Model Predictive Control for Energy Systems Management

Workshop: Modeling and Optimization of Heat and Power Systems

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Kgs. Lyngby, Denmark. January 2015

Industrial Ph.D. Project

Project

Stochastic Model Predictive Control with Applications in Smart Energy Systems

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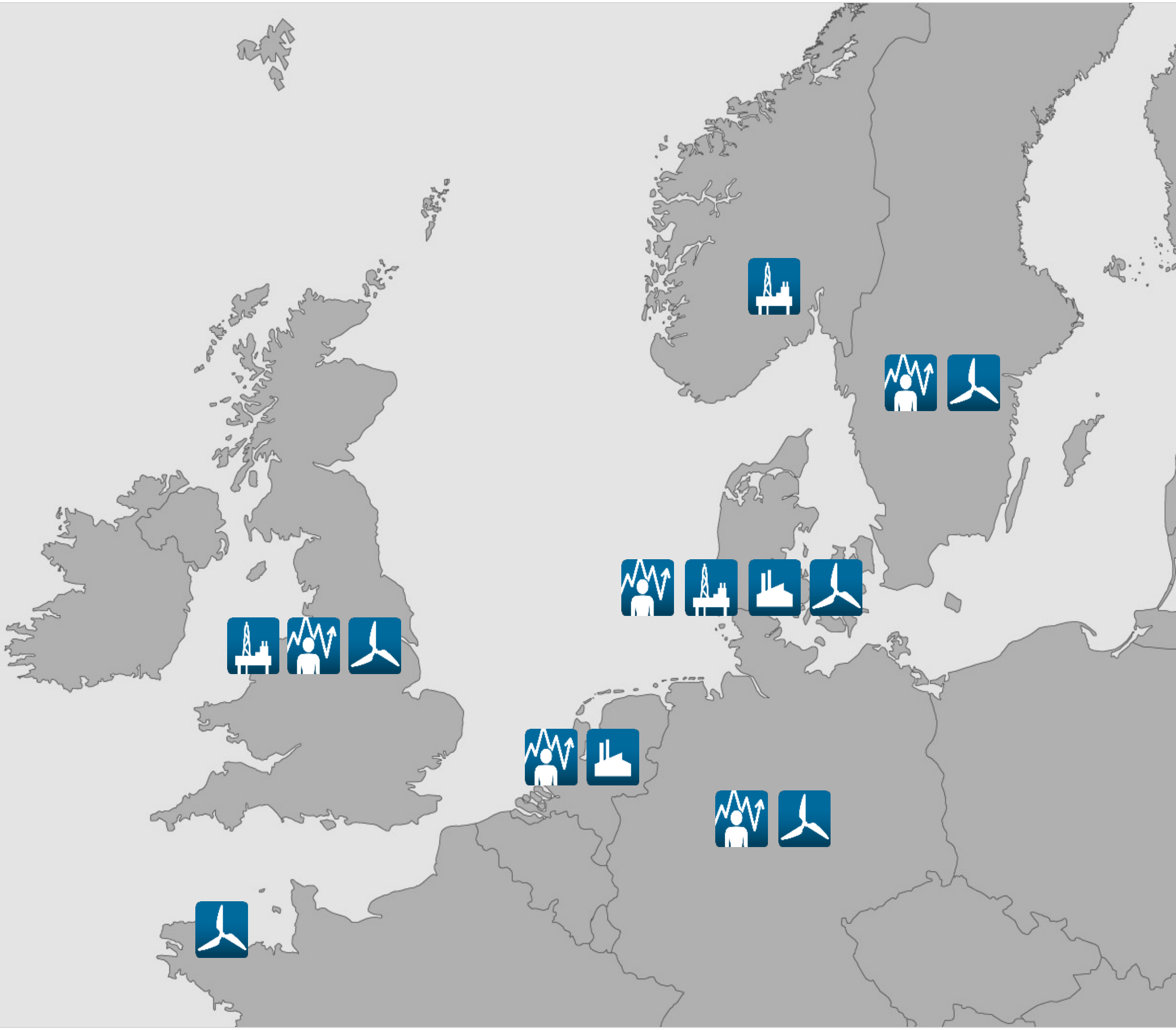
DONG Energy

DONG Energy is an integrated energy company that procures, produces, distributes and trades energy products in Northern Europe.

- Headquartered in Denmark
- Mainly owned by the Danish state
- Around 6,500 employees
- DKK 73.1 billion (EUR 9.8 billion) in revenue in 2013



Exploration & Production

Wind Power

Thermal Power

Customers & Markets

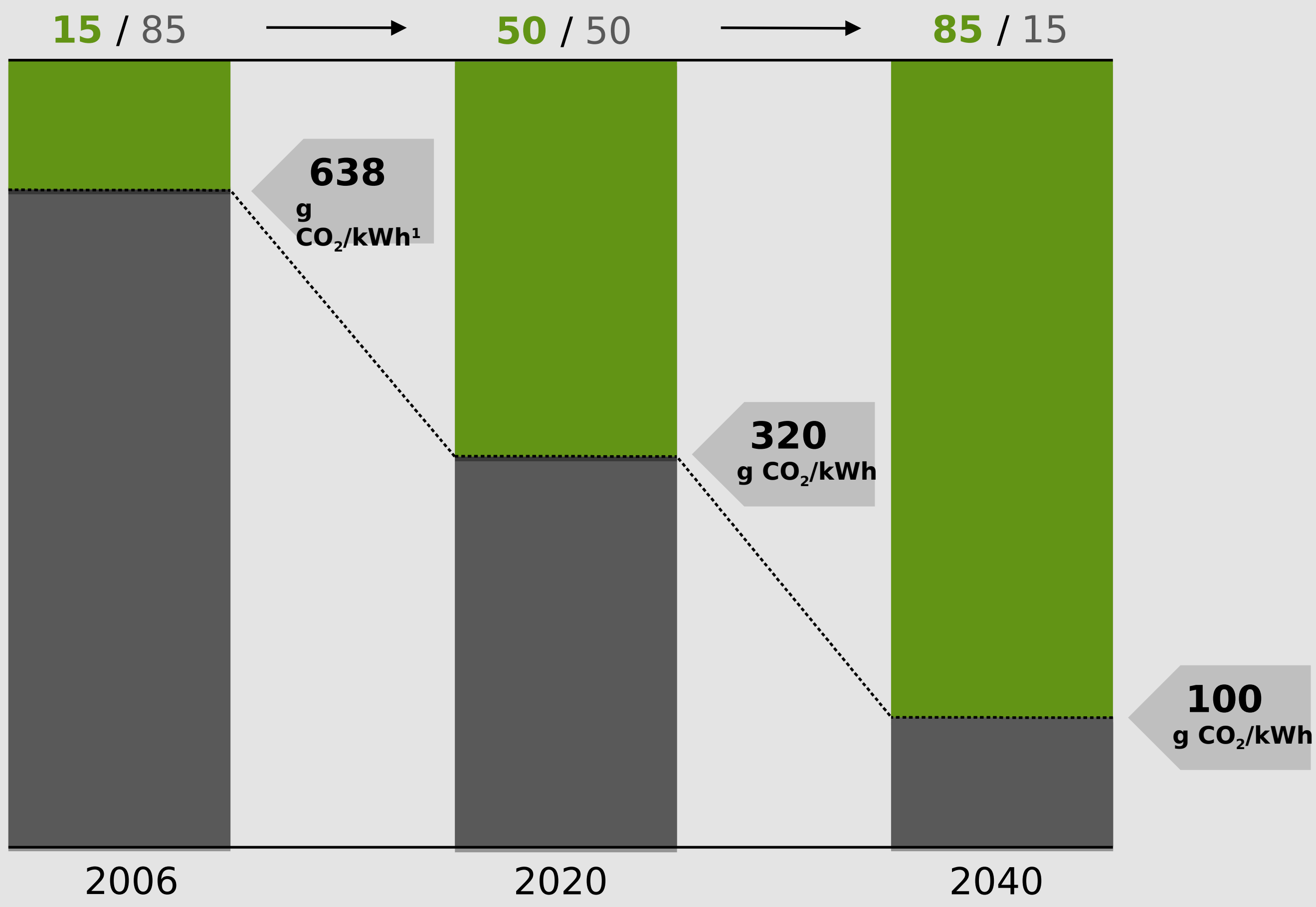
DONG Energy: Clean Energy Plan

Vision

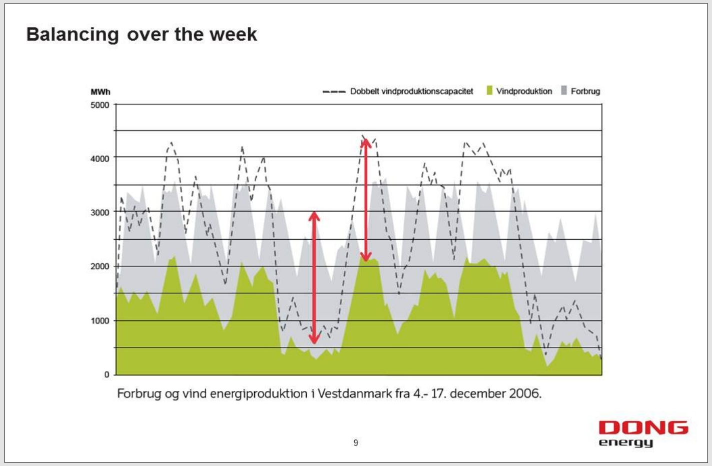
- To provide reliable energy without CO_2 emissions

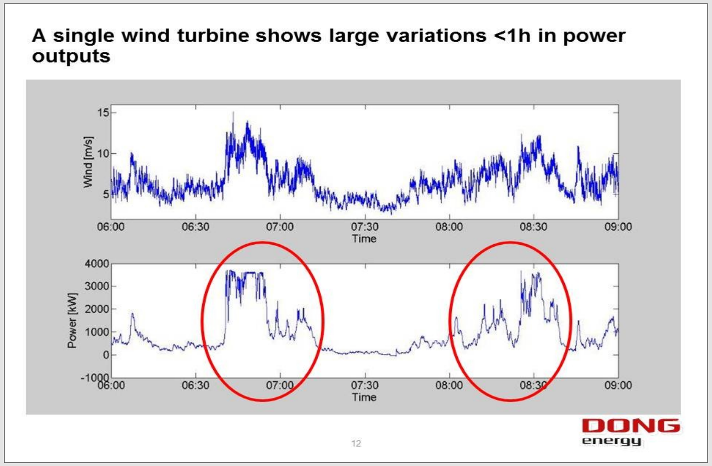
Strategic Goals

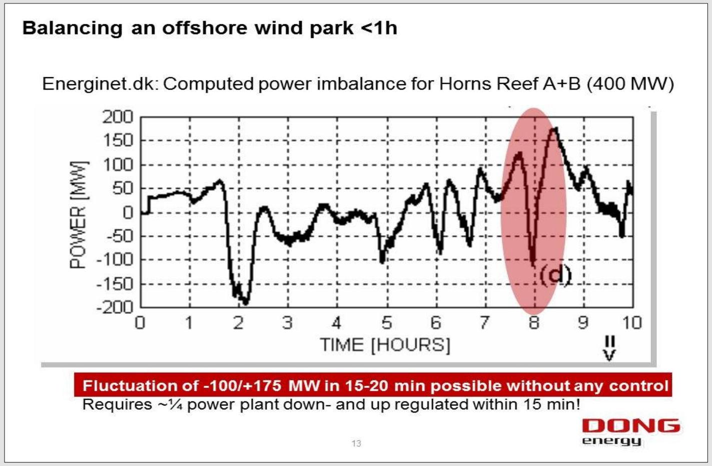
- Eliminate 50% of CO_2-emission per kWh before 2020
- Eliminate 85% of CO_2-emission per kWh before 2040

