Coupling Pumped Hydro Energy Storage With Unit Commitment

Kenneth Bruninx[1] **Yury Dvorkin**[2,3] Erik Delarue[1]
Hrvoje Pandzic[4] William D'haeseleer[1] Daniel Kirschen[2]

[1]KU Leuven [2]New York University

[3]University of Washington [4]University of Zagreb

June 29, 2016

Introduction

- State-of-the-art unit commitment (UC) models:
  - Stochastic UC (SUC) is the least-cost benchmark, but computationally expensive
  - (Improved) Interval UC (IUC) approximates the SUC cost and reliability performance and is solved faster
  - Robust UC (RUC) is tractable, but limits representation of uncertain quantities (arguably, there is enough historical data to obtain high quality scenarios for day-ahead SUC)
  - Deterministic UC (DUC) accounts for uncertainty using exogenously computed dynamic/probabilistic reserve requirements
- Energy storage:
  - Battery/compressed air/electrostatic/flywheel energy storage (ES) are emerging: many successful demonstration projects, fewer commercial
  - Pumped-hydro ES (PHES) have been and will be around for decades
    - Tens of approved projects in the US and hundreds worldwide

Introduction

- State-of-the-art unit commitment (UC) models:
  - Stochastic UC (SUC) is the least-cost benchmark, but computationally expensive
  - (Improved) Interval UC (IUC) approximates the SUC cost and reliability performance and is solved faster
  - Robust UC (RUC) is tractable, but limits representation of uncertain quantities (arguably, there is enough historical data to obtain high quality scenarios for day-ahead SUC)
  - Deterministic UC (DUC) accounts for uncertainty using exogenously computed dynamic/probabilistic reserve requirements
- Energy storage:
  - Battery/compressed air/electrostatic/flywheel energy storage (ES) are emerging: many successful demonstration projects, fewer commercial
  - Pumped-hydro ES (PHES) have been and will be around for decades
    - Tens of approved projects in the US and hundreds worldwide
- This presentation:
  - Coupling PHES with stochastic, interval, and deterministic UC models
  - Assessing the arbitrage and reserve value of PHES on a model of the Belgian power system

PHES in SUC

$$\min \overbrace{\sum_{t \in T} \sum_{i \in I} suc_{t,i}}^{\text{Start-up cost}} + \overbrace{\sum_{t \in T} \sum_{i \in I} \sum_{s \in S} \pi_s \left[c^{\text{F}}_{t,i,s} + c^{\text{CO}_2}_{t,i,s} + + c^{\text{R}}_{t,i,s} \right]}^{\text{Expected operating costs (includes fuel, emission, and ramp costs)}}$$

$$+ \underbrace{\sum_{t \in T} \sum_{s \in S} \pi_s \cdot ENS_{t,s} \cdot VOLL}_{\text{Expected cost of ENS}} \qquad (1)$$

PHES in SUC

$$\min \overbrace{\sum_{t\in T}\sum_{i\in I} suc_{t,i}}^{\text{Start-up cost}} + \overbrace{\sum_{t\in T}\sum_{i\in I}\sum_{s\in S}\pi_s\left[c^{\mathrm{F}}_{t,i,s} + c^{\mathrm{CO_2}}_{t,i,s} + + c^{\mathrm{R}}_{t,i,s}\right]}^{\text{Expected operating costs (includes fuel, emission, and ramp costs)}}$$
$$+ \underbrace{\sum_{t\in T}\sum_{s\in S}\pi_s \cdot ENS_{t,s} \cdot VOLL}_{\text{Expected cost of ENS}} \qquad (1)$$

subject to:

- Binary logic on conventional generators
- Minimum up- and down-time constraints
- Start-up and shut down trajectories
- Dispatch constraints on conventional generators
- Dispatch constraints on renewables
- Power balance constraint
- Dispatch constraints on PHES

