Políticas Afines para el Despacho y la Gestión del Almacenamiento Energético

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Complex Energy Systems Workshop

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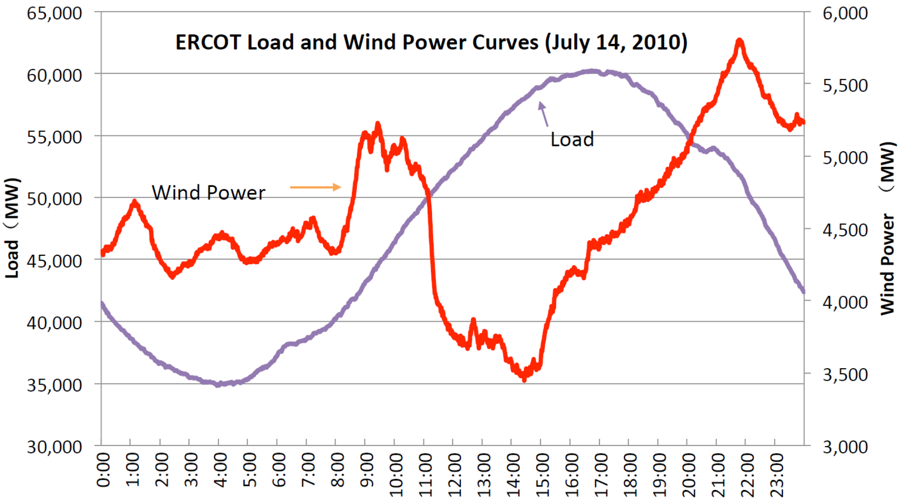
New paradigms in power system operations

The challenge of uncertainty



The value of energy storage

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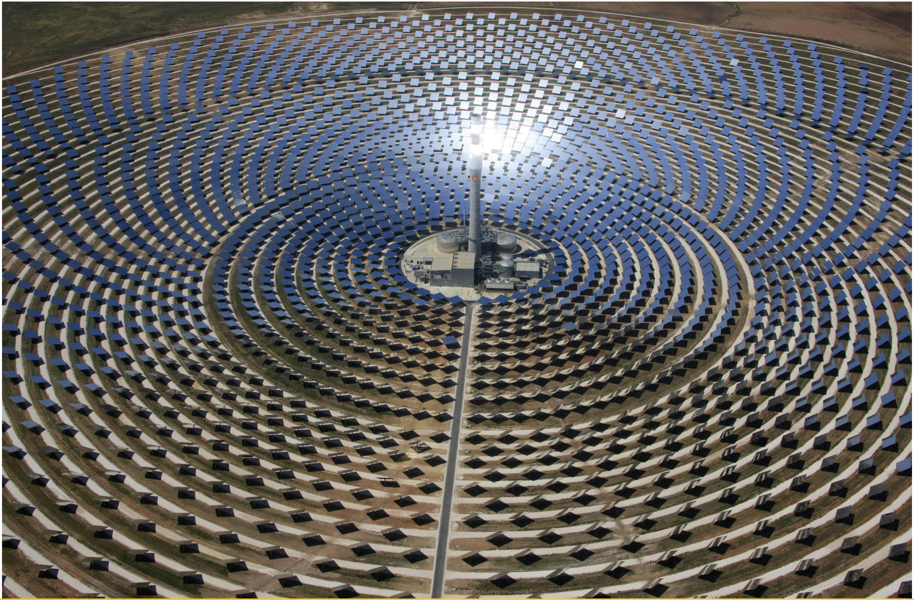
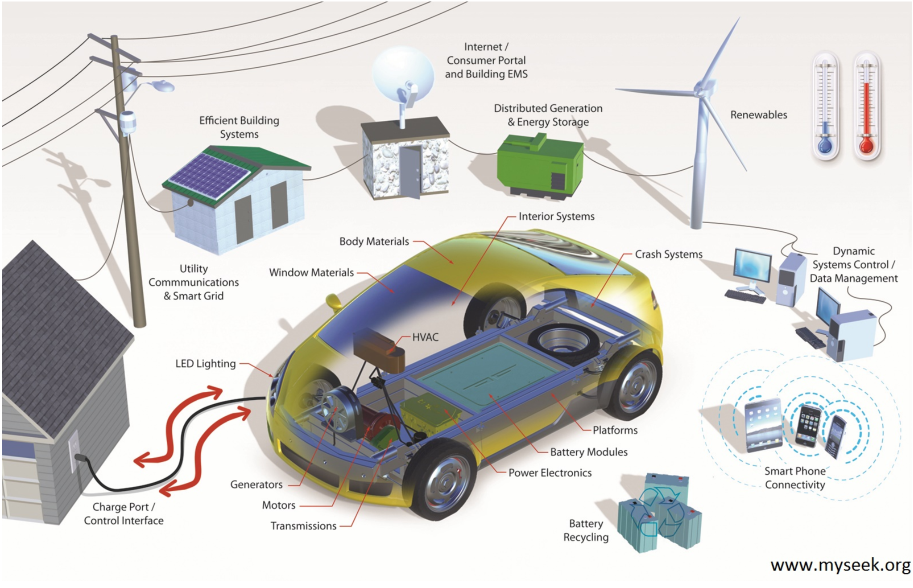
The value of energy storage



The value of energy storage



Research Questions

In general

How should *flexible resources* operate under a significant presence of wind and solar power?

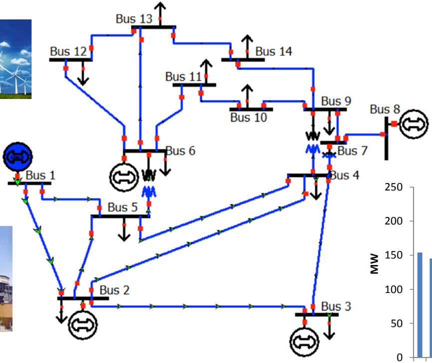
In particular

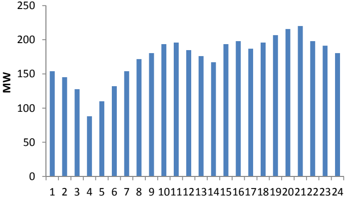
How should *energy storage resources* respond to the very-short-term variations of variable energy sources?

Outline

Outline

Day-ahead Unit Commitment and real-time Economic Dispatch



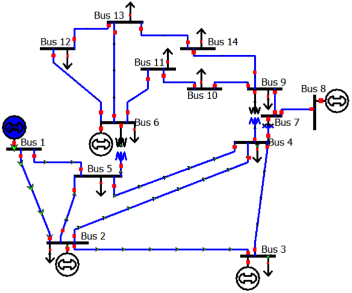


$x =$

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Gen 1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0
Gen 2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
...				...				...				...				...				...				
Gen N	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0

Deterministic UC

x_{it}: On/off decision (binary)
p^g_{it}: Power dispatch (MW)



$$\min_{\boldsymbol{x},\,\boldsymbol{p}} \left\{ \boldsymbol{c}^\top x + \sum_{i\in\mathcal{N}_g}\sum_{t\in\mathcal{T}} C^g_i\, p^g_{it} \right\}$$

s.t. $\boldsymbol{x} \in X$

$$x_{it}\,\underline{p}^g_{it} \le p^g_{it} \le x_{it}\,\overline{p}^g_{it} \qquad \forall i \in \mathcal{N}^g, t \in \mathcal{T}$$

$$0 \le p^r_{it} \le \overline{p}^r_{it} \qquad \forall i \in \mathcal{N}^r,\ t \in \mathcal{T}$$

$$\underline{p}^{s+}_{it} \le p^{s+}_{it} \le \overline{p}^{s+}_{it} \qquad \forall i \in \mathcal{N}^s,\ t \in \mathcal{T}$$

$$\underline{p}^{s-}_{it} \le p^{s-}_{it} \le \overline{p}^{s-}_{it} \qquad \forall i \in \mathcal{N}^s,\ t \in \mathcal{T}$$

$$-RD_{it} \le p^g_{it} - p^g_{i,t-1} \le RU_{it} \qquad \forall i \in \mathcal{N}^g, t \in \mathcal{T}$$

$$0 \le q^s_{i0} + \sum_{\tau\in[1:t]} \left(\sigma^s_i\, p^{s-}_{i\tau} - p^{s+}_{i\tau} \right) \le \overline{q}^s_i \qquad \forall i \in \mathcal{N}^s,\ t \in \mathcal{T}$$

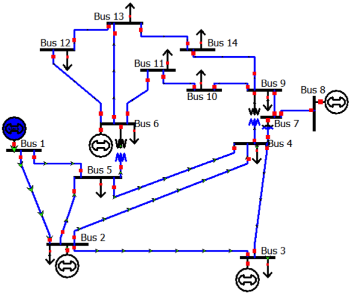
$$-f^{max}_l \le \boldsymbol{\alpha}^{grs}_l\, \boldsymbol{p}_t - \boldsymbol{\alpha}^d_l\, \boldsymbol{d}_t \le f^{max}_l \qquad \forall l \in \mathcal{N}^l,\ t \in \mathcal{T}$$

$$\sum_{j\in\mathcal{N}^d} d_{jt} = \sum_{i\in\mathcal{N}^g} p^g_{it} + \sum_{i\in\mathcal{N}^r} p^r_{it} + \sum_{i\in\mathcal{N}^s} \left(p^{s+}_{it} - p^{s-}_{it} \right) \qquad \forall t \in \mathcal{T}$$

