Potential of Hydro Power and Storage for the Integration of Wind Generation

CMU Electricity Conference

March 9th, 2011

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Outline

- Introduction
- Control Concept & Modeling
- Case 1: Wind and Run-of River Power Plants
- Case 2: Generation/Storage Dispatch
- Conclusions

Introduction

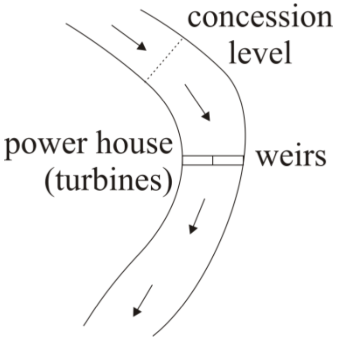
- Goal
  - up to 20% wind penetration by 2030

- Challenges:
  - Intermittency and variability
  - Missing infrastructure

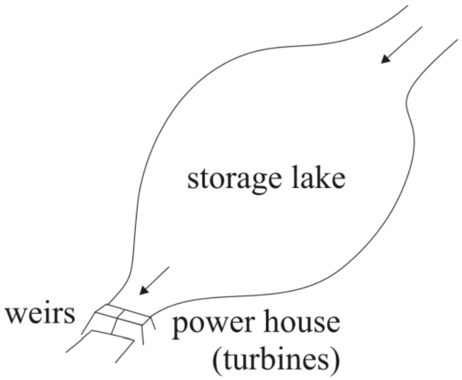
- Balancing Potential:
  - Storage
  - Demand response
  - Conventional generation
  - Curtailment

Hydro Power

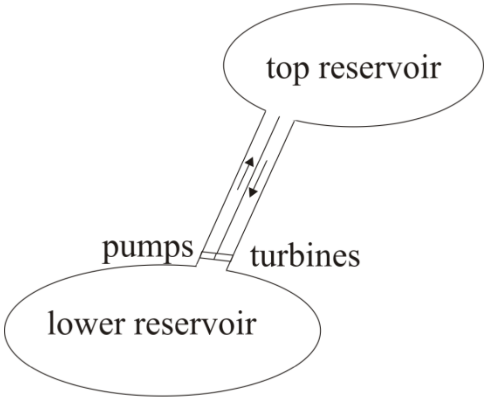
- Types of Hydro Power



Run-of River Power Plant



Storage Power Plant



Pumped Hydro Power Plant

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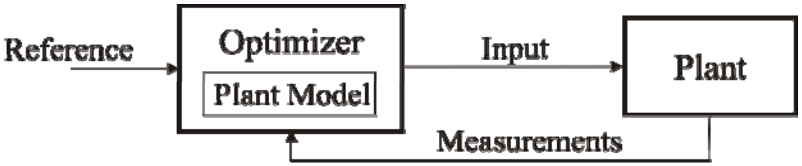
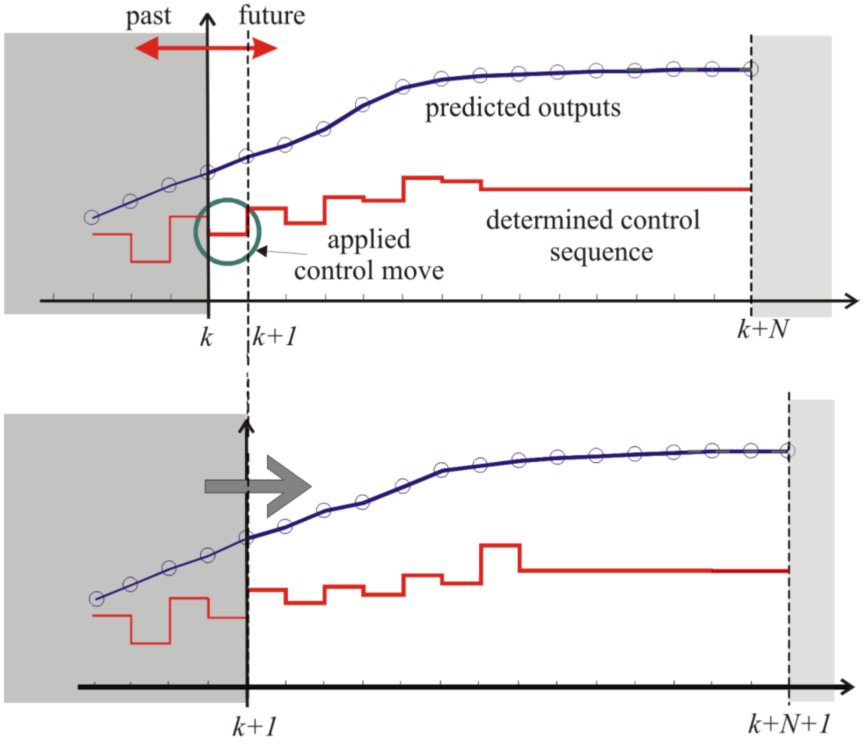
Control Concept

- Predictive Control
  - Use model of plant to be controlled to predict influence of input

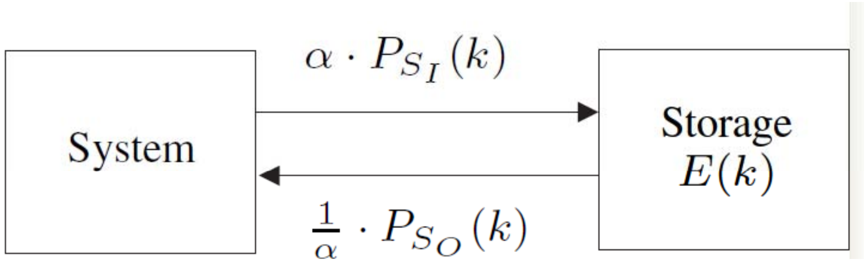




  - Choose input sequence which gives best performance over horizon
  - Apply first step and measure new state

Modeling: Storage

- Storage



$$E_S(k+1) = E_S(k) + \alpha \cdot P_{S_I}(k) \cdot T - \frac{1}{\alpha} \cdot P_{S_O}(k) \cdot T$$

