Cornell University

# Secure Planning and Operations of Systems with Stochastic Sources, Energy Storage and Active Demand

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CERTS
CONSORTIUM FOR ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

# Overview

Directions for improving software for ISO markets:

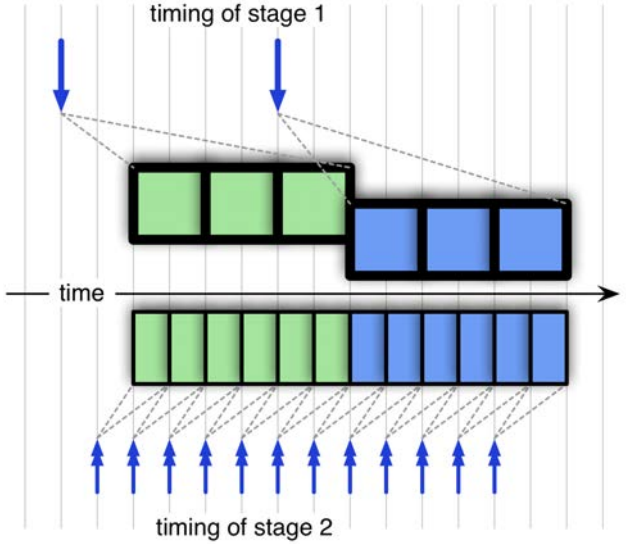
- dispatch/pricing via OPF with AC network models
- improved handling of increased uncertainty through stochastic optimization
- dispatch of storage, time-flexible demand
- endogenous reserve requirements
- ramping products
- move to receding horizon

# Two Stages

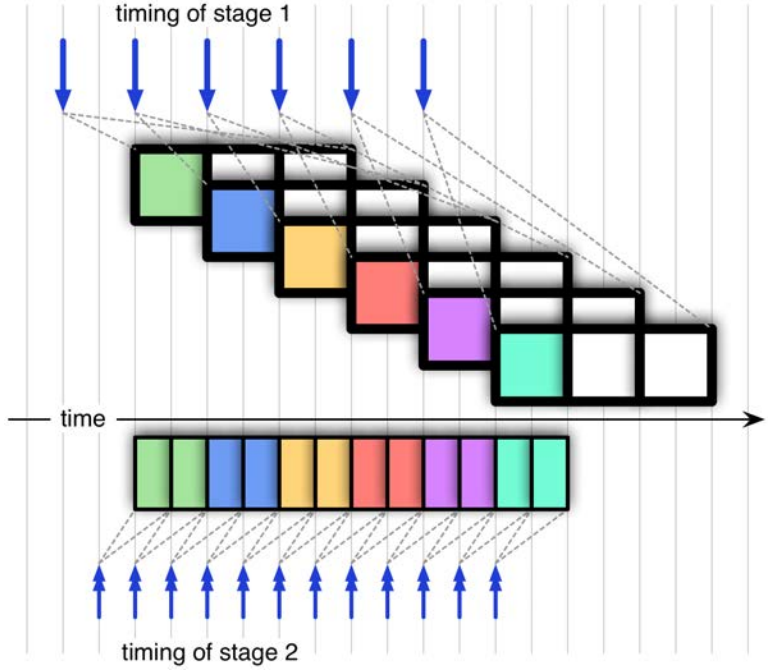
- stage 1 – day-ahead / hour-ahead
  - multiperiod – determines contracts for energy, reserve/ramping capacity and unit commitment
- stage 2 – real-time / balancing
  - determines balancing energy, real-time prices

This paper focuses on the problem formulation for the first stage, presenting a *secure*, *stochastic*, unit-commitment/ multi-period AC OPF, with storage, flexible demand, and endogenous contingency and load-following reserve requirements for use in a receding horizon context.

# Receding Horizon




Traditional Approach – Stage 1 runs *once-per-day*, finds hourly solution for *full day*; stage 2 runs intra-hour, finds single period solution subject to *day-ahead* contracts.




Receding Horizon Approach – Stage 1 runs *hourly*, finds solution for *first hour* with hourly full-day look-ahead; stage 2 runs intra-hour, finds single period solution subject to *hour-ahead* contracts.

# Focus

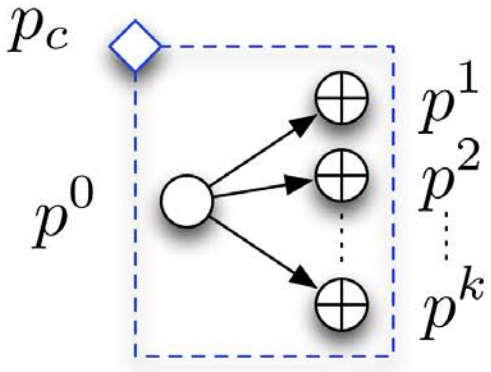
- handling uncertainty in multi-period planning
- load following ramping reserves
- storage and time-flexible demand

# Handling Uncertainty

Begin with single period problem, that is, making the OPF stochastic and secure.

- two types of uncertainty
  - wind, load (continuous, distribution)
  - contingencies (discrete, low probability)
- both handled by selecting sets of individual probability weighted scenarios, so that:
  - overall stochastic cost is approximated adequately,
  - credible, low probability, high impact events are included to ensure security,
  - number of scenarios is minimized to keep computational cost reasonable.

# Problem Structure – Contingencies



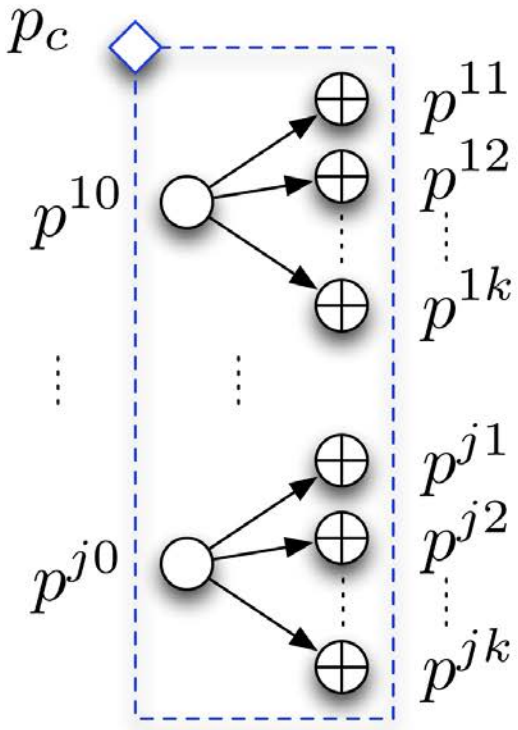

base power flow scenario

contingency state power flow

energy contract, incs/decs, reserves

transition constraint (e.g. ramp limit)

# Problem Structure – Wind



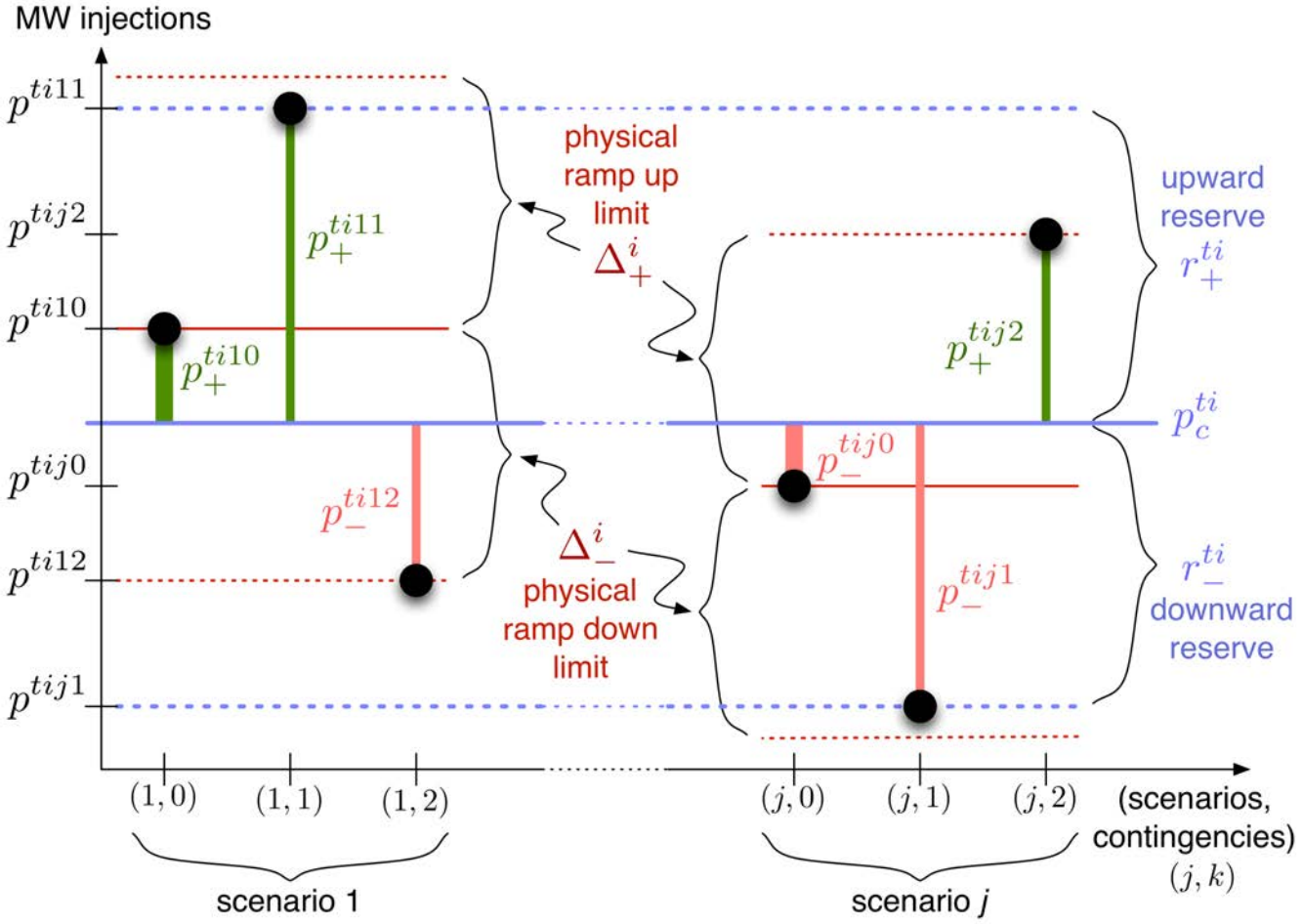

base power flow scenario

contingency state power flow

energy contract, incs/decs, reserves

transition constraint (e.g. ramp limit)

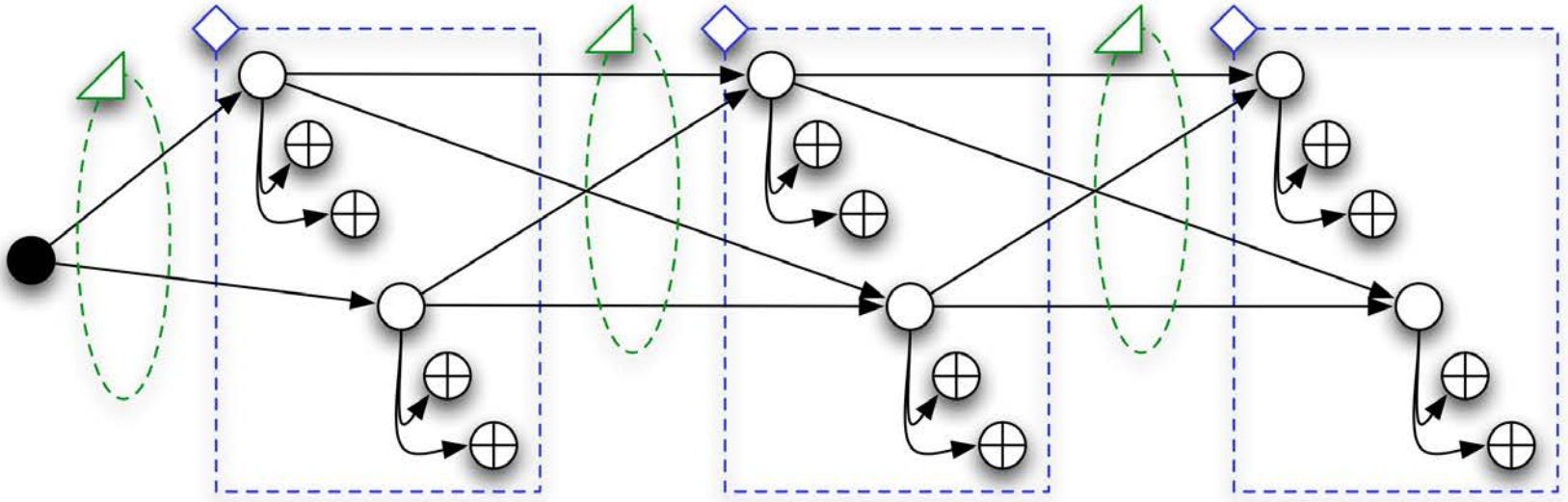
# Reserves


MW injections
$p^{ti11}$
$p^{tij2}$
$p^{ti10}$
$p^{tij0}$
$p^{ti12}$
$p^{tij1}$
$p_+^{ti11}$
$p_+^{ti10}$
$p_-^{ti12}$
physical ramp up limit
$\Delta_+^i$
$\Delta_-^i$
physical ramp down limit
$p_+^{tij2}$
$p_-^{tij0}$
$p_-^{tij1}$
upward reserve
$r_+^{ti}$
$p_c^{ti}$
$r_-^{ti}$
downward reserve
$(1,0)$
$(1,1)$
$(1,2)$
$(j,0)$
$(j,1)$
$(j,2)$
(scenarios, contingencies)
$(j,k)$
scenario 1
scenario $j$

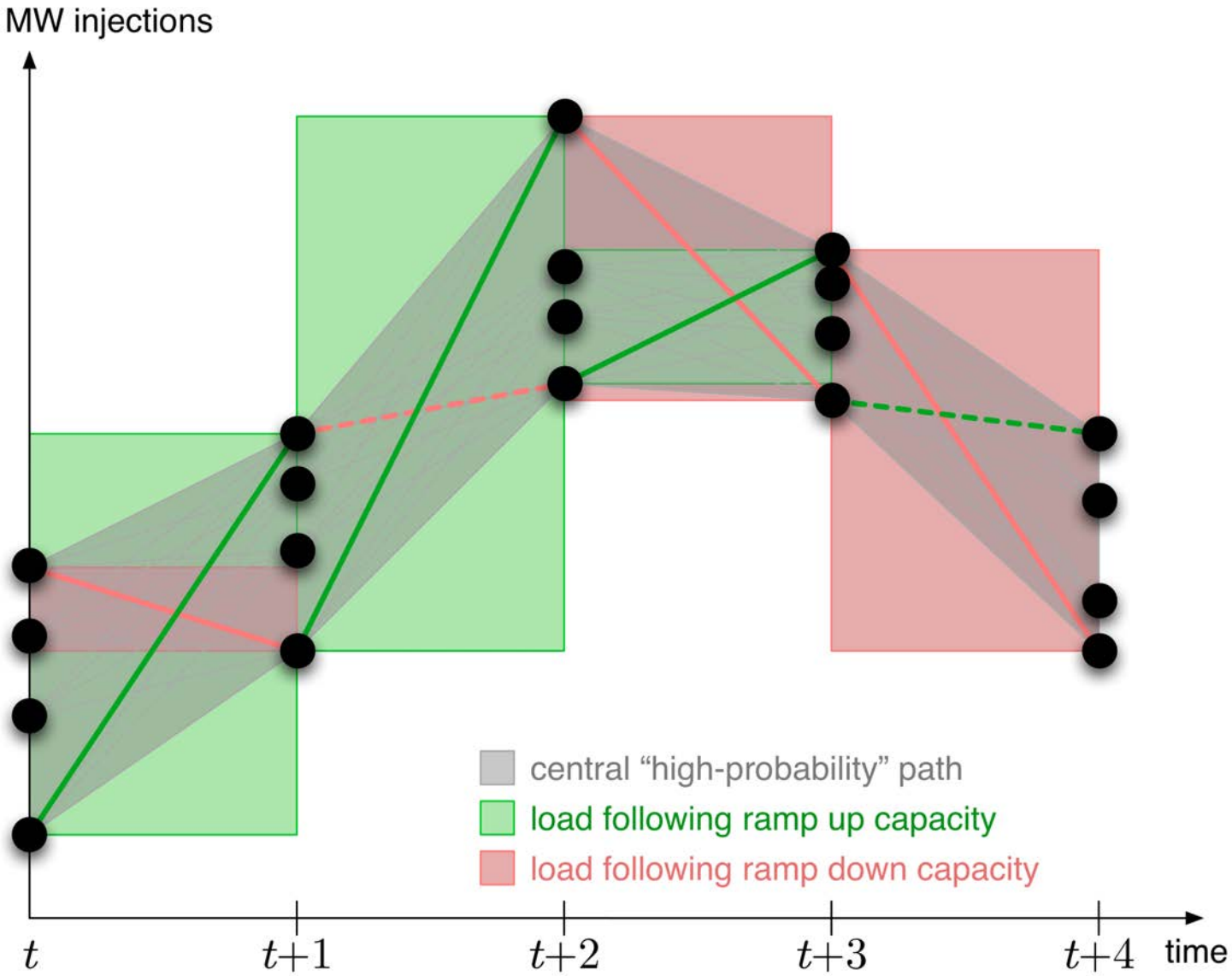
# Extending to Multiple Periods

- number of possible states explodes due to path dependence
- treating each trajectory as a scenario requires too many trajectories to capture the range of possible outcomes in each period
- our approach – enforce feasibility of a central path, the high probability path defined by the set of base scenarios

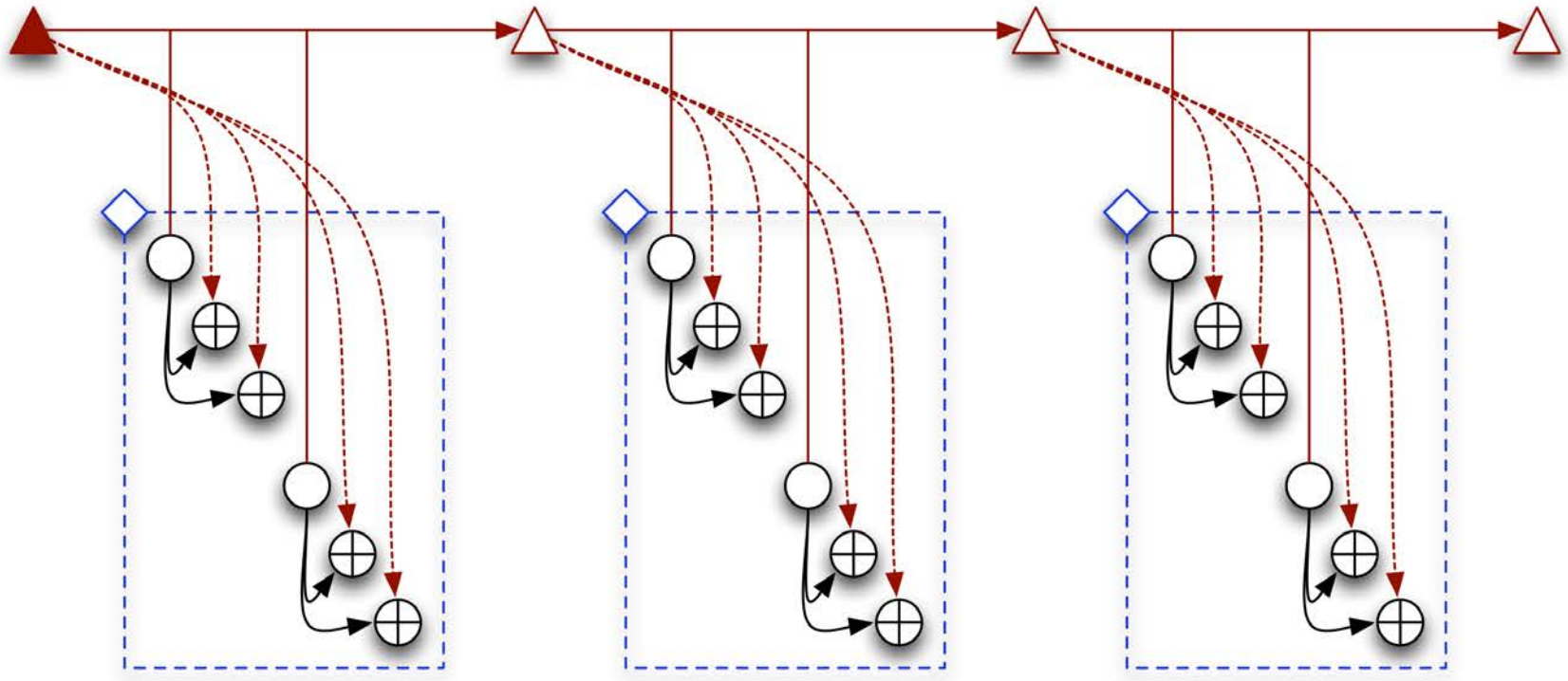
# Ramping



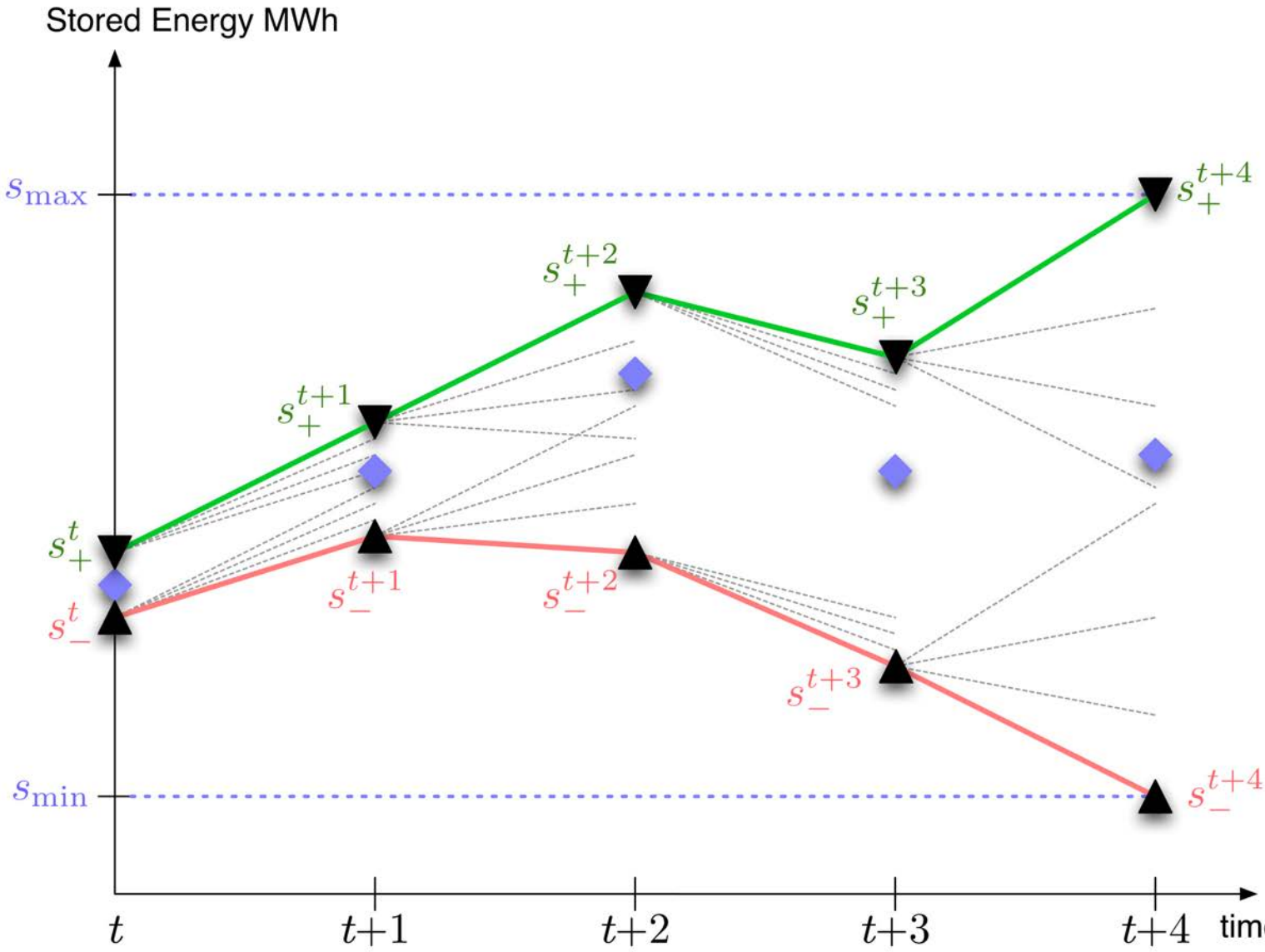
# Ramping – Load Following Reserve



# Storage



# Storage


Stored Energy MWh
$s_{\max}$
$s_{\min}$
$s_+^t$
$s_-^t$
$s_+^{t+1}$
$s_+^{t+2}$
$s_+^{t+3}$
$s_+^{t+4}$
$s_-^{t+1}$
$s_-^{t+2}$
$s_-^{t+3}$
$s_-^{t+4}$
$t$
$t+1$
$t+2$
$t+3$
$t+4$
time

# Notation

| | |
|---|---|
| $\Delta$ | Length of scheduling time slice in hours, typically 1 hour. |
| $t$ | Index over time periods. |
| $T$ | Set of indices of time periods in planning horizon, typically $\{1 \dots n_t\}$. |
| $j$ | Index over scenarios. |
| $J^t$ | Set of indices of all scenarios considered at time $t$. |
| $k$ | Index over post/contingency cases ($k = 0$ for base case, i.e. no contingency occured). |
| $K^{tj}$ | Set of indices of all contingencies considered in scenario $j$ at time $t$. |
| $i$ | Index over injections (generation units, storage units and dispatchable or curtailable loