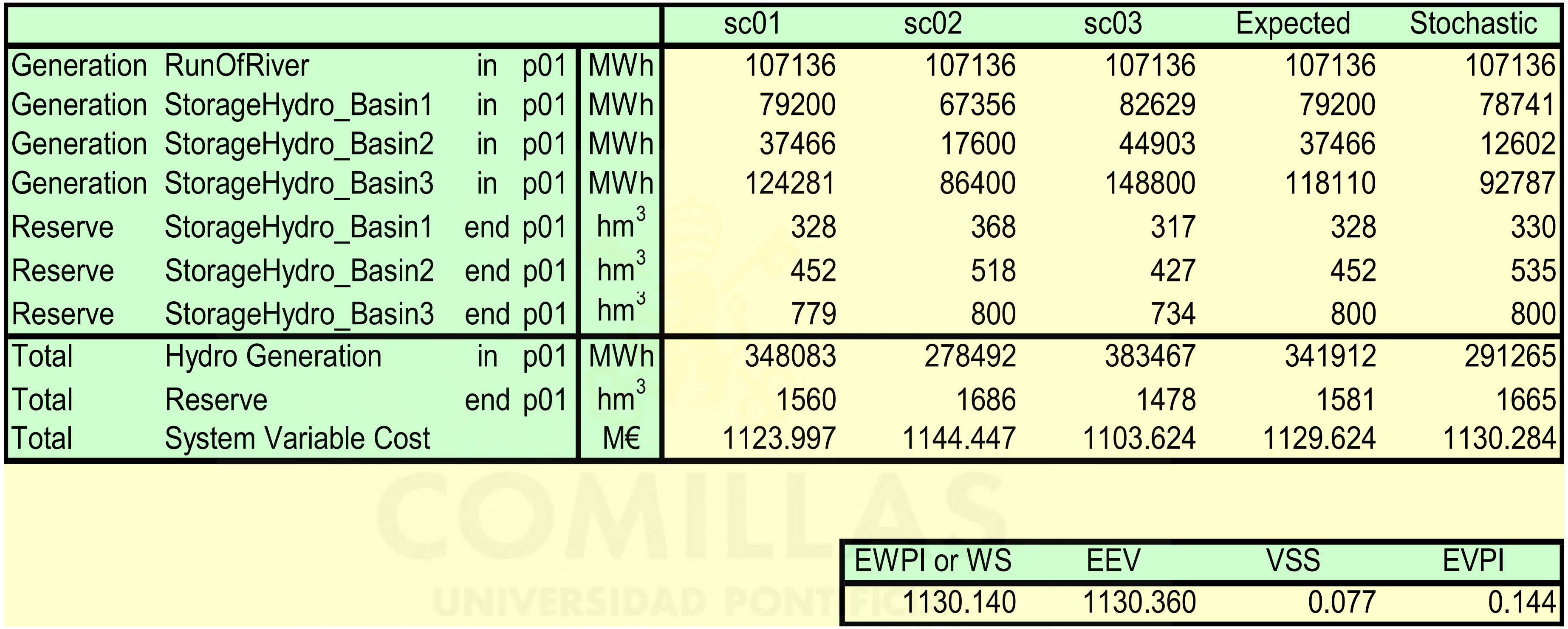
Stochastic measures

- *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


Fortune-teller

- EVPI = RP - WS
- VSS = EEV - RP
- WS ≤ RP ≤ EEV EVPI ≥ 0 VSS ≥ 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	MWh	348083	278492	383467	341912	291265
Total	Reserve	end	p01	hm^3	1560	1686	1478	1581	1665
Total	System Variable Cost			M€	1123.997	1144.447	1103.624	1129.624	1130.284

EWPI or WS	EEV	VSS	EVPI
1130.140	1130.360	0.077	0.144

- 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 m^3/s to km^3 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://www.iit.comillas.edu/aramos/

Andres.Ramos@comillas.edu

arght@mit.edu