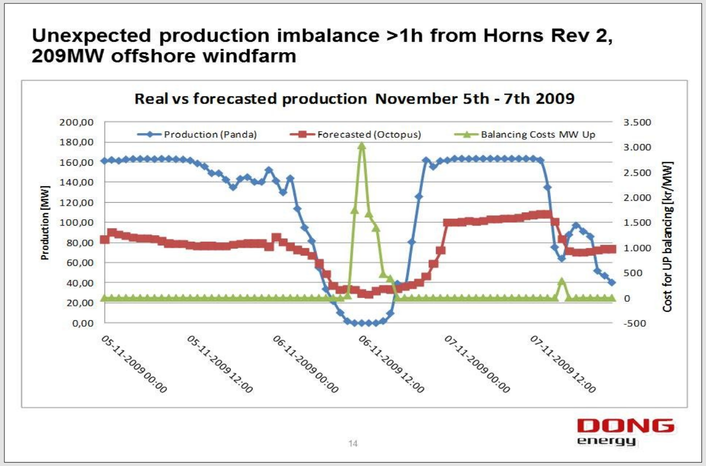


Challenges









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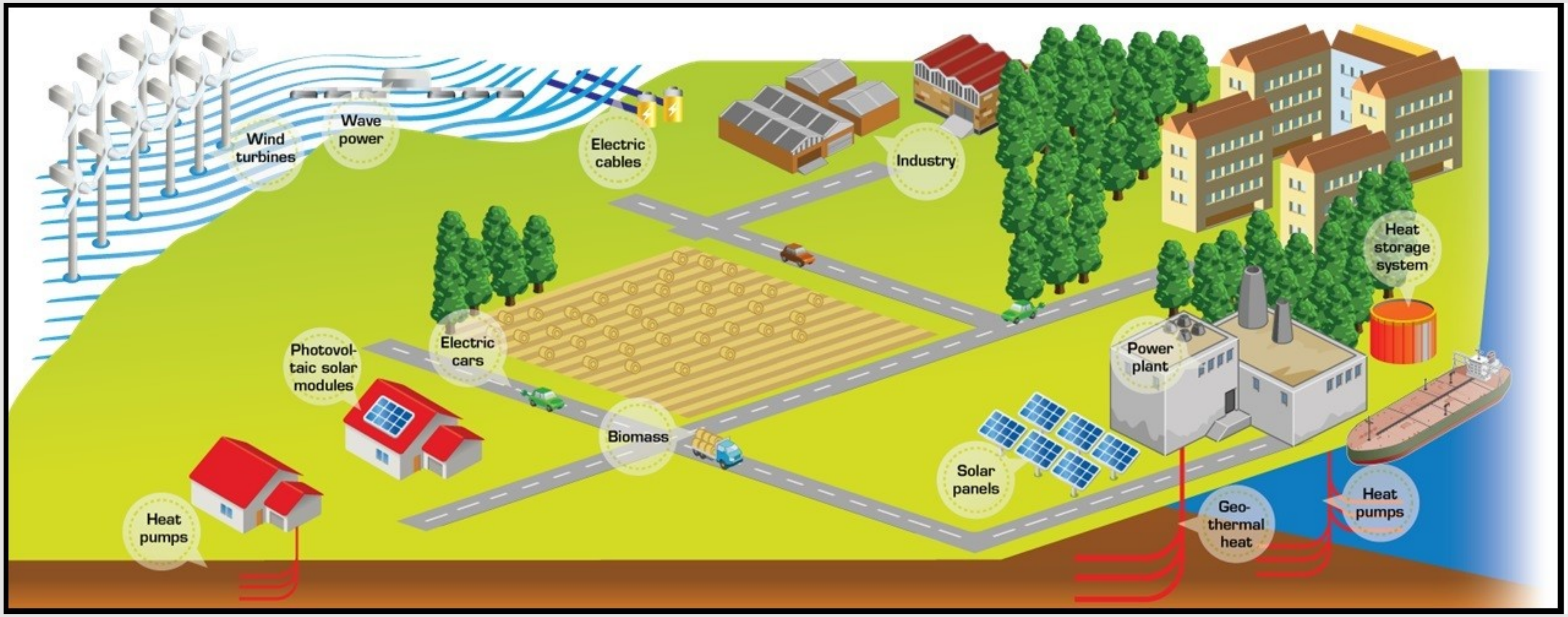
Power Production Planning



- **Constraints**: Power balance, reserves, production limits, ramp limits, storage limits
- **Costs**: Imbalances, fuel, maintenance

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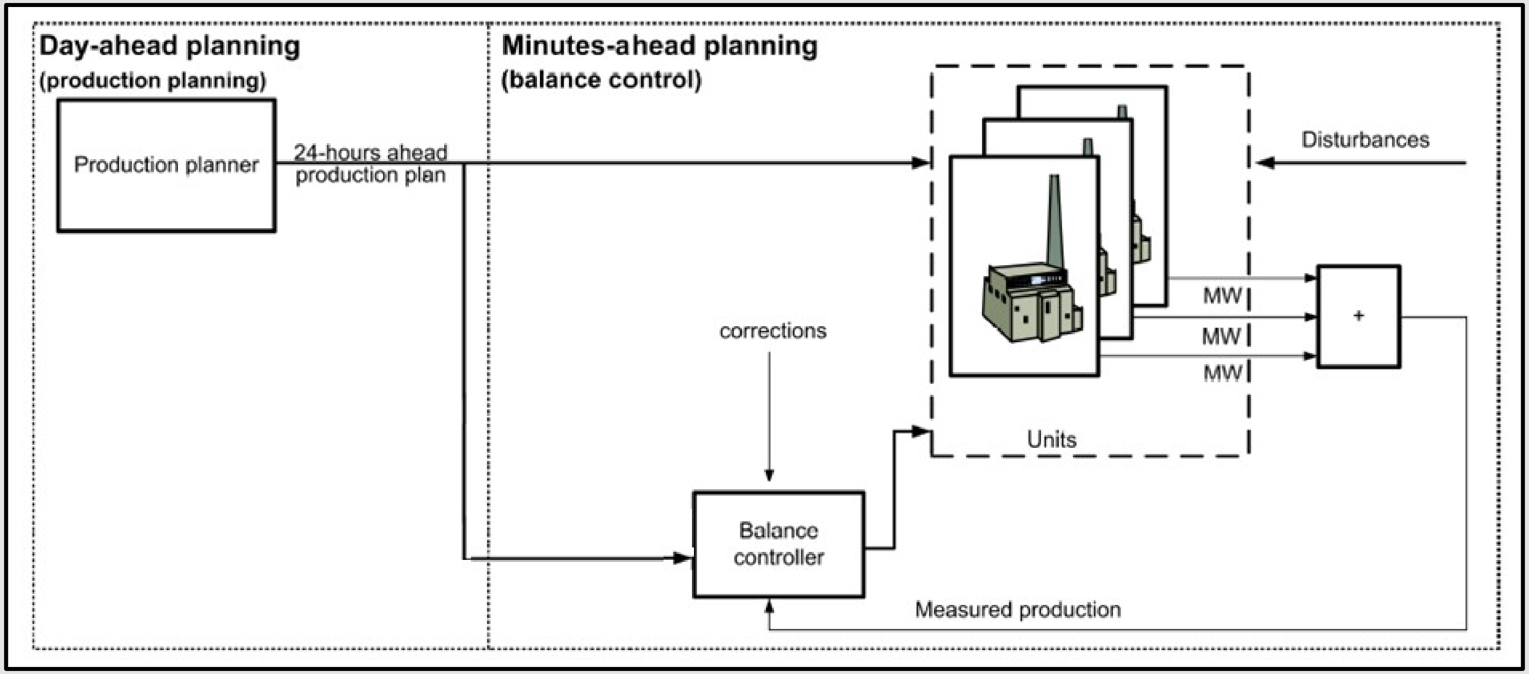
Hierarchical Control Structure



