Integrating Wind Power Predictability and Locational Flexibility in Power System Balancing

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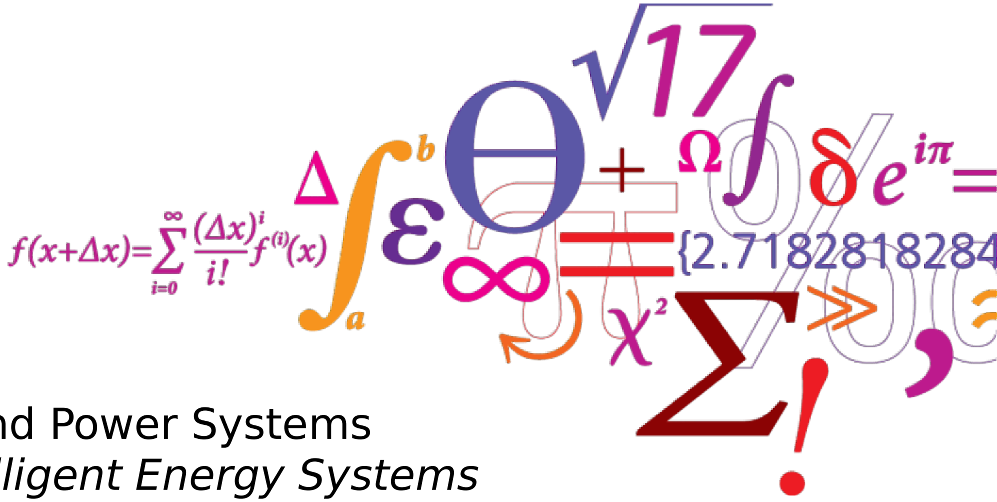

Modeling and Optimization of Heat and Power Systems
Mathematics and Informatics for Intelligent Energy Systems

DTU Electrical Engineering
Department of Electrical Engineering

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Contents

Part I

- Operational Strategies for Predictive Dispatch of Control Reserves [1]

Part II

- Locational Flexibility and Robust Reserve Procurement [2]

[1] S. Delikaraoglou, K. Heussen, and P. Pinson, "Operational strategies for predictive dispatch of control reserves in view of stochastic generation" in Power Systems Computation Conference (PSCC), Wroclaw, Poland, Aug 18-22, 2014. IEEE, 2014, pp. 1–7.

[2] M. Bucher, S. Delikaraoglou, K. Heussen, P. Pinson and G. Andersson, "On Quantification of Flexibility in Power Systems" (submitted) in PowerTech 2015

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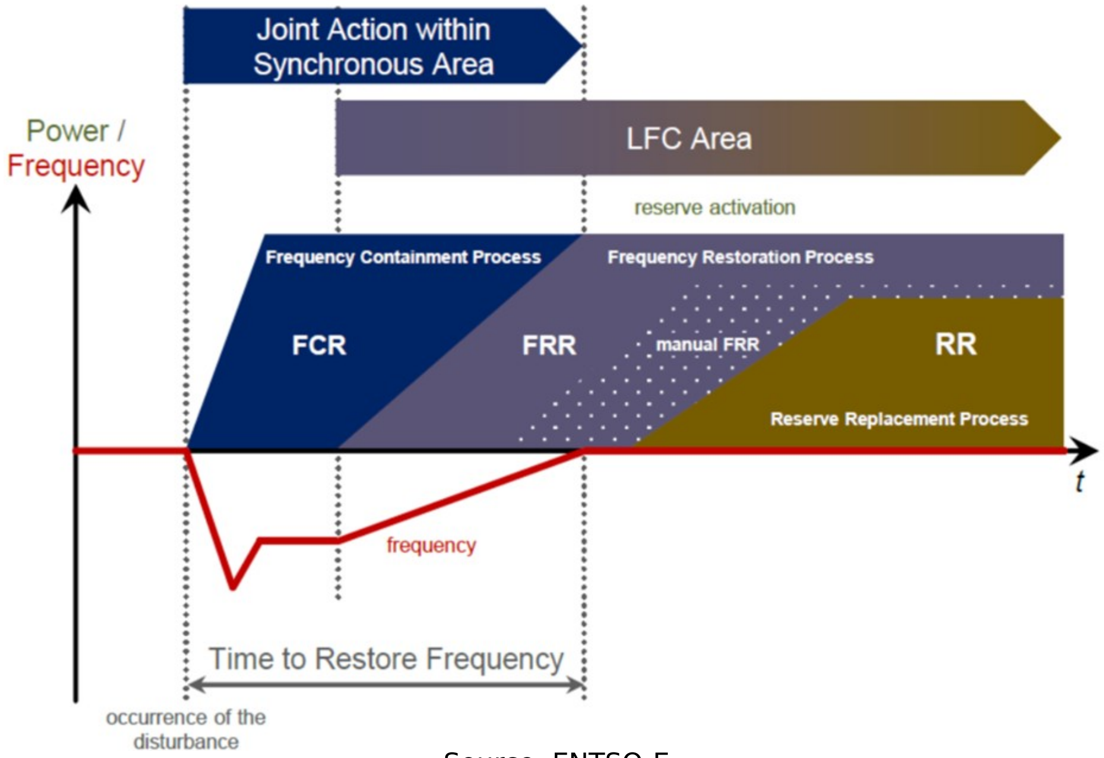
The problem

- Increasing penetration of **stochastic** and **partly predictable** generation
  ✉ Increased needs for balancing reserves

- Conventional balancing operation is mainly **reactive**



Source: ENTSO-E

The problem

- Increasing penetration of **stochastic** and **partly predictable** generation Increased needs for balancing reserves

- Conventional balancing operation is mainly **reactive**

  – Manual Reserves Long minimum activation time (i.e. 1h)
    - Designed for thermal plants
    - Unable to follow intra-hour wind fluctuations

  – Wind power predictability not considered
    - Exhausts automatic reserves
    - Endangering grid security Static reserve needs based on N-1 criterion

The main idea

Reconsider market product definition & the dispatch of manual reserves to find "better" operational strategy.

1. **Predictive dispatch of manual reserves** i.e. make use of predictability of wind power (applied by Energinet.dk)

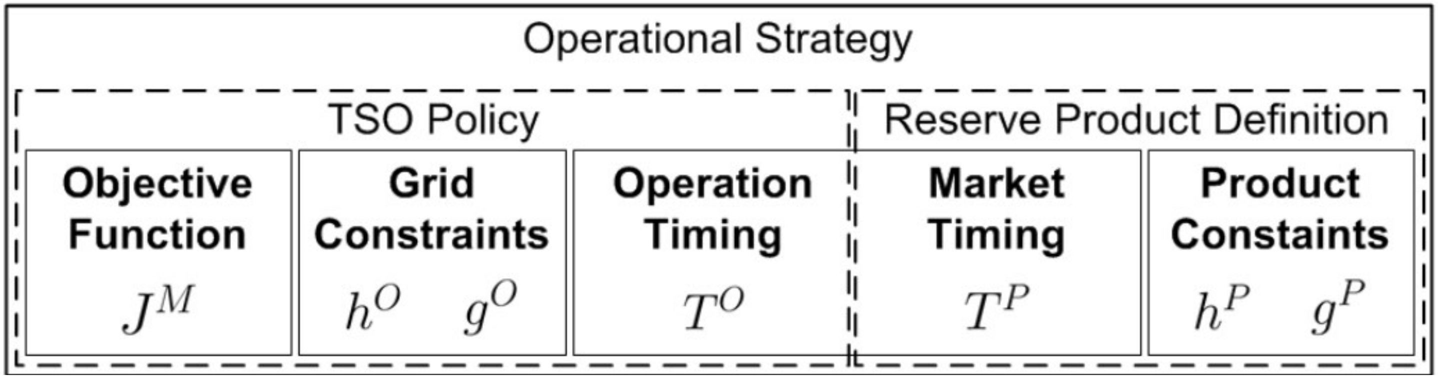
2. Consider **probabilistic aspects** of **short-term forecast uncertainty**

3. Investigate variants of operation strategy, considering alternate ***TSO Dispatch strategy*** & ***product constraints***
   a) Respond to intermittency
   b) Enable participation other balancing resources e.g. demand response

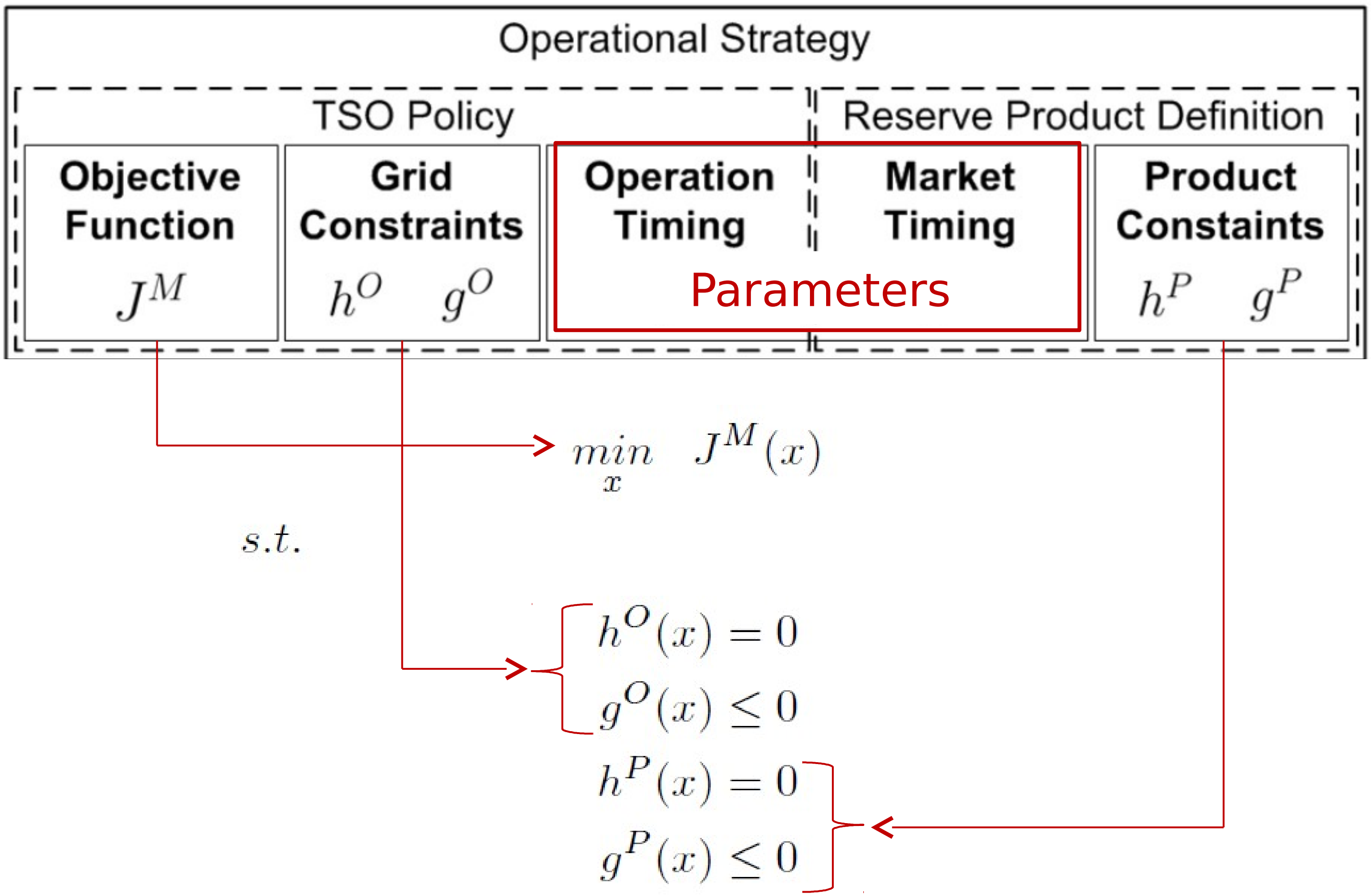
4. Evaluation based on generic **performance criteria**

Definition of Operational Strategy

- Link between the available balancing power products and the decision-making policy of the TSO
- Different problem formulations to be compared in same evaluation framework



Definition of Operational Strategy



Predictive Dispatch of Regulating Power

Deterministic Dispatch

$$\min_{P^M} \quad J^M(P^M)$$

$s.t.$

Point forecasts

$$h^M(P^M, \hat{P}^{imb}) = 0$$
$$g^M(P^M, \hat{P}^{imb}) \leq 0$$

$$h^A(P^A, P^{imb}, P^{M,*}) = 0$$

$$g^A(P^A, P^{imb}, P^{M,*}) \leq 0$$

Optimal schedule of manual reserves

Remaining imbalances covered by automatic reserves

Stochastic Dispatch

Scenarios modeling Uncertainty

$$\min_{P^M, P^A} \quad J^{M,st1}(P^M) + \mathbb{E}_s[J_s^{M,st2}(P_s^A)]$$

$s.t.$

$$h_s(P^M, P_s^A, P_s^{imb}) = 0 \quad \forall s$$
$$g_s(P^M, P_s^A, P_s^{imb}) \leq 0 \quad \forall s$$

2 - stage stochastic programming problem

Joint optimization of manual & automatic reserves

Mathematical Formulation – Objective Functions

Objective J_I^M: Cost minimization

$$\min_{P^M, P^A} J_I^M = \sum_{t=1}^{T} \Big(\sum_{m=1}^{M} \lambda_t^{up}(m) p_t^{up}(m) - \sum_{n=1}^{N} \lambda_t^{dn}(n) p_t^{dn}(n) \Big) + \sum_{t=1}^{T} \sum_{s=1}^{S} \pi_s (c^{a,up} P_{t,s}^{a,up} - c^{a,dn} P_{t,s}^{a,dn})$$

Deployment of:

1. Manual up/down reserve blocks
2. Automatic reserves

Objective J_{II}^M: Minimum automatic reserves utilization

$$\min_{P^M, P^A} J_{II}^M = \sum_{t=1}^{T} \sum_{s=1}^{S} \pi_s (P_{t,s}^{a,up} + P_{t,s}^{a,dn}) \, dt$$