Current practice: reserve-based rules

r_{it}: Power reserve (MW)

R_t: Reserve requirement (MW)



Reserve provided $\quad p_{it} + r_{it} \leq p_i^{max} x_{it} \quad \forall i \in \mathcal{N}^g, t \in \mathcal{T}$

System reserve requirement $\quad \sum_{i \in \mathcal{N}^g} r_{it} \geq R_t \quad \forall t \in \mathcal{T}$

- Uncertainty not explicitly modeled
- How to select reserve requirements?
- Transmission not fully understood

Literature: Robust Optimization for UC and ED

Single-stage approaches (no recourse)

- **UC with security**: Street, Oliveira and Arroyo (2011)
- **ED with statistical models**: Xie, Gu, Zhu and Genton (2014)

Two-stage approaches

- **UC with demand response**: Zhao and Zeng (2012); Zhao, Wang, Watson and Guan (2013)
- **UC with load uncertainty**: Bertsimas, Litvinov, Sun, Zhao and Zheng (2013)
- **UC with $N-k$ security**: Wang, Watson and Guan (2013)
- **Automatic Gen. Control**: Zheng, Zhao, Litvinov and Zhao (2012)
- **Do-not-exceed limit for wind power**: Zhao, Zheng and Litvinov (2014)

Affine policies

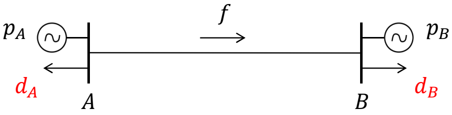
- **Automatic Gen. Control**: Jabr (2013)
- **Stochastic ED, storage**: Warrington, Goulart, Mariethoz and Morari (2013)

Outline

Example

p_A: Power dispatch (MW)

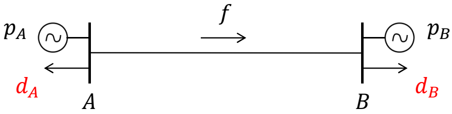
d_A: Load (MW)



$$
\begin{aligned}
\min_{\boldsymbol{p}} \quad & 10\,p_A + 20\,p_B && \text{(operational cost)} \\
\text{s.t.} \quad & 0 \le p_A \le 200 && \text{(production bounds)} \\
& 0 \le p_B \le 200 && \text{(production bounds)} \\
& f(\boldsymbol{p}, \boldsymbol{d}) = (p_A - d_A) - (p_B - d_B) \le 60 && \text{(transmission capacity)} \\
& p_A + p_B \ge d_A + d_B && \text{(power demand)}
\end{aligned}
$$

- If we know $(d_A, d_B) = (100, 100)$ then $(p_A^*, p_B^*) = (130, 70)$
- But what if all we know is that $d_A \in [80, 120]$, $d_B \in [80, 120]$?

Example



$(p'_A, p'_B) = (120, 120)$ is a *robust* solution

For *any* $d_A \in [80, 120]$, $d_B \in [80, 120]$ we have

$$f(\boldsymbol{p}', \boldsymbol{d}) = (p'_A - d_A) - (p'_B - d_B) \leq 60 \qquad \text{(transmission capacity)}$$
$$p'_A + p'_B \geq d_A + d_B \qquad \text{(power demand)}$$

Table: Power flow under $\boldsymbol{p}' = (120, 120)$

d_A	d_B	$f(\boldsymbol{p}', \boldsymbol{d})$
80	80	0
80	120	40
120	80	-40
120	120	0

How to represent adaptive decisions?