Limits on

- Storage size
- Charging and discharging rate

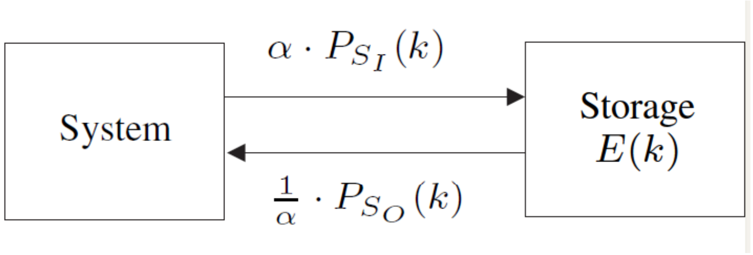
No simultaneous charging and discharging

$$\begin{array}{rcl} 0 \leq & E_S(k) & \leq E_S^{max} \\ 0 \leq & P_{S_I}(k) & \leq P_S^{max} \\ 0 \leq & P_{S_O}(k) & \leq P_S^{max} \end{array}$$

$$P_{S_I}(k) \cdot P_{S_O}(k) = 0$$

Modeling: Hydro Power

- Pumped Hydro Power Plant



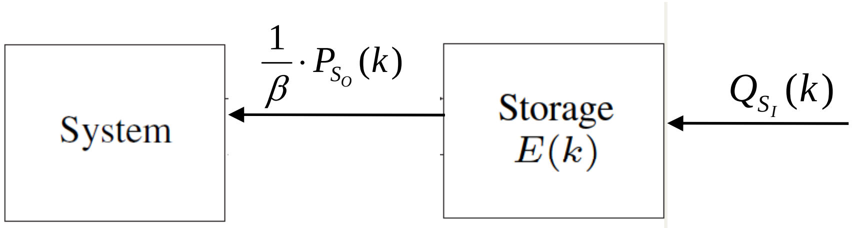
System

$\alpha \cdot P_{S_I}(k)$

$\frac{1}{\alpha} \cdot P_{S_O}(k)$

Storage
$E(k)$

- Storage Power Plant



System

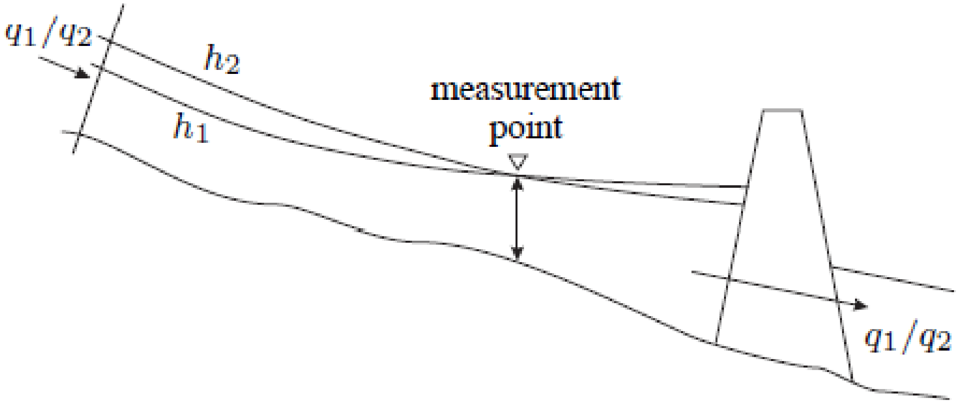
$\frac{1}{\beta} \cdot P_{S_O}(k)$

Storage
$E(k)$

$Q_{S_I}(k)$

Modeling: Hydro Power

- Run-of River Power Plant
  - Retention differentiates a river from a tank

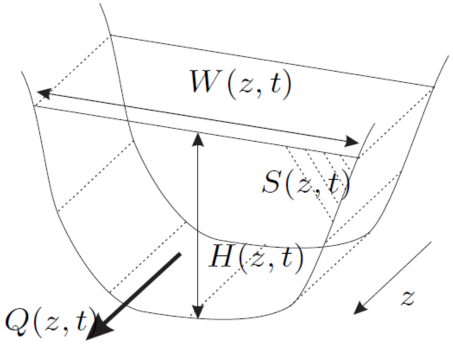


  - Goal:
    - Minimize discharge variations
    - Minimize deviations of water levels from reference value (and keep within limits)

Modeling: Hydro Power

- Saint Venant Equations

$$\begin{aligned}\frac{\partial Q}{\partial z}+\frac{\partial S}{\partial t} &= 0\\ \frac{1}{g}\cdot\frac{Q}{S}+\frac{1}{2g}\cdot\frac{\partial}{\partial z}\left(\frac{Q^2}{S^2}\right)+\frac{\partial H}{\partial z} &= 0\end{aligned}$$



=> dependency between water discharge and water level at each individual point in the river

=> Linearization and discretization in time and space

$$x(k+1) \quad = \quad Ax(k)+Bu(k)$$

- Dependency between discharge and electric power

$$P_H=\eta\rho\Delta H_T g\cdot Q_T$$

Modeling: Generation and Load

- Conventional Generation
  - Capacity limit $0 \leq P_{cG}(k) \leq P_{cG}^{max}$
  - Ramp rate $-\Delta P_{cG}^{max} \leq P_{cG}(k+1) - P_{cG}(k) \leq \Delta P_{cG}^{max}$

- Intermittent Generation
  - Predictions of output P_{iG}^{max} available
  - Allow curtailment $0 \leq P_{iG}(k) \leq P_{iG}^{max}(k)$

- Load
  - Predictions of demand P_L^{ref} available
  - Allow demand control $\gamma \cdot P_L^{ref}(k) \leq P_L(k) \leq P_L^{ref}(k)$

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Case 1: Wind and Run-of River Plants

- Objective Function

minimize discharge changes

$$
\begin{aligned}
f = \sum_{k=0}^{N-1} \big(& \delta q_H^T(k) W_q \delta q_H(k) + \Delta h_c^T(k) W_c \Delta h_c(k) \\
& + \delta P_{HW}^T(k) W_G \delta P_{HW}(k)\big)
\end{aligned}
$$

minimize level deviations

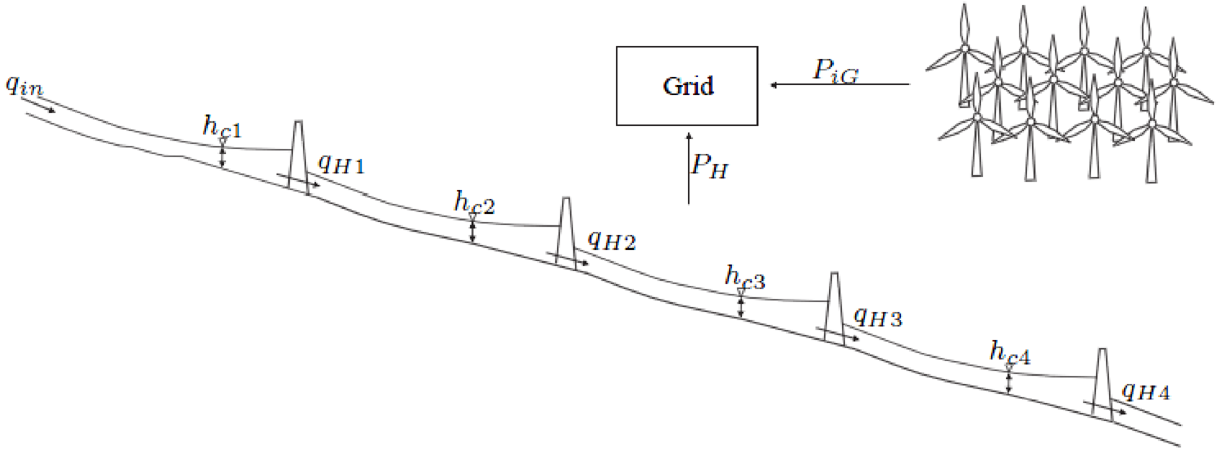
smoothen wind power

- Constraints
  - River flow model
  - Constraints on water level and turbine/weir discharges

$$
\begin{array}{rcl}
h_c^{min} \leq & h_c(k) & \leq h_c^{max} \\
q_T^{min} \leq & q_T(k) & \leq q_T^{max} \\
\delta q_T^{min} \leq & \delta q_T(k) & \leq \delta q_T^{max} \\
q_W^{min} \leq & q_W(k) & \leq q_W^{max} \\
\delta q_W^{min} \leq & \delta q_W(k) & \leq \delta q_W^{max}
\end{array}
$$