Expected automatic reserve energy utilization

Mathematical Formulation - Constraints

Grid constraint (power balance) h^O:

$$P_t^{up} - P_t^{dn} + P_{t,s}^{a,up} - P_{t,s}^{a,dn} = \Delta P_{t,s}^{w} \quad \forall t, \forall s$$

Power Balance

Reserve products h^P, g^P:

$$P_t^{up} = \sum_{m=1}^{M} p_t^{up}(m) \quad \forall t$$

$$P_t^{dn} = \sum_{n=1}^{N} p_t^{dn}(n) \quad \forall t$$

$$0 \leq p_t^{up}(m) \leq p_t^{up,max}(m) \quad \forall t, \forall m$$

$$0 \leq p_t^{dn}(n) \leq p_t^{dn,max}(n) \quad \forall t, \forall n$$

Definition of energy offers for Up/Down regulation

$$P_t^{up} = P_\tau^{up} \quad t \geq \tau \text{ and } t \leq \tau + T_{min}^{up} - 1$$

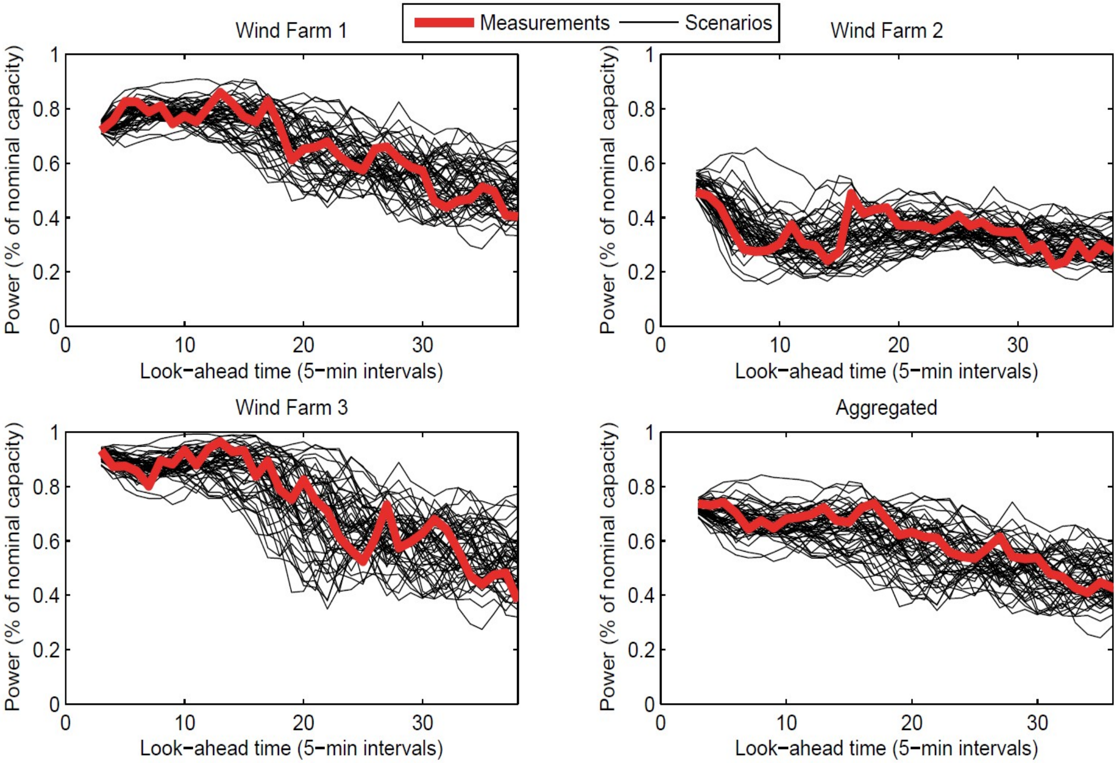
$$P_t^{dn} = P_\tau^{dn} \quad t \geq \tau \text{ and } t \leq \tau + T_{min}^{up} - 1$$

Time resolution of the balancing market ✉

Re-dispatch on specific time steps

Modeling of Uncertainty

- Wind uncertainty modeling using scenarios
- Temporal interdependence structure of forecast errors
- Predictive densities approximated by Beta distributions



Case Study
Parameters of Operational Strategies

Variation with respect to:

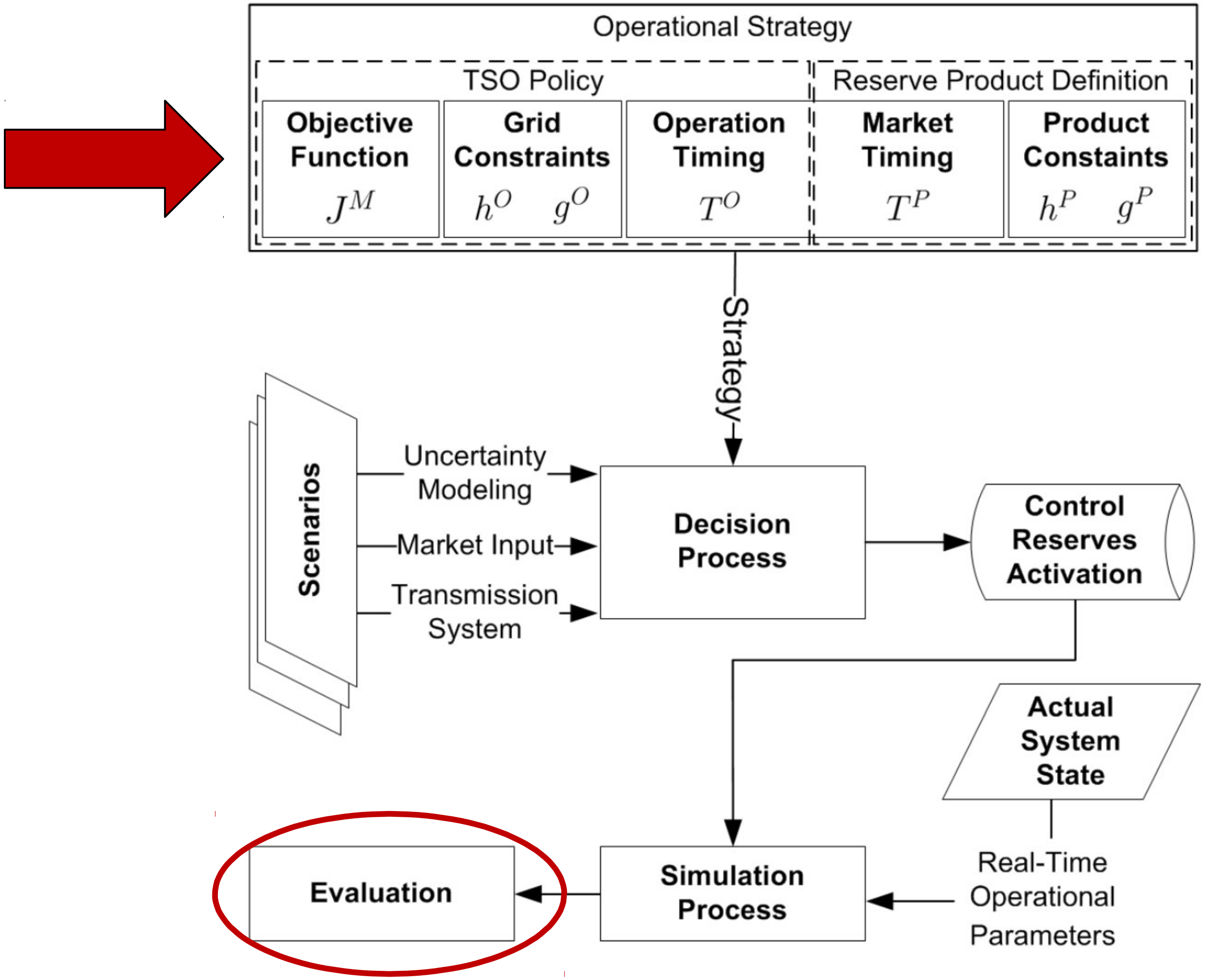
1. **Minimum up time** ✉ More frequent re-dispatching
2. **Lower lead-time** ✉ Improved wind forecasts
3. **Objective function** ✉ TSO interests during balancing