Multistage adaptive decision making problems

Decisions at time t can adapt to the information revealed so far

Observation		$\boldsymbol{d}_1$	$\boldsymbol{d}_2$	$\cdots$	$\boldsymbol{d}_t$	$\cdots$	$\boldsymbol{d}_T$
Decision	$\boldsymbol{x}$	$\boldsymbol{p}_1$	$\boldsymbol{p}_2$		$\boldsymbol{p}_t$		$\boldsymbol{p}_T$
Time		$t=1$	$t=2$	$\cdots$	t	$\cdots$	$t=T$

Key observation

$\boldsymbol{p}_t$ can be seen as a function of $\boldsymbol{d}_{[t]} = (\boldsymbol{d}_1, \ldots, \boldsymbol{d}_t)$

Decision rule $\boldsymbol{p}_t\left(\boldsymbol{d}_{[t]}\right)$

Multistage robust UC

$$\min_{\boldsymbol{x},\,\boldsymbol{p}(\cdot)} \left\{ \boldsymbol{c}^\top x + \max_{\overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r} \sum_{i\in\mathcal{N}_g} \sum_{t\in\mathcal{T}} C_i^g \, p_{it}^g(\overline{\boldsymbol{p}}^r_{[t]}) \right\}$$

s.t. $\boldsymbol{x} \in X$

$$x_{it}\, \underline{p}_{it}^g \leq p_{it}^g(\overline{\boldsymbol{p}}^r_{[t]}) \leq x_{it}\, \overline{p}_{it}^g \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^g, t \in \mathcal{T}$$

$$0 \leq p_{it}^r(\overline{\boldsymbol{p}}^r_{[t]}) \leq \overline{p}_{it}^r \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^r, t \in \mathcal{T}$$

$$\underline{p}_{it}^{s+} \leq p_{it}^{s+}(\overline{\boldsymbol{p}}^r_{[t]}) \leq \overline{p}_{it}^{s+} \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^s, t \in \mathcal{T}$$

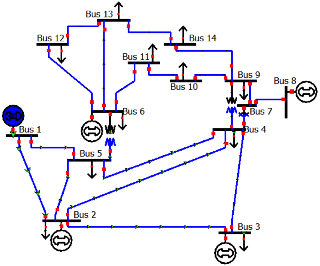
$$\underline{p}_{it}^{s-} \leq p_{it}^{s-}(\overline{\boldsymbol{p}}^r_{[t]}) \leq \overline{p}_{it}^{s-} \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^s, t \in \mathcal{T}$$

$$-RD_{it} \leq p_{it}^g(\overline{\boldsymbol{p}}^r_{[t]}) - p_{i,t-1}^g(\overline{\boldsymbol{p}}^r_{[t-1]}) \leq RU_{it} \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^g, t \in \mathcal{T}$$

$$0 \leq q_{i0}^s + \sum_{\tau\in[1:t]} \left(\sigma_i^s \, p_{i\tau}^{s-}(\overline{\boldsymbol{p}}^r_{[\tau]}) - p_{i\tau}^{s+}(\overline{\boldsymbol{p}}^r_{[\tau]}) \right) \leq \overline{q}_i^s \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, i \in \mathcal{N}^s, t \in \mathcal{T}$$

$$-f_l^{max} \leq \boldsymbol{\alpha}_l^{grs}\, \boldsymbol{p}_t(\overline{\boldsymbol{p}}^r_{[t]}) - \boldsymbol{\alpha}_l^d\, \boldsymbol{d}_t \leq f_l^{max} \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, l \in \mathcal{N}^l, t \in \mathcal{T}$$

$$\sum_{j\in\mathcal{N}^d} d_{jt} = \sum_{i\in\mathcal{N}^g} p_{it}^g(\overline{\boldsymbol{p}}^r_{[t]}) + \sum_{i\in\mathcal{N}^r} p_{it}^r(\overline{\boldsymbol{p}}^r_{[t]}) + \sum_{i\in\mathcal{N}^s} \left(p_{it}^{s+}(\overline{\boldsymbol{p}}^r_{[t]}) - p_{it}^{s-}(\overline{\boldsymbol{p}}^r_{[t]}) \right) \qquad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r, t \in \mathcal{T}$$



Dynamic uncertainty set for wind and solar power

$\overline{p}^r_{it}$: available power at renewable unit i and time t (MW)

$$\overline{\mathcal{P}}^r = \Big\{ \overline{\boldsymbol{p}}^r \; : \; \exists \, \boldsymbol{u}, \, \boldsymbol{v} \quad \text{s.t.}$$

$$\overline{p}^r_{it} = f_{it} + g_{it} \, u_{it} \quad \forall \, i \in \mathcal{N}^r, \, t \in \mathcal{T}$$

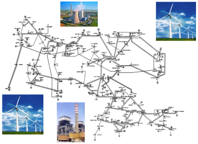
$$\boldsymbol{u}_t = \sum_{l=1}^{L} \boldsymbol{A}^l \, \boldsymbol{u}_{t-l} + \boldsymbol{B} \, \boldsymbol{v}_t \quad \forall \, t \in \mathcal{T}$$