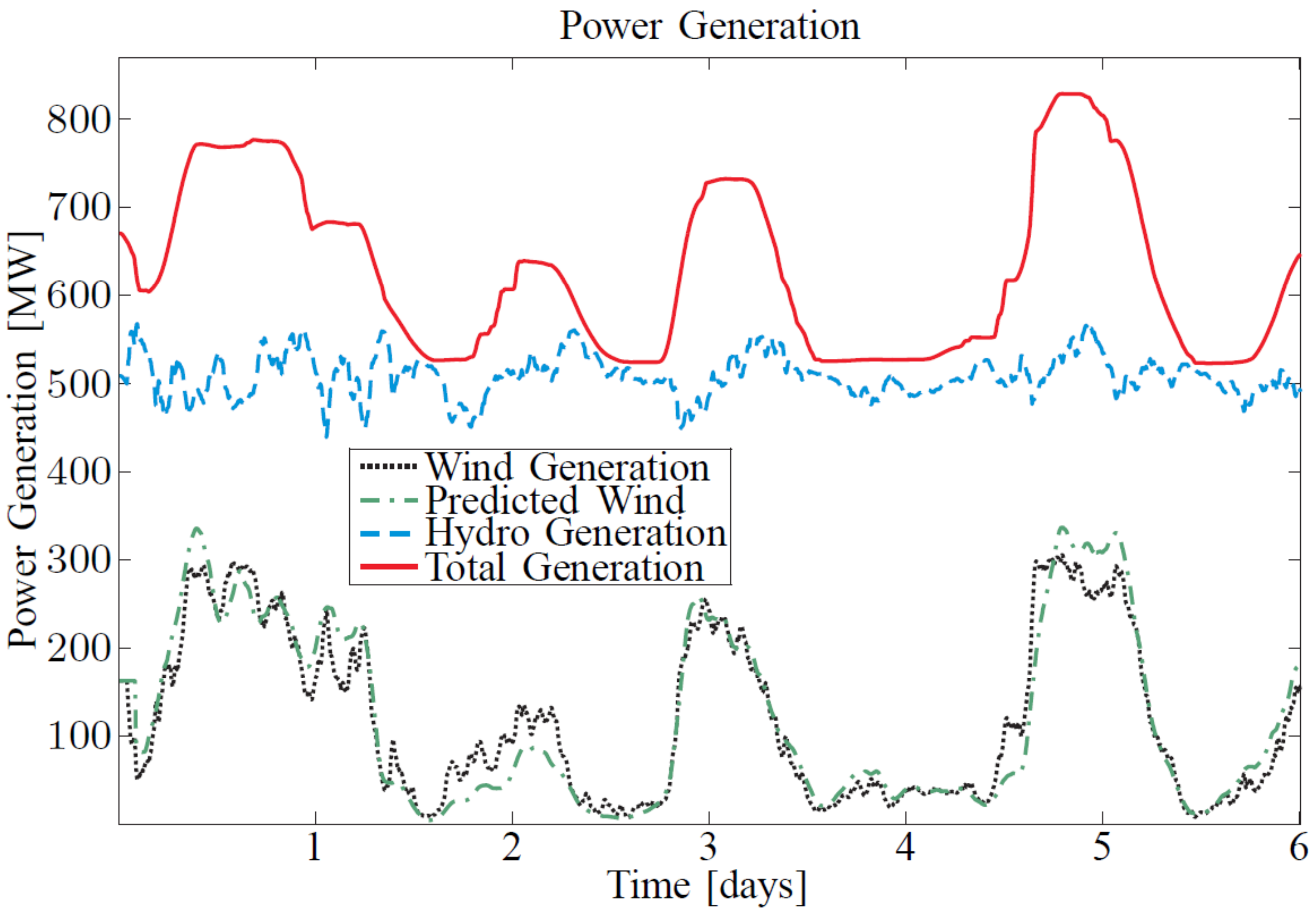
Case 1: Test System

- Cascade of four run of river power plants (20km apart)



- Operating Point: 3000m^3/s (1200m^3/s through weirs)
- Water Level Constraints: ±12cm
- Weir discharge and inflow constant
- 10% rms prediction error
- 2 hours prediction horizon, 5 minute resolution

Case 1: Simulation Results



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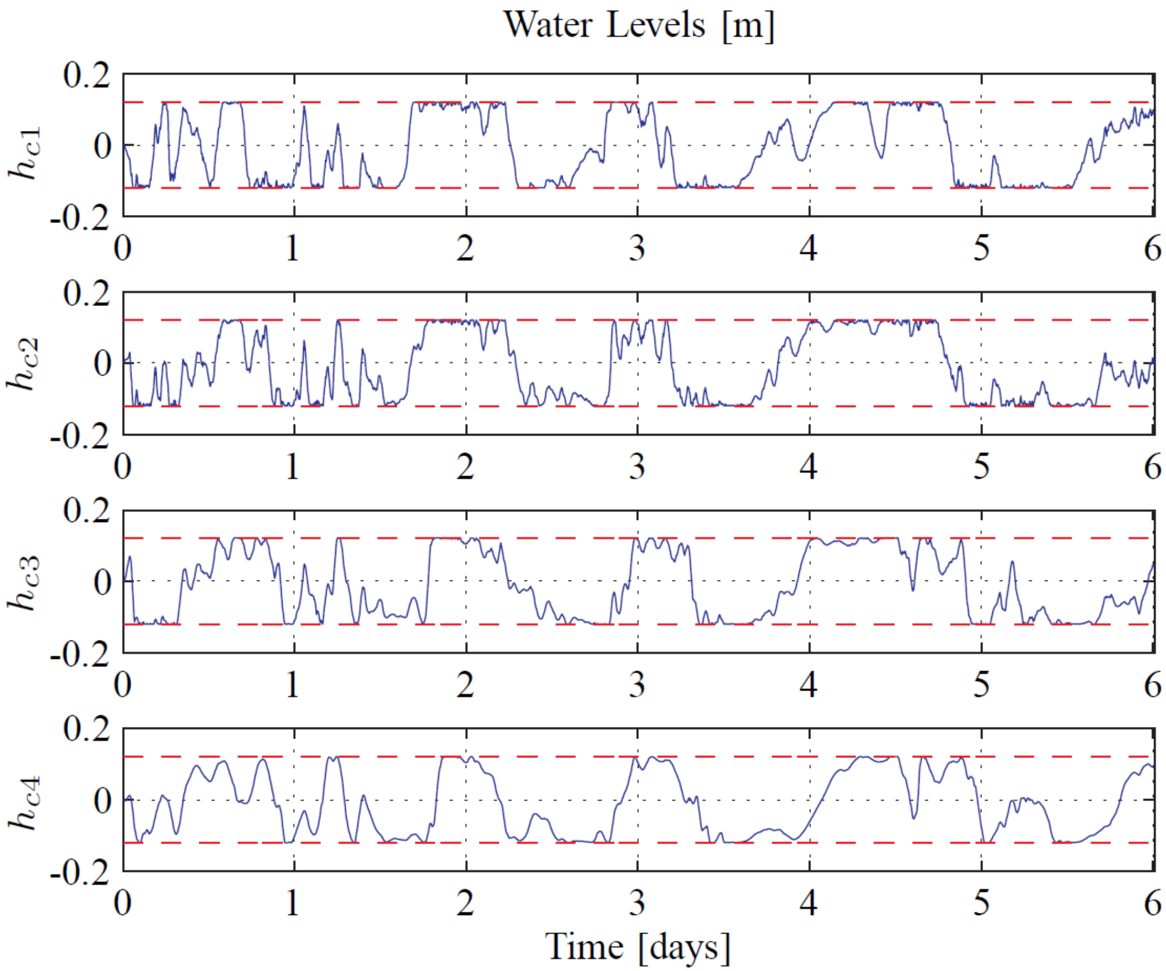

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Case 2: Generation/Storage Dispatch

- Economic Objectives
  - Minimize generation costs $C_{EC}(P_{G,i}) = a_i \cdot P_{G,i}^2 + b_i \cdot P_{G,i} + c_i$
  - Minimize conversion losses $C_{EC}(P_{SI_i}, P_{SO_i}) = a_i \cdot \left((1-\alpha) \cdot P_{SI,i} + \frac{1-\alpha}{\alpha} \cdot P_{SO,i} \right)$
- Environmental Objectives
  - Minimize CO2 emissions/cost (natural gas, coal)

$$C_{EV}(P_{G,i}) = d_i \cdot P_{G,i} + e_i \cdot \Delta P_{G,i}$$

  - Minimize impact on water flow (hydro)

$$C_{EV}(q_{H,i}, h_{Hc,i}) = d_i \cdot \delta q_{H,i}^2(k) + e_i \cdot \Delta h_c^2$$

- Quality of Service
  - Minimize demand side management

$$C_{QS}(P_L, P_L^{ref}) = f \cdot \left(P_L - P_L^{ref} \right)^2$$

  - Minimize wind curtailment

$$C_{QS}(P_{iG}) = f \cdot (P_{iG}^{max} - P_{iG})^2$$

Case 2: Simulation Setup

- Thermal Power Plants

	Capacity	Ramp Rate	Economic Cost	Environmental Cost
Coal	700 MW	25 MW / 0.5h	$0.02P_G^2 + 5P_G + c$	$4P_G + \Delta P_G$
Natural Gas	500 MW	100 MW / 5min	$0.06P_G^2 + 20P_G + c$	$2P_G + 10\Delta P_G$
Nuclear	450 MW	3 MW / h	$0.01P_G^2 + 2P_G + c$	P_G

- Renewable

	River Flow	Weir discharge	Economic Cost	Environmental Cost
Hydro (4 plants)	3000 m3/s	1200 m3/s	$0.5P_G + c$	$\Delta h^2 + 250\delta q^2$

