Robust Reserve Modeling for Wind Power Integration in Ramp-Based Unit Commitment

Germán Morales-España*,‡
Ross Baldick†, Javier García-Gonzalez‡ and Andres Ramos‡

*Royal Institute of Technology (KTH), Stockholm-Sweden
‡Universidad Pontificia Comillas, Madrid-Spain
†University of Texas, Austin-Texas

FERC: Increasing Real-Time And Day-Ahead Market Efficiency Through Improved Software

Short-term Generation Planning

- Wind Energy has been firmly penetrating current power systems worldwide
- High penetration of intermittent generation demands different long-, medium-, and short-temp practices
- Unit Commitment (UC): essential tool for day-ahead planning
  - Decide on units' physical operation (e.g., on-off) at minimum cost
  - UC is a (non-convex) computationally demanding problem

Short-term Generation Planning

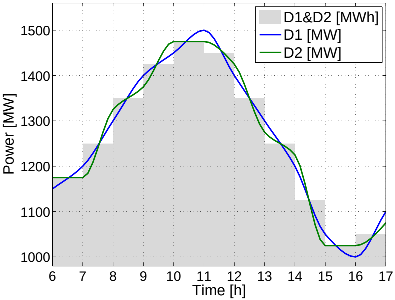
- Wind Energy has been firmly penetrating current power systems worldwide
- High penetration of intermittent generation demands different long-, medium-, and short-temp practices
- Unit Commitment (UC): essential tool for day-ahead planning
    - Decide on units' physical operation (e.g., on-off) at minimum cost
    - UC is a (non-convex) computationally demanding problem
- Wind introduces uncertainty ⇒ more difficult planning
- Adequate resources must be scheduled
    - So the system can face real-time uncertainty
    - Otherwise: *ad-hoc* measures needed ⇒ ↑costs

Outline

Outline

Unique Energy Profile $\Rightarrow \infty$ Power Profiles

Demand Example[1]



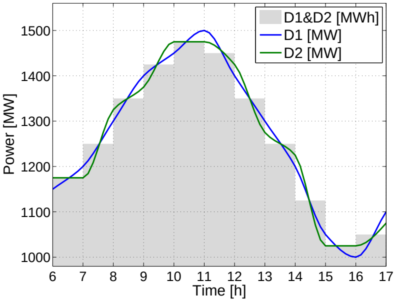
Some Demand requirements

	Hour	D1	D2
Ramp [MW/h]	9-10	50	100
Ramp [MW/h]	10-11	50	0

[1] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Unique Energy Profile ⇒ ∞ Power Profiles

Demand Example[1]



Some Demand requirements

	Hour	D1	D2
Ramp [MW/h]	9-10	50	100
Ramp [MW/h]	10-11	50	0
Max P [MW]	10-11	1500	1475
Min P [MW]	15-16	1000	1025

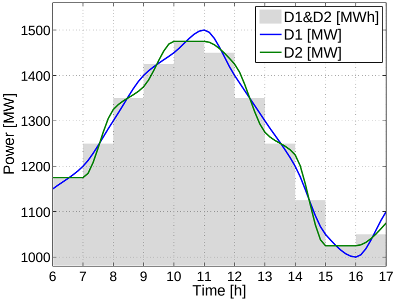
⇓

Panning 1 Energy Profile ⇒ cannot guarantee ∞ power profiles

[1] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Unique Energy Profile ⇒ ∞ Power Profiles

Demand Example[1]



Some Demand requirements

	Hour	D1	D2
Ramp [MW/h]	9-10	50	100
Ramp [MW/h]	10-11	50	0
Max P [MW]	10-11	1500	1475
Min P [MW]	15-16	1000	1025

⇓

Panning 1 Energy Profile ⇒ cannot guarantee ∞ power profiles

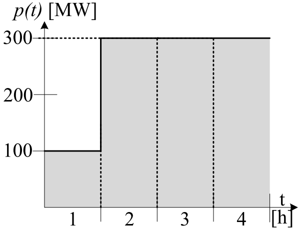
Planning 1 Power Profile ⇒ guarantees the unique energy profile

[1] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Energy Scheduling

Generation levels are usually considered as energy blocks.
Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 200 MW/h

Traditional UC



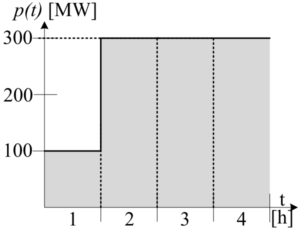
[2] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

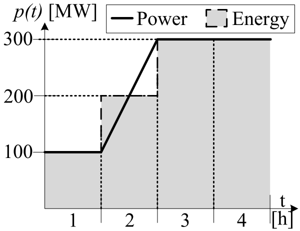
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300\text{MW}$; $\underline{P} = 100\text{MW}$; Up/Down ramp rate: 200 MW/h

Traditional UC



Feasible energy profile



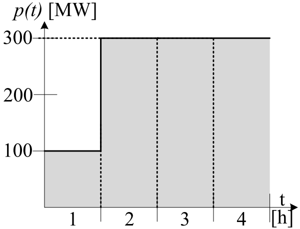
[2] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

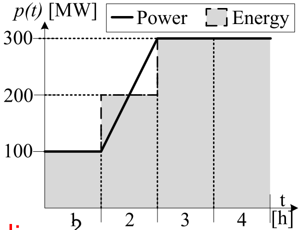
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300\text{MW}$; $\underline{P} = 100\text{MW}$; Up/Down ramp rate: 200 MW/h

Traditional UC



Feasible energy profile



Infeasible energy delivery[2]

Overestimated ramp availability

⇓

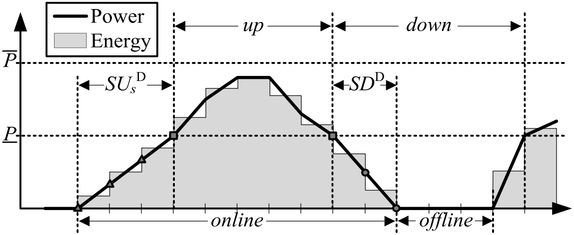
A clear difference between power and energy is required in UCs

[2] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Outline

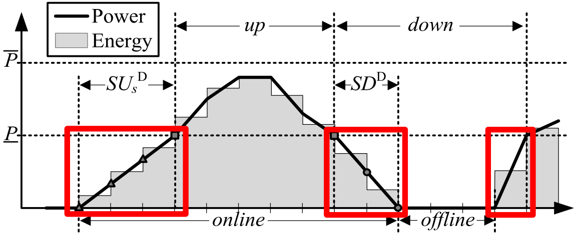
Production Below Unit's Minimum Output?

