Analysis of storage and water value in power systems for policymaking on renewable energies

Session 70: Policy-Enabling Models for the Power Sector

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Future context for Hydrothermal Coordination Model

As intermittent renewable energy sources production increases (e.g. solar and wind), the potential deployment of energy storage also increases.

Additionally, Battery Energy Storage Systems (BESS) cost is expected to decrease in next 10 to 15 years.

Intra-day storage (e.g. BESS) dispatch could change seasonal storage (e.g. hydro units) dispatch and opportunity costs (i.e. the water value).

In the next future, high penetration of intermittent generation is going to stress the electric system operation. Storage hydro, pumped storage hydro plants, and BESS are going to play a much more important role due to their flexibility and complementary use with intermittent generation

Q. What is the water value used for?

A. The water value has been mainly used to coordinate medium-term hydrothermal scheduling and short-term operation

Medium- or Long-term hydrothermal dispatch

output

Water Value

input

Bid curves in Day-ahead market

Cost minimization unit commitment

Existing Medium- or Long-term hydrothermal dispatch models only give the water value in a weekly or monthly basis.
Hourly signals are neglected due to the time resolution.

So, Research Questions…

- Are short-term storage decisions changing the water value of long-term storage?
- How much do short-term storage decisions affect the water value of long-term?

Hypothesis: Short-term energy storage decisions in energy and reserve markets impact the water value (or opportunity cost) of long-term storage.

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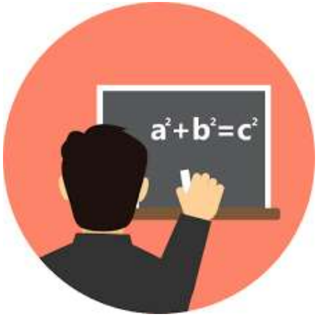
Mathematical Formulation and Models



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General Formulation

Objective function

- Minimize the total expected variable costs plus penalties for energy and power not served

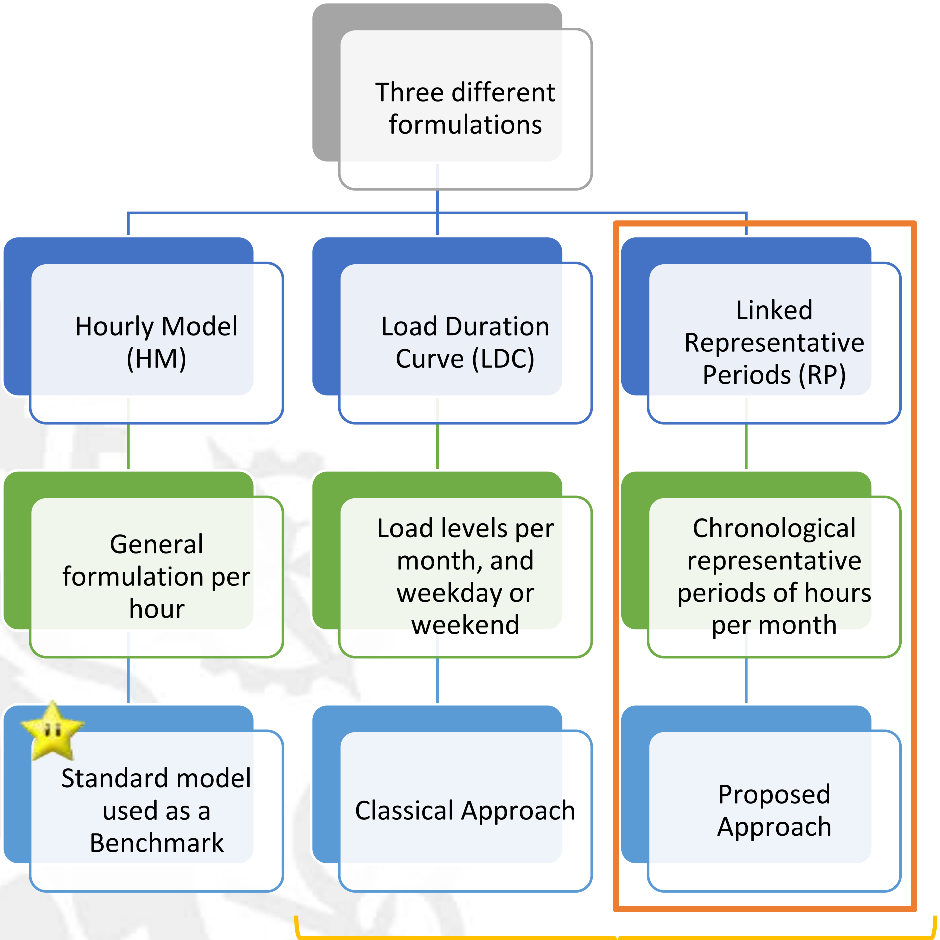
Variables

- binary: Commitment, startup and shutdown of thermal units
- Thermal, hydro units, renewable and pumped storage hydro output
- storage levels (reservoirs and BESS)

Operational constraints

- **Water balance with stochastic inflows**
- Load balance and operating reserve
- Detailed hydro basin modeling
- Thermal, storage hydro and pumped-storage hydro operation constraints

Mixed integer linear programming (MIP)

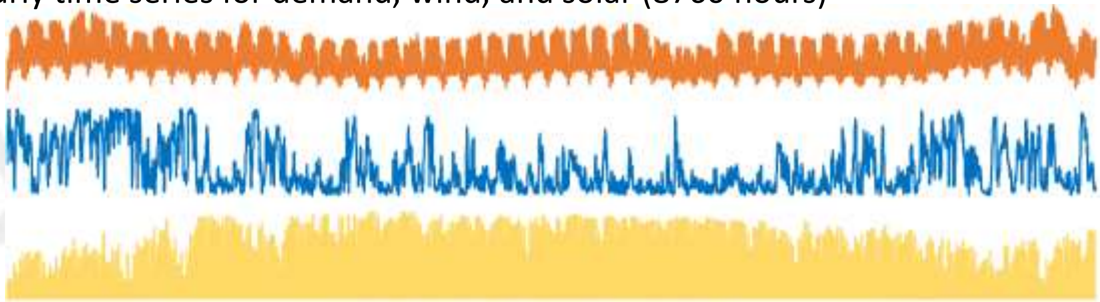


Load Levels and representative periods can be obtained via a clustering procedure (e.g. k-means or k-medoids)

Demand and Variable Renewable Energy Sources

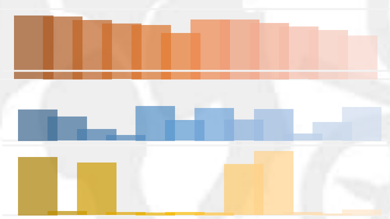
Hourly Model

Hourly time series for demand, wind, and solar (8760 hours)



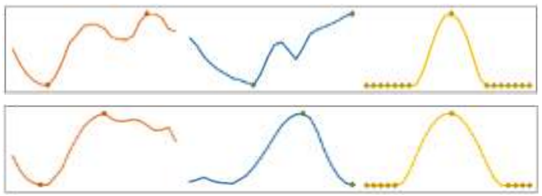
Load Duration Curve Model

Monthly demand, wind, and solar with several load levels. All the weekdays (weekends) of the same month are similar. For example: 12 load levels.



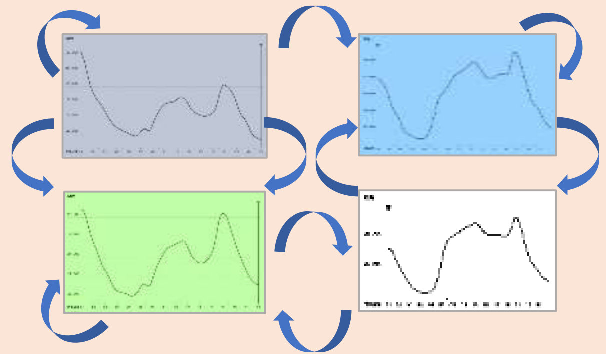
Linked Representative Periods

Time series for demand, wind, and solar per representative period. For example: two representative periods each one with 24h.



Linked Representative Periods – Proposed Approach

We include **transition matrix and cluster index** information into the representative periods, so that it is possible to link chronological information among the representatives such as storage levels and unit commitments



Transition Matrix: Square matrix used to describe the transitions among representative periods.

	rp01	rp02	rp03	rp04	rp05	rp06	rp07	rp08	rp09	rp10	rp11	rp12
rp01	2	4	1	0								
rp02	3	4	2	3				1				
rp03	0	2	1	2								
rp04	2	3	0	1								
rp05					0	3	0	2				
rp06					2	3	1	2				
rp07					1	1	2	0				
rp08					2	1	1	6	1			
rp09									1	2	0	2
rp10									0	1	0	2
rp11									2	0	12	1
rp12									2	0	3	2

Cluster Index: Each hour belongs to only one hour of one representative period.

h1 to h24 → rp3.k1 to rp3.k24
h25 to h48 → rp2.k1 to rp2.k24

⋮

h3985 to h4008 → rp24.k1 to rp24.k24
h4009 to h4032 → rp21.k1 to rp21.k24

⋮

h8713 to h8736 → rp46.k1 to rp46.k24
h8737 to h8760 → rp46.k1 to rp46.k24

Note: Representative periods are selected for each uncertainty node in the scenario tree. For instance, there are 4 representative periods per month in the transition matrix shown in this slide.

RP Storage Balance Constraint

In the linked representative periods we have two storage balance equations:

- Inter-day storage balance (among an aggregation of hours, e.g. month):

$$R_{m-1,r}^{inter,\omega'} - R_{m,r}^{inter,\omega} + \sum_{ci(p,rp,k)\in mp(m,p)} \Bigg[i_{rp,k,r}^{\omega} - S_{rp,k,r}^{\omega} + \sum_{r'\in up(r)} S_{rp,k,r'}^{\omega} + \sum_{h\in up(r)} P_{rp,k,h}^{\omega}/c_h - \sum_{h\in dw(r)} P_{rp,k,h}^{\omega}/c_h + \sum_{h\in up(r)} C_{rp,k,h}^{\omega}/c_h \Bigg] = 0 : \mu_{m,r}^{inter,\omega} \quad \forall \omega, m, r\ \omega' \epsilon\ a(\omega)$$

Terms use for BESS

- Intra-day storage balance (inside the representative period):

$$R_{rp,k-1,r}^{intra,\omega'} - R_{rp,k,r}^{intra,\omega} + i_{rp,k,r}^{\omega} - S_{rp,k,r}^{\omega} + \sum_{r'\in up(r)} S_{rp,k,r'}^{\omega} + \sum_{h\in up(r)} P_{rp,k,h}^{\omega}/c_h - \sum_{h\in dw(r)} P_{rp,k,h}^{\omega}/c_h + \sum_{h\in up(r)} C_{rp,k,h}^{\omega}/c_h = 0 : \mu_{rp,k,r}^{intra,\omega} \quad \forall \omega, rp, k, r\ \omega' \epsilon\ a(\omega)$$

rp: representative period, k: hour inside a rp, $ci(p,rp,k)$: cluster index, $mp(m,p)$: relation among hours and months