- **Day-ahead planning**: Main load distribution and on/off decisions
- **Minutes-ahead planning**: Corrections due to e.g. fluctuations in the renewable energy production

Example: Unit Commitment Problem

- Minimize cost of operation, subject to production limits and power balance

  controllable production + wind power production = demand

- Prediction horizon is 6 hours and resolution is 5 minutes

Unit	Marginal Cost	Startup Cost	Minimum Production	Maximum Production
1	10 Euro/MW	3000 Euro	4 MW	20 MW
2	15 Euro/MW	2000 Euro	2 MW	10 MW
3	25 Euro/MW	1000 Euro	1 MW	5 MW

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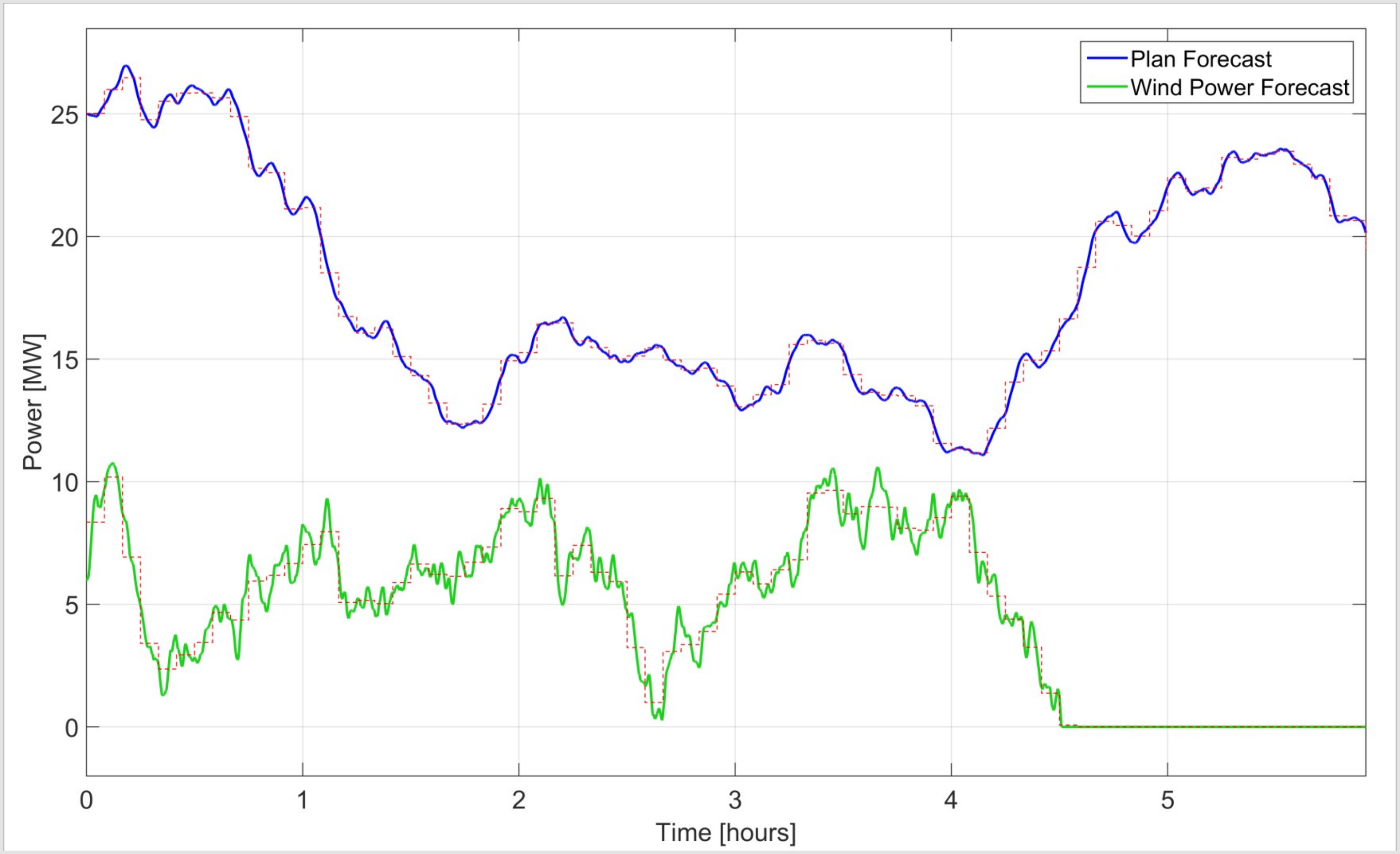
Example: Forecast Data



