# A stochastic integer programming approach to the optimal thermal and wind generator scheduling problem

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*York University*

*Industrial Optimization Seminar*
*Fields Institute for Research in Mathematical Science*

*March 6th, 2012*

# Outline

Overview

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Problem statement

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Stochastic programming model

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- Computational challenge and solution

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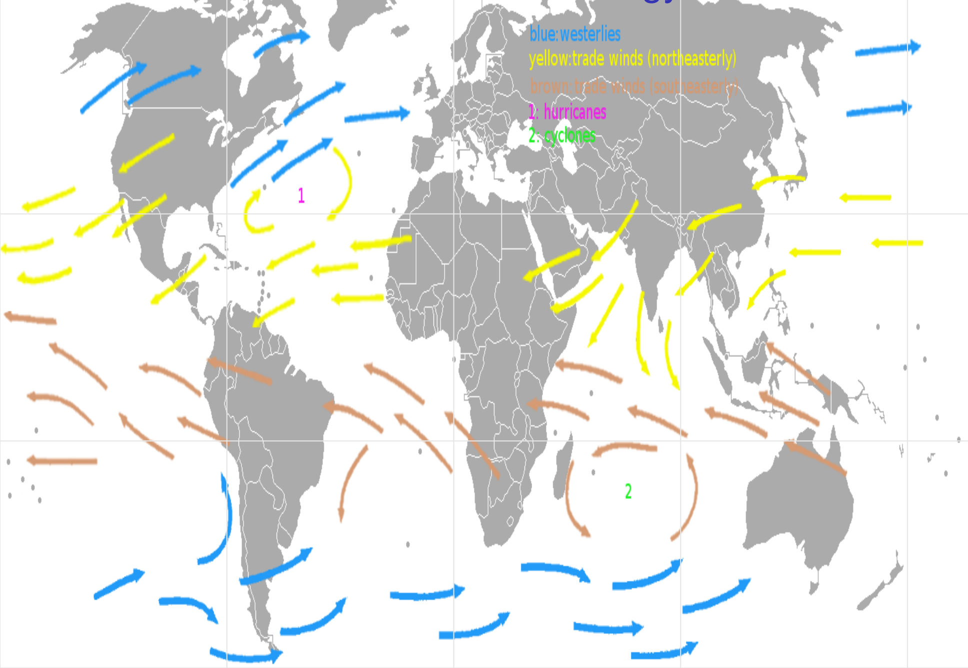
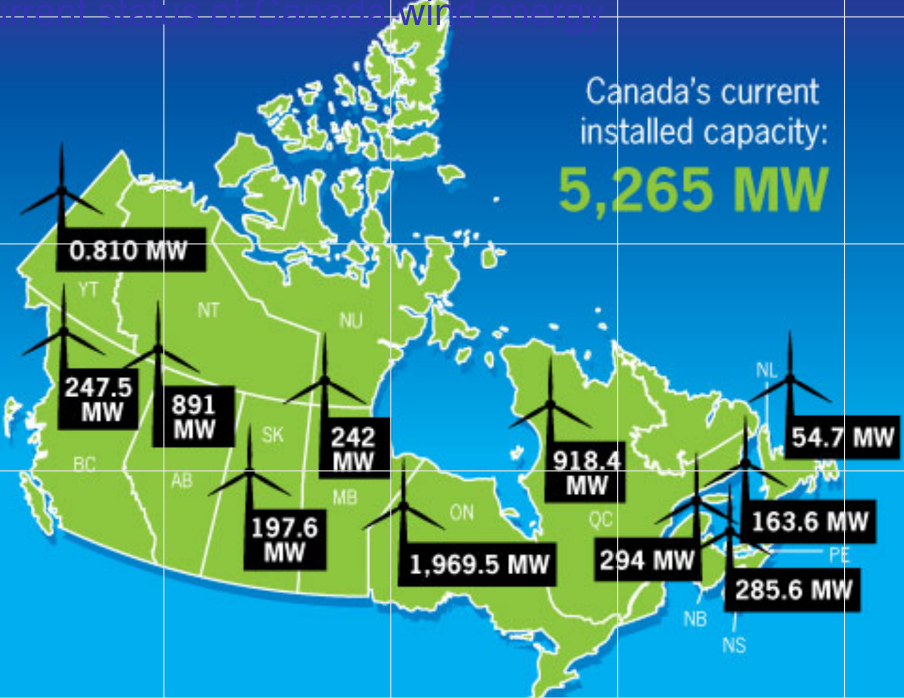
Computational challenge and solution

Benchmarking report

# Wind as a clean and renewable energy source

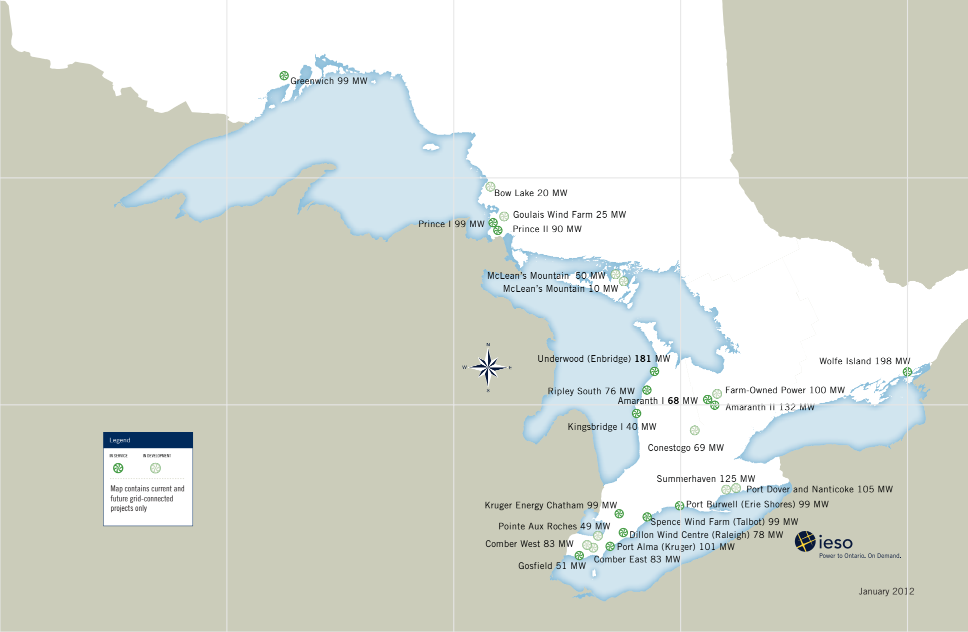


# Current status of Canada wind energy



# Current status of Ontario wind energy

## ONTARIO WIND GENERATORS



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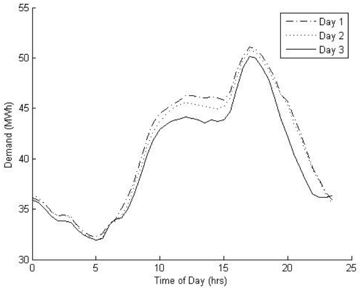
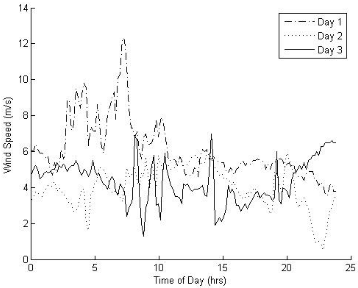
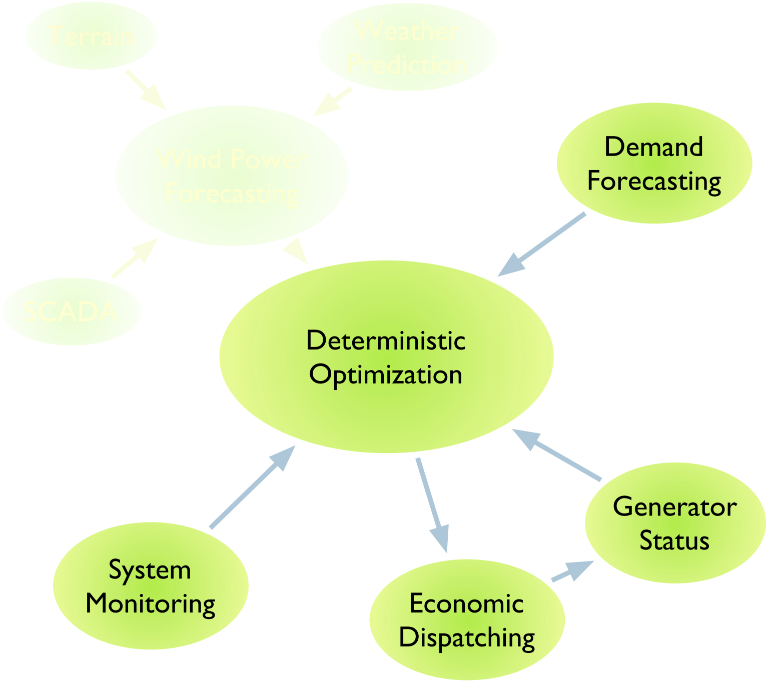
# Increasing wind and increasing system volatility




(a) Daily Demand Curves




(b) Daily Wind Speed Curves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System Monitoring
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Generator Status

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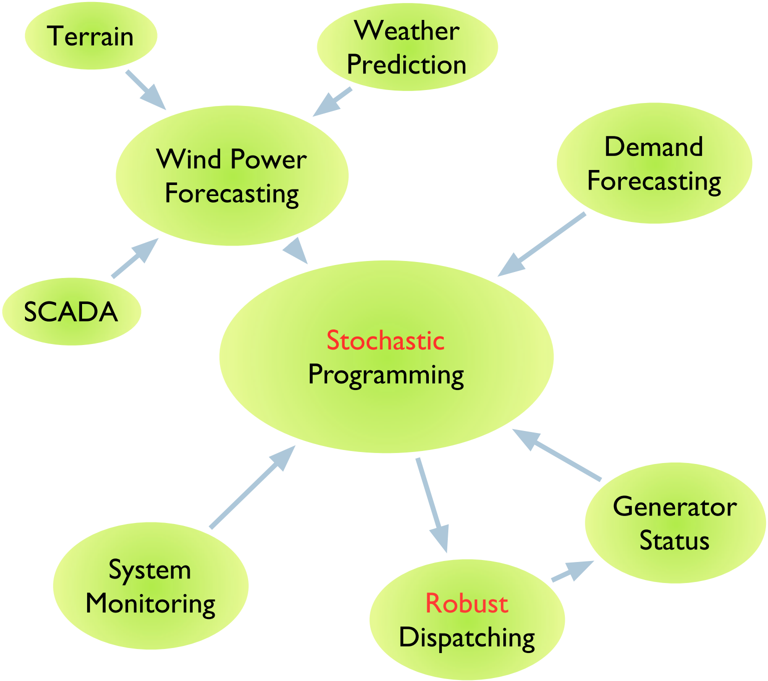
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8. lower energy cost for the society!