	S1	S2	S3	S4	S5	S6
T^{up}_{min} (min)	60	60	60	60	30	30
T^{lt} (min)	15	30	15	30	15	15
Objective	J^M_I	J^M_I	J^M_{II}	J^M_{II}	J^M_I	J^M_{II}

Evaluate with respect to **Performance Metrics**:

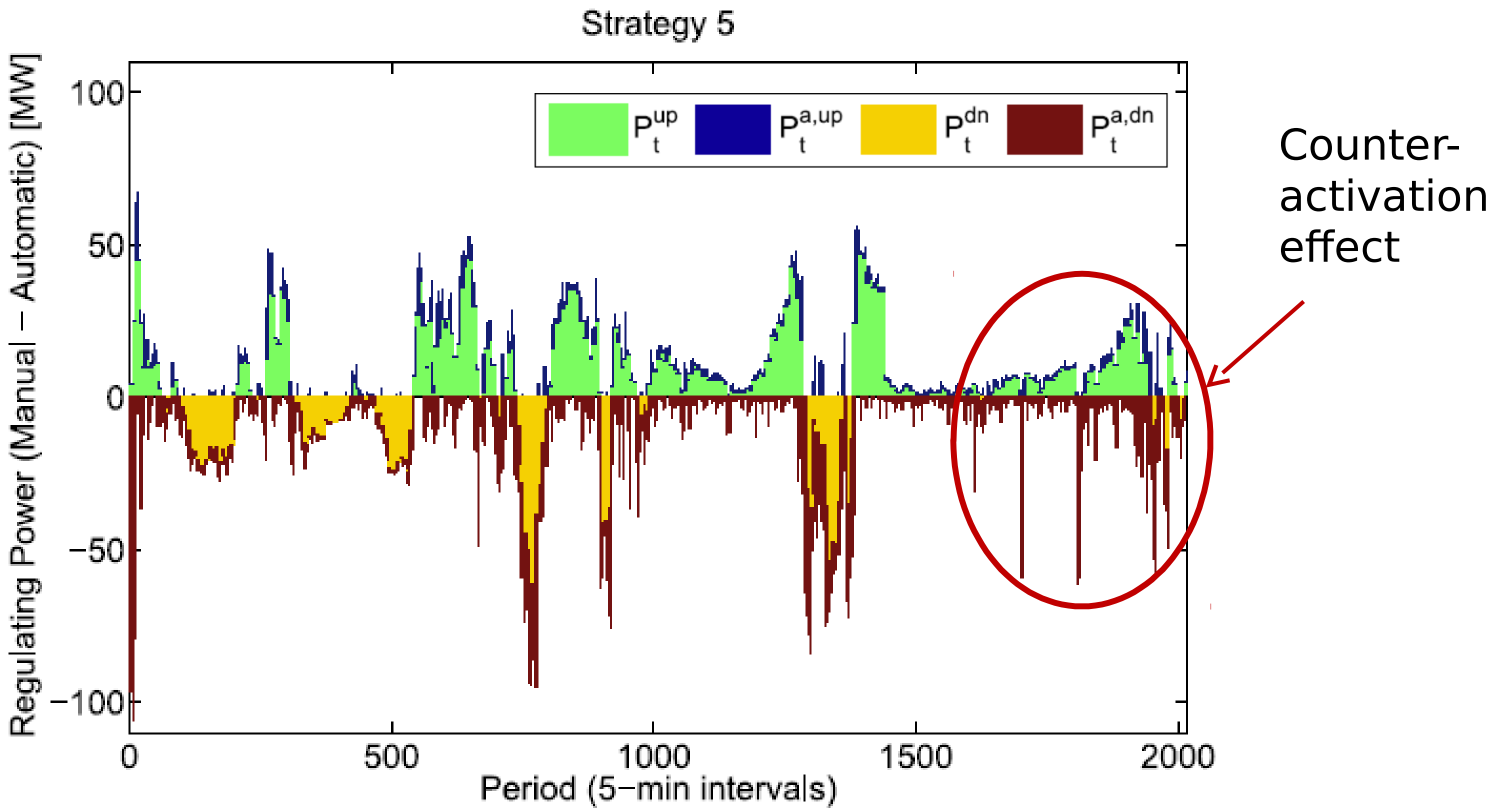
4. Total operating cost
5. Maximum power capacity
6. Energy utilization