RP Storage Balance Constraint

In the linked representative periods we have two storage balance equations:

- Inter-day storage balance (among an aggregation of hours, e.g. month):

$$R^{inter,\omega'}_{m-1,r} - R^{inter,\omega}_{m,r} + \sum_{ci(p,rp,k)\in mp(m,p)} \left[i^{\omega}_{rp,k,r} - S^{\omega}_{rp,k,r} + \sum_{r'\in up(r)} S^{\omega}_{rp,k,r'} \right.$$

$$+ \sum_{h\in up(r)} P^{\omega}_{rp,k,h} / c_h - \sum_{h\in dw(r)} P^{\omega}_{rp,k,h} / c_h$$

$$\left. + \sum_{h\in up(r)} C^{\omega}_{rp,k,h} / c_h \right] = 0 : \boldsymbol{\mu^{inter,\omega}_{m,r}} \quad \forall \omega, m, r \ \omega' \epsilon \ a(\omega)$$

We have two dual variables per each equation. Therefore, which one is the storage/water value?

representative period):

$$\sum_{r'\in up(r)} S^{\omega}_{rp,k,r'}$$

$$+ \sum_{h\in up(r)} P^{\omega}_{rp,k,h} / c_h - \sum_{h\in dw(r)} P^{\omega}_{rp,k,h} / c_h$$

$$+ \sum_{h\in up(r)} C^{\omega}_{rp,k,h} / c_h = 0 : \boldsymbol{\mu^{intra,\omega}_{rp,k,r}} \quad \forall \omega, rp, k, r \ \omega' \epsilon \ a(\omega)$$

rp: representative period, k: hour inside a rp, $ci(p,rp,k)$: cluster index, $mp(m,p)$: relation among hours and months

Storage Value using Linked Representative Periods

In fact, we need both dual variables:

$$\mu_{pr}^{\omega} = \sum_{(rp,k)\in ci(p,rp,k)} \sum_{m\in mp(m,p)} \frac{1}{p_m^{\omega}} \left(\frac{\mu_{rp,k,r}^{intra,\omega}}{w_{rp}} + \mu_{m,r}^{inter,\omega} \right)$$

Therefore, we can obtain hourly the storage/water value for short- and long-term storage using the linked representative periods formulation, which allows us to determine the interaction between BESS and hydro reservoir in a stochastic hydrothermal coordination model

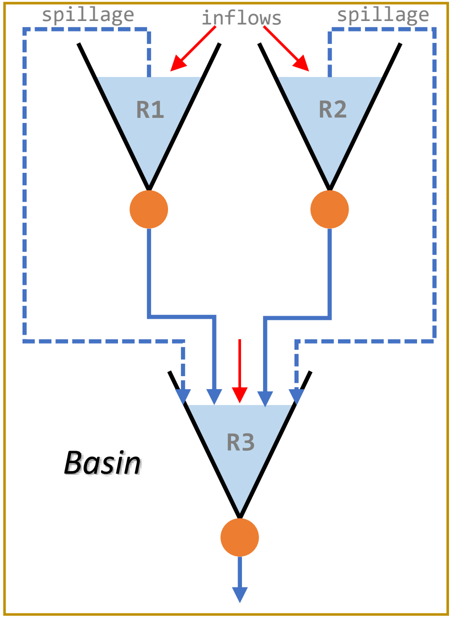
p_m^{ω}: scenario probability at uncertainty node m (aggregation of hours)

w_{rp}: weight of representative period rp

Case Study

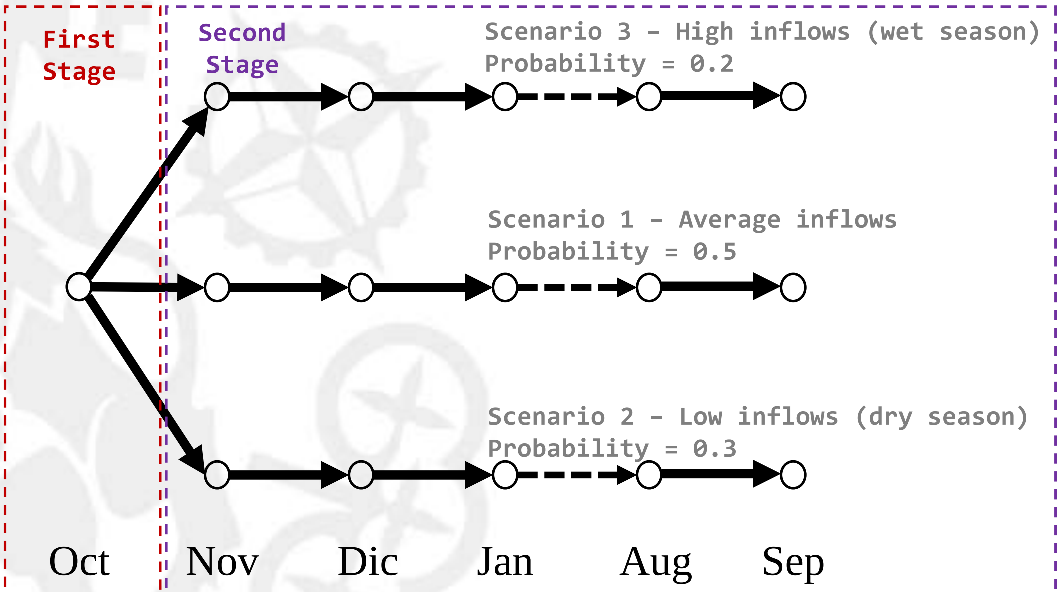
Stylized Spanish Case for 2030

- Time scope: 1 year (2030)
- Hourly demand profile was taken from Vision 1 in Ten-Year Network Development Plan 2016 of ENTSO-E
- Hourly wind and solar production profiles. The total renewable penetration is 37%
- 8 generation technologies are considered:
  - Nuclear: 1 unit
  - Coal: 4 units
  - CCGT: 4 units
  - OCGT: 3 units
  - Fuel oil gas: 1 unit
  - Run of river: 1 unit
  - Hydro: 3 plant in a hydro subsystem (Basin)
  - BESS: 1 battery energy storage systems (1 cycle per day: 4h = 800MWh/200MW)
- Scenario tree representing monthly uncertainty on hydro inflows