# Stochastic programming model: key decision variables

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All other variables are dependent on the variable $v$.

# Stochastic programming model

$$\min \overbrace{\sum_{\substack{h\in H\\ j\in J_s}} (c_j^u y_{jh} + c_j^d z_{jh} + c_j^m v_{jh})}^{\text{first stage}} + \overbrace{\sum_{s\in\mathcal{S}} \pi^s \Big( \sum_{\substack{h\in H\\ j\in J_f}} (c_j^u y_{jh}^s + c_j^d z_{jh}^s + c_j^m v_{jh}) + \sum_{\substack{h\in H\\ j\in J}} c_j^p p_{jh}^s \Big)}^{\text{second stage}}$$

$$s.t.\ (\mathbf{y}_{J_s}, \mathbf{z}_{J_s}, \mathbf{v}_{J_s}) \in \mathcal{U}_{J_s} \quad (1)$$

$$(\mathbf{y}_{J_f}, \mathbf{z}_{J_f}, \mathbf{v}_{J_f}) \in \mathcal{U}_{J_f}^s, \forall s \in \mathcal{S} \quad (2)$$

$$(\mathbf{p}^s, \mathbf{w}^s) \in \mathcal{C}^s, \forall s \in \mathcal{S} \quad (3)$$

$$(\mathbf{p}^s, \mathbf{w}^s) \in \mathcal{N}^s, \forall s \in \mathcal{S} \quad (4)$$

$$(\mathbf{p}^s, \mathbf{w}^s) \in \mathcal{R}^s, \forall s \in \mathcal{S} \quad (5)$$

# Stochastic programming model: unit commitment constraints

The unit commitment constraints for a generator $j \in J$ is defined as:

$$\mathcal{U}_j := \begin{cases} y_{jh} \geqslant v_{jh} - v_{j,h-1} & \forall h \in H & \text{(6a)} \\ z_{jh} \geqslant v_{j,h-1} - v_{jh} & \forall h \in H & \text{(6b)} \\ y_{j,h-\overline{T}_j+1} + \cdots + y_{jh} \leqslant v_{jh} & \forall h \in H & \text{(6c)} \\ z_{j,h-\underline{T}_j+1} + \cdots + z_{jh} \leqslant 1 - v_{jh} & \forall h \in H & \text{(6d)} \\ v_{j,h-1} - v_{jh} + y_{jh} - z_{jh} = 0 & \forall h \in H & \text{(6e)} \\ v_{jh} \in \{0, 1\}, y_{jh}, z_{jh} \in [0, 1] & \forall h \in H & \text{(6f)} \end{cases}$$

The constraint sets $\mathcal{U}_J, \mathcal{U}_{J_s}, \mathcal{U}_{J_f}$ are defined accordingly:

$$\mathcal{U}_J := \bigcap_{j \in J} \mathcal{U}_j, \mathcal{U}_{J_s} := \bigcap_{j \in J_s} \mathcal{U}_j, \mathcal{U}_{J_f} := \bigcap_{j \in J_f} \mathcal{U}_j \qquad (7)$$

# Stochastic programming model: reserve constraints

$$
\mathcal{R}^s := \begin{cases} \sum_{j \in J} rs^s_{jh} \geqslant \eta_s \sum_{l \in L} d^s_{lh} & \forall h \in H \quad \text{(8a)} \\ \sum_{j \in J} rs^s_{jh} + \sum_{j \in J} ro^s_{jh} \geqslant \eta \sum_{l \in L} d^s_{lh} & \forall h \in H \quad \text{(8b)} \end{cases}
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- We assume the contingency constraint is implemented exogenously following NERC N-1 rule.

# Stochastic programming model: network constraints

$$
\mathcal{N}^s := \begin{cases}
\sum_{j \in J_m} p^s_{jh} + \sum_{i \in I_m} w^s_{ih} + \sum_{nm \in E} f^s_{nmh} = & \\
\sum_{mn \in E} f^s_{mnh} + \sum_{l \in L_m} d^s_{lh} + gsh_m & \forall m \in V, h \in H \quad \text{(9a)} \\
f^s_{mnh} = b_{mn}(\theta^s_{mh} - \theta^s_{nh} - \gamma^s_{mnh}) & \forall mn \in E, h \in H \quad \text{(9b)} \\
-\bar{f}_{mn} \leqslant f^s_{mnh} \leqslant \bar{f}_{mn} & \forall mn \in E, h \in H \quad \text{(9c)} \\
\underline{\gamma}_{mn} \leqslant \gamma^s_{mnh} \leqslant \overline{\gamma}_{mn} & \forall mn \in E, h \in H \quad \text{(9d)} \\
\theta^s_{ref,h} = 0 & \forall h \in H \quad \text{(9e)}
\end{cases}
$$

# Stochastic programming model: capacity constraints

$$
\mathcal{C}^s := \begin{cases}
\underline{P}_j v_{jh} \leqslant p^s_{jh} & \forall j \in J, h \in H \quad \text{(10a)} \\
p^s_{jh} + rs^s_{jh} \leqslant \overline{P}_j v_{jh} & \forall j \in J, h \in H \quad \text{(10b)} \\
p^s_{jh} + rs^s_{jh} + ro^s_{jh} \leqslant \overline{P}_j & \forall j \in J, h \in H \quad \text{(10c)} \\
p^s_{j,h-1} - p^s_{j,h} \leqslant \underline{R}_j & \forall j \in J, h \in H \quad \text{(10d)} \\
p^s_{jh} - p^s_{j,h-1} + rs^s_{jh} + ro^s_{jh} \leqslant \overline{R}_j & \forall j \in J, h \in H \quad \text{(10e)} \\
rs^s_{jh} \leqslant \overline{RS}_j & \forall j \in J, h \in H \quad \text{(10f)} \\
ro^s_{jh} \leqslant \overline{RO}_j & \forall j \in J, h \in H \quad \text{(10g)} \\
w^s_{lh} \leqslant \tilde{w}^s_{lh} & \forall l \in L, h \in H \quad \text{(10h)}
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- stochastic integer programming problem is much more challenging!
- both the first stage and the second stage of the stochastic unit commitment model are integer problem!
- cutting-plane method is very effective for integer problem;
- how about stochastic integer problem?