Startup (SU) and Shutdown (SD) power trajectories are ignored at UC scheduling stage: Why?



Production Below Unit's Minimum Output?

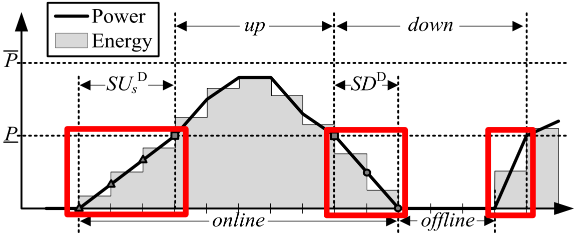
Startup (SU) and Shutdown (SD) power trajectories are ignored at UC scheduling stage: Why?



- Insignificant impact is assumed?
- To avoid complex models causing prohibitive solving times?

Production Below Unit's Minimum Output?

Startup (SU) and Shutdown (SD) power trajectories are ignored at UC scheduling stage: Why?



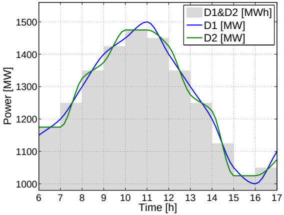
- Insignificant impact is assumed?
- To avoid complex models causing prohibitive solving times?
- Ignoring them change commitment decisions ⇒ ↑ costs[3]

[3] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation of start-up and shut-down ramping in unit commitment," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1288–1296, 2013

Ramp-Based Scheduling Approach

The UC was reformulated for better scheduling (↓ costs)[4],

- Some new features:
  - Linear piece-wise power scheduling
  - SU & SD power trajectories
  - Operating-reserve constraints depending on ramp availability



[4] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Outline

Stochastic Programing

Stochastic programming is promising but computationally demanding so:

- Many simplifications are needed:
  - Reducing quantity of scenarios
  - Removing crucial constraints (e.g. Network constraints)

Stochastic Programing

Stochastic programming is promising but computationally demanding so:

- Many simplifications are needed:
  - Reducing quantity of scenarios
  - Removing crucial constraints (e.g. Network constraints)
- How to reduce solving times?
  - Computer power (e.g., clusters)
  - Solving algorithms (e.g., solvers, decomposition techniques)

Stochastic Programing

Stochastic programming is promising but computationally demanding so:

- Many simplifications are needed:
  - Reducing quantity of scenarios
  - Removing crucial constraints (e.g. Network constraints)
- How to reduce solving times?
  - Computer power (e.g., clusters)
  - Solving algorithms (e.g., solvers, decomposition techniques)
  - Improving the MIP-Based UC formulation $\Rightarrow \downarrow$ solving times

Improvements in MIP Formulations

Better system representation is pointless if the models cannot be solved fast enough

- Tightness: defines the search space (relaxed feasible region)
- Compactness: defines the searching speed (data to process)

Improvements in MIP Formulations

Better system representation is pointless if the models cannot be solved fast enough

- Tightness: defines the search space (relaxed feasible region)
- Compactness: defines the searching speed (data to process)
- *Convex hull*: The tightest formulation ⇒ MIP solved as LP[5,6]

[5] C. Gentile, G. Morales-Espana, and A. Ramos, "A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints," *European Journal of Operational Research*, 2014, Under Review

[6] G. Morales-Espana, C. Gentile, and A. Ramos, "Tight MIP formulations of the power-based unit commitment problem," *Optimization Letters*, 2014, Under Review

Improvements in MIP Formulations

Better system representation is pointless if the models cannot be solved fast enough

- Tightness: defines the search space (relaxed feasible region)
- Compactness: defines the searching speed (data to process)
- *Convex hull*: The tightest formulation ⇒ MIP solved as LP[5,6]
- Beware of what matters in good MIP formulations
  - ↑ Binaries ⇒ ↑ Solving time **False myth**

[5] C. Gentile, G. Morales-Espana, and A. Ramos, "A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints," *European Journal of Operational Research*, 2014, Under Review

[6] G. Morales-Espana, C. Gentile, and A. Ramos, "Tight MIP formulations of the power-based unit commitment problem," *Optimization Letters*, 2014, Under Review

Improvements in MIP Formulations

Better system representation is pointless if the models cannot be solved fast enough

- Tightness: defines the search space (relaxed feasible region)
- Compactness: defines the searching speed (data to process)
- *Convex hull*: The tightest formulation ⇒ MIP solved as LP[5,6]
- Beware of what matters in good MIP formulations
  - ↑ Binaries ⇒ ↑ Solving time **False myth**

Tight and Compact MIP formulations dramatically reduce the computational burden of UC problems [7,8]

[5] C. Gentile, G. Morales-Espana, and A. Ramos, "A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints," *European Journal of Operational Research*, 2014, Under Review

[6] G. Morales-Espana, C. Gentile, and A. Ramos, "Tight MIP formulations of the power-based unit commitment problem," *Optimization Letters*, 2014, Under Review

[7] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation of start-up and shut-down ramping in unit commitment," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1288–1296, 2013

[8] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013

Outline

Adaptive Robust Optimization (ARO) for UC (I)

- The ARO-UC formulation:

$$\min_{\boldsymbol{x}} \quad \left(\mathbf{b}^\top \boldsymbol{x} + \max_{\boldsymbol{\xi} \in \Xi} \min_{\boldsymbol{p}, \boldsymbol{w}} \mathbf{c}^\top \boldsymbol{p}(\boldsymbol{\xi}) \right)$$

$$\text{s.t.} \quad \mathbf{F}\boldsymbol{x} \leq \mathbf{f},\ \boldsymbol{x} \text{ is binary} \qquad (1)$$

$$\mathbf{H}\boldsymbol{p}(\boldsymbol{\xi}) + \mathbf{J}\boldsymbol{w} \leq \mathbf{h},\ \forall \boldsymbol{\xi} \in \Xi \qquad (2)$$

$$\mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p}(\boldsymbol{\xi}) \leq \mathbf{g},\ \forall \boldsymbol{\xi} \in \Xi \qquad (3)$$

$$\boldsymbol{w} = \boldsymbol{\xi},\ \forall \boldsymbol{\xi} \in \Xi \qquad (4)$$

  - $\boldsymbol{x}$ are the nonadaptive (first-stage) commitment related decisions,
  - $\boldsymbol{p}$ are the fully adaptive units' (second-stage) dispatch decisions, and
  - uncertainty set Ξ is defined by $\xi_{bt} \in [\underline{\mathrm{w}}_{bt}, \overline{\mathrm{w}}_{bt}]\ \forall t \in \mathcal{T},\ b \in \mathcal{B}^{\mathrm{w}}$.