	Capacity	Non-Usage
Wind	1000 MW	$0.01 \cdot \left(P_G^{ref} - P_G\right)^2$

Case 2: Simulation Setup

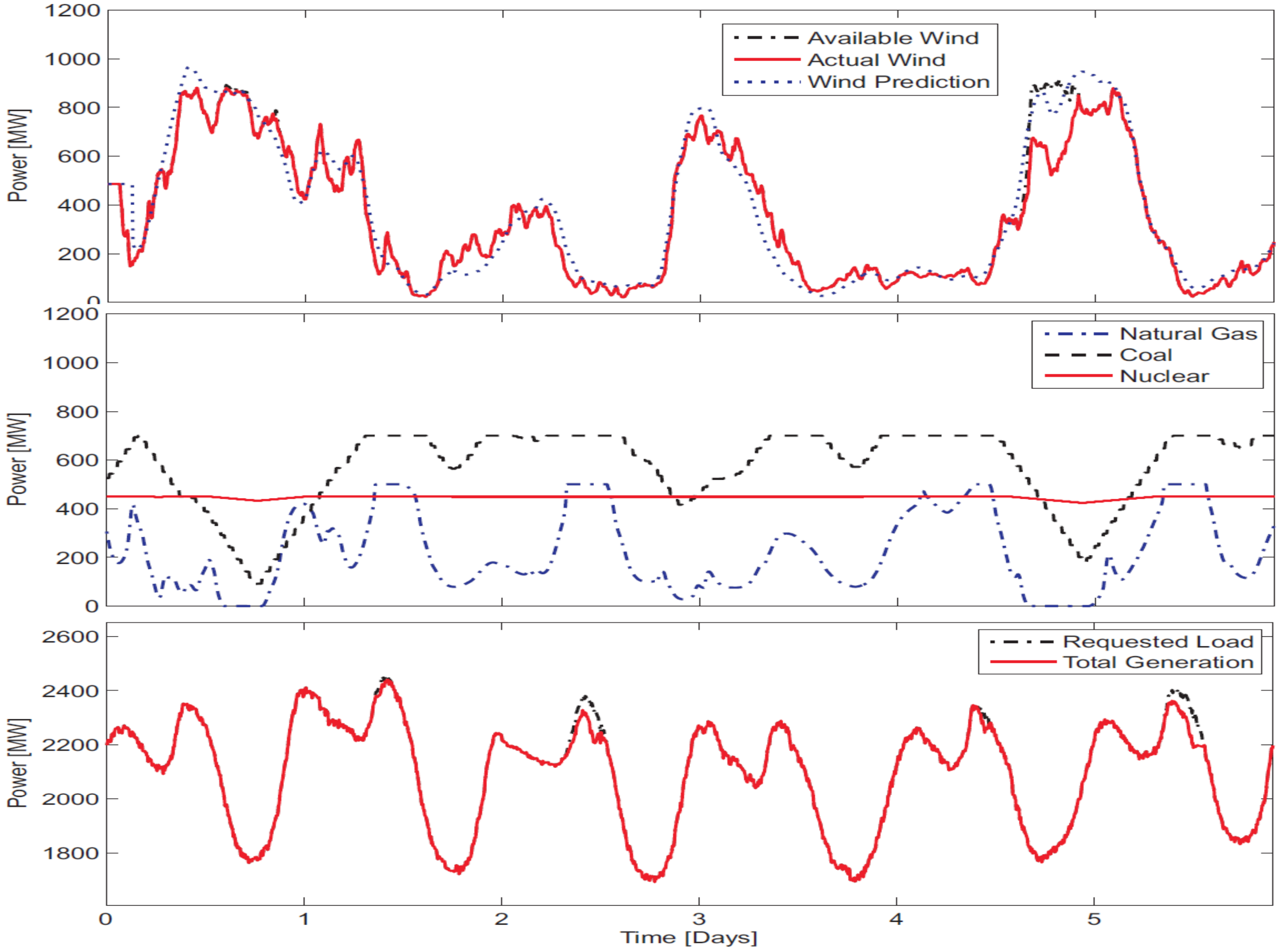
- Storage

	Capacity	Economic Cost
Storage	400 MWh	$5P_{loss}$

- Load

	Maximum	Critical	Quality of Service
Load	2500 MW	70%	$100 \cdot \left(P_L^{ref} - P_L\right)^2$

Case 2: Simulation Results



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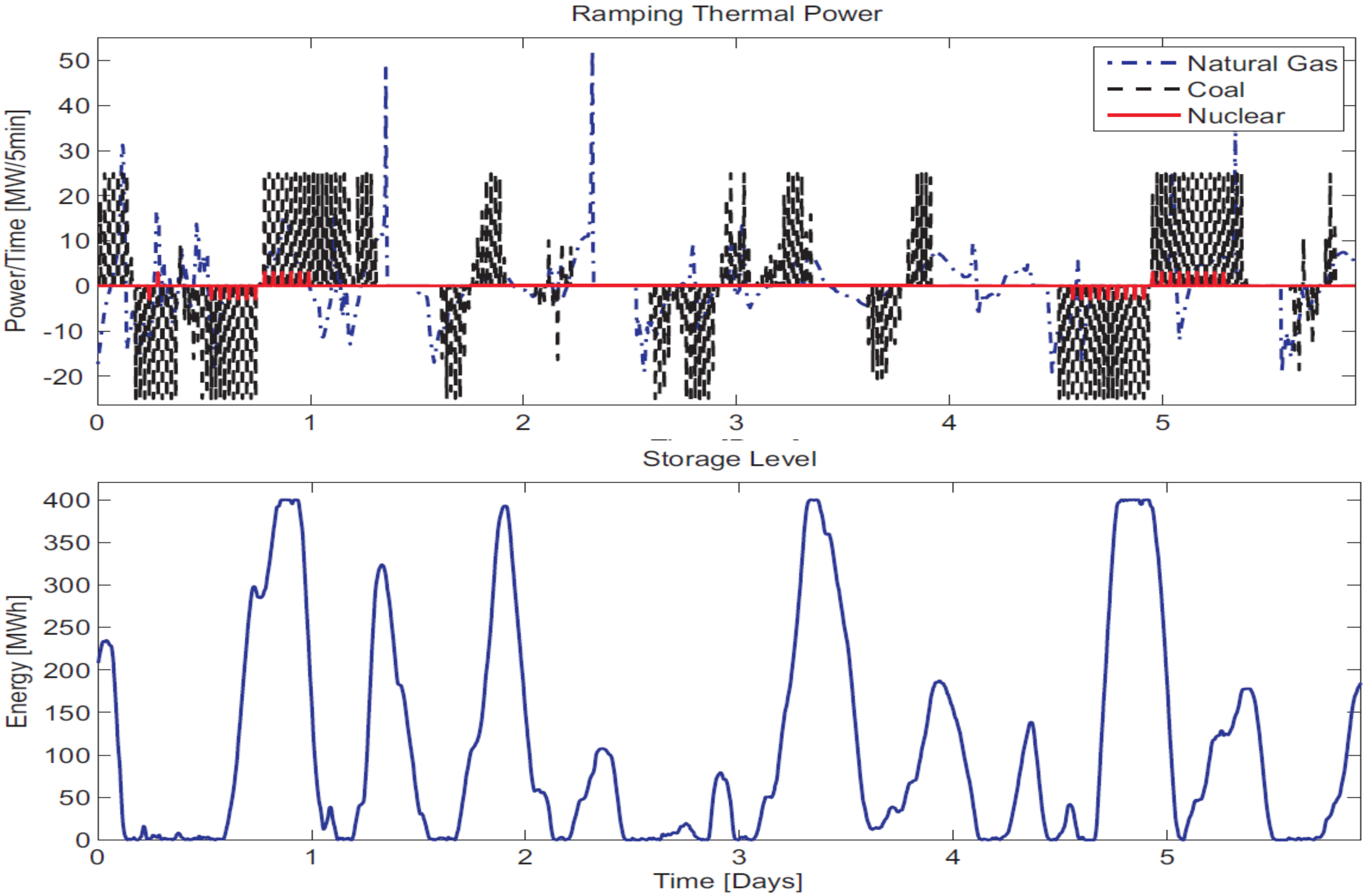
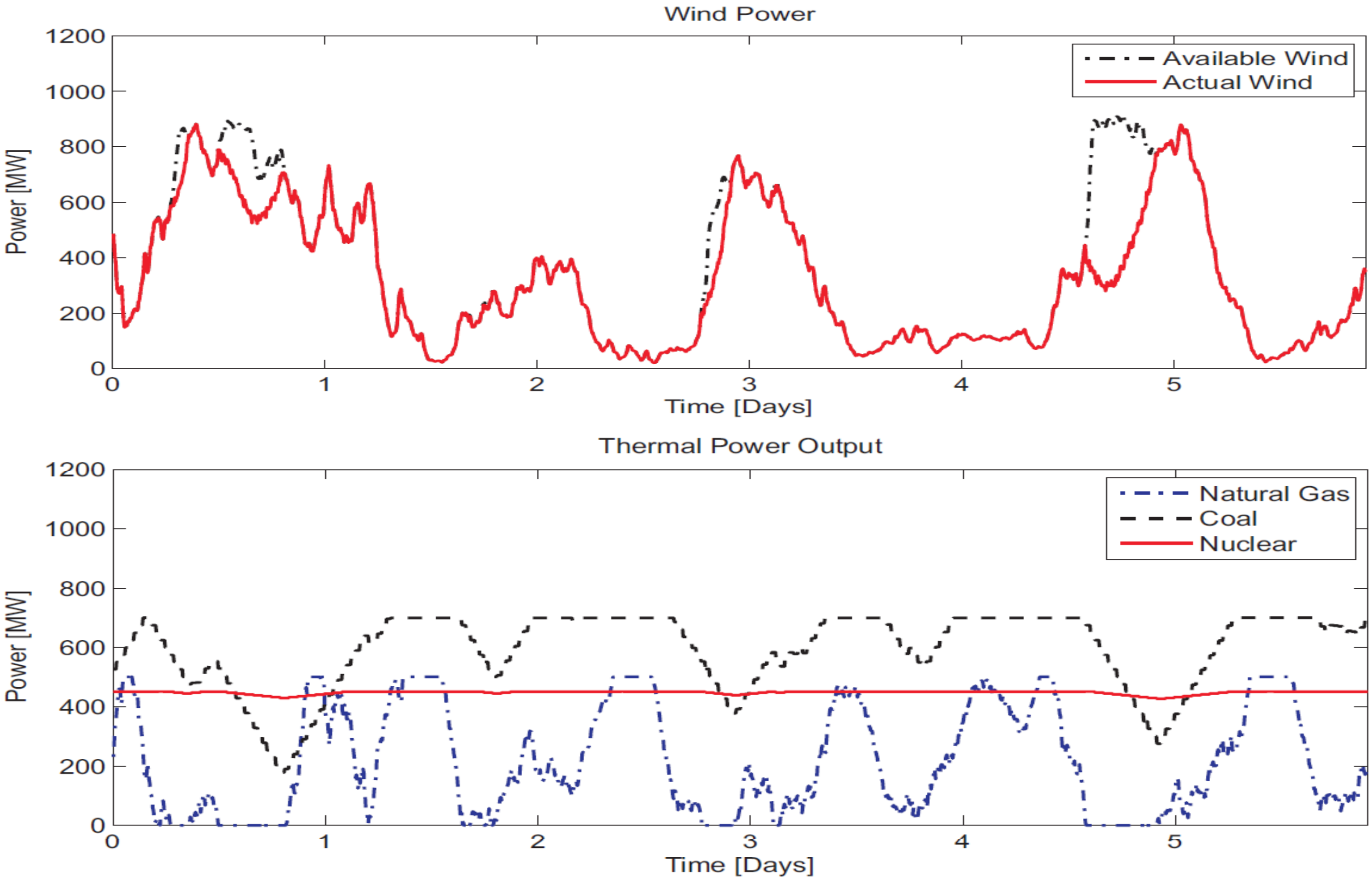