# Our solution: scenario crossing deep cuts

## Definition

$C_{sh} \subset J$ is a $(s,h)$-*cover* if

$$\sum_{j \in C_{sh}} \overline{P}_j + \sum_{i \in I} \tilde{w}^s_{ih} < (1+\eta_s) \sum_{l \in L} d^s_{lh}.$$

If in addition

$$\sum_{j \in C_{sh}} \overline{P}_j + \sum_{i \in I} \tilde{w}^s_{ih} + \underline{P}_i \geqslant (1+\eta_s) \sum_{l \in L} d^s_{ld} \quad \forall i \in J - C_{sh}, \tag{11}$$

then the cover $C$ is simple.

# Our solution: scenario crossing deep cuts

**PROPOSITION**

*If* $(1+\eta_s)\sum_{l\in L} d_{lh_1}^{s_1} - \sum_{i\in I}\tilde{w}_{ih_1}^{s_1} \leqslant (1+\eta_s)\sum_{l\in L} d_{lh_2}^{s_2} - \sum_{i\in I}\tilde{w}_{ih_2}^{s_2}$*, then (i) a* $(s_1,h_1)$*-cover is also a* $(s_2,h_2)$*-cover; (ii) any* $(s_2,h_2)$*-cover has a* $(s_1,h_1)$*-cover subset.*

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PROPOSITION

*Let $C$ be a $(s,h)$-cover and $\Delta_h^s = \sum_{l \in L} d_{lh}^s - \sum_{j \in C} \overline{P}_j - \sum_{i \in I} \tilde{w}_{ih}^s$. Then the strengthened $(s,h)$-cut*

$$\sum_{j \in J-C} \frac{p_{jh}^s}{max\{\underline{P}_j, \Delta_h^s\}} + \sum_{i \in I} \frac{w_{ih}^s}{\Delta_h^s} \geqslant 1 \tag{12}$$

*is valid for $\rho^s(\cdot)$. If in addition,*

$$\Delta_h^s \leqslant \overline{P}_j, \forall j \in J - C,$$

*and (11) holds strictly for some indices, then (12) is facet-defining for $\rho^s(\cdot)$.*

# Our solution: scenario crossing deep cuts

## Definition

Two generators $a$ and $b$ are symmetric if $a$ and $b$ have identical physical features and are located on one bus.

## Proposition

*Assume there are $\kappa$ symmetric pairs in the electricity grid. Let $\Omega^s$ be the feasible set of $(\mathbf{v}^s, \mathbf{y}^s, \mathbf{z}^s)$ in $\rho^s(\lambda^s)$, and $\Omega^{s\prime}$ be the reduced feasible set after applying the $\kappa$ symmetry cuts:*

$$y^s_{ah} + v^s_{a,h-1} + v^s_{b,h-1} \geqslant y^s_{bh}, \text{ for all symmetric pairs (a,b)},$$

*then*

$$|\Omega^{s\prime}| = \frac{|\Omega^s|}{2^\kappa},$$

*i.e., the feasible region shrinks exponentially.*

# Numerical test: RTS-96 system

Table: Generator Mix

| Type | Technology | No. units | Capacity(MW) | list of units |
|---|---|---|---|---|
| U12 | Oil/Steam | 5 | 60 | 16-20 |
| U20 | Oil/CT | 4 | 80 | 1-2,5-6 |
| U50 | Hydro | 6 | 300 | 25-30 |
| U76 | Coal/Steam | 4 | 304 | 3-4, 7-8 |
| U100 | Oil/Steam | 3 | 300 | 9-11 |
| U155 | Coal/Steam | 4 | 620 | 21-22, 31-32 |
| U197 | Oil/Steam | 3 | 591 | 12-14 |
| U350 | Coal/3 Steam | 1 | 350 | 33 |
| U400 | Nuclear | 2 | 800 | 23-24 |
| W150 | Wind | 1 | 150 | . |
| W100 | Wind | 1 | 100 | . |

# Numerical test: RTS-96 system

Table: Bus Generator Incidence

| Bus | Generators | Bus | Generator | Bus | Generator |
|---|---|---|---|---|---|
| 1 | 1-4 | 7 | 9-11 | 18 | 23 |
| 2 | 5-8 | 13 | 12-14 | 21 | 24 |
| 4 | W150 | 15 | 16-21 | 22 | 25-30 |
| 5 | W100 | 16 | 22 | 23 | 31-33 |