Simulation setup



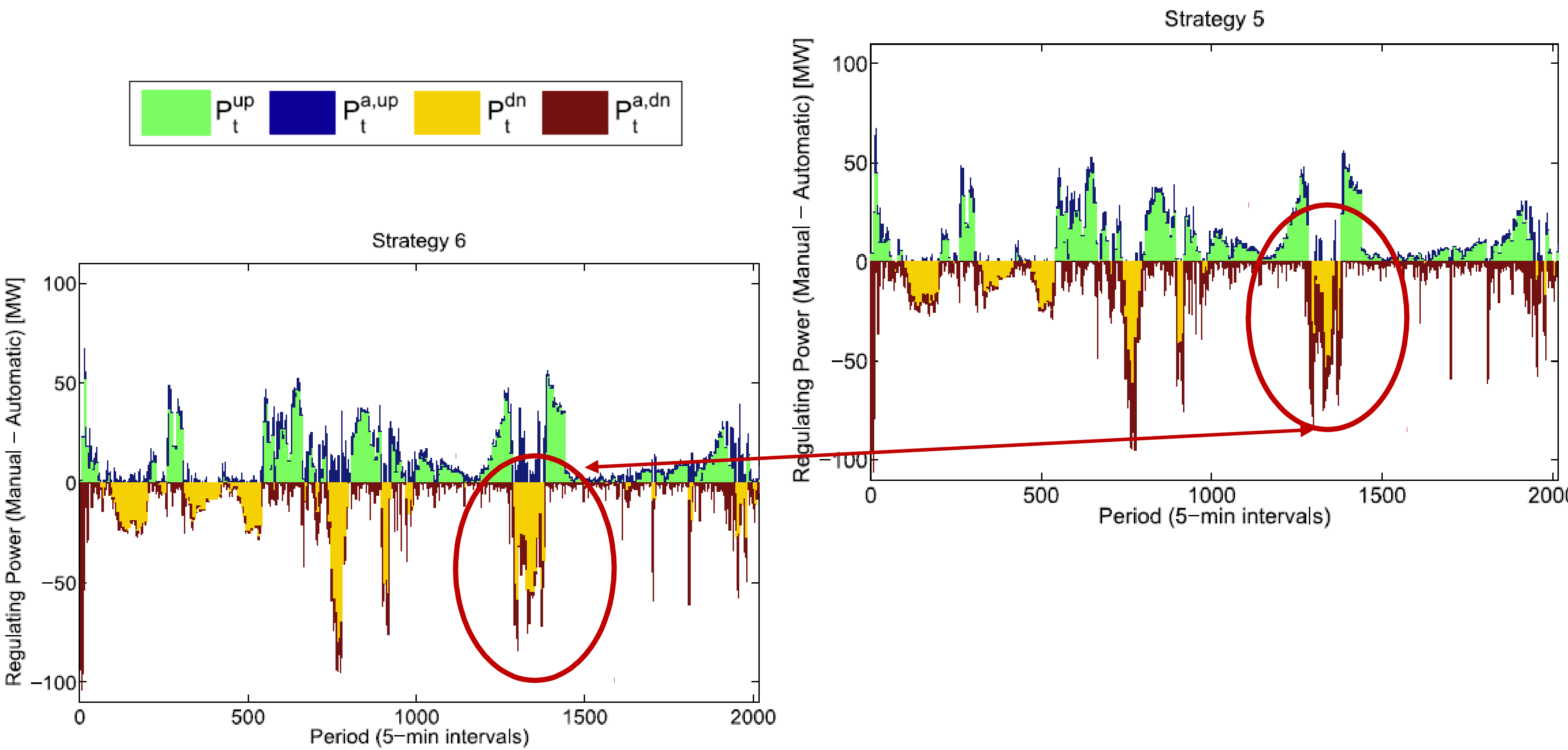
Simulation Results
Manual and automatic reserve dispatch

- Period of 1 month
- 5-minute resolution
- Real wind power data from AEMO



Simulation Results
Manual and automatic reserve dispatch

Strategies S3, S4, S6 (obj. function J_{II}^{M}) higher amounts of manual reserves



Evaluation of Operational Strategies

- Performance Metrics
  - Objective function J_I^M ✉ Reduced total balancing costs
  - Shorter lead time ✉ Marginal effect on balancing operation
  - Lower minimum up time ✉ Highest positive effect on cost & reserve needs (Importance of market rules & product definition)

	S1	S2	S3	S4	S5	S6
T_{min}^{up} (min)	60	60	60	60	30	30
T^{lt} (min)	15	30	15	30	15	15
Objective	J_I^M	J_I^M	J_{II}^M	J_{II}^M	J_I^M	J_{II}^M

Performance Metric	S1	S2	S3	S4	S5	S6
Total Cost ($\times 10^3$€)	652.83	662.29	907.01	909.51	**602.49**	810.58
Max P_t^{up} (MW)	**46.27**	46.36	48.09	47.97	46.95	53.73
Max P_t^{dn} (MW)	**52.69**	54.29	76.25	79.51	66.39	80
Max $P_t^{a,up}$ (MW)	35.94	37.26	65.20	73.13	**30.30**	39.25
Max $P_t^{a,dn}$ (MW)	104.76	102.37	100.73	**96.69**	105.97	103.93
E^M (GWh)	**2.17**	2.21	2.53	2.56	2.23	2.54
E^A (GWh)	1.25	1.23	1.06	1.05	1.04	**0.86**

Summary & Conclusions

- Framework for the definition of operational strategies and evaluation using performance criteria
- Variations of predictive operational strategies to cope with increased wind uncertainty

- Trade-offs - balancing cost vs. reliability
- Limited effect of shorter lead time
- Significant impact of balancing product definition (Min Up Time) on power system flexibility

Summary & Conclusions

- Framework for the definition of operational strategies and evaluation using performance criteria
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- Trade-offs - balancing cost vs. reliability
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- Significant impact of balancing product definition (Min Up Time) on power system flexibility

- Future work:
  - Consider “Flexibility” w.r.t. further variations on balancing products (e.g. energy & ramping)
  - Network representation
  - Different time resolution dispatch optimization & simulation

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Goals

- Determining (explicitly) the operational flexibility that is available at a certain point in the system
  - helpful in planning, operation, investment, visualization (compared to stochastic approaches)

- Characterizing the uncertainty arising at some bus in same metric
  - comparable: explicit information about flexibility needs (compared to «scenarios»), combination of uncertainty and flexibility in one framework

- Using explicit information directly in a robust procurement process
  - Less computational intensive than stochastic optimization

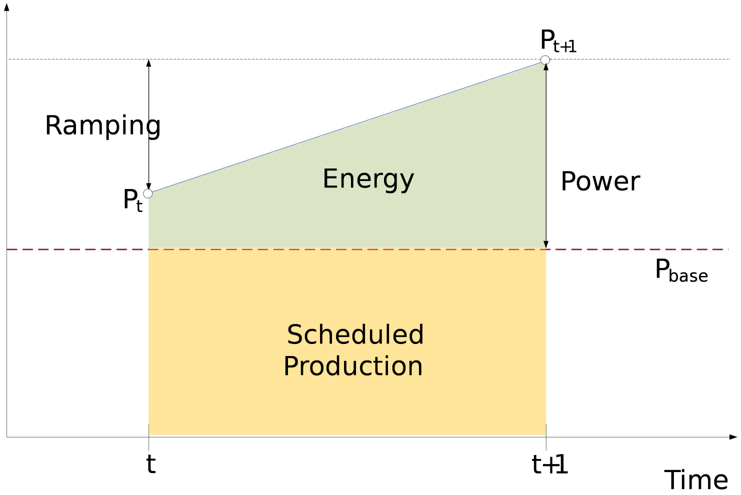
- Unified/applicable to different types of units using common metric

Definitions

- *Operational flexibility:*

The ability of a power system to counteract a disturbance sufficiently fast in order to keep the system secure.

Metric:
- Ramping rate *R*
- Power capacity *P*
- Energy *E*



- *Locational flexibility:*

Operational flexibility that can be accessed at a given bus in the grid.

Locational Flexibility Characterization = Flexibility Set

1. Determine flexibility of every single unit.
   Formulation based on Power Nodes [3] over multiple time steps.

2. Attach a «flexibility drain» = generic disturbance at bus of interest

3. Impose system-wide constraints: transmission limits, power balance

4. From 1.-3.: Build set of feasible system states.
   Find limits of the disturbance by projecting on the dimensions of the «flexibility drain»

[3] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, "Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation," Systems Journal, IEEE, vol. 6, no. 1, pp. 140–151, March 2012.