Case 2: Reference



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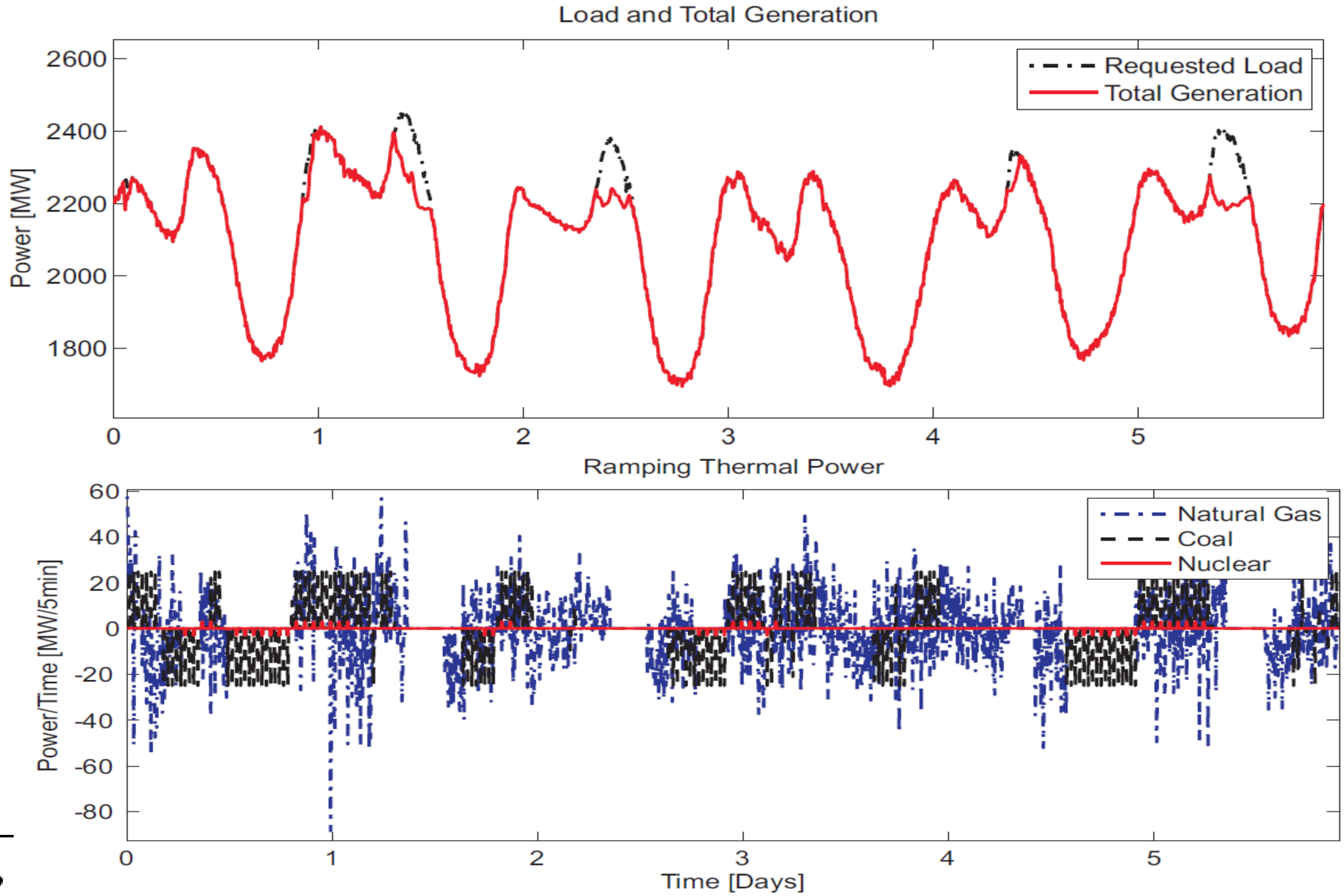