Scenario tree

- Stochastic optimization: Best decision when future is uncertain (with a known probability)
- Discrete probability function (i.e., scenario tree)



Models and Sensitivities

Hourly Model (HM) used as a benchmark for results

- 8760 hours

Load Duration Curve Model (LDC) – Classical Approach

- 12 load levels per month: 6 for weekdays and 6 for weekend

Linked Representative Periods – Proposed Approach

- 1 representative period with 24h per month (1RPx24h)
- 1 representative period with 48h per month (1RPx48h)
- 1 representative period with 96h per month (1RPx96h)
- 2 representative periods with 24h per month (2RPx24h)
- 4 representative periods with 24h per month (4RPx24h)

?

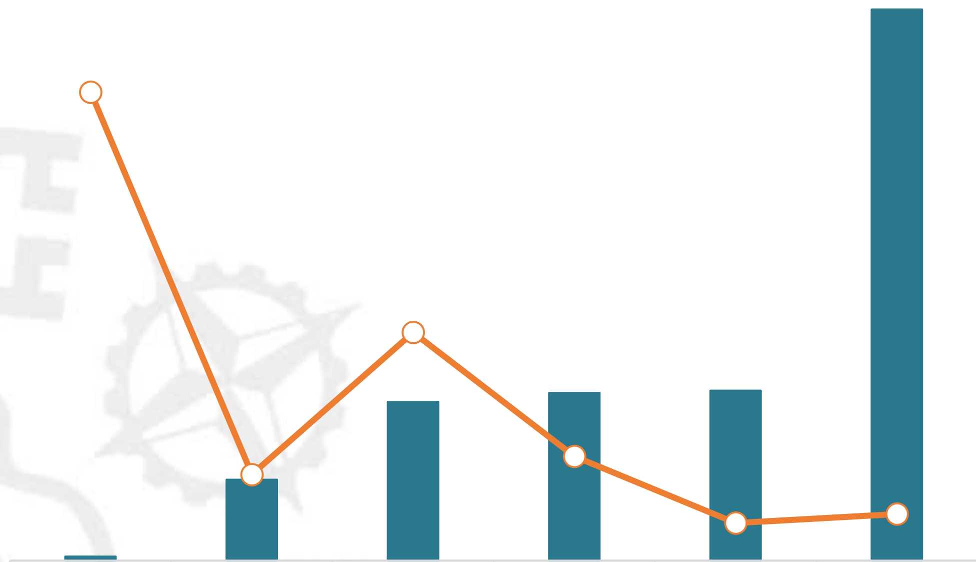
Is it better to have longer rp per month sharing information? or is it better to have shorter rp per month sharing information among them and between months?

Results

Spoiler Alert!...

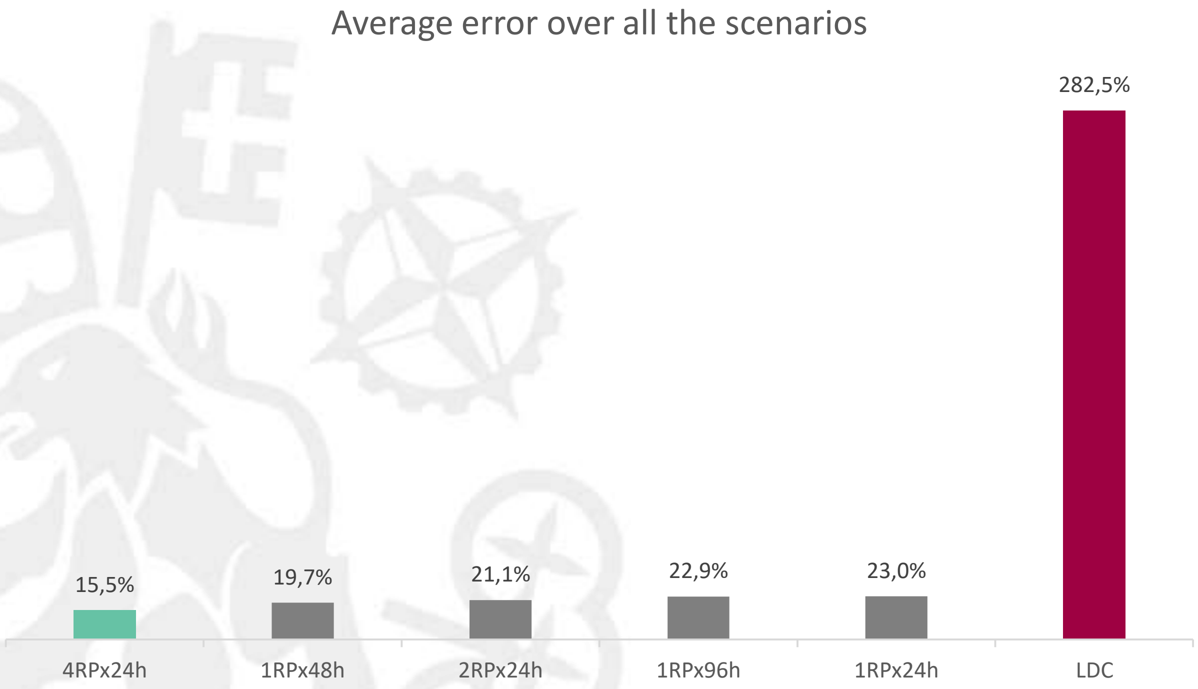
Criterion	Best performance	Second best performance	Second worst performance	Worst performance
Objective Function	4RPx24h	2RPx24h	1RPx24h	LDC
CPU Time	1RPx24h	LDC	1RPx96h	4RPx24h
Production	4RPx24h	2RPx24h	1RPx24h	LDC
Reservoir Level	1RPx96h	1RPx48h	1RPx24h	LDC
BESS number of cycles	4RPx24h	1RPx48h	1RPx24h	LDC
Marginal Cost	4RPx24h	1RPx96h	1RPx24h	LDC
Water value	4RPx24h	2RPx24h	LDC	1RPx24
BESS storage value	4RPx24h	1RPx48h	1RPx24h	LDC