Adaptive Robust Optimization (ARO) for UC (I)

- The ARO-UC formulation:

$$\min_{\boldsymbol{x}} \quad \left(\mathbf{b}^\top \boldsymbol{x} + \max_{\boldsymbol{\xi}\in\Xi} \min_{\boldsymbol{p},\boldsymbol{w}} \mathbf{c}^\top \boldsymbol{p}\left(\boldsymbol{\xi}\right)\right)$$

$$\text{s.t.} \quad \mathbf{F}\boldsymbol{x} \leq \mathbf{f},\ \boldsymbol{x} \text{ is binary} \tag{1}$$

$$\mathbf{H}\boldsymbol{p}\left(\boldsymbol{\xi}\right) + \mathbf{J}\boldsymbol{w} \leq \mathbf{h},\ \forall \boldsymbol{\xi} \in \Xi \tag{2}$$

$$\mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p}\left(\boldsymbol{\xi}\right) \leq \mathbf{g},\ \forall \boldsymbol{\xi} \in \Xi \tag{3}$$

$$\boldsymbol{w} = \boldsymbol{\xi},\ \forall \boldsymbol{\xi} \in \Xi \tag{4}$$

  - $\boldsymbol{x}$ are the nonadaptive (first-stage) commitment related decisions,
  - $\boldsymbol{p}$ are the fully adaptive units' (second-stage) dispatch decisions, and
  - uncertainty set Ξ is defined by $\xi_{bt} \in [\underline{\mathrm{w}}_{bt}, \overline{\mathrm{w}}_{bt}]\ \forall t \in \mathcal{T},\ b \in \mathcal{B}^{\mathrm{w}}$.
- The max-min form requires solving a bilinear + MIP problem[9]

[9] D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 52–63, Feb. 2013

Adaptive Robust Optimization (ARO) for UC (II)

- The ARO-UC formulation introducing wind curtailment:

$$\min_{\boldsymbol{x}} \quad \left(\mathbf{b}^\top \boldsymbol{x} + \max_{\boldsymbol{\xi} \in \Xi} \min_{\boldsymbol{p},\boldsymbol{w}} \mathbf{c}^\top \boldsymbol{p}(\boldsymbol{\xi}) \right)$$

$$\text{s.t.} \quad \mathbf{F}\boldsymbol{x} \leq \mathbf{f}, \ \boldsymbol{x} \text{ is binary} \quad (5)$$

$$\mathbf{H}\boldsymbol{p}(\boldsymbol{\xi}) + \mathbf{J}\boldsymbol{w}(\boldsymbol{\xi}) \leq \mathbf{h}, \ \forall \boldsymbol{\xi} \in \Xi \quad (6)$$

$$\mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p}(\boldsymbol{\xi}) \leq \mathbf{g}, \ \forall \boldsymbol{\xi} \in \Xi \quad (7)$$

$$\cancel{\boldsymbol{w} = \boldsymbol{\xi}, \ \forall \boldsymbol{\xi} \in \Xi}$$

$$\boldsymbol{w} \leq \boldsymbol{\xi}, \ \forall \boldsymbol{\xi} \in \Xi \quad (8)$$

  - $\boldsymbol{x}$ are the nonadaptive (first-stage) commitment related decisions,
  - $\boldsymbol{p}$ are the fully adaptive units' (second-stage) dispatch decisions, and
  - $\boldsymbol{w}$ are the fully adaptive wind (second-stage) dispatch decisions
  - uncertainty set Ξ is defined by $\xi_{bt} \in [\underline{\mathrm{w}}_{bt}, \overline{\mathrm{w}}_{bt}] \ \forall t \in \mathcal{T}, \ b \in \mathcal{B}^{\mathrm{w}}$.

The Second-Stage of the ARO-UC

- By fixing first-stage variable $\boldsymbol{x}$, we obtain the completely adaptable linear formulation:

$$\max_{\boldsymbol{\xi}\in\boldsymbol{\Xi}} \min_{\boldsymbol{p},\boldsymbol{w}} \quad \mathbf{c}^{\top}\boldsymbol{p}\left(\boldsymbol{\xi}\right)$$

$$\text{s.t.} \quad \mathbf{H}\boldsymbol{p}\left(\boldsymbol{\xi}\right)+\mathbf{J}\boldsymbol{w}\left(\boldsymbol{\xi}\right)\leq\mathbf{h},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{9}$$

$$\mathbf{B}\boldsymbol{p}\left(\boldsymbol{\xi}\right)\leq\tilde{\mathbf{g}},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{10}$$

$$\boldsymbol{w}\left(\boldsymbol{\xi}\right)\leq\boldsymbol{\xi},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{11}$$

where $\tilde{\mathbf{g}}=\mathbf{g}-\mathbf{A}\boldsymbol{x}$.

The Second-Stage of the ARO-UC

- By fixing first-stage variable $\boldsymbol{x}$, we obtain the completely adaptable linear formulation:

$$\max_{\boldsymbol{\xi}\in\boldsymbol{\Xi}} \min_{\boldsymbol{p},\boldsymbol{w}} \quad \mathbf{c}^{\top}\boldsymbol{p}(\boldsymbol{\xi})$$

$$\text{s.t.} \quad \mathbf{H}\boldsymbol{p}(\boldsymbol{\xi}) + \mathbf{J}\boldsymbol{w}(\boldsymbol{\xi}) \leq \mathbf{h},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{9}$$

$$\mathbf{B}\boldsymbol{p}(\boldsymbol{\xi}) \leq \tilde{\mathbf{g}},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{10}$$

$$\boldsymbol{w}(\boldsymbol{\xi}) \leq \boldsymbol{\xi},\ \forall\boldsymbol{\xi}\in\boldsymbol{\Xi} \tag{11}$$

where $\tilde{\mathbf{g}} = \mathbf{g} - \mathbf{A}\boldsymbol{x}$.