PHES in SUC

- Dispatch constraints on PHES are enforced scenario-wise
  - State-of-charge ($e_{t,i,s}$) constraint:

$$e_{t,i,s} = e_{t-1,i,s} + \Delta\tau \cdot \Big(\overbrace{g^{\mathrm{P}}_{t,i,s} \cdot \aleph^{\mathrm{P}}}^{\text{Pumping mode}} - \overbrace{g^{\mathrm{T}}_{t,i,s} / \aleph^{\mathrm{T}}}^{\text{Turbining mode}} \Big) \tag{2}$$

  - Minimum and maximum state-of-charge and charging/discharging power limits:

$$E^{\min}_i \le e_{t,i,s} \le E^{\max}_i \tag{3}$$

$$0 \le g^{\mathrm{P}}_{t,i,s} \le P^{\max}_i \tag{4}$$

$$0 \le g^{\mathrm{T}}_{t,i,s} \le P^{\max}_i \tag{5}$$

PHES in SUC

- Dispatch constraints on PHES are enforced scenario-wise
  - State-of-charge ($e_{t,i,s}$) constraint:

$$e_{t,i,s} = e_{t-1,i,s} + \Delta\tau \cdot \Big(\overbrace{g^{\mathrm{P}}_{t,i,s} \cdot \aleph^{\mathrm{P}}}^{\text{Pumping mode}} - \overbrace{g^{\mathrm{T}}_{t,i,s} / \aleph^{\mathrm{T}}}^{\text{Turbining mode}} \Big) \quad (2)$$

  - Minimum and maximum state-of-charge and charging/discharging power limits:

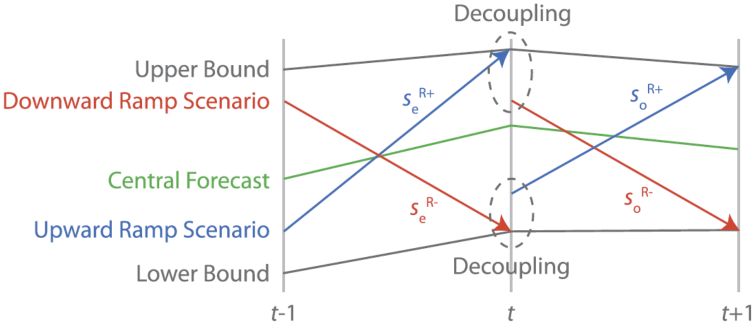
$$E_i^{\min} \leq e_{t,i,s} \leq E_i^{\max} \quad (3)$$

$$0 \leq g^{\mathrm{P}}_{t,i,s} \leq P_i^{\max} \quad (4)$$

$$0 \leq g^{\mathrm{T}}_{t,i,s} \leq P_i^{\max} \quad (5)$$

- Reserve needs are accounted for by considering a set of scenarios
- More scenarios → More variables and constraints → More computational power needed
- How to enforce feasibility on transitions between scenarios?

PHES in IUC



- Five scenarios: central forecast and 4 ramp scenarios that enforce the required capacity bounds and ramping feasibility within a given range
- Base case is represented by the central forecast
- Ramp scenarios are modeled via scenarios $s_e^{R+}, s_e^{R-}, s_o^{R+}, s_o^{R-}$
- Reserve needs are accounted for by the ramp scenarios

PHES in IUC

Modifications relative to the SUC formulation[1]:

- Objective function accounts for the cost under the the central forecast and does not allow load curtailment:

$$\min \overbrace{\sum_{t\in T}\sum_{i\in I} suc_{t,i}}^{\text{Start-up cost}} + \overbrace{\sum_{t\in T}\sum_{i\in I}\left[c^{F}_{t,i,cf} + c^{CO_2}_{t,i,cf} + +c^{R}_{t,i,cf}\right]}^{\text{Operating cost under the central forecast (cf))}} \qquad (6)$$

- Unit commitment and economic dispatch constraints are enforced for five scenarios
- Additional constraints for the ramp scenarios
- Dispatch constraints on PHES

[1] K. Bruninx, Y. Dvorkin, E. Delarue, H. Pandzic, W. D'haeseleer and D. S. Kirschen, "Coupling Pumped Hydro Energy Storage With Unit Commitment," IEEE Trans. Sustain. Energy, vol. 7, no. 2, pp. 786-796, April 2016.