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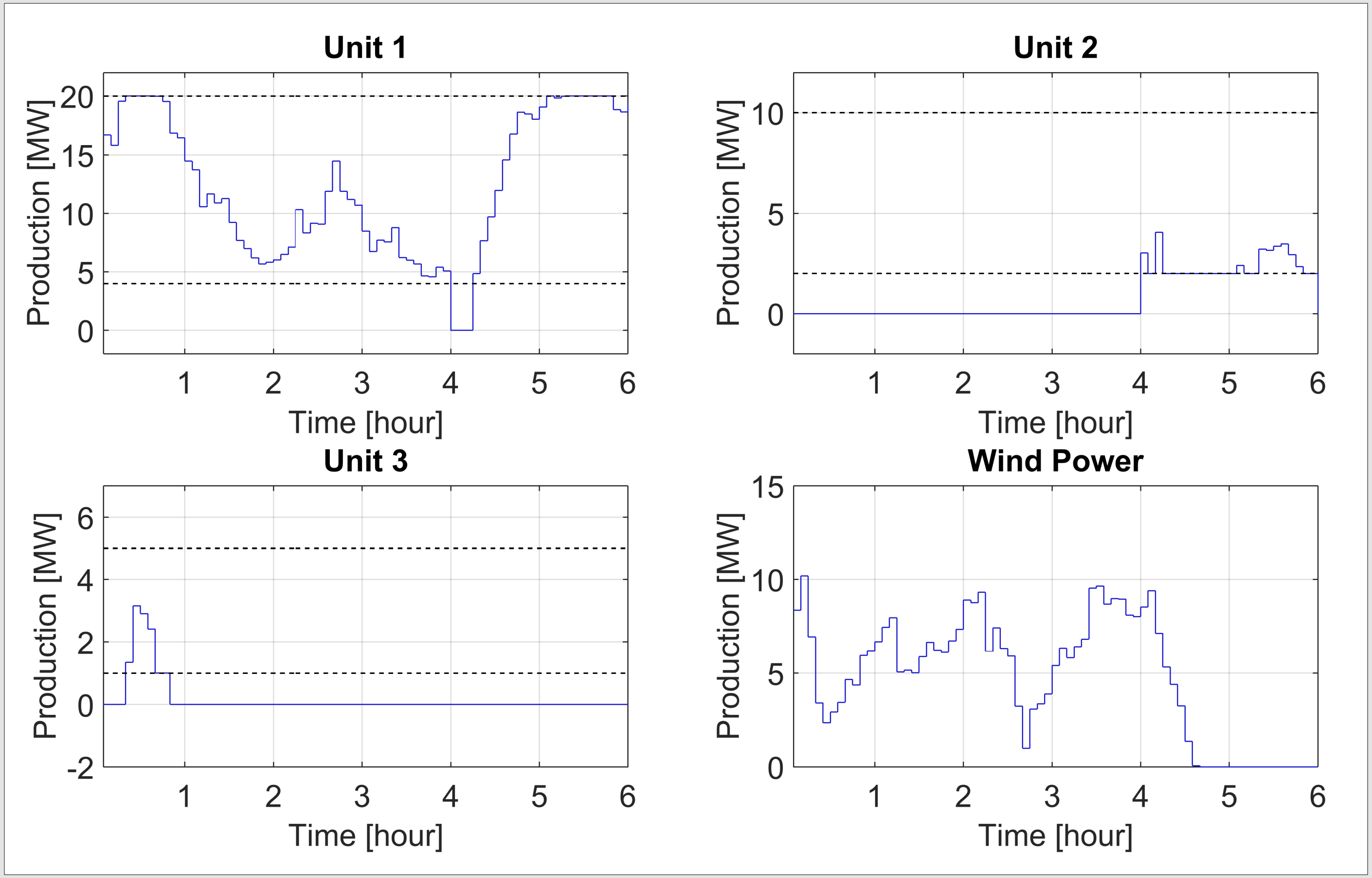
Example: Unit Commitment Solution



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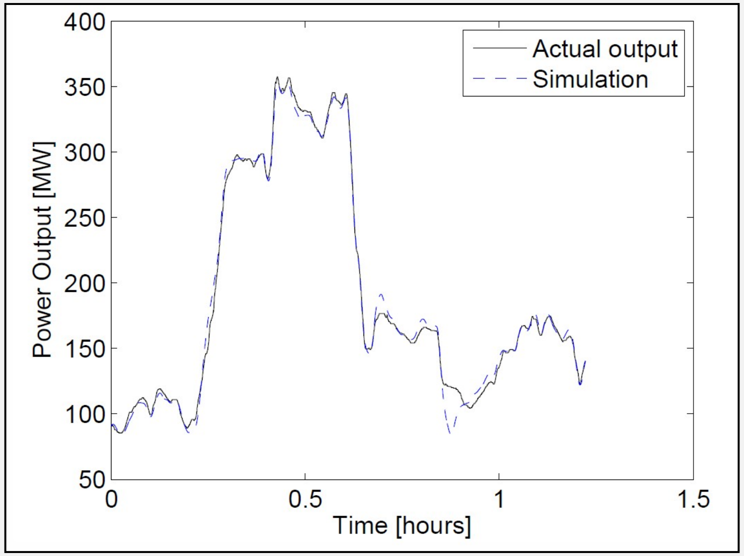
Example: Dynamic Model

- **Thermal Power Plant Model**

$$Z_j(s) = \frac{1}{(\tau_j s + 1)^3} U_j(s), \quad j \in \mathcal{M}$$

- **Validation**



- **Portfolio Model**

$$Z_T(s) = \sum_{j=1}^{\mathcal{M}} Z_j(s)$$

- **State-Space Form**

$$x_{k+1} = Ax_k + Bu_k$$
$$z_{k+1} = Cx_{k+1}$$

- **Input & Output**

$$u_k = \begin{bmatrix} u_{1,k} \\ u_{2,k} \\ u_{3,k} \end{bmatrix}, \quad z_k = \begin{bmatrix} z_{1,k} \\ z_{2,k} \\ z_{3,k} \\ z_{T,k} \end{bmatrix}$$

- $u_{j,k}$: power production set-point
- $z_{j,k}$: power production
- $z_{T,k}$: total power production

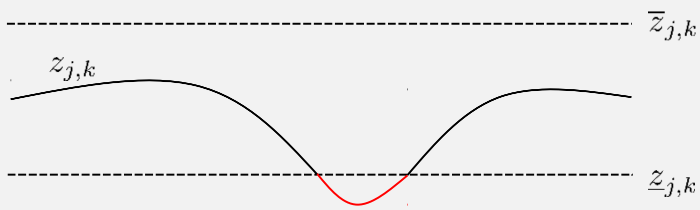
Example: Economic MPC Optimization Problem