- Since the uncertainty affecting every one of the constraints (11) is independent of each other. i.e., $\xi_{bt} \in [\underline{\mathrm{w}}_{bt}, \overline{\mathrm{w}}_{bt}]$ for all $t\in\mathcal{T}$, $b\in\mathcal{B}^{\mathrm{w}}$,
- $\Rightarrow$ The ARO solution is equivalent to the static robust optimization (SRO) solution[10]

[10] A. Ben-Tal, A. Goryashko, E. Guslitzer, and A. Nemirovski, "Adjustable robust solutions of uncertain linear programs," en, *Mathematical Programming*, vol. 99, no. 2, pp. 351–376, Mar. 2004

The SRO solution for the ARO

The ARO solution of

$$\begin{aligned} \max_{\boldsymbol{\xi}\in\boldsymbol{\Xi}} \min_{\boldsymbol{p},\boldsymbol{w}} \quad & \mathbf{c}^{\top}\boldsymbol{p}(\boldsymbol{\xi}) \\ \text{s.t.} \quad & \mathbf{H}\boldsymbol{p}(\boldsymbol{\xi}) + \mathbf{J}\boldsymbol{w}(\boldsymbol{\xi}) \leq \mathbf{h}, \ \forall \boldsymbol{\xi} \in \boldsymbol{\Xi} \\ & \mathbf{B}\boldsymbol{p}(\boldsymbol{\xi}) \leq \tilde{\mathbf{g}}, \ \forall \boldsymbol{\xi} \in \boldsymbol{\Xi} \\ & \boldsymbol{w}(\boldsymbol{\xi}) \leq \boldsymbol{\xi}, \ \forall \boldsymbol{\xi} \in \boldsymbol{\Xi} \end{aligned}$$

is then obtained by solving the SRO-equivalent problem

$$\begin{aligned} \min_{\boldsymbol{p},\boldsymbol{w}} \quad & \mathbf{c}^{\top}\boldsymbol{p} \\ \text{s.t.} \quad & \mathbf{H}\boldsymbol{p} + \mathbf{J}\boldsymbol{w} \leq \mathbf{h} \\ & \mathbf{B}\boldsymbol{p} \leq \tilde{\mathbf{g}} \\ & \boldsymbol{w} \leq \underline{\mathbf{w}} \end{aligned}$$

Reformulating the ARO-UC

- By considering wind curtailment, the ARO-UC then becomes

$$
\begin{array}{rl}
\min & \mathbf{b}^\top \boldsymbol{x} + \max \min \mathbf{c}^\top \boldsymbol{p} \\
\text{s.t.} & \mathbf{F}\boldsymbol{x} \le \mathbf{f},\ \boldsymbol{x} \text{ is binary} \\
& \mathbf{H}\boldsymbol{p} + \mathbf{J}\boldsymbol{w} \le \mathbf{h},\ \forall \boldsymbol{\xi} \in \Xi \\
& \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p} \le \mathbf{g},\ \forall \boldsymbol{\xi} \in \Xi \\
& \boldsymbol{w} \le \boldsymbol{\xi},\ \forall \boldsymbol{\xi} \in \Xi
\end{array}
\equiv
\begin{array}{rl}
\min & \mathbf{b}^\top \boldsymbol{x} + \mathbf{c}^\top \boldsymbol{p} \\
\text{s.t.} & \mathbf{F}\boldsymbol{x} \le \mathbf{f},\ \boldsymbol{x} \text{ is binary} \\
& \mathbf{H}\boldsymbol{p} + \mathbf{J}\boldsymbol{w} \le \mathbf{h} \\
& \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p} \le \mathbf{g} \\
& \boldsymbol{w} \le \underline{\mathbf{w}}
\end{array}
$$

- Which is a considerably simpler problem, we avoid
  - The local optimum of the bilinear program
  - Further complexity when trying to solve the bilinear + MIP

Reformulating the ARO-UC

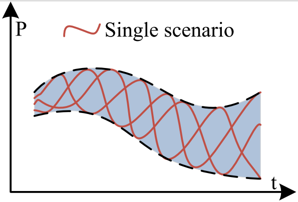
- By considering wind curtailment, the ARO-UC then becomes

$$\begin{array}{ll} \min & \mathbf{b}^\top \boldsymbol{x} + \max \min \mathbf{c}^\top \boldsymbol{p} \\ \text{s.t.} & \mathbf{F}\boldsymbol{x} \le \mathbf{f},\ \boldsymbol{x} \text{ is binary} \\ & \mathbf{H}\boldsymbol{p} + \mathbf{J}\boldsymbol{w} \le \mathbf{h},\ \forall \boldsymbol{\xi} \in \Xi \\ & \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p} \le \mathbf{g},\ \forall \boldsymbol{\xi} \in \Xi \\ & \boldsymbol{w} \le \boldsymbol{\xi},\ \forall \boldsymbol{\xi} \in \Xi \end{array} \quad \equiv \quad \begin{array}{ll} \min & \mathbf{b}^\top \boldsymbol{x} + \mathbf{c}^\top \boldsymbol{p} \\ \text{s.t.} & \mathbf{F}\boldsymbol{x} \le \mathbf{f},\ \boldsymbol{x} \text{ is binary} \\ & \mathbf{H}\boldsymbol{p} + \mathbf{J}\boldsymbol{w} \le \mathbf{h} \\ & \mathbf{A}\boldsymbol{x} + \mathbf{B}\boldsymbol{p} \le \mathbf{g} \\ & \boldsymbol{w} \le \underline{\mathbf{w}} \end{array}$$

- Which is a considerably simpler problem, we avoid
  - The local optimum of the bilinear program
  - Further complexity when trying to solve the bilinear + MIP
- The worst-case scenario of the ARO-UC can be known a priori
  - ⇔ all adaptive (second-stage) variables are continuous.
- This key worst-case scenario guarantees feasibility to the UC solution