PHES in IUC

- State-of-charge ($e_{t,i,s}$) constraint related to the central forecast (cf):

$$e_{t,i,s} = e_{t-1,i,cf} + \Delta\tau \cdot \overbrace{(g^{P}_{t,i,s} \cdot \aleph^{P}}^{\text{Pumping mode}} - \overbrace{g^{T}_{t,i,s} / \aleph^{T}}^{\text{Turbining mode}}), \quad \forall s \in S \quad (7)$$

PHES in IUC

- State-of-charge ($e_{t,i,s}$) constraint related to the central forecast (cf):

$$e_{t,i,s} = e_{t-1,i,cf} + \Delta\tau \cdot \overbrace{(g^{\mathrm{P}}_{t,i,s} \cdot \aleph^{\mathrm{P}}}^{\text{Pumping mode}} - \overbrace{g^{\mathrm{T}}_{t,i,s}/\aleph^{\mathrm{T}}}^{\text{Turbining mode}}), \quad \forall s \in S \quad (7)$$

- Constraints on initial state of the decoupled ramp scenarios:

$$g^{\mathrm{P}}_{i,t,s} = g^{\mathrm{T}}_{i,t,s} = 0, \quad \forall s \in \{S^{\mathrm{R+}}_{e}, S^{\mathrm{R-}}_{e}\}, \forall t | \mathrm{mod}(t) = 1 \quad (8)$$

$$g^{\mathrm{P}}_{i,t,s} = g^{\mathrm{T}}_{i,t,s} = 0, \quad \forall s \in \{S^{\mathrm{R+}}_{o}, S^{\mathrm{R-}}_{o}\}, \forall t | \mathrm{mod}(t) = 0 \quad (9)$$

PHES in IUC

- State-of-charge ($e_{t,i,s}$) constraint related to the central forecast (cf):

$$e_{t,i,s} = e_{t-1,i,cf} + \Delta\tau \cdot \overbrace{\left(g^{\mathrm{P}}_{t,i,s} \cdot \aleph^{\mathrm{P}}\right.}^{\text{Pumping mode}} - \overbrace{g^{\mathrm{T}}_{t,i,s}/\aleph^{\mathrm{T}}}^{\text{Turbining mode}} \left.\right), \quad \forall s \in S \qquad (7)$$

- Constraints on initial state of the decoupled ramp scenarios:

$$g^{\mathrm{P}}_{i,t,s} = g^{\mathrm{T}}_{i,t,s} = 0, \quad \forall s \in \left\{S^{\mathrm{R+}}_{e}, S^{\mathrm{R-}}_{e}\right\}, \forall t | \mathrm{mod}(t) = 1 \qquad (8)$$

$$g^{\mathrm{P}}_{i,t,s} = g^{\mathrm{T}}_{i,t,s} = 0, \quad \forall s \in \left\{S^{\mathrm{R+}}_{o}, S^{\mathrm{R-}}_{o}\right\}, \forall t | \mathrm{mod}(t) = 0 \qquad (9)$$

- Feasibility of the PHES output under the worst-case ramp scenarios:

$$e_{i,t,cf} - \Delta\tau \cdot g^{\mathrm{T-}}_{i,t,s}/\aleph^{\mathrm{T}} - \Delta\tau \cdot g^{\mathrm{P-}}_{i,t,s} \cdot \aleph^{\mathrm{P}} \geq E^{\min}_{i}, \quad \forall s \in \left\{S^{\mathrm{R-}}_{e}, S^{\mathrm{R-}}_{o}\right\} \qquad (10)$$

$$e_{i,t,cf} + \Delta\tau \cdot g^{\mathrm{T+}}_{i,t,s}/\aleph^{\mathrm{T}} + \Delta\tau \cdot g^{\mathrm{P+}}_{i,t,s} \cdot \aleph^{\mathrm{P}} \leq E^{\max}_{i}, \quad \forall s \in \left\{S^{\mathrm{R+}}_{e}, S^{\mathrm{R+}}_{o}\right\} \qquad (11)$$