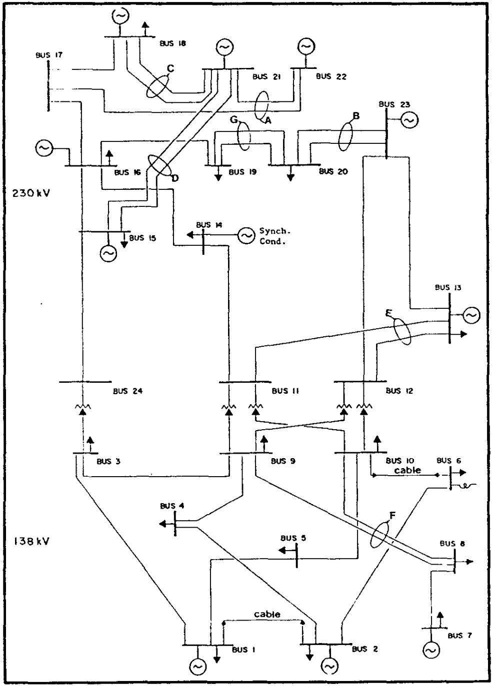


**Figure 1 - IEEE One Area RTS-96**

- 30 generators;
- 24 buses;
- 34 lines;
- installed capacity 3,405MW.

# Effect of symmetry cut

| Optimal schedule 1 | | | Optimal schedule 2 | | |
|---|---|---|---|---|---|
| Gen | switch on | switch off | Gen | switch on | switch off |
| 7 | 6 | 23 | 8 | 6 | 23 |
| 3 | 7 | 23 | 3 | 7 | 23 |
| 4 | 7 | 23 | 4 | 7 | 23 |
| 8 | 7 | 23 | 7 | 7 | 23 |
| 13 | 7 | 21 | 13 | 7 | 21 |
| 12 | 8 | 22 | 12 | 8 | 22 |
| 14 | 8 | 22 | 14 | 8 | 22 |
| 17 | 8 | 12 | 16 | 8 | 12 |
| 20 | 8 | 12 | 18 | 8 | 12 |
| 2 | 10 | 11 | 1 | 10 | 11 |

Table: Optimal Schedule for Two-scenario Instance. Generators not shown in the table are always on. No wind curtailment nor demand shedding appears in this optimal schedule. The optimal objective value is $798,256. Total demands for the two scenarios over the 24 hrs are 56811.5MW and 56571.8MW.

# Benchmarking report

| | CPLEX B&B | | CPLEX D& S | | Cover Cuts | | | Both cuts | |
|---|---|---|---|---|---|---|---|---|---|
| S | nodes | seconds | nodes | seconds | nodes | seconds | Ncuts | node | second |
| 2 | 3027 | 78 | 3453 | 75 | 2460 | 53 | 2 | 48 | 37 |
| 5 | 1051 | 73 | 2544 | 224 | 185 | 17 | 10 | 25 | 10 |
| 10 | 3715 | 703 | 3137 | 870 | 1741 | 529 | 12 | 117 | 101 |
| 15 | 37040 | 5053 | 44838 | 21500 | 1631 | 1064 | 23 | 1103 | 1176 |
| 20 | 5279 | 5023 | 8684 | 4096 | 3592 | 3359 | 29 | 237 | 282 |
| 25 | 7281 | 4191 | 23533 | 18998 | 1667 | 2920 | 42 | 621 | 1305 |

Table: Statistics of running time. The number of cuts shown in table is for cover cuts; the number of symmetry cuts is constantly 36, which is not shown in the table.

| S | 2 | 5 | 10 | 15 | 20 | 25 | mean | median |
|---|---|---|---|---|---|---|---|---|
| cover cut | 29% | 76% | 24% | 78% | 17% | 30% | 42% | 29% |
| both cuts | 50% | 86% | 85% | 76% | 93% | 68% | 76% | 80% |

Table: Reduction rate of running time

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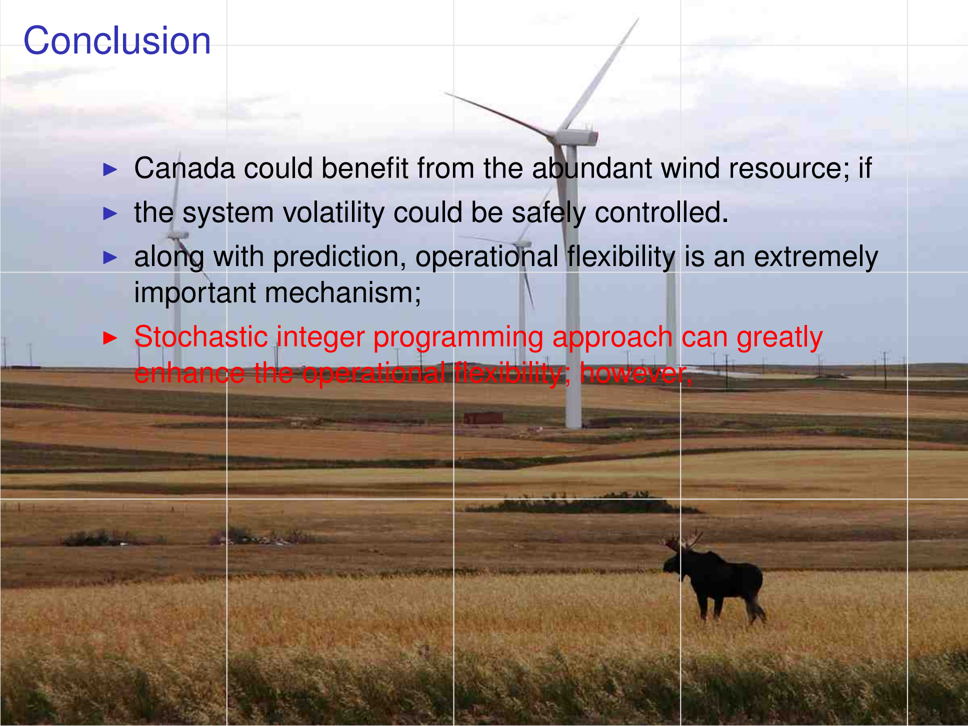

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- computational efficiency is its bottleneck.
- We build a mathematically rigorous stochastic optimization model for the problem.
- Our research on cross-scenario deep cuts speeds up the state-of-art CPLEX solver significantly!