Stochastic vs. Robust Approaches

Stochastic

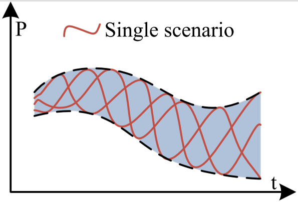


Feasible for a discrete (finite) number of scenarios

[11] G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review

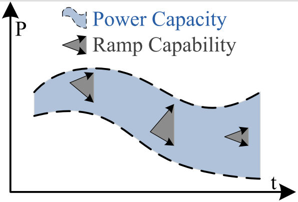
Stochastic vs. Robust Approaches

Stochastic



Feasible for a discrete (finite) number of scenarios

Robust

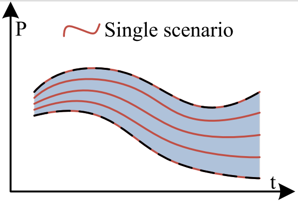


Feasible for a continuous (infinite) region of uncertainty

[11] G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review

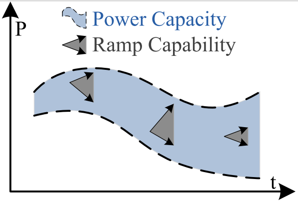
Stochastic vs. Robust Approaches

Stochastic



Feasible for a discrete (finite) number of scenarios

Robust



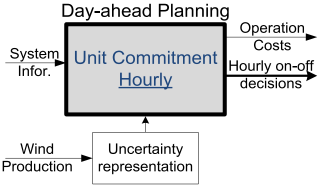
Feasible for a continuous (infinite) region of uncertainty

Need for a clear difference between Power-Capacity and Ramp-Capability Requirements[11]

[11] G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review

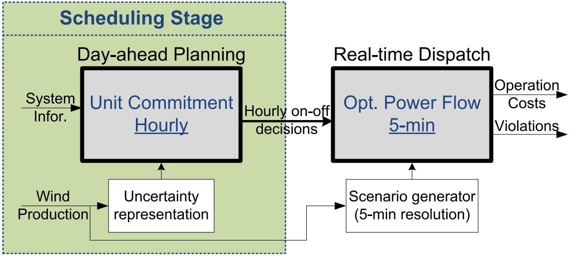
Outline

Scheduling & Evaluation Stages



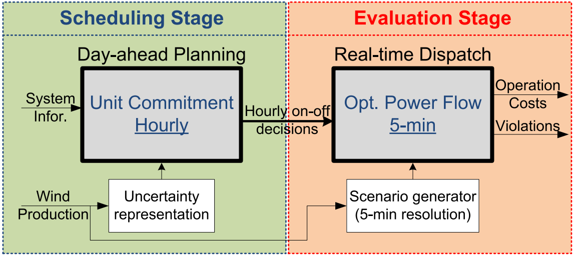
- What about the performance in real-time operation?

Scheduling & Evaluation Stages



- What about the performance in real-time operation?
- Real-time simulator to evaluate the performance of on-off decisions
  - Demand-balance & Transmission violation costs: 5000 \$/MWh

Scheduling & Evaluation Stages



- What about the performance in real-time operation?
- Real-time simulator to evaluate the performance of on-off decisions
  - Demand-balance & Transmission violation costs: 5000 $/MWh
- The operation costs are taken from the real-time dispatch

Uncertainty Representation in 4 UC Models

	Traditional Energy-Based[12]	Proposed Ramp-Based
Deterministic	Reserve Levels	Reserve Levels
Stochastic	Scenarios	Scenarios
Robust	—	Feasible Reserve Region

- Study case: IEEE 118bus-54units
  - 24 hours time span
  - UCs solved till 0.05% opt. tolerance
- Wind uncertainty: $\pm 25\%$ error
  - Scheduling: 20 scenarios
  - Evaluating: out-of-sample 200 scenarios

[12] FERC, "RTO unit commitment test system," Federal Energy and Regulatory Commission, Washington DC, USA, Tech. Rep., Jul. 2012, p. 55

Traditional UCs: Deterministic vs Stochastic

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	**1040.7**	**2089**		
Stochastic	**955.5**	**1159**		

- The stochastic approach lowered average production costs by 8.2%
  - and it lowered # of constraint violations by 45%

Traditional UCs: Deterministic vs Stochastic

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	**1040.7**	**2089**		
Stochastic	**955.5**	**1159**		

- The stochastic approach lowered average production costs by 8.2%
  - and it lowered # of constraint violations by 45%
- But the deterministic approach solved more than 110x faster

Traditional vs Proposed (I)

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	**836.2**	**252**
Stochastic	**955.5**	**1159**		

- Compared with the trad. stch, the Ramp-based Deterministic[13]
  - lowered average production costs by 11.4% and # of constraint violations by ∼78%

[13] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Traditional vs Proposed (I)

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	**836.2**	**252**
Stochastic	**955.5**	**1159**		

- Compared with the trad. stch, the Ramp-based Deterministic[13]
  - lowered average production costs by 11.4% and # of constraint violations by ∼78%
  - and it solved more than 9000x faster

[13] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Traditional vs Proposed (II)

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	836.2	252
Stochastic	**955.5**	**1159**	**829.0**	**126**

- Compared with the trad. stch, the Ramp-based Stochastic
  - lowered average production costs by 12.1%
    and # of constraint violations by ∼89%

Traditional vs Proposed (II)

	Traditional Energy-Based		Proposed Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	836.2	252
Stochastic	**955.5**	**1159**	**829.0**	**126**

- Compared with the trad. stch, the Ramp-based Stochastic
  - lowered average production costs by 12.1% and # of constraint violations by ∼89%
  - and it solved ∼100x faster

Traditional vs Proposed (III)

	Traditional Energy-Based		Proposed in this Thesis Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	836.2	252
Stochastic	**955.5**	**1159**	829.0	126
Robust	—		**821.1**	**0**

- Compared with the trad. stch, the Ramp-based Robust[14]
  - lowered average production costs by 13%
    and # of constraint violations by ~100%

[14] G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review

Traditional vs Proposed (III)

	Traditional Energy-Based		Proposed in this Thesis Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1040.7	2089	836.2	252
Stochastic	**955.5**	**1159**	829.0	126
Robust	—		**821.1**	**0**

- Compared with the trad. stch, the Ramp-based Robust[14]
  - lowered average production costs by 13% and # of constraint violations by ∼100%
  - and it solved ∼950x faster

[14] G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review

In-sample Simulation: 20 Scheduling Scenarios

	Traditional Energy-Based		Proposed in this Thesis Ramp-Based	
	Costs [k$]	# viol.	Costs [k$]	# viol.
Deterministic	1011.9	162	823.8	15
Stochastic	**943.6**	**108**	**819.2**	**0**
Robust			821.0	0

- Compared with the trad. Stch, the Ramp-Based
  - Deterministic lowered costs by 12.7%
  - Stochastic lowered costs by 13.2%
  - Robust lowered costs by 13%
- The Robust presents 0.24% higher costs than the ramp-based Stch.