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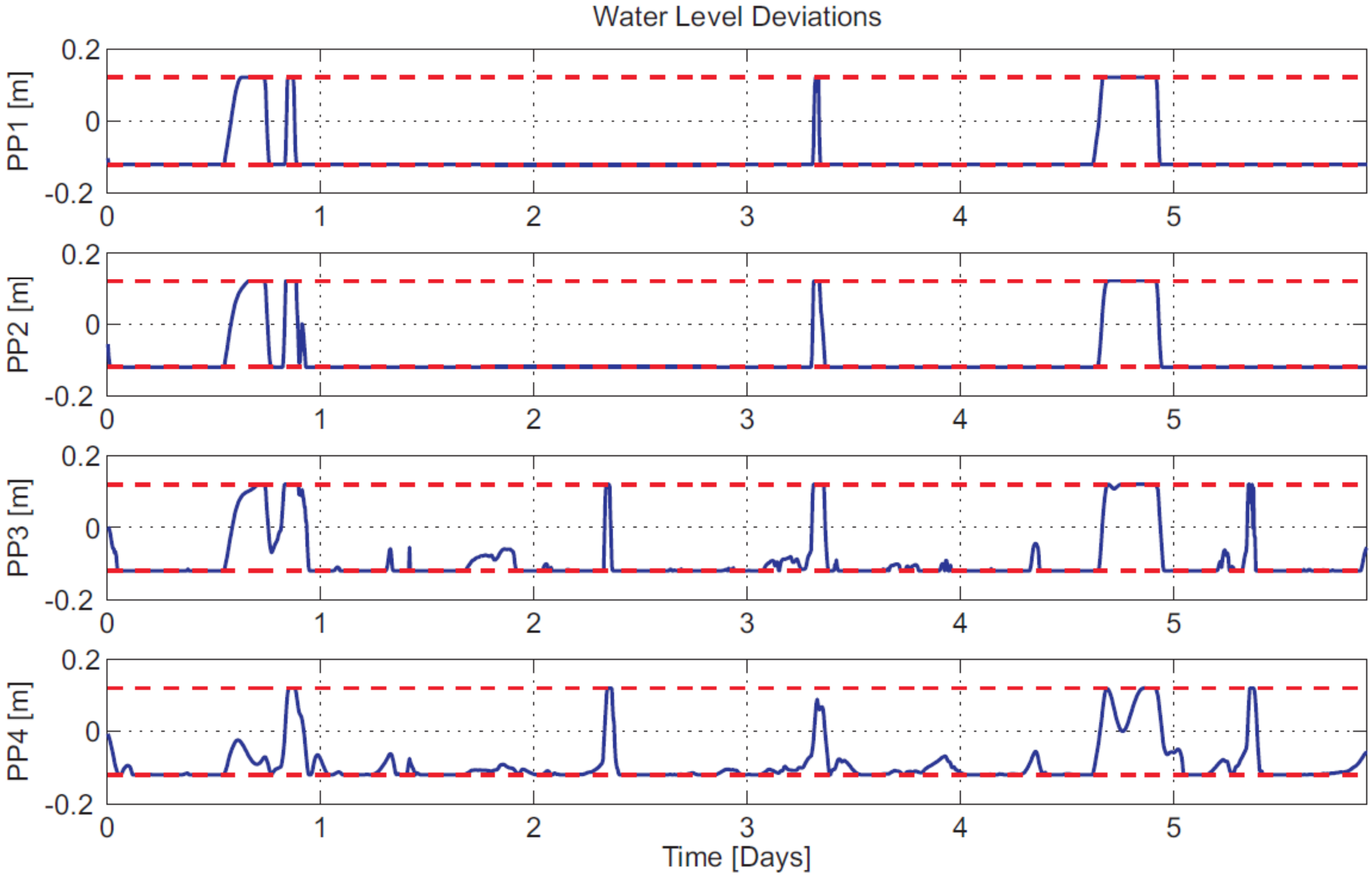

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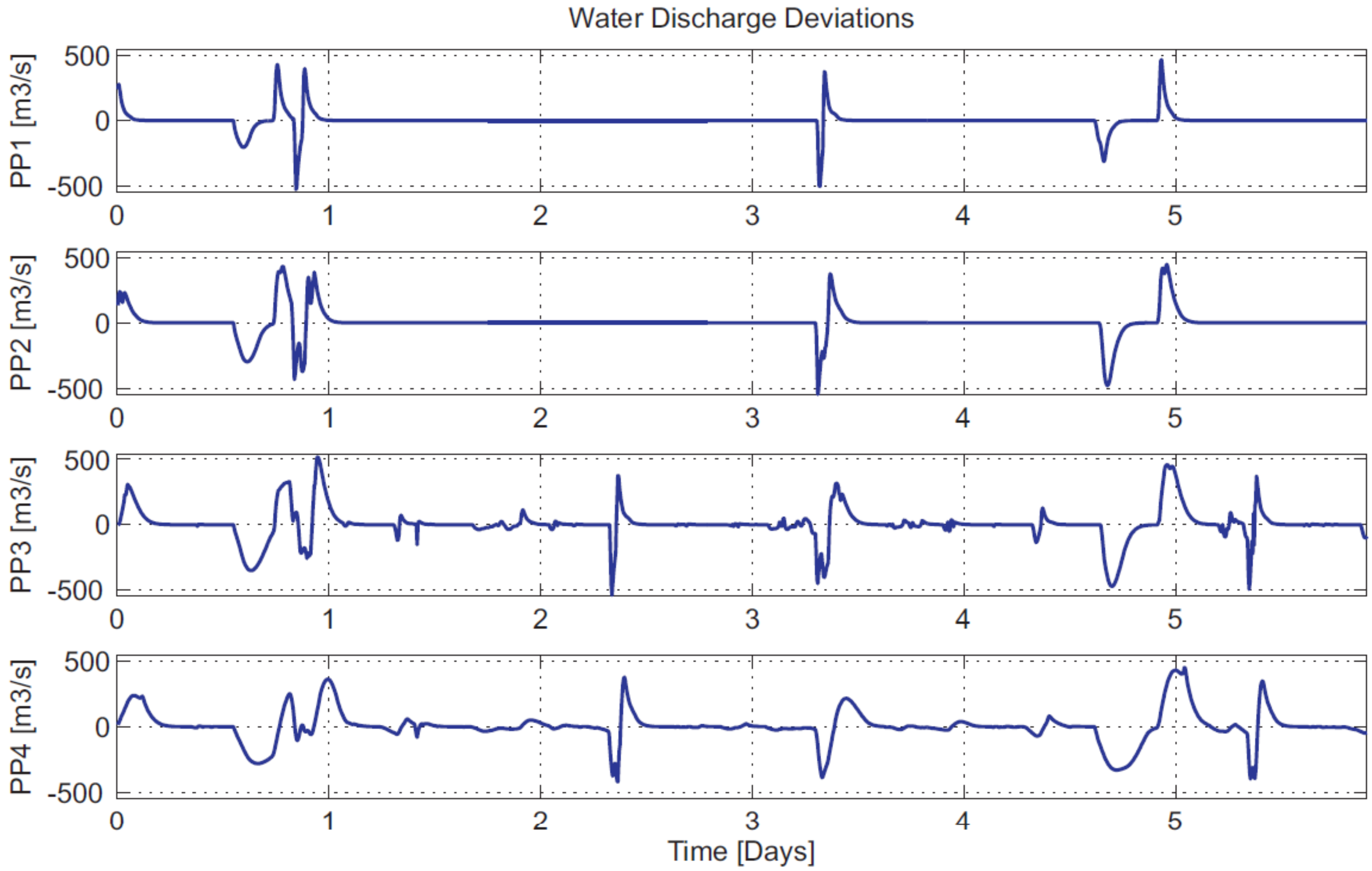
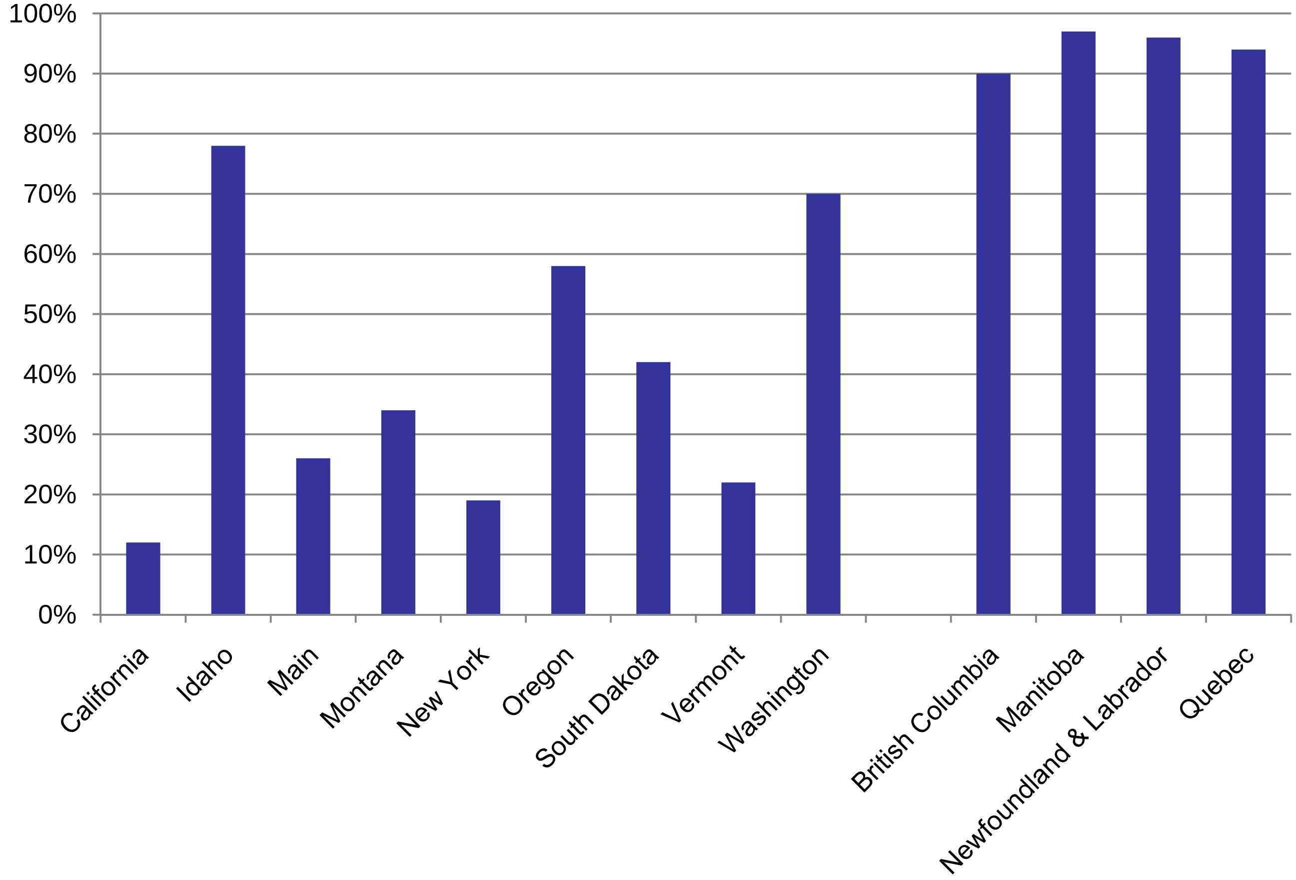


Conclusions

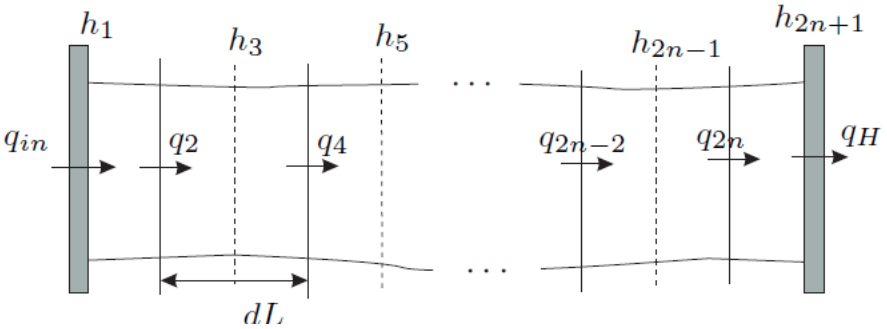
- Electric power systems field is currently in a major transition
  - ⇒ Major challenges need to be resolved
- Predictive control allows for full exploitation of device potentials
- Storage reduces need for fast-ramping backup generation and required ramp rates if optimally controlled
- Existing hydro power provides storage capacity
- Coordination achieves overall optimal performance
- Integration of intermittent renewable generation asks for hybrid solution

Conventional Hydro Power



Modeling: Hydro Power

- Linear Model
  - River Flow



$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned}$$

$$x(k) = \begin{bmatrix} h_1(k) \\ q_2(k) \\ \vdots \\ q_{2n}(k) \\ h_{2n+1}(k) \\ q_{in}(k) \\ q_H(k) \end{bmatrix}, u(k) = \begin{bmatrix} \delta q_{in}(k) \\ \delta q_H(k) \end{bmatrix}, y(k) = \begin{bmatrix} h_c(k) \\ q_H(k) \end{bmatrix}$$

  - Discharge to Electric Power

$$P_H = \eta \rho \Delta H_T g \cdot Q_T$$

Case 1: Simulation Results

- Smoothness of Total Power Output

$$I = \frac{\sum_{k=1}^{n_{steps}} \Delta P_{total}(k)/n_{steps}}{P_{total,av}}$$

SIMULATION SCENARIOS

Case	Prediction Horizon	Prediction Error (rms)	Wind Penetration
A	2 hours	0%	35%
B	2 hours	10%	35%
C	2 hours	10%	50%
D	1 hour	10%	35%

SMOOTHNESS INDEX VALUES

Wind %	Ref. W+H	A	B	C	D
35%	0.0045	0.0017	0.0018		0.0020
50%	0.0066			0.0027	

Case 2: Generation/Storage Dispatch

- Objective Function

$$\min \sum_{k=0}^{N-1} \left(\sum_i C_{EC,i} + \sum_i C_{EV,i} + C_{QS} \right)$$

- Constraints
  - Ramp rates
  - Capacities
  - Water level limits
  - Generation = Demand