Objective function performance

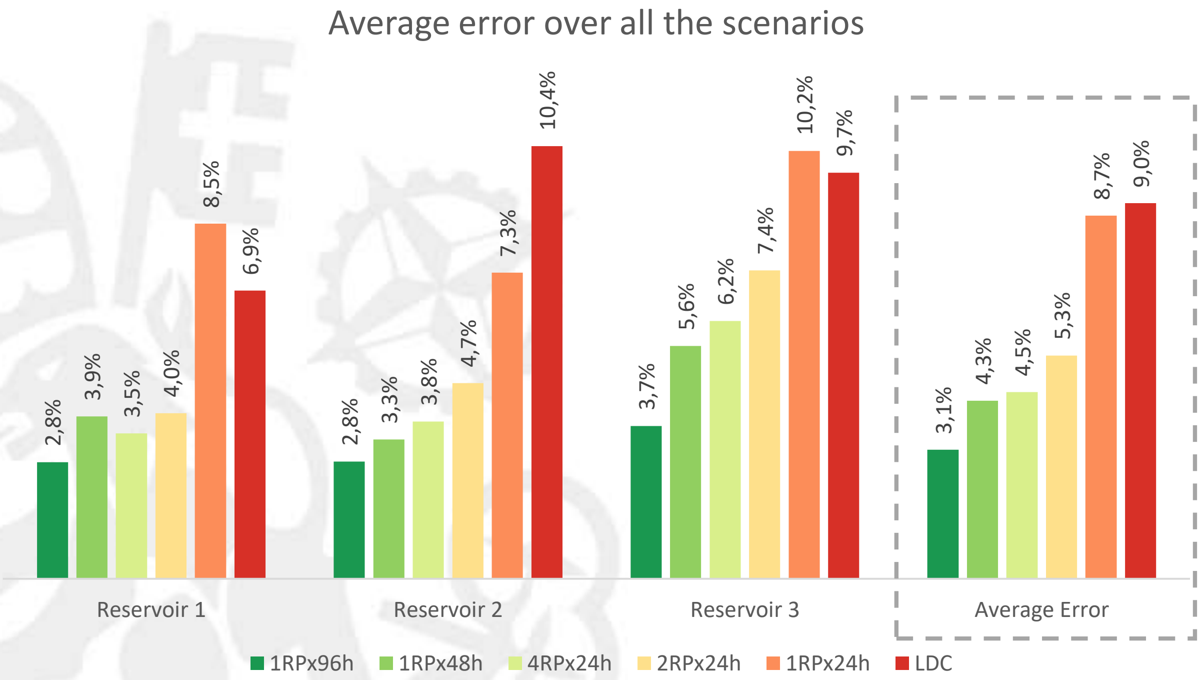


	4RPx24h	2RPx24h	1RPx96h	1RPx48h	1RPx24h	LDC
OF Error [%]	0,09%	1,71%	3,37%	3,55%	3,60%	11,67%
CPU Time [%]	9,92%	1,83%	4,83%	2,21%	0,80%	0,99%