Outline

Conclusions

- More accurate (adequate) system representation
  - $\Rightarrow$ better exploitation of unit's flexibility in real-time

Conclusions

- More accurate (adequate) system representation
  - ⇒ better exploitation of unit's flexibility in real-time
- To tackle uncertainty: first, we must be able to deal with certainty
  - ⇒ an adequate deterministic UC can beat an inadequate Stch one
  - ⇒ an adequate Stch UC outperforms an inadequate Stch one

Conclusions

- More accurate (adequate) system representation
  - ⇒ better exploitation of unit's flexibility in real-time
- To tackle uncertainty: first, we must be able to deal with certainty
  - ⇒ an adequate deterministic UC can beat an inadequate Stch one
  - ⇒ an adequate Stch UC outperforms an inadequate Stch one
- An adequate robust reserve-based UC
  - Decreases operating costs
  - Overcomes the disadvantages of stochastic UCs

Questions

Thank you for your attention

Contact Information:
gmorales@kth.se
german.morales@iit.upcomillas.es

Future Work

- System Representation. To formulate Ramp-based models for:
  - Dynamic ramping
  - Other technologies, e.g., hydro, combined cycle units
- MIP Modeling
  - Further tightening of the robust UC model
  - To compact stochastic UCs without losing accuracy
  - To propose tight & compact formulations for other complex UC problems, e.g., combined cycle units
- Uncertainties
  - Further introduction of uncertainties, e.g., generators and lines outages
  - Model 15-min and 30-min reserves
- Pricing. How to obtain prices for:
  - the new ramp-based approach?
  - the robust approach?

For Further Reading

A. Ben-Tal, A. Goryashko, E. Guslitzer, and A. Nemirovski, "Adjustable robust solutions of uncertain linear programs," en, *Mathematical Programming*, vol. 99, no. 2, pp. 351–376, Mar. 2004.

D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, and T. Zheng, "Adaptive robust optimization for the security constrained unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 1, pp. 52–63, Feb. 2013.

M. Carrion and J. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1371–1378, 2006.

FERC, "RTO unit commitment test system," Federal Energy and Regulatory Commission, Washington DC, USA, Tech. Rep., Jul. 2012, p. 55.

C. Gentile, G. Morales-Espana, and A. Ramos, "A tight MIP formulation of the unit commitment problem with start-up and shut-down constraints," *European Journal of Operational Research*, 2014, Under Review.

For Further Reading (cont.)

- X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000.
- T. Li and M. Shahidehpour, "Price-based unit commitment: a case of lagrangian relaxation versus mixed integer programming," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 2015–2025, Nov. 2005.
- G. Morales-Espana, R. Baldick, J. Garcia-Gonzalez, and A. Ramos, "Robust reserve modelling for wind power integration in ramp-based unit commitment," *IEEE Transactions on Power Systems*, 2014, Under review.
- G. Morales-Espana, C. Gentile, and A. Ramos, "Tight MIP formulations of the power-based unit commitment problem," *Optimization Letters*, 2014, Under Review.
- G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013.
- G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014.

For Further Reading (cont.)

G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation of start-up and shut-down ramping in unit commitment," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1288–1296, 2013.

J. Ostrowski, M. F Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 39–46, Feb. 2012.

Outline

- More Numerical Results
- Other Numerical Results

UC Costs and # SU

	Traditional Energy-Based		Proposed in this Thesis Ramp-Based	
	UC Costs [k$]	# SU	UC Costs [k$]	# SU
Deterministic	33.98	10	55.49	16
Stochastic	33.73	10	54.76	12
Robust			51.98	14

CPU time comparisons (I)

	Traditional Energy-Based		Proposed in this Thesis Ramp-Based	
	Costs [k$]	runtime [s]	Costs [k$]	runtime [s]
Deterministic	1040.7	766.2	836.2	8.75
Stochastic	955.5	86400	829.0	867.9
Robust			821.1	90.5

CPU time comparisons (II)

	Traditional Energy-Based		Proposed in this Thesis	
	Costs [k$]	runtime [s]	Costs [k$]	runtime [s]
Deterministic	1040.7	766.2	1040.7	4.5
Stochastic	**955.5**	86400	955.5	206.5

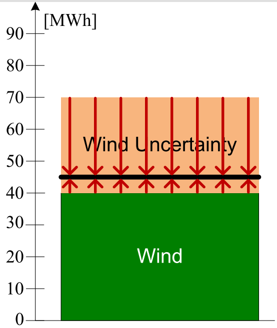
- The Stochastic formulation lowers average production costs by 8.2%
- But it takes more than 24 hours to solve
- The proposed Tight and Compact Stch UC[15] solved above 418x faster

[15] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013

ARO-UC Example

Demand = 45; wind uncertainty set $\Xi := \{\xi \in [40, 70]\}$;
and thermal unit: $\underline{P} = 20\text{MW}$; $\overline{P} = 40\text{MW}$

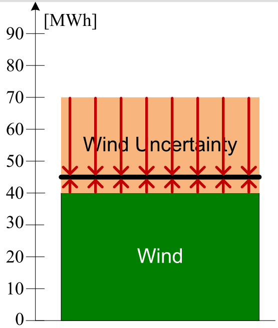
Thermal unit Off



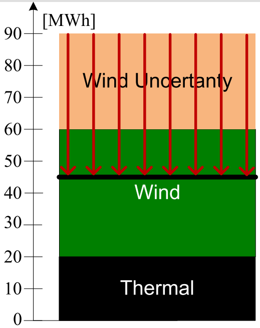
ARO-UC Example

Demand $= 45$; wind uncertainty set $\Xi := \{\xi \in [40, 70]\}$;
and thermal unit: $\underline{P} = 20\text{MW}$; $\overline{P} = 40\text{MW}$