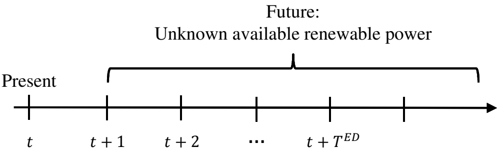
$$\| \boldsymbol{v}_t \| \leq \Gamma \quad \forall \, t \in \mathcal{T}$$

$$0 \leq \overline{p}^r_{it} \leq \overline{p}^{r,max}_{it} \quad \forall \, i \in \mathcal{N}^r, \, t \in \mathcal{T} \Big\}$$

Temporal and spatial correlations represented

Policy-guided look-ahead ED for real-time operations





$$\min_{\hat{\boldsymbol{p}}_t,\ldots,\hat{\boldsymbol{p}}_{t+T^{ED}}} \sum_{\tau=t}^{t+T^{ED}} \sum_{i\in\mathcal{N}_g} C_i^g \, \hat{p}_{i\tau}^g$$

s.t. $\hat{\boldsymbol{p}}_t \in \Omega_t(\boldsymbol{p}_{[t-1]}^{realized}, \overline{\boldsymbol{p}}_t^{r,realized})$

$$\hat{\boldsymbol{p}}_\tau \in \Omega_\tau(\hat{\boldsymbol{p}}_{[\tau-1]}, \overline{\boldsymbol{p}}_\tau^{r,forecast}) \quad \forall \tau \in [t+1 : t+T^{ED}]$$

$$-RD_{i,t+1} \leq p_{i,t+1}^g(\overline{\boldsymbol{p}}_{[t+1]}^r) - \hat{p}_{it}^g \leq RU_{i,t+1} \quad \forall \overline{\boldsymbol{p}}_{[t+1]}^r \in \overline{\mathcal{P}}_{[t+1]}^r\left(\overline{\boldsymbol{p}}_{[t]}^{r,realized}\right), \; i \in \mathcal{N}^g$$

$$\sum_{k=t}^{\tau}\left(\sigma_i^s \, p_{ik}^{s-}(\overline{\boldsymbol{p}}_{[k]}^{r,forecast}) - p_{ik}^{s+}(\overline{\boldsymbol{p}}_{[k]}^{r,forecast})\right)$$

$$= \sum_{k=t}^{\tau}\left(\sigma_i^s \, \hat{p}_{ik}^{s-} - \hat{p}_{ik}^{s+}\right) \quad \forall i \in \mathcal{N}^s, \; \tau \in [t+1 : t+T^{ED}]$$

Outline

Solution method

Challenges

- Dynamic uncertainty set couples time periods
- Energy storage couples time periods
- Dispatchable wind and solar power

Proposed method

1. Simple affine policy
2. Constraint generation
3. Simple reformulation for bound constraints
4. Outer approximation for inter-temporal constraints
5. Algorithmic speed-ups

1. Simple affine policy

How to optimize over a functional space?

$p^g_{it}(\overline{\boldsymbol{p}}^r_{[t]})$ is the adaptive decision at time t

We restrict the dependence to a simple affine policy

Conventional units: $$p^g_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^g_{it} + W^g_{it} \sum_{j \in \mathcal{N}^r} \overline{p}^r_{jt}$$

Renewable units: $$p^r_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^r_{it} + W^r_t \, \overline{p}^r_{it}$$

Storage units: $$p^{s+}_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^{s+}_{it} + W^{s+}_{it} \sum_{j \in \mathcal{N}^r} \overline{p}^r_{jt}$$

$$p^{s-}_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^{s-}_{it} + W^{s-}_{it} \sum_{j \in \mathcal{N}^r} \overline{p}^r_{jt}$$

"Traditional" method: Duality-based reformulation

Example: production bound

$$p^g_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^g_{it} + \sum_{s=1}^{t} \sum_{j \in \mathcal{N}^r} W^g_{itjs}\, \overline{p}^r_{js} \;\leq\; x_{it}\, \overline{p}^g_{it} \quad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r$$

$$\boldsymbol{a}(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b(\boldsymbol{x}, \boldsymbol{w}) \quad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r \quad \Leftrightarrow \quad \max_{\boldsymbol{Q}\overline{\boldsymbol{p}}^r \leq \boldsymbol{q}} \boldsymbol{a}^\top \overline{\boldsymbol{p}}^r \;\leq\; b$$

$$\Leftrightarrow \quad \min_{\boldsymbol{\pi} \geq 0:\, \boldsymbol{\pi}^\top \boldsymbol{Q} = \boldsymbol{a}^\top} \boldsymbol{\pi}^\top \boldsymbol{q} \;\leq\; b$$

$$\Leftrightarrow \quad \exists\, \boldsymbol{\pi} \geq 0 \text{ s.t. } \boldsymbol{\pi}^\top \boldsymbol{Q} = \boldsymbol{a}^\top,\ \boldsymbol{\pi}^\top \boldsymbol{q} \;\leq\; b$$