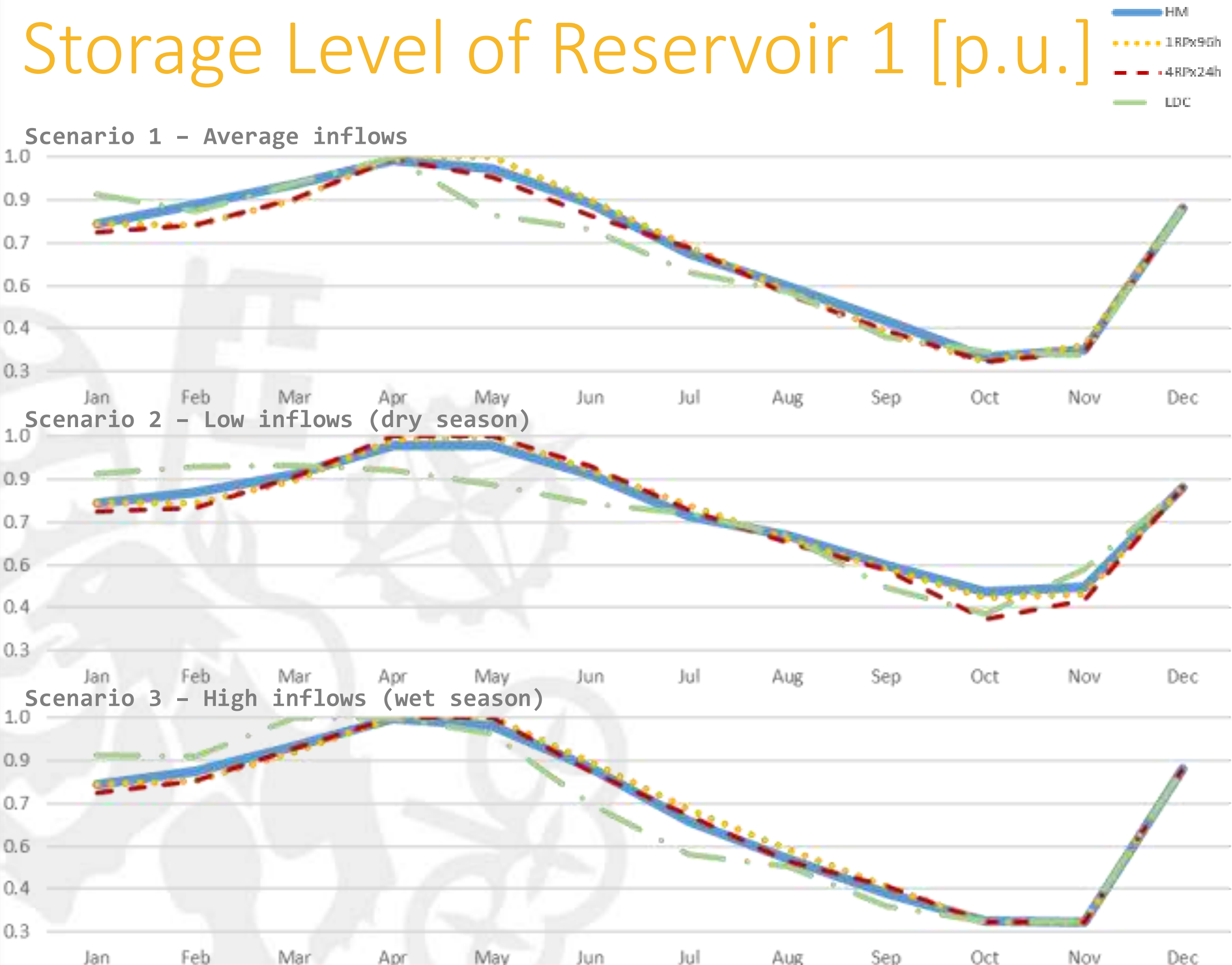
Operational Planning Results
Error on Production - Summary



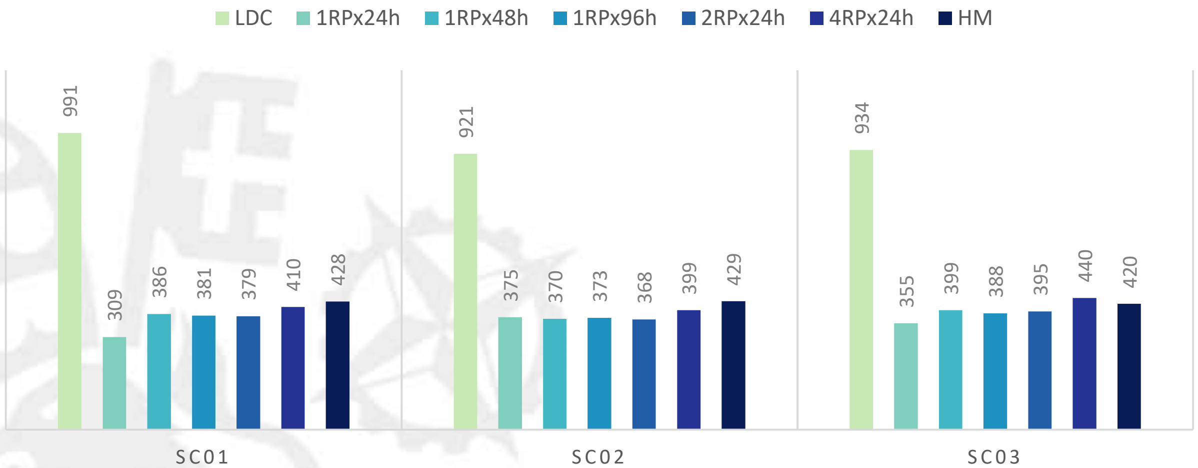
Operational Planning Results
Error on Hydro Reservoir Level



Storage Level of Reservoir 1 [p.u.]