Thermal unit Off



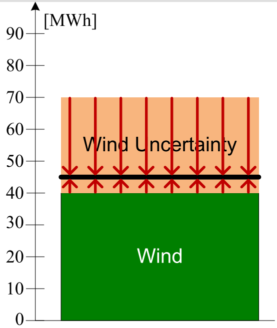
Thermal unit On



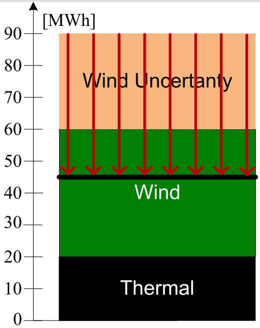
ARO-UC Example

Demand $= 45$; wind uncertainty set $\Xi := \{\xi \in [40, 70]\}$;
and thermal unit: $\underline{P} = 20\text{MW}$; $\overline{P} = 40\text{MW}$

Thermal unit Off



Thermal unit On

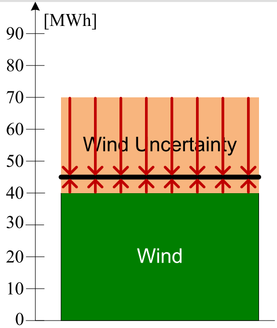


- ARO-UC without curt. $\Rightarrow nse \neq 0 \; \forall \xi < 45$

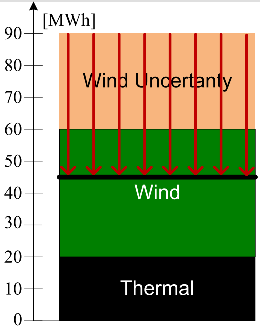
ARO-UC Example

Demand $= 45$; wind uncertainty set $\Xi := \{\xi \in [40, 70]\}$;
and thermal unit: $\underline{P} = 20\text{MW}$; $\overline{P} = 40\text{MW}$

Thermal unit Off



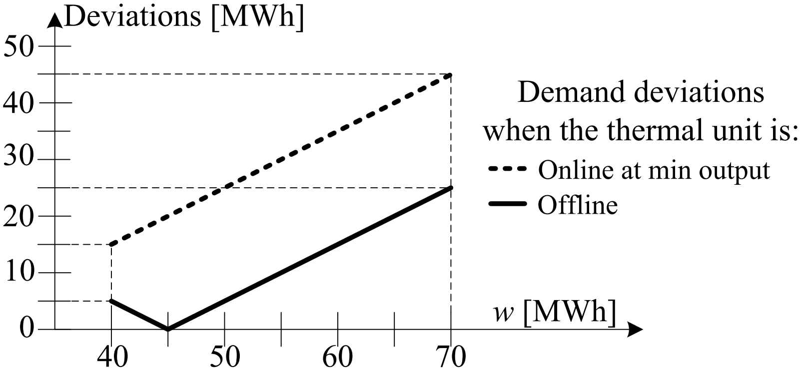
Thermal unit On



- ARO-UC without curt. $\Rightarrow nse \neq 0 \; \forall \xi < 45$
- ARO-UC allowing curt. $\Rightarrow nse = 0 \; \forall \xi \in \Xi$

ARO-UC Example

Demand = 45; wind uncertainty $\xi = [40, 60]$;
and thermal unit: $\overline{P} = 40\text{MW}$; $\underline{P} = 20\text{MW}$

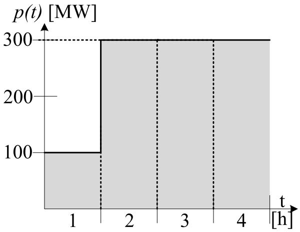


Energy Scheduling

Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300\text{MW}$; $\underline{P} = 100\text{MW}$; Up/Down ramp rate: 200 MW/h

Traditional UC



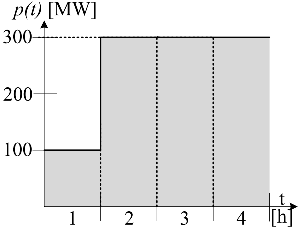
[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

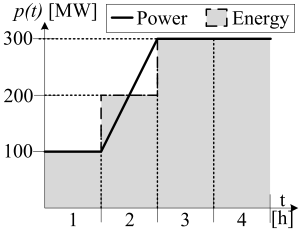
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 200 MW/h

Traditional UC



Feasible energy profile



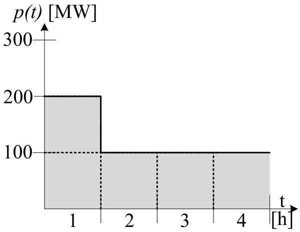
[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 100 MW/h

Traditional UC



Feasible energy profile

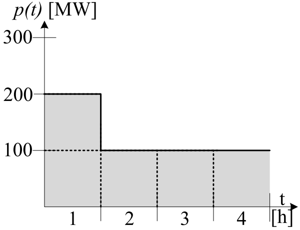
[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

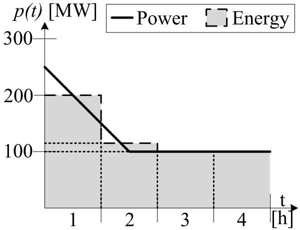
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 100 MW/h

Traditional UC



Feasible energy profile



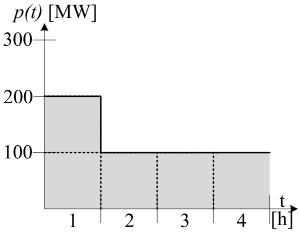
[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

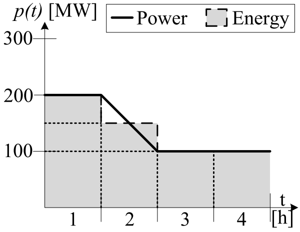
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 100 MW/h

Traditional UC



Feasible energy profile



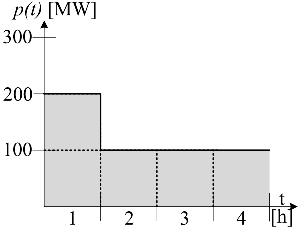
[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Energy Scheduling

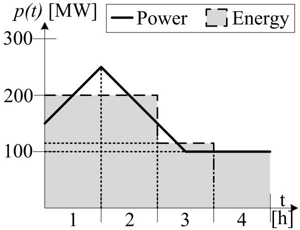
Generation levels are usually considered as energy blocks.