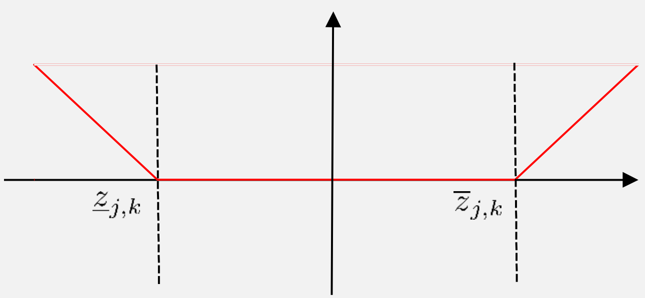
$$
\begin{aligned}
\underset{u,x,y,w}{\text{minimize}} \quad & \phi = \sum_{k=0}^{N-1} p_k^T u_k + q_{k+1}^T \rho_{k+1} \\
\text{s.t.} \quad & x_{k+1} = A x_k + B u_k, && k \in \mathcal{N} \\
& z_{k+1} = C x_{k+1}, && k \in \mathcal{N} \\
& \underline{u}_k \leq u_k \leq \overline{u}_k, && k \in \mathcal{N} \\
& \Delta \underline{u}_k \leq \Delta u_k \leq \Delta \overline{u}_k, && k \in \mathcal{N} \\
& \underline{z}_{k+1} - \rho_{k+1} \leq z_{k+1} \leq \overline{z}_{k+1} + \rho_{k+1}, && k \in \mathcal{N} \\
& \rho_{k+1} \geq 0, && k \in \mathcal{N}
\end{aligned}
$$

$$\mathcal{N} = 0, 1, \ldots, N$$

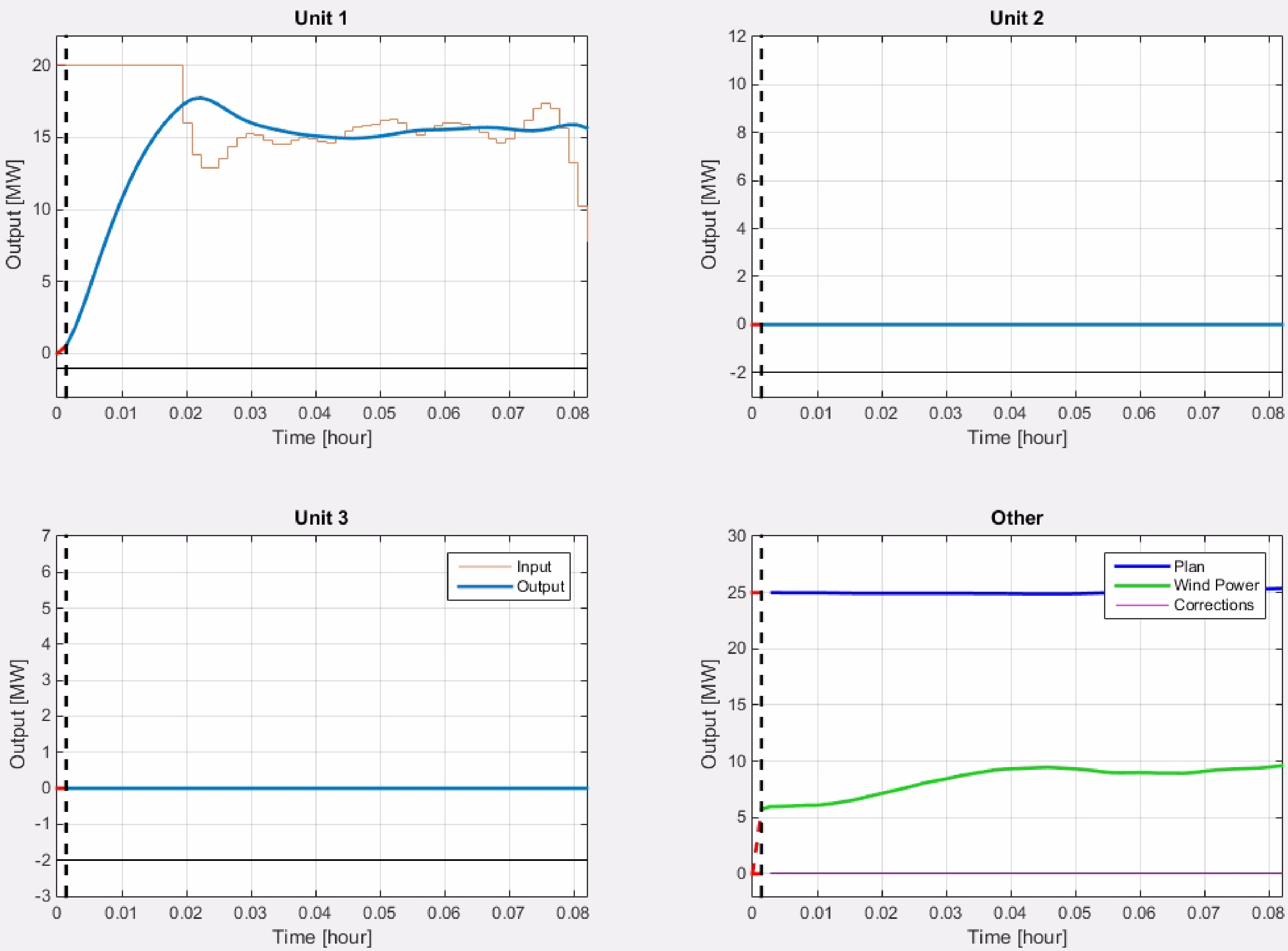
- Minimize cost of operation, subject to production limits and power balance
- Prediction horizon is 5 minutes and resolution is 5 seconds
- Uses feedback and updated forecasts
- Accounts for accumulated disturbances that are not handled in the market

Soft output constraints



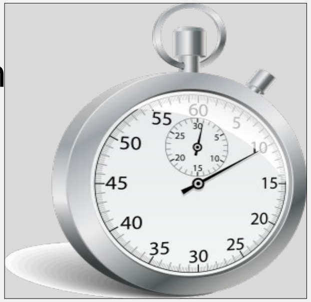


Closed Loop Simulation



Challenges

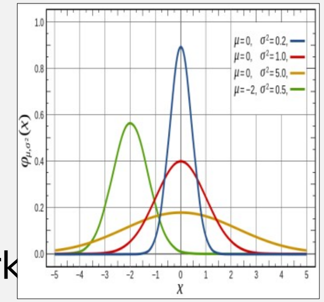
Efficient Solution of the Economic MPC optimization problem



- The time available for solving the Economic MPC optimization problem restricted to seconds
- A virtual power plant may consist of several thousands of units

=> Efficient algorithms for Economic MPC is required

Formulation of the Economic MPC optimization problem



- The controlled system is stochastic due to the intermittent nature of renewable energy
- The performance of MPC depends on the quality of the model