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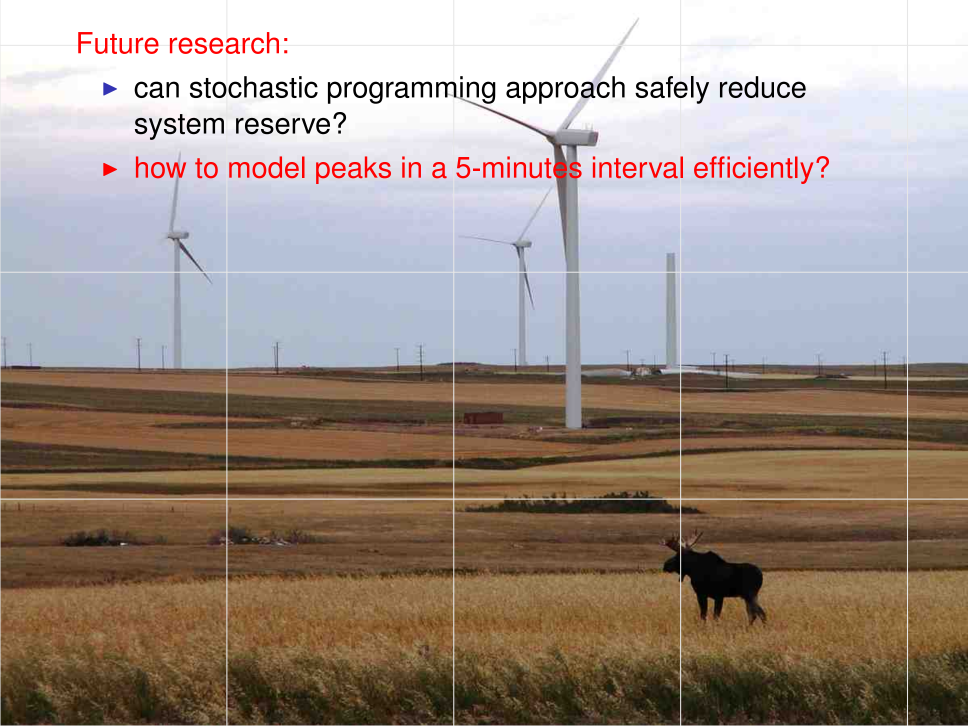

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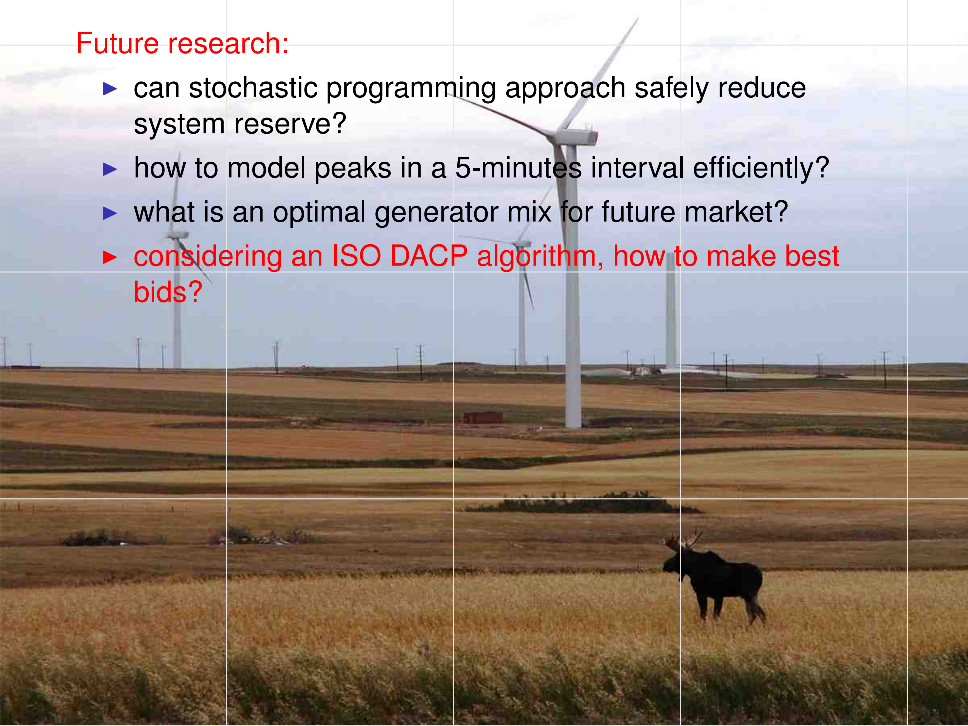