N^o variables $=$ N^o robust constraints $\times$ $\mathrm{Dim}\,(\boldsymbol{\pi})$

Problem: huge reformulation obtained

118-bus system: 14000 robust constraints, $\mathrm{Dim}\,(\boldsymbol{\pi}) = 9500$

$\Rightarrow$ 133 million variables

2. Constraint generation

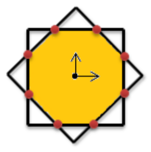
Theorem: We only need the *extreme points* of $\overline{\mathcal{P}}^r$

$$\boldsymbol{a}(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b(\boldsymbol{x}, \boldsymbol{w}) \quad \forall \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r$$

$$\Leftrightarrow \quad \max_{\overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r} \boldsymbol{a}(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b(\boldsymbol{x}, \boldsymbol{w})$$

$$\Leftrightarrow \quad \max_{\overline{\boldsymbol{p}}^r \in \{\overline{\boldsymbol{p}}_1^{r*}, \ldots, \overline{\boldsymbol{p}}_L^{r*}\}} \boldsymbol{a}(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b(\boldsymbol{x}, \boldsymbol{w})$$

$$\Leftrightarrow \quad \boldsymbol{a}(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b(\boldsymbol{x}, \boldsymbol{w}) \quad \forall \overline{\boldsymbol{p}}^r \in \{\overline{\boldsymbol{p}}_1^{r*}, \ldots, \overline{\boldsymbol{p}}_L^{r*}\}$$



There could be an exponential number of extreme points

But we can add them iteratively on an as-needed basis!

Master Problem

$$\min_{(\boldsymbol{x}, \boldsymbol{w}, \boldsymbol{W}, z) \in \Omega} \quad z$$

$$\text{s.t.} \quad \boldsymbol{a}_k(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b_k(\boldsymbol{x}, \boldsymbol{w}, z) \quad \forall k \in \mathcal{K}, \ \overline{\boldsymbol{p}}^r \in P_k$$

3. Simple reformulation for bound constraints

The key is the dependence on *total available renewable power* :

$$p^g_{it}(\overline{\boldsymbol{p}}^r_{[t]}) = w^g_{it} + W^g_{it} \sum_{j \in \mathcal{N}^r} \overline{p}^r_{jt}$$

Direct reformulation

$$w^g_{it} + W^g_{it} \sum_{j \in \mathcal{N}^r} \overline{p}^r_{jt} \leq x_{it}\, \overline{p}^g_{it} \quad \forall\, \overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r$$

$$\Leftrightarrow \quad w^g_{it} + W^g_{it}\; \overline{p}^{r,total}_t \leq x_{it}\, \overline{p}^g_{it} \quad \forall\, \overline{p}^{r,total}_t \in \left\{ \overline{p}^{r,total,min}_t,\, \overline{p}^{r,total,max}_t \right\}$$

4. Outer approximation for inter-temporal constraints

Inter-temporal robust constraints in the problem:

$$\max_{\overline{\boldsymbol{p}}^{r,total} \in \overline{\mathcal{P}}^{r,total}_{[t_1:t_2]}} \sum_{t=t_1}^{t_2} a_t^{total}(\boldsymbol{W})\, \overline{p}_t^{r,total} \;\leq\; b(\boldsymbol{x}, \boldsymbol{w}, z)$$

- $\overline{\mathcal{P}}^{r,total}_{[t_1:t_2]}$: projection of $\overline{\mathcal{P}}^{r}$ unto total available renewable power

$$\overline{p}_t^{r,total} = \sum_{j \in \mathcal{N}^r} \overline{p}_{jt}^{r}$$

Low-dimensional outer approximation

$$\widehat{\mathcal{P}}^{r,total}_{[t_1:t_2]} \;\supset\; \overline{\mathcal{P}}^{r,total}_{[t_1:t_2]}$$

5. Algorithmic speed-ups

One-tree Benders implementation

Avoid solving many MIPs

Constraint screening using fast computed upper bounds

Avoid solving too many subproblems

$$\max_{\overline{\boldsymbol{p}}^r \in \overline{\mathcal{P}}^r} \boldsymbol{a}_k(\boldsymbol{W})^\top \overline{\boldsymbol{p}}^r \leq b_k(\boldsymbol{x}, \boldsymbol{w}, z)$$

Outline

Computational experiments

Questions

1. How efficient is the proposed algorithm?
2. How critical is exploiting the policy and capturing correlations?
3. What is the effect of larger energy storage capacities?