=> Deterministic models may not be adequate in the proposed framework

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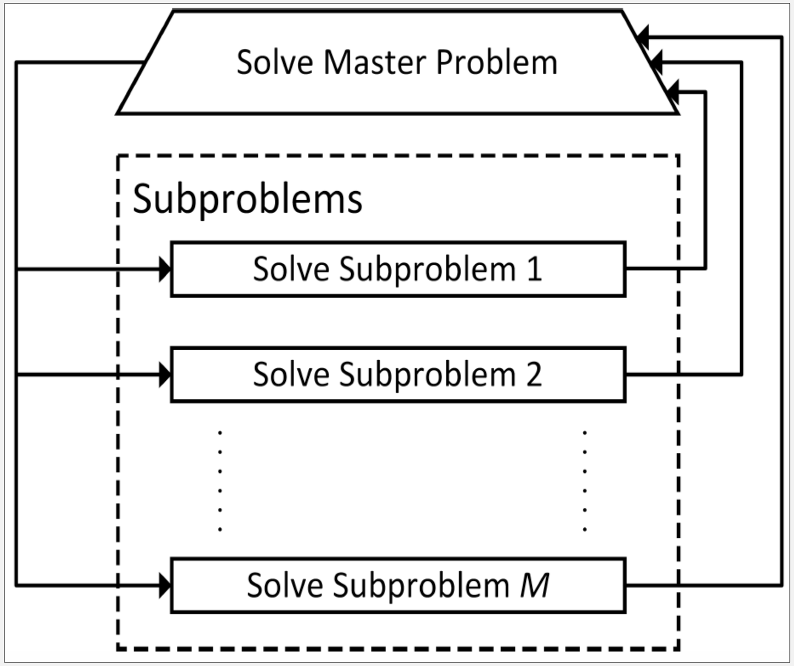
Decomposition Methods for Economic MPC

Flowchart



- **Dantzig-Wolfe Decomposition**
  - Master Problem size increases
  - Few iterations required
  - High accuracy
  - Warm-start capable
  - Linear programming
- **Alternating Direction Method of Multipliers (ADMM)**
  - Master Problem size is constant
  - Many iterations required
  - Low accuracy
  - Warm-start capable
  - Convex programming
- **Subproblems**
  - Simple and highly structured
  - Solved using structure-exploiting interior point methods

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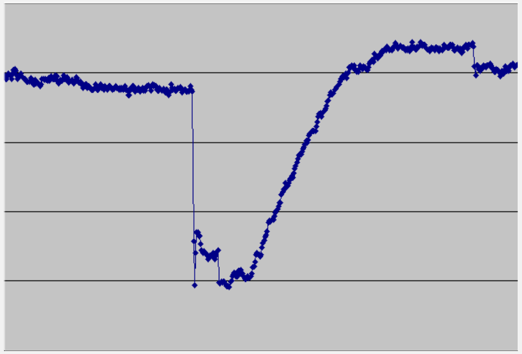
Uncertainty

Output Variations



Mean-Variance Economic MPC

- Includes information on the uncertainty in the economic MPC optimization problem
- Two-stage stochastic programming problem
- Convex relaxation of the problem may be solved efficiently using ADMM

Linear Stochastic System

Linear Stochastic State-Space System

$$
\begin{aligned}
x_{k+1} &= Ax_k + Bu_k + w_k, && k \in \mathcal{N} \\
y_{k+1} &= C_y x_{k+1} + v_{k+1}, && k \in \mathcal{N} \\
z_{k+1} &= C_z x_{k+1}, && k \in \mathcal{N}
\end{aligned}
$$

where $\mathcal{N} = \{0, 1, \dots, N-1\}$ is the prediction horizon and $x_0 = \bar{x}_0$ is the initial state

Definitions

- $x_k \in \mathbb{R}^{n_x}$: system state
- $u_k \in \mathbb{R}^{n_u}$: manipulable input
- $z_k \in \mathbb{R}^{n_z}$: controlled variable
- $y_k \in \mathbb{R}^{n_y}$: measured output
- $w_k \in \mathbb{R}^{n_x}$: process noise
- $v_k \in \mathbb{R}^{n_y}$: measurement noise

Vector notation $u = (u_0^T, u_1^T, u_2^T, \dots, u_{N-1}^T)^T$

Mean-Variance Economic MPC

Mean-Variance Economic MPC (MV-EMPC)

- Mean-Variance Economic MPC optimal control problem is defined as

$$\underset{u \in \mathcal{U}}{\text{minimize}} \quad \lambda E\left[\psi_{\text{eco}}(u;\bar{x}_0,w)\right] + (1-\lambda)V\left[\psi_{\text{eco}}(u;\bar{x}_0,w)\right]$$