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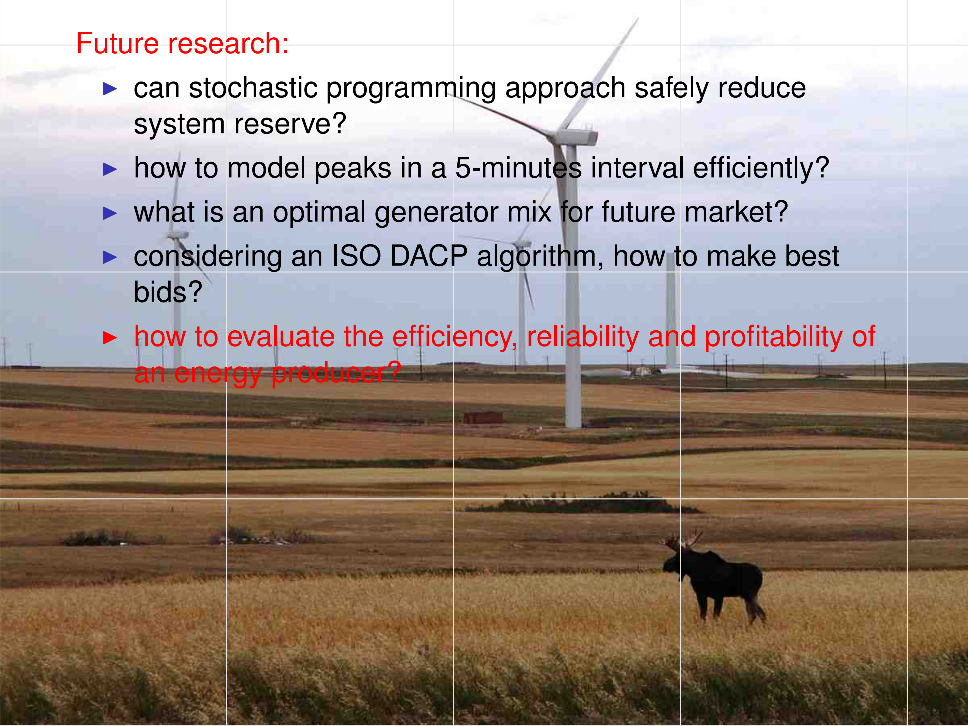

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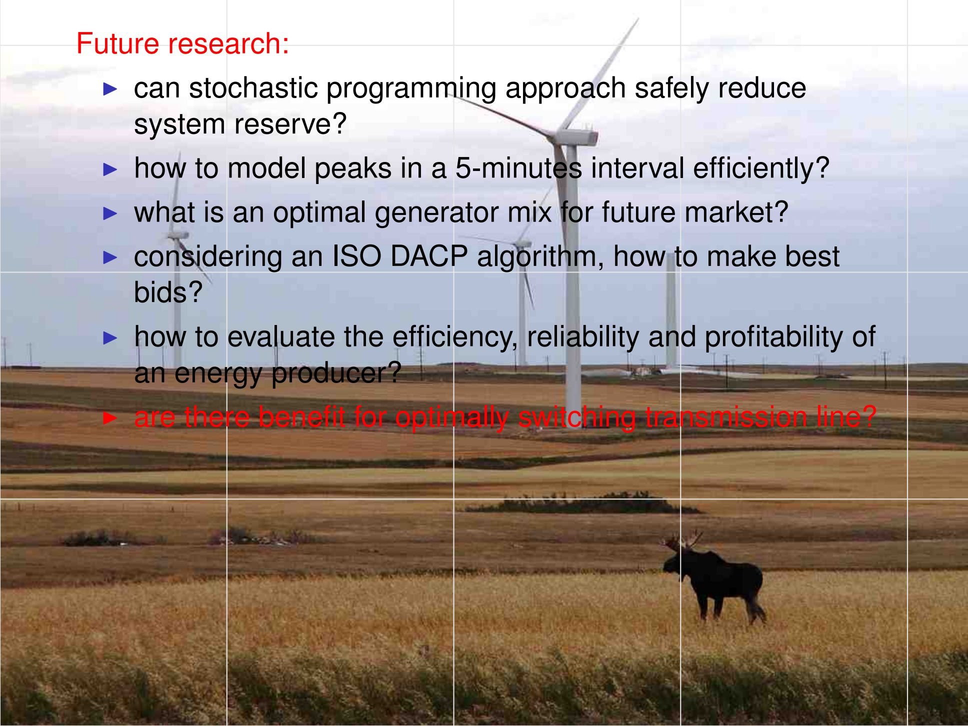

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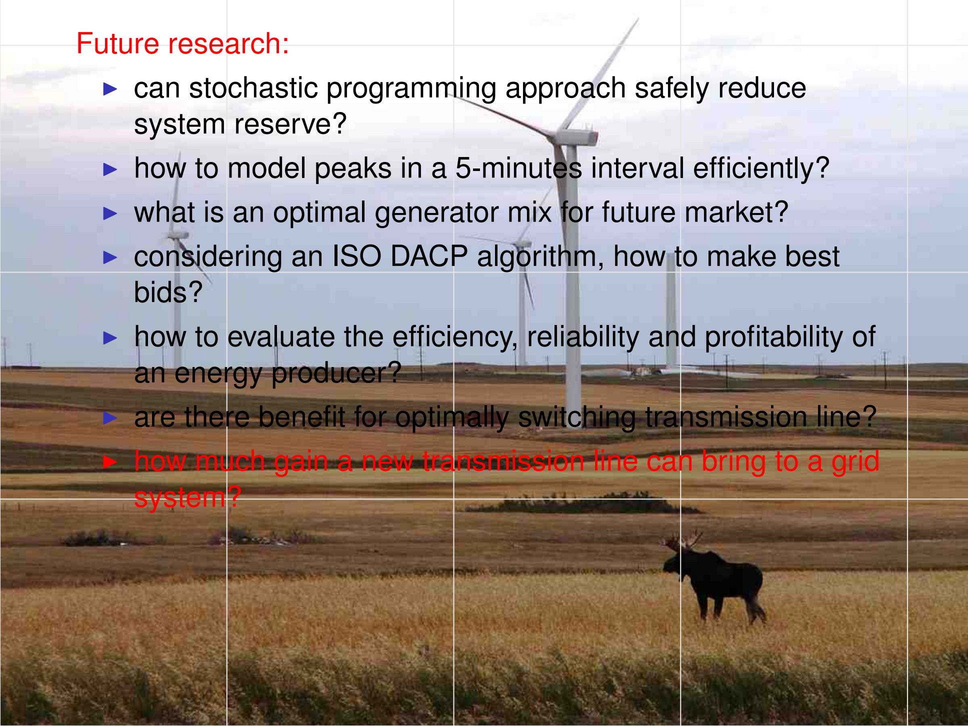