2736-bus Polish test case

- 289 conventional generators (28880 MW of total capacity)
- 60 wind farms (10689 MW installed)
- 30 solar farms (6299 MW installed)
- 10 storage units (600 MW of total output capacity)
- 2011 demand nodes (17831 MW average, 22594 MW peak)
- 100 transmission lines
- Wind and solar data from NREL: average renewable penetration of 35%

1. How efficient is the proposed algorithm?

Solution time (hours) (time limit of 6 hours)

Γ	0.25	0.5	1	2	3	4
CG	T	T	T	T	T	T
CG + OTB	T	T	T	T	T	T
CG + OTB + OA	1.53	2.16	1.50	1.79	1.59	2.64
CG + OTB + OA + CS	0.96	2.04	1.27	1.45	1.30	0.79

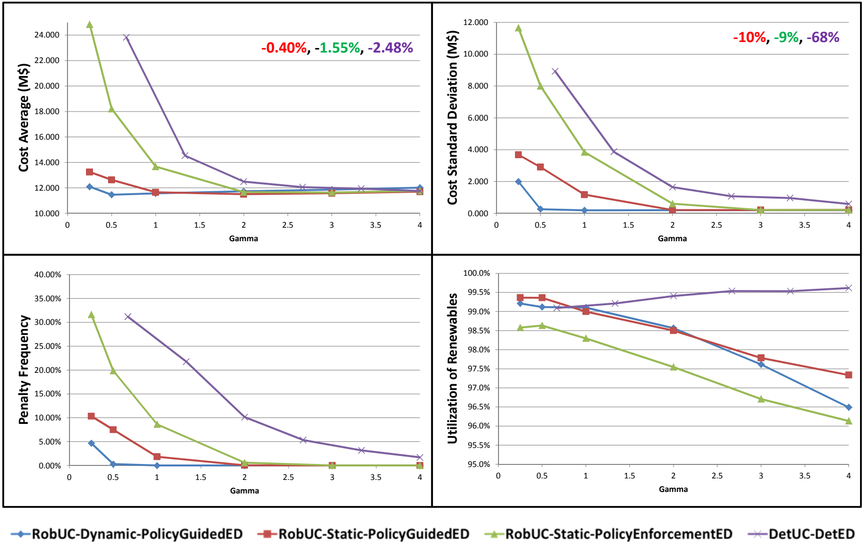
CG: constraint generation

OTB: one-tree Benders

OA: outer approximation for temporal constraints

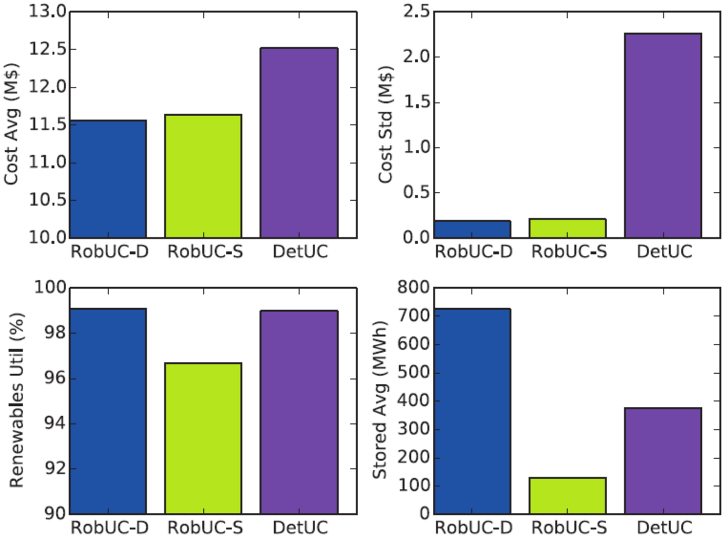
CS: constraint screening

2. How critical is exploiting the policy and capturing correlations?

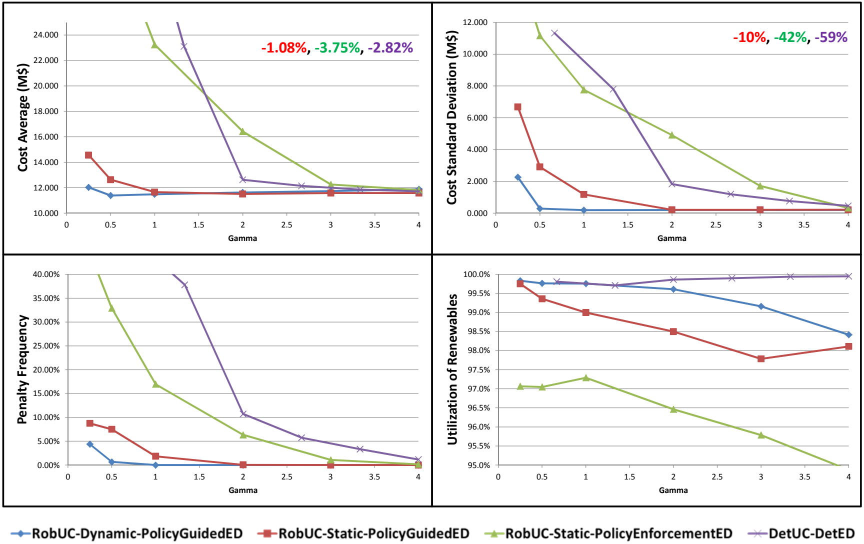


100 one-day rolling-horizon simulations

2. How critical is exploiting the policy and capturing correlations?



3. What is the effect of larger energy storage capacities?



Same simulations under tripled energy storage capacities

Outline

Can we use decision rules to price flexibility?

What if a generator "absorbs" most of the uncertainty in renewables?

Example

Suppose $d_t^{total} \in [200, 400]$ MW and

$$\text{Generator A}: \quad p_A = 100\text{MW} + 0.9\left(d_t^{total} - 300\text{MW}\right) \in [10, 190] \ \text{MW}$$

$$\text{Generator B}: \quad p_B = 100\text{MW} + 0.1\left(d_t^{total} - 300\text{MW}\right) \in [90, 110] \ \text{MW}$$

$$\text{Generator C}: \quad p_C = 100\text{MW}$$

How should we compensate generators and storage units that provide flexibility?

Summary

- Multistage robust unit commitment with energy storage
- Dynamic uncertainty set integrates wind and solar power
- Effective policy-guided look-ahead dispatch
- Specialized and efficient solution method

Work presented

Multistage Robust Unit Commitment
with Dynamic Uncertainty Sets and Energy Storage
Á. Lorca and X.A. Sun
IEEE Transactions on Power Systems, 2017

Related work

- **Adaptive Robust Optimization with Dynamic Uncertainty Sets for Economic Dispatch under Significant Wind**
  Á. Lorca and X.A. Sun. *IEEE Transactions on Power Systems*, 2015
- **Multistage Adaptive Robust Optimization for the Unit Commitment Problem**
  Á. Lorca, X.A. Sun, E. Litvinov and T. Zheng. *Operations Research*, 2016
- **The Adaptive Robust Multi-Period Alternating Current Optimal Power Flow Problem**
  Á. Lorca and X.A. Sun. *IEEE Transactions on Power Systems*, 2017

Research Team: OCM-Lab

OCM: Optimization, Control, and Markets

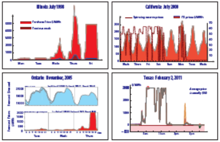
Team

- **Professors:** Daniel Olivares, Matías Negrete, Álvaro Lorca
- **Students:** approx 18 (graduate, undergraduate, visiting)
- **Colaboration:** UC Berkeley, UT Austin, Notre Dame, Toronto, Waterloo.
- **Presence:** Institute for Complex Engineering Systems, Solar Energy Research Center, Energy Research Center UC
- **Grants:** FONDEF + 2 Fondecyt

Expertise

- Power System Operations and Planning
- Optimization Methods and Stochastic Modeling
- Control and Market Design

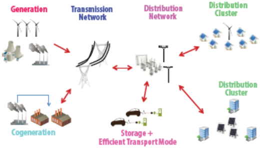
For more information: ocm.ing.puc.cl



Electricity Markets Design

Loads as Stochastic Batteries

Demand Response

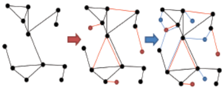


Smart Grids

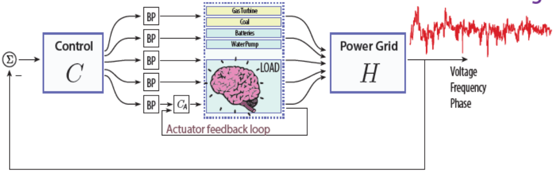
$/MWh

Energy Services

Energy Services



Algorithms



Grid as a Control System with Many Resources

Políticas Afines para el Despacho y la Gestión del Almacenamiento Energético

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Complex Energy Systems Workshop
Instituto de Sistemas Complejos de Ingeniería
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