Example: $\overline{P} = 300$MW; $\underline{P} = 100$MW; Up/Down ramp rate: 100 MW/h

Traditional UC



Feasible energy profile



Infeasible energy delivery[16]

Overestimated ramp availability

⇓

A clear difference between power and energy is required in UCs

[16] X. Guan, F. Gao, and A. Svoboda, "Energy delivery capacity and generation scheduling in the deregulated electric power market," *IEEE Transactions on Power Systems*, vol. 15, no. 4, pp. 1275–1280, Nov. 2000

Outline

- More Numerical Results
- Other Numerical Results

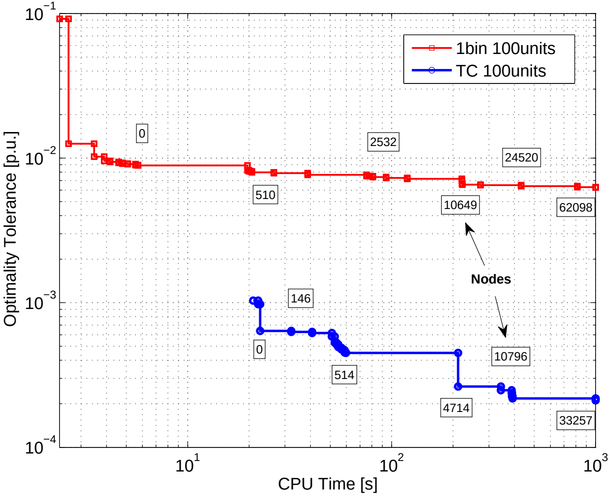
Ramp-based: Some Details per Unit

	1bin[17]	*Ramp-Based*[18]
Co-optimization	No	Yes
SU costs	3 types	3 types
SU ramps	–	3 types
SD ramps	–	1
Operating ramps	2 types	6 types
Online reserves	1	4
Offline reserves	–	2

[17] M. Carrion and J. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1371–1378, 2006

[18] G. Morales-Espana, A. Ramos, and J. Garcia-Gonzalez, "An MIP formulation for joint market-clearing of energy and reserves based on ramp scheduling," *IEEE Transactions on Power Systems*, vol. 29, no. 1, pp. 476–488, 2014

Convergence Evolution



Performance of Stochastic UCs

- 10 generating units for a time span of 4 days
- 10 to 200 scenarios in demand
- 4 formulations tested –modeling the same MIP problem:
  - *TC*[19]: Proposed Tight & Compact
  - *1bin*[20], *3bin*[21], *Sh*[22]
- Different Solvers
  - Cplex 12.5.1, Gurobi 5.5, XPRESS 24.01.04

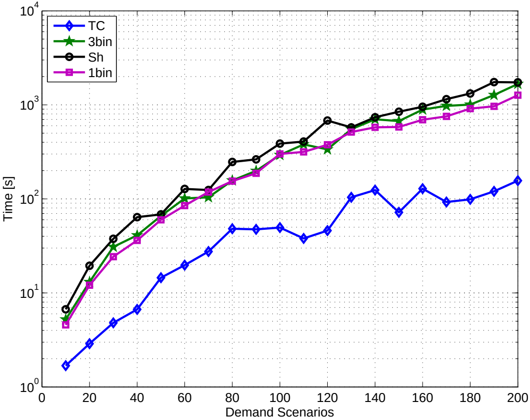
[19] G. Morales-Espana, J. M. Latorre, and A. Ramos, "Tight and compact MILP formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4897–4908, Nov. 2013

[20] M. Carrion and J. Arroyo, "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem," *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1371–1378, 2006

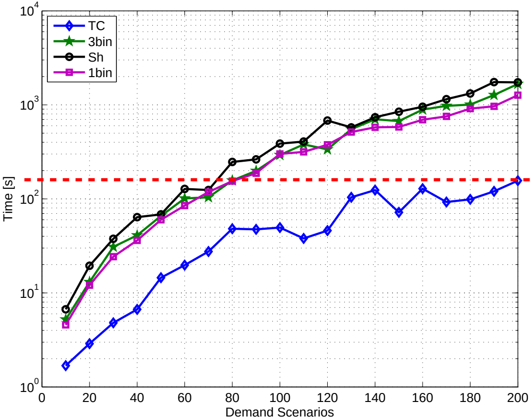
[21] J. Ostrowski, M. F Anjos, and A. Vannelli, "Tight mixed integer linear programming formulations for the unit commitment problem," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 39–46, Feb. 2012

[22] T. Li and M. Shahidehpour, "Price-based unit commitment: a case of lagrangian relaxation versus mixed integer programming," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 2015–2025, Nov. 2005

Stochastic: Cplex

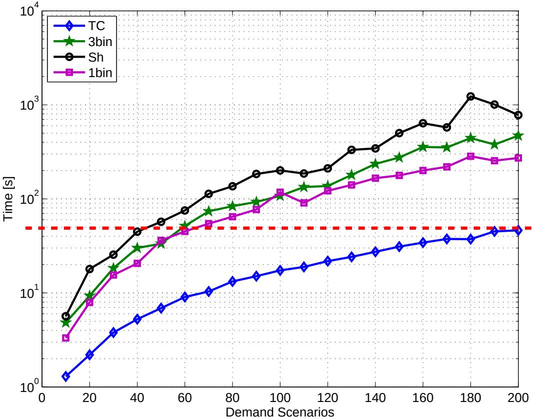


Stochastic: Cplex



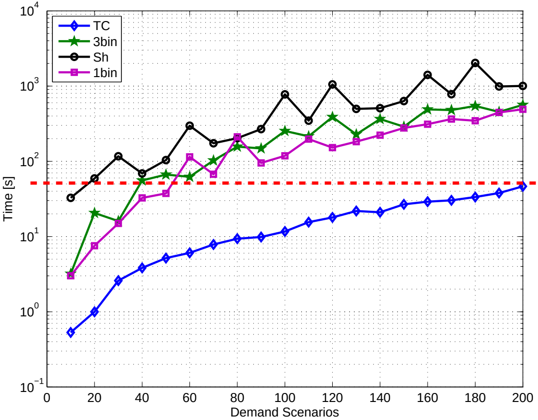
TC deals with 200 scenarios within the time that others deal with 80

Stochastic: Gurobi



TC deals with 200 scenarios within the time that others deal with 60

Stochastic: XPRESS



TC deals with 200 scenarios within the time that others deal with 50