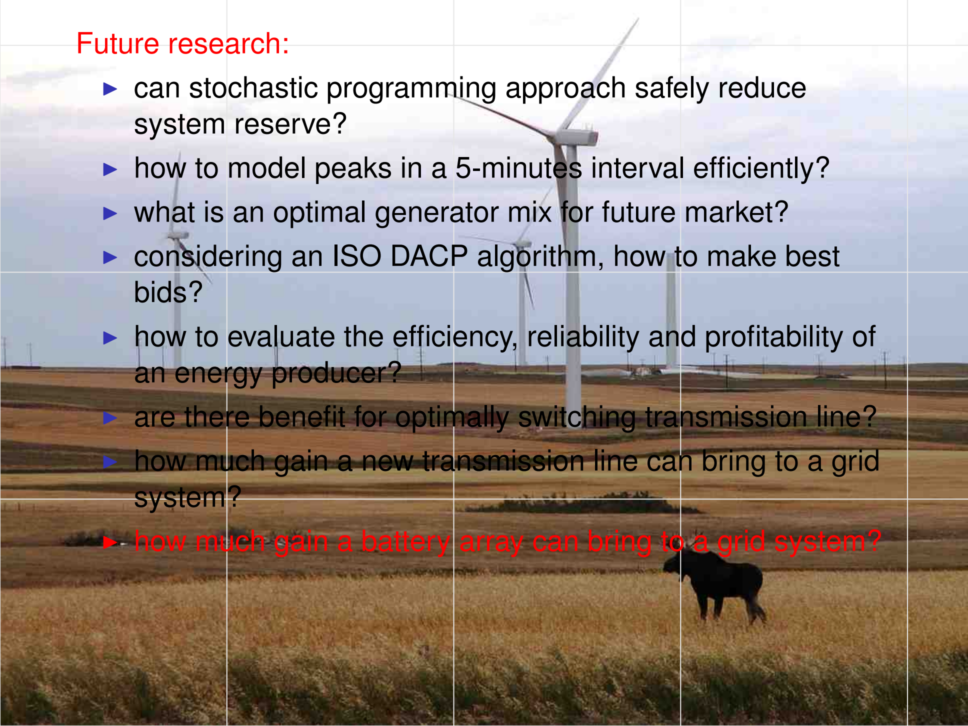

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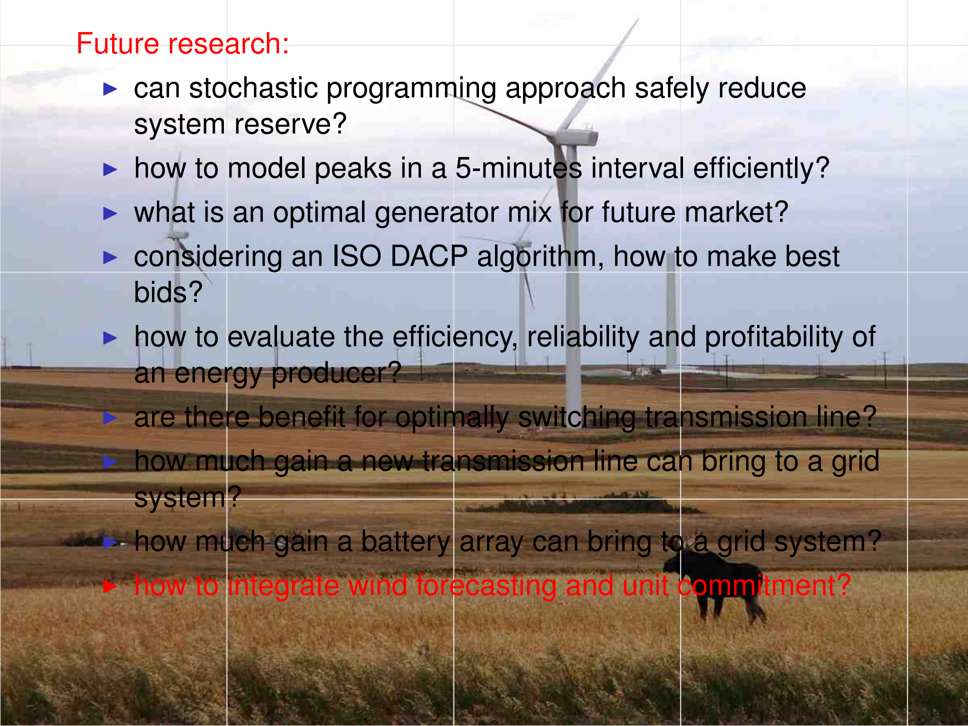

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Paper and slides are available upon request, please contact:

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