Locational Flexibility Characterization = Flexibility Set

Flexibility set F = all possible set points of the system that are stable

State variables of flexible units

State variables of «flexibility drain»

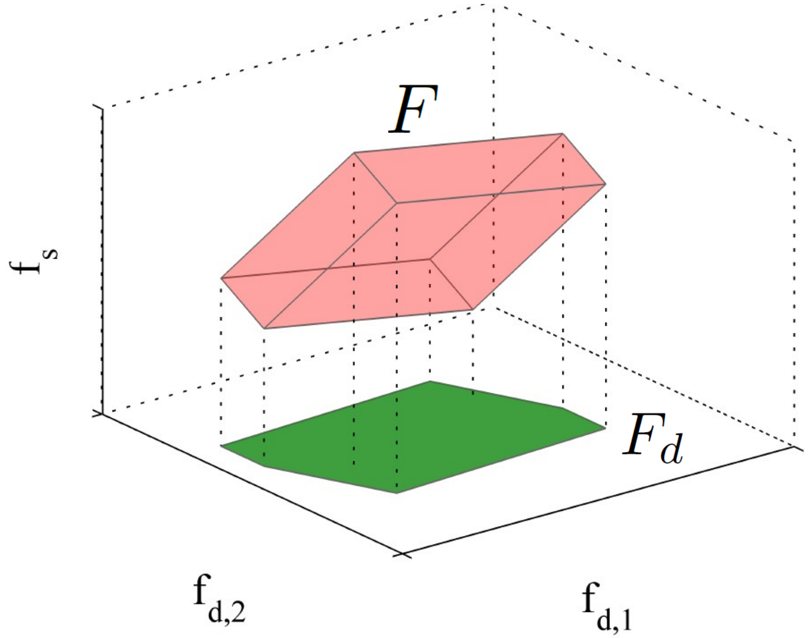
$$F = \{(f_d, f_s) \in \mathbb{R}^{n_d+n_s} | C_s f_s + C_d f_d \le b\}$$

Limitations of system:

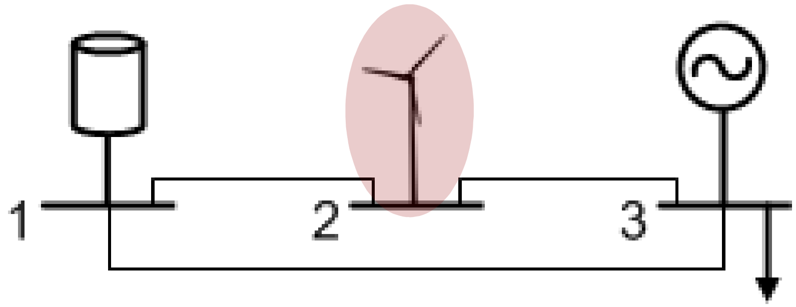
- Grid constraints
- Generation constraints
- …

Explicit Formulation of Locational Flexibility (Projection)

$$F_d = \{f_d \in \mathbb{R}^{n_d} | \ \exists \ f_s, (f_d, f_s) \in F\}$$
$$= \{f_d \in \mathbb{R}^{n_d} | \ G f_d \leq g\}$$



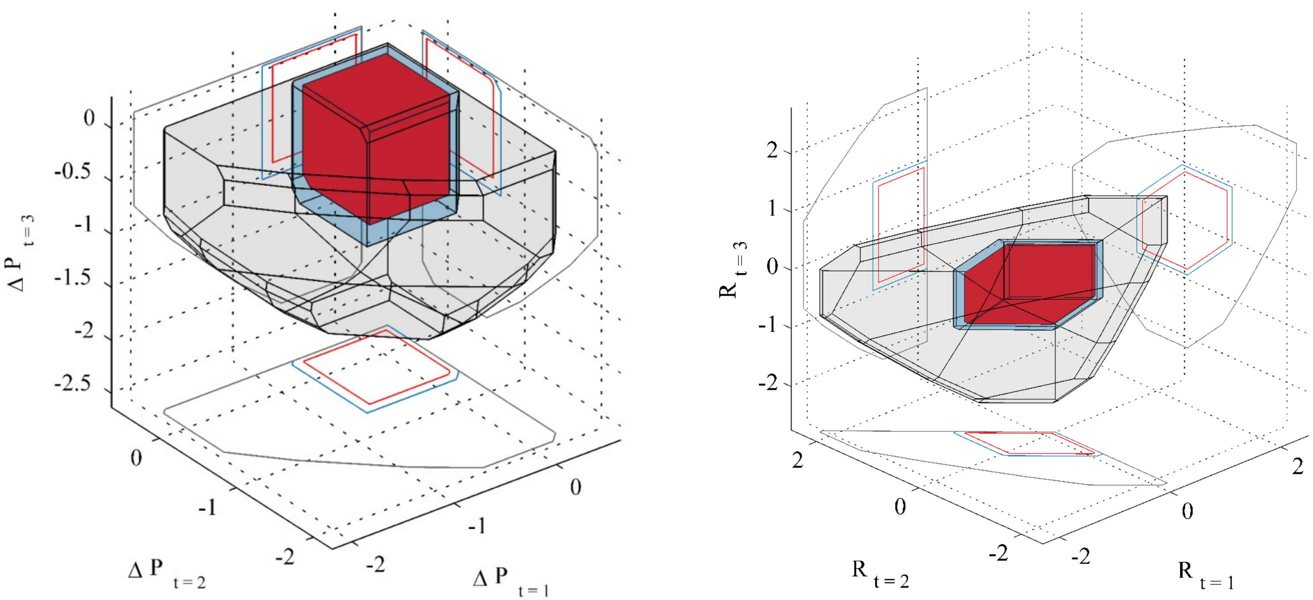
Case Studies (I)



Type	Bus	E_{max}	$P_{min}/P_{act}/P_{max}$	R_{min}/R_{max}	Cost E/P/R
Storage	1	0.05/0.1	0.05/50%/1	-1/1	0/10/1
Wind farm	2	-	0/1/1	-1/1	0/2/1
Conv. Gen.	3	-	0/1/2	-0.05/0.05	0/3/50
Load	3	-	2	-	-

From-To Bus	Capacity (p.u.)
1-2	0.3-0.45
1-3	0.3-0.45
2-3	0.7

Case Studies (I) – Locational Flexibility at Bus 2



Line ratings:

- Low
- Medium
- Infinite

Possible combinations of power disturbances and ramping rates at bus 2 for three time steps ~ Bounds of evolution of a forecast error

Reserve Procurement with Explicit Flexibility Needs

- Goal: Procure sufficient capacity for re-dispatching considering explicit flexibility needs.