Operational Planning Results
BESS Number of Cycles

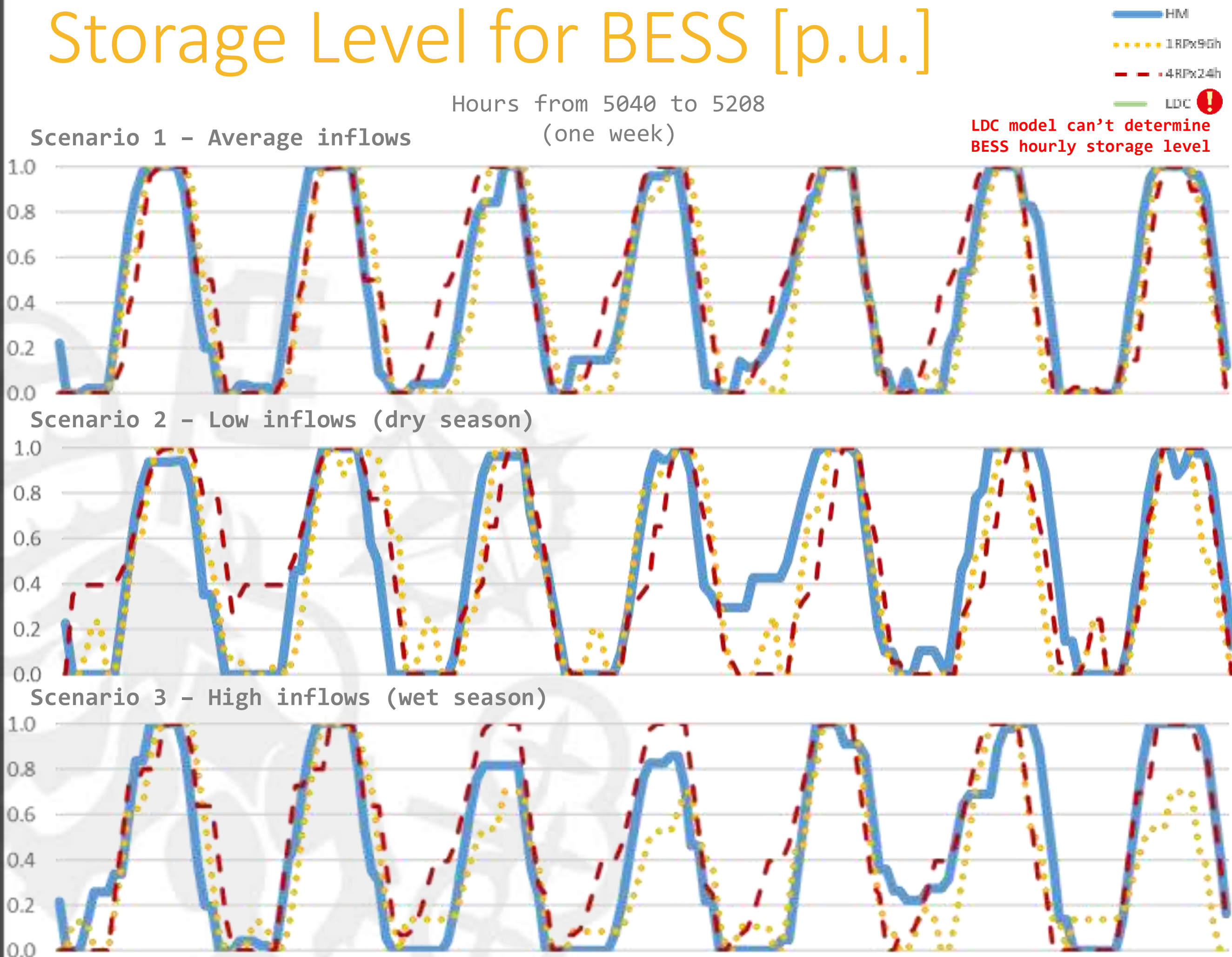


Scen	LDC	1RPx24h	1RPx48h	1RPx96h	2RPx24h	4RPx24h
sc01	-132%	28%	10%	11%	11%	4%
sc02	-115%	13%	14%	13%	14%	7%
sc03	-122%	15%	5%	8%	6%	-5%

|Error| > 10%
5%<|Error| ≤ 10%
|Error| ≤ 5%

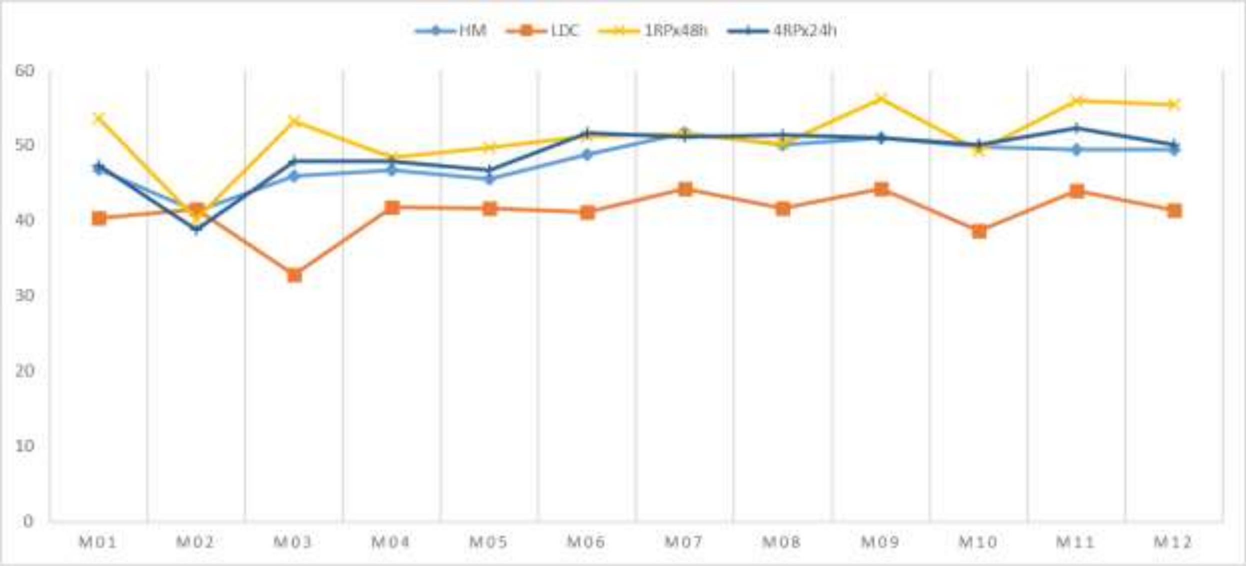
The full cycles are estimated using the total charge/discharge energy and divided by the energy capacity of the BESS
Cycle life as the minimum of the full charge/discharge rounded.

Storage Level for BESS [p.u.]



Economic Planning Results
Marginal Cost (Price) Error

Scen	LDC	1RPx24h	1RPx48h	1RPx96h	2RPx24h	4RPx24h
sc01	14.3%	8.9%	7.2%	4.6%	6.3%	2.7%
sc02	11.3%	6.0%	7.3%	3.8%	4.9%	4.6%
sc03	16.0%	14.9%	11.0%	10.0%	9.3%	4.2%



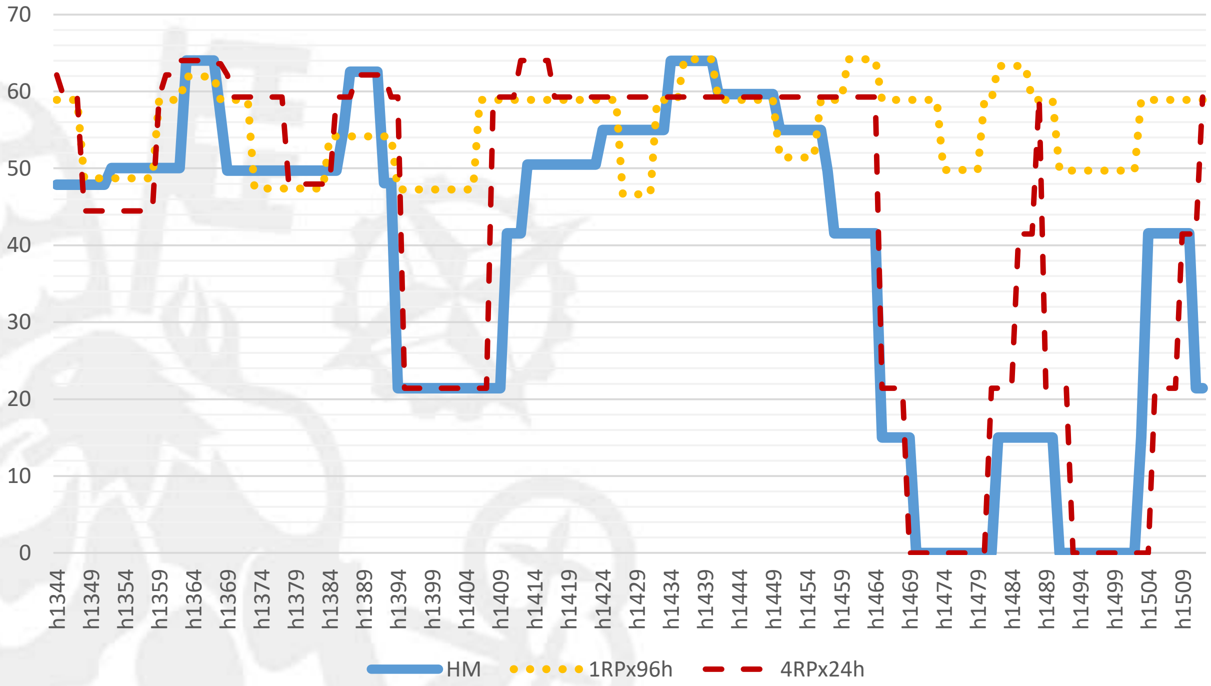
Economic Planning Results
The Water Value Error

Scen	Storage Tech	LDC	1RPx24h	1RPx48h	1RPx96h	2RPx24h	4RPx24h
sc01	Reservoir1_Basin1	18.5%	14.8%	4.8%	0.3%	5.4%	0.1%
sc01	Reservoir2_Basin1	9.4%	14.8%	4.8%	0.3%	5.0%	0.1%
sc01	Reservoir3_Basin1	28.3%	0.5%	5.2%	0.3%	6.9%	0.2%
sc02	Reservoir1_Basin1	9.9%	6.0%	7.2%	0.7%	1.6%	1.2%
sc02	Reservoir2_Basin1	9.1%	6.0%	7.2%	0.7%	1.6%	1.2%
sc02	Reservoir3_Basin1	20.5%	12.7%	15.1%	1.2%	2.9%	2.7%
sc03	Reservoir1_Basin1	8.5%	26.9%	12.0%	16.5%	10.7%	2.3%
sc03	Reservoir2_Basin1	4.4%	26.9%	14.9%	16.0%	11.2%	1.5%
sc03	Reservoir3_Basin1	6.1%	47.7%	9.4%	19.8%	6.7%	6.9%

|Error| > 10%
5%<|Error| ≤ 10%
|Error| ≤ 5%

Note: Hourly Model is the benchmark

Storage Value for BESS [€/MWh]



Conclusions

Recap…

- Are short-term storage decisions changing the water value of long-term storage?
  - A. Yes, the classical approach (LDC) shows the worst performance when we consider short-term storage (BESS) in the hydrothermal coordination problem
- How much do short-term storage decisions affect the water value of long-term?
  - A. The LDC approach underestimate the water value between 5% to 30% for long-term hydro reservoirs

Hypothesis: Short-term energy storage decisions in energy and reserve markets impact the water value (or opportunity cost) of long-term storage.

Summary…

The context	Increase of short-term energy storage (e.g. BESS) in power systems due to the accommodation of renewable energy sources. This changes the opportunity cost of seasonal storage (e.g. hydro reservoirs).
The drawback	No hourly water value in classical hydrothermal coordination methodologies. This doesn´t enable the co-optimization of short-term and long-term storage.
Our contribution	Propose a new optimization model for hydrothermal coordination in which hourly water values (short-term signals) are co-optimize with seasonal storage (long-term water value signals).
The potential use	1. Analysis of energy and reserve markets in the short-term operation for policymaking 2. Medium-term hydrothermal dispatch considering short-term energy storage such as BESS

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