PHES in DUC

Modifications relative to the SUC formulation:

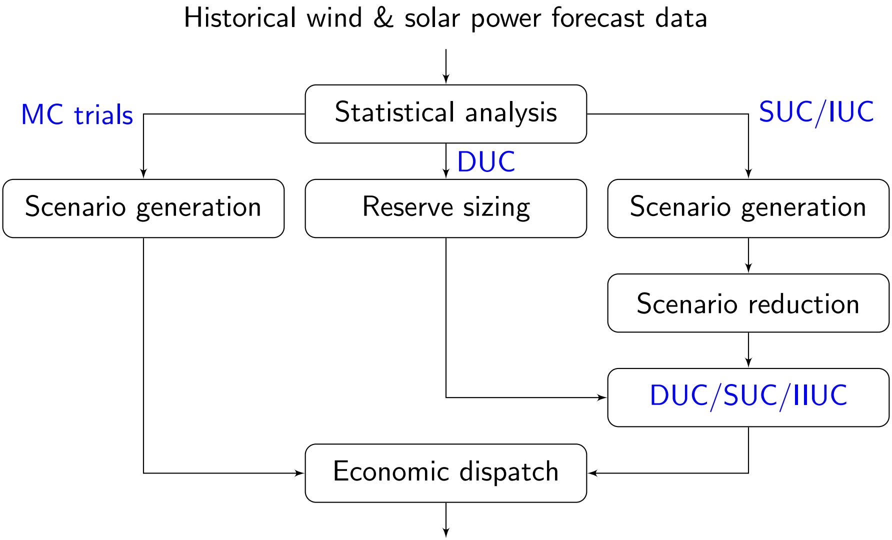
- Objective function and all unit commitment/economic dispatch constraints are enforced for the central forecast only
- Hourly reserve requirements are computed based on a statistical analysis of the historical wind power forecast errors[2]
- PHES can provide upward reserve by:
  - Reducing the pumping power
  - Increasing the turbining power
- PHES can provide downward reserve by:
  - Increasing the pumping power
  - Reducing the turbining power

[2] K. Bruninx and E. Delarue, "A statistical description of the error on wind power forecasts for probabilistic reserve sizing," IEEE Trans. Sustain. Energy, vol. 5, no. 3, pp. 9951002, Jul. 2014.

Test System And Data

- A realistic model of the Belgian power system operated by Elia
- Peak and lowest hourly demands are estimated at 14 GW and 6GW
- Dispatchable generation resources total 13,920 MW (71 generators)
- No intra-area transmission congestion
- Yearly wind power penetration is estimated at 30% (energy-wise)
- PHES: E^{max} =3,924 MWh, $E^{\text{min}} = 0.1 \cdot E^{\text{max}}$ =392.4 MWh, P^{max} =1,308 MW, $\aleph^{\text{T}} = \aleph^{\text{P}}$ =0.87.
- Penalty for CO_2 emissions is set to €10/ton
- *VOLL* is set to €10,000/ton
- SUC is solved with 50 scenarios for each day
- IUC is solved with 95-percentile bounds
- Numerical results:
  - One representative day
  - Four representative weeks

Experimental Setup



- UC decisions are tested against random realizations of uncertainty in Monte Carlo (MC) trials

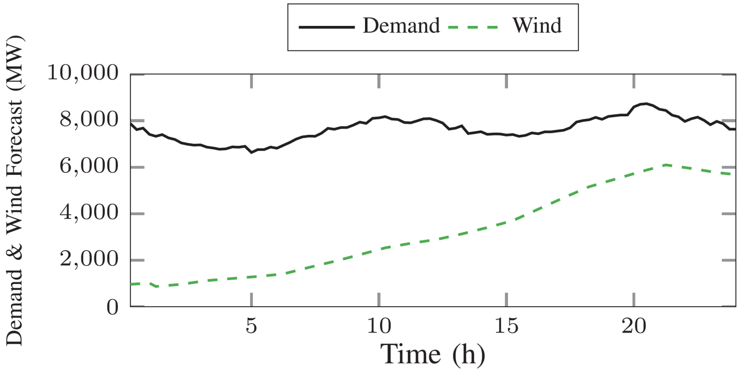
Performance Assessment

- Reliability and cost performance:
  - Evaluated using MC simulations
  - The error of the MC simulation is 1% with a 95% confidence level
  - Up to 500 MC trials

Performance Assessment

- Reliability and cost performance:
  - Evaluated using MC simulations
  - The error of the MC simulation is 1% with a 95% confidence level
  - Up to 500 MC trials
- Computational performance:
  - Models are implemented in GAMS 24.4 and solved with CPLEX 12.6
  - Simulations are run on a ThinKing HPC cluster using a 2.8 GHz machine with 20 cores and 64GB of RAM
  - The duality gap was set to 0.5%

Numerical Results for the Representative Day



Numerical Results for the Representative Day

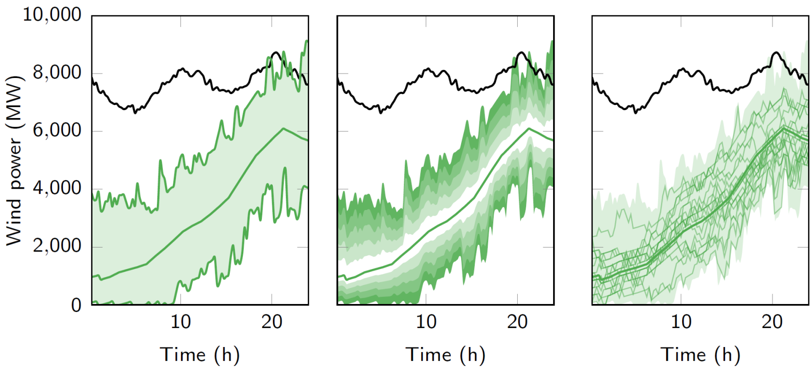
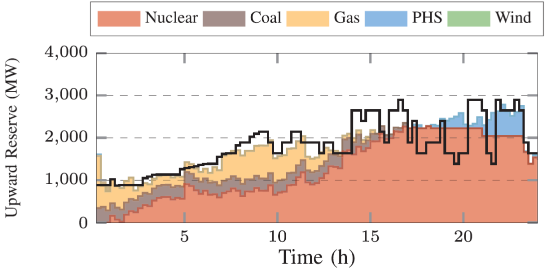
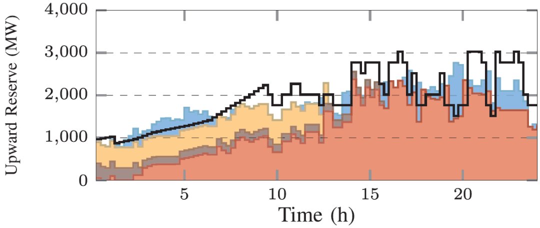


Figure: Wind power uncertainty in A) DUC, B) IUC, C) SUC.

Upward Reserve Provision in IIUC



(a) PHES is not allowed to offer regulating services.



(b) PHES is allowed to offer regulating services.

Upward Reserve Provision in IIUC

- Effect of the PHES on the allocation of regulation reserve:
  - Significantly replaces gas- and coal-fired generation
  - Moderately reduces nuclear power generation reserve capacity.
  - PHES is scheduled to provide regulation reserve during hours with relatively low net load values
- The expected operational costs savings are 0.5%
- Wind power curtailment is reduced by 919 MWh (36%)

Best Week for PHES – W52 (Lowest Net Load)

	DUC		IIUC		SUC
	Arb.	Arb. + Reg.	Arb.	Arb. + Reg.	Arb. + Reg.
TC (M€)	3.3	3.3	3.5	3.1	3.5
ENS (MWh)	0	0	0	0	85.0
WUF (%)	85.8	86.7	83.8	86.5	91.0
SW (%)	74.0	74.8	72.2	74.6	79.0

(c) Week 52 (lowest residual demand)

- The IIUC model is cheaper (in terms of the Total Cost(TC)) than both the DUC and SUC (!)
- The IIUC model is more reliable than the SUC (no ENS)
- However, this improvement in cost and reliability metrics comes at expense of lower wind utilization factor (WUF)

Worst Week for PHES – W9 (Highest Net Load)

	DUC		IIUC		SUC
	Arb.	Arb. + Reg.	Arb.	Arb. + Reg.	Arb. + Reg.
TC (M€)	28.7	28.5	29.2	28.5	28.1
ENS (MWh)	0	0	0	0	16.0
WUF (%)	100	100	100	100	100
SW (%)	13.5	13.5	13.5	13.5	13.5

(b) Week 9 (highest residual demand)

- The IIUC model is more expensive (in terms of the Total Cost(TC)) than the SUC and even than the DUC (in case when it does not provide regulation reserve)
- The IIUC model has better reliability performance (no ENS, unlike in the SUC model)

Summary of the Numerical Results for Four Weeks

- Total cost of operations under the IIUC model without PHES regulation reserve is €56.7M
- Total cost of operations under the IIUC model with PHES regulation reserve is €54M
- Value of PHES regulation services under the IIUC model: $56.7 - 54 =$€ 2.7M $\approx 4.8\%$

Summary of the Numerical Results for Four Weeks

- Total cost of operations under the IIUC model without PHES regulation reserve is €56.7M
- Total cost of operations under the IIUC model with PHES regulation reserve is €54M
- Value of PHES regulation services under the IIUC model: $56.7 - 54 =$€ 2.7M $\approx 4.8\%$
- Cost savings of the IIUC model relative to DUC: $TC[DUC] - TC[IIUC] = 54.4 - 54 =$€$0.4$M $\approx 0.76\%$
- Cost savings of the IIUC model relative to SUC: $TC[SUC] - TC[IIUC] = 54.2 - 54 =$€$0.2$M $\approx 0.38\%$

Computational Performance

Comparison of the CPU Time (s) per Run of the DUC, IIUC and SUC. P(75) is the 75th Percentile

	DUC		IIUC		SUC
	Arb.	Arb. + Reg.	Arb.	Arb. + Reg.	Arb. + Reg.
Median	67	138	228	244	+50,000
P(75)	93	191	507	328	+50,000
P(90)	241	342	768	579	+50,000

- SUC is the most computationally expensive model (expected)
- DUC is faster than IIUC but not significantly
- Introducing regulations services does not affect computing times uniformly

Summary & Conclusion

- PHES is coupled with DUC, SUC and IIUC
- The proposed modeling solutions account for the energy-limited nature of PHES operations
- PHES model enables simultaneous provision of energy arbitrage and regulation services
- The proposed IIUC model systematically achieves significant cost savings relative to the DUC model and requires significantly less computing time than SUC
- IIUC model achieves higher savings for higher wind penetration levels
- DUC is the fastest approach

Thank you!

Reference:

- K. Bruninx, Y. Dvorkin, E. Delarue, H. Pandzic, W. D'haeseleer and D. S. Kirschen, "Coupling Pumped Hydro Energy Storage With Unit Commitment," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 786-796, April 2016. **[pdf]**