- $\lambda \in [0,1]$ is a risk-aversion parameter

Monte-Carlo Approximation

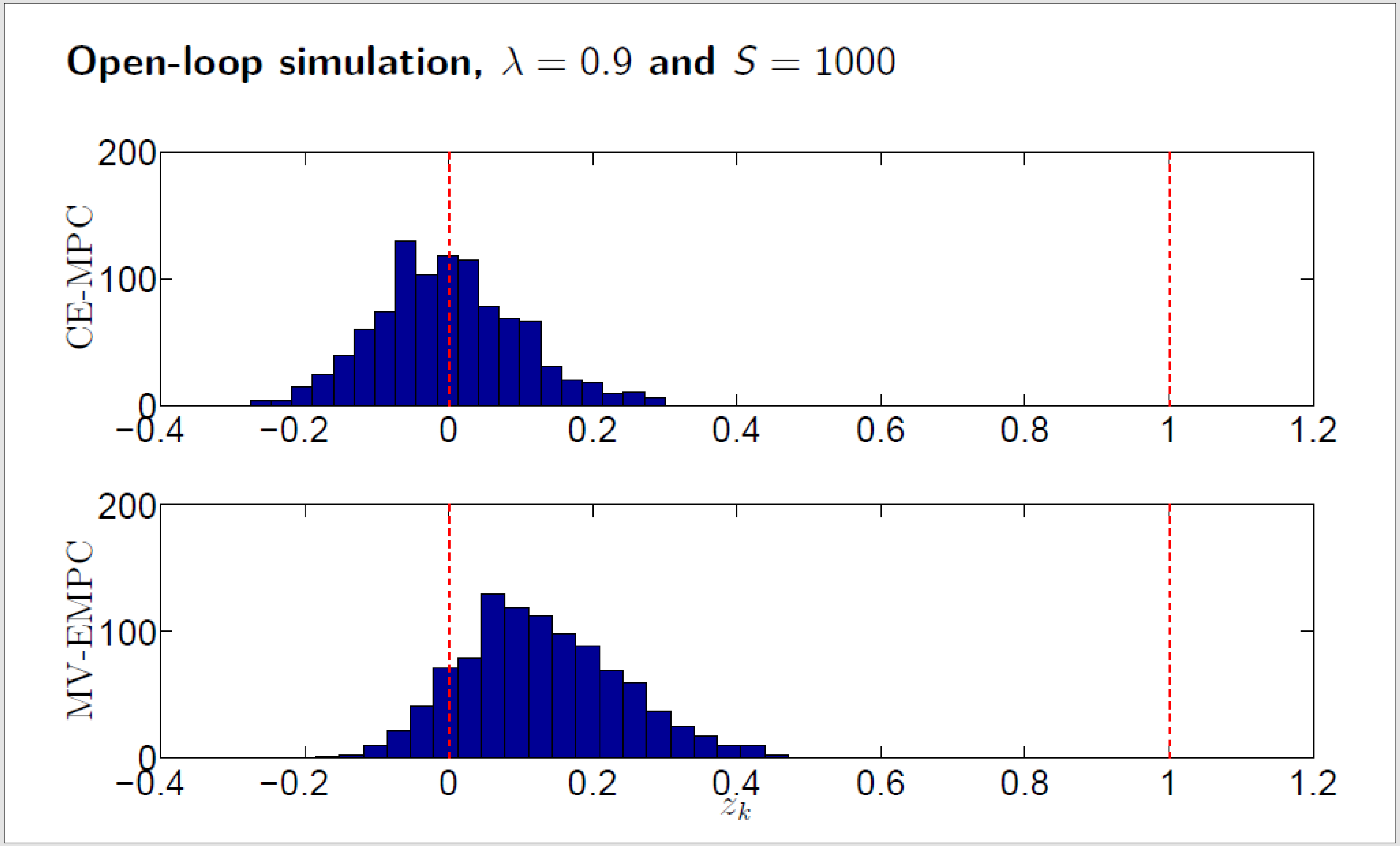
- $w^i = (w_1^i, w_2^i, \ldots, w_{N-1}^i)^T$ is sampled from the distribution of w for $i \in \mathcal{S} = \{1, 2, \ldots, S\}$
- Expected value estimate

$$\mu := \frac{1}{S}\sum_{i\in\mathcal{S}} \psi_{\text{eco}}(u;\bar{x}_0,w^i)$$

- Variance estimate

$$s^2 := \frac{1}{S-1}\sum_{i\in\mathcal{S}} \left(\psi_{\text{eco}}(u;\bar{x}_0,w^i) - \mu\right)^2$$

Output Distribution



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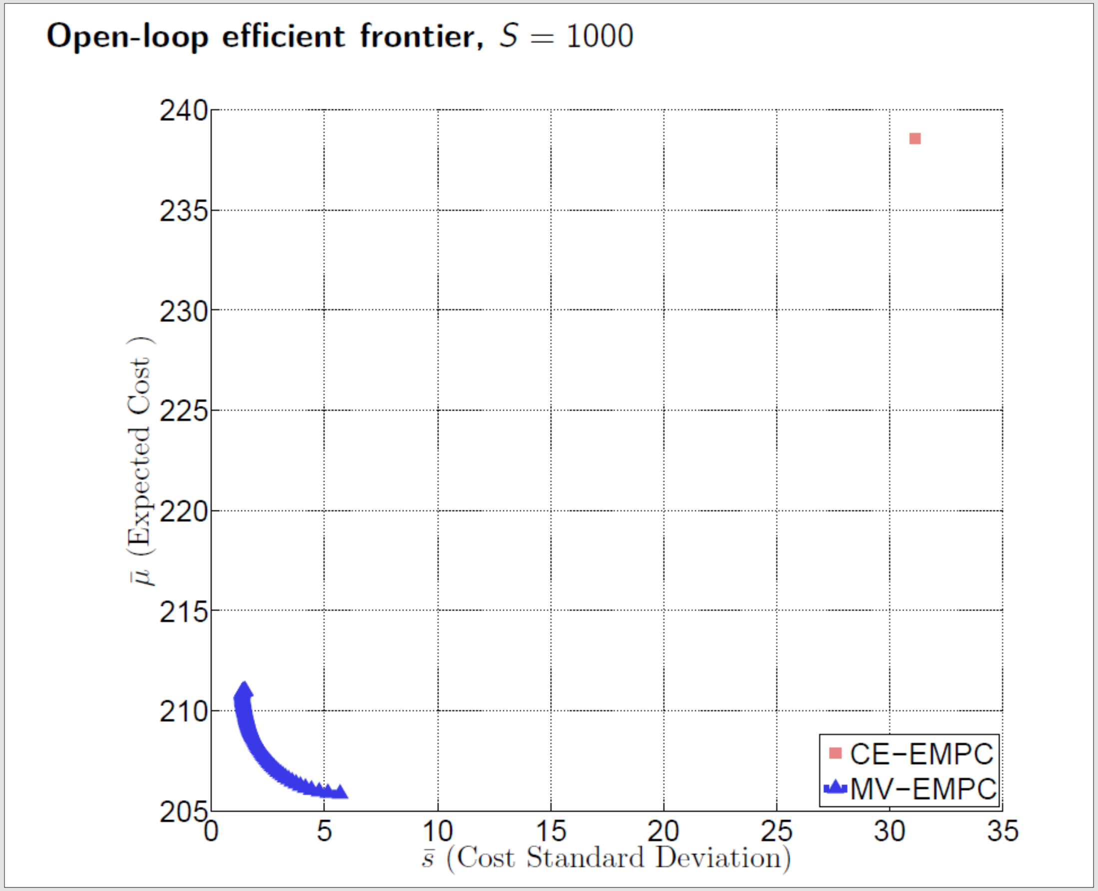
Efficient Frontier



Conclusions

Economic MPC for Energy Systems Management

- Modern control method for optimization of energy systems
- Well suited for Microgrids and VPP technologies
- Preliminary simulations indicate cost reductions
- Introduces new modelling and optimization challenges

Current Work

- Economic MPC for real-time control in isolated power systems
- Concepts for combining unit commitment and Economic MPC
- Stochastic methods for integration of uncertainty

Thanks! Questions and Comments?