- Possible Applications:
  - Operation
    - Sufficient capacity available for predicted situation?
  - Procurement/Planning
    - As addition to current procurement mechanisms, to check whether sufficient capacity for buses with explicit flexibility needs is available
    - Incentive for wind park to limit uncertainty by itself
  - Investment
    - Where to invest in flexibility

Reserve Procurement – Robust Optimization (I)

Reserves

$$\min_{\Delta b_i, f_s} \; C_{prod}^T \Delta b_i + \mathcal{L}(\Delta b_i)$$

$$\text{s.t.} \; \Delta b_i^{min} \leq \Delta b_i \leq \Delta b_i^{max}$$

$$\mathcal{L}(\Delta b_i) = \max_{\delta} \quad \min_{f_s} C_{op}^T f_s$$

Day-ahead dispatch

$$\text{s.t.} \; C_s f_s + C_d \delta \leq b_0 + \Delta b_i$$

$$f_s \geq 0$$

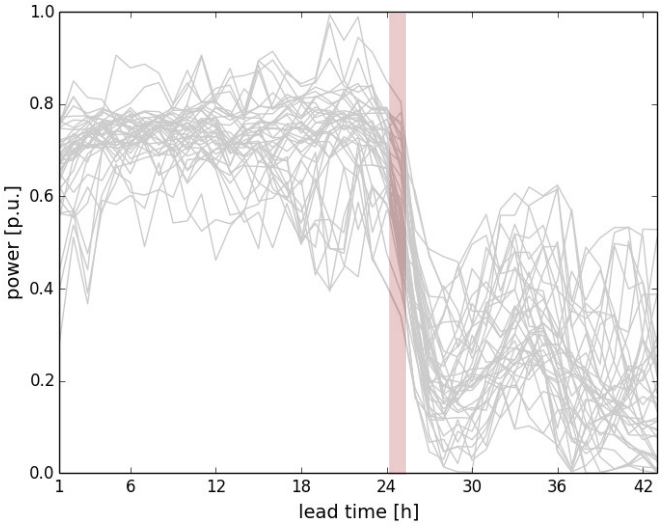
$$\text{s.t.} \quad \delta \in \mathcal{W}$$

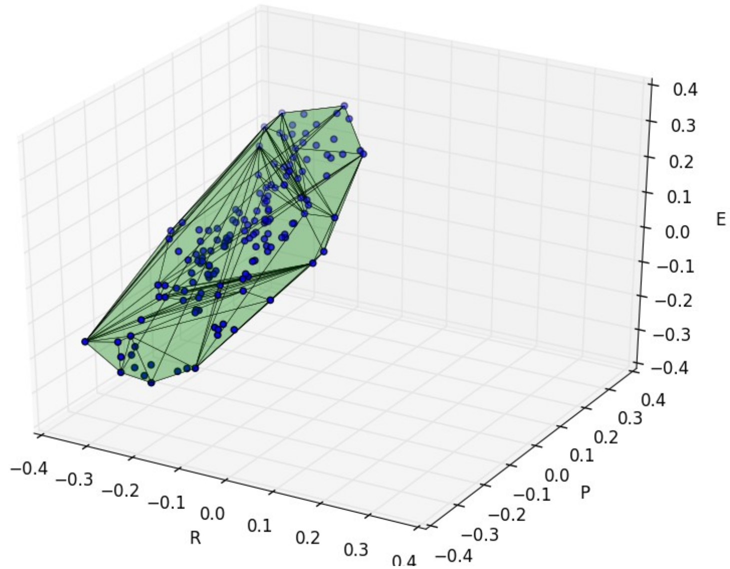
Uncertainty set

Reserve Procurement – Uncertainty Set (I)

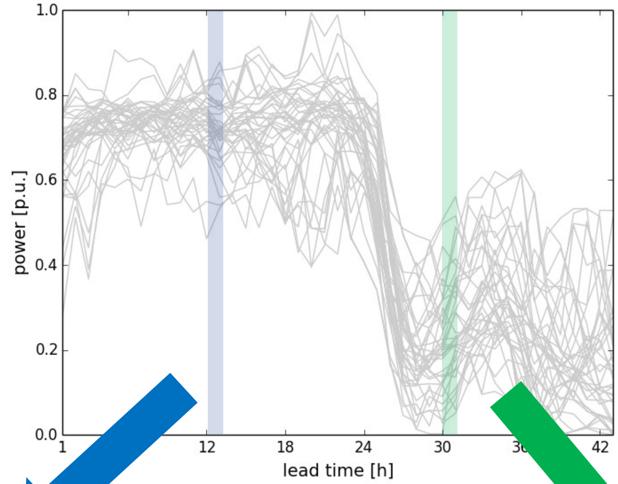
Express flexibility needs in [*R*,*P*,*E*] metric

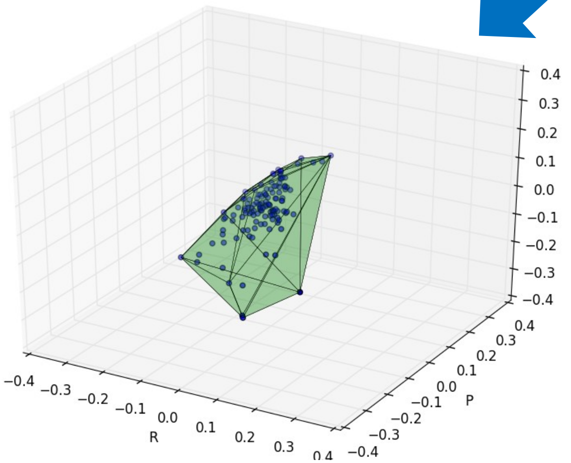
$$\mathcal{W} = \{\delta : S\delta \leq h\}$$

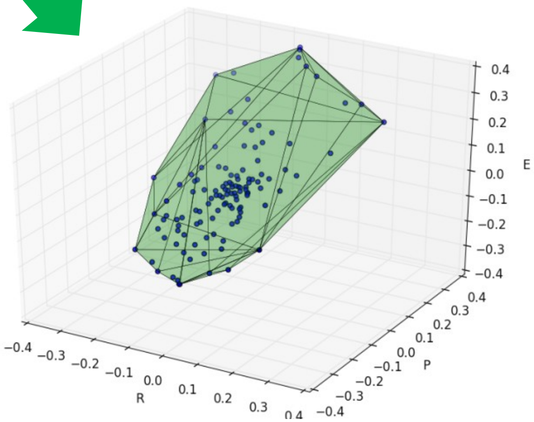




Reserve Procurement – Uncertainty Set (II)







Reserve Procurement – Robust Optimization (II)

$$\mathcal{L}(\Delta b_i) = \max_{\delta} \quad \min_{f_s} C_{op}^T f_s$$
$$\text{s.t. } C_s f_s + C_d \delta \leq b_0 + \Delta b_i$$
$$f_s \geq 0$$
$$\text{s.t.} \quad \delta \in \mathcal{W}$$

DUAL

$$\max_{\mu} \; (C_d \delta - \Delta b_i - b)\, \mu$$

$$s.t.$$

$$-C_s^T \mu \leq C_o^T p$$
$$\mu \geq 0$$

Reserve Procurement – Robust Optimization (III)

Bilinear Term

$$\min_{\Delta b_i} C_{proc}^T \Delta b_i \quad + \max_{\delta,\mu} C_d \delta\mu + (\Delta b_i - b)\mu$$

$$s.t.$$

$$-C_s^T \mu \le C_{op}^T$$

$$\mu \ge 0$$

$$s.t.$$

$$\Delta b_i^{min} \le \Delta b_i \le \Delta b_i^{max}$$

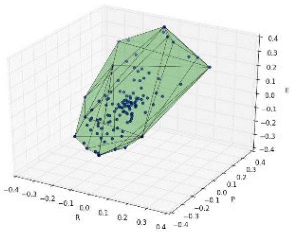
Reserve Procurement – Robust Optimization (IV)

- $\mathcal{W}$ Polyhedral set ✉ Optimal solution one of the vertices
- Δb_i not in the bilinear problem ✉ Finite number of vertices

Worst-case recourse cost

$$\min_{\Delta b_i, C_{op}^{wc}, f_{s,v}} \quad C_{proc}^T \Delta b_i + \boxed{C_{op}^{wc}}$$

$s.t.$



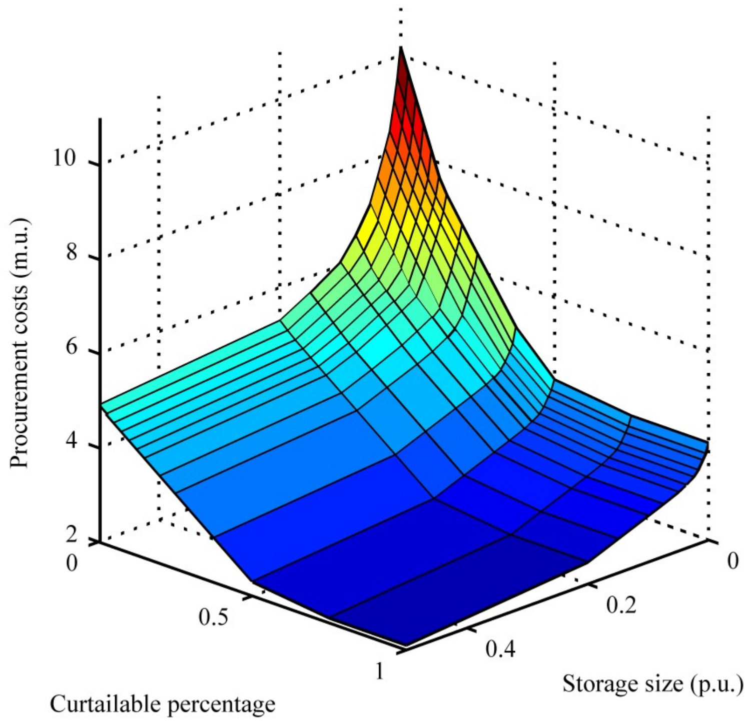
$$C_{op}^{wc} \geq C_{op}^T f_{s,v}, \ \forall v = A, ..., H$$

$$C_s f_{s,v} + C_d \delta_v \leq b + \Delta b_i, \ \forall v = A, ..., H$$

$$\Delta b_i^{min} \leq \Delta b_i \leq \Delta b_i^{max}$$

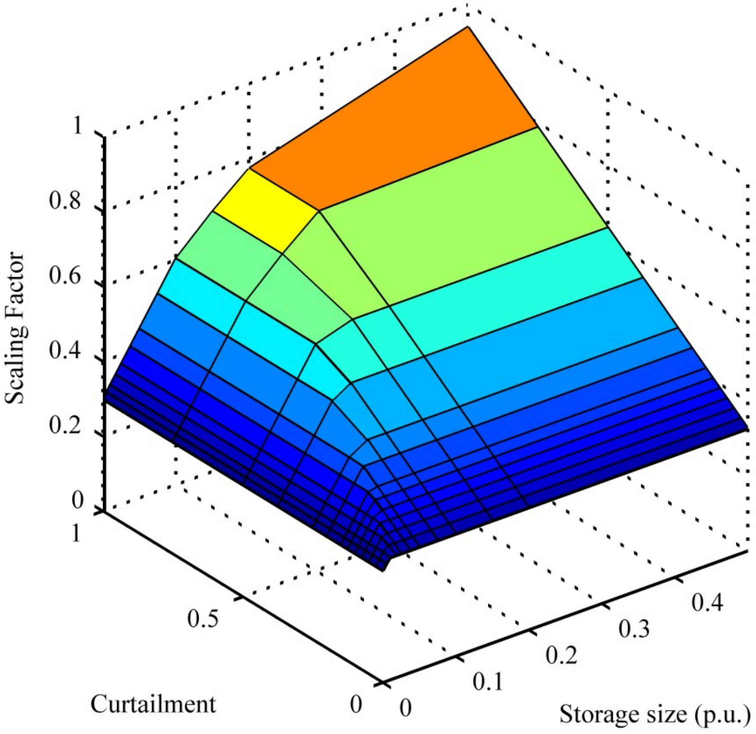
$$f_{s,v} \geq 0$$

Case Studies (II) –
Procurement Cost vs. Storage and Curtailment



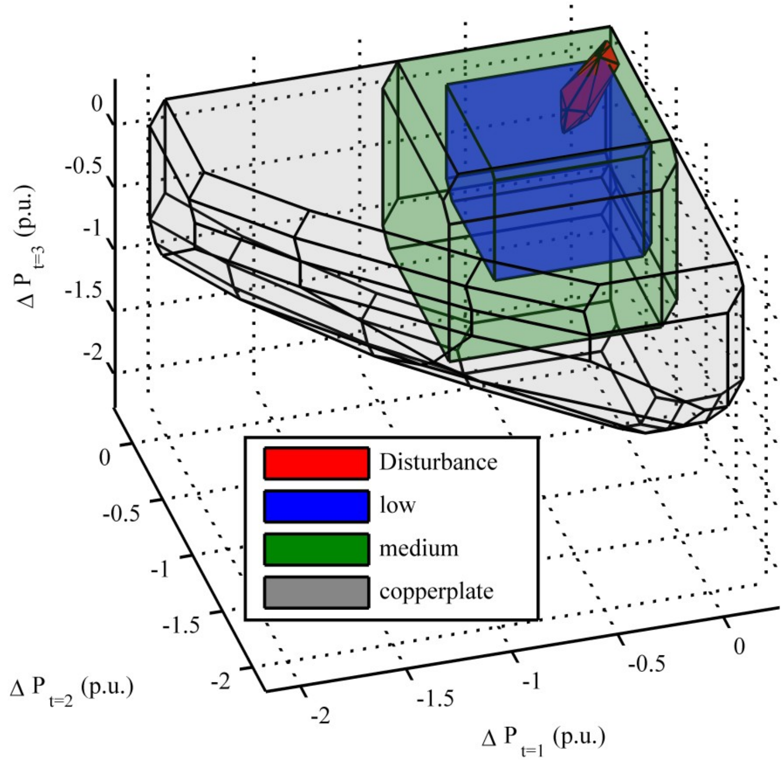
Upper limit of maximum disturbances at bus 2 for different storage capacities and curtailment possibilities.

Case Studies (III) – Uncertainty Scaling



Scaling factor of the uncertainty polytope vs. curtailment and storage size

Case Studies (IV) – Maximal Flexibility



Maximal flexibility for three different transfer capacity levels.

Summary & Conclusions

- Locational flexibility to define the ability of the system to counteract a certain disturbance at a given node in terms of [R,P,E].

- Unified framework to quantify and compare the available flexibility with the forecast uncertainty.

- Robust procurement algorithm to guarantee sufficient locational flexibility for the worst-case realization of the uncertainty.

Thank you for your attention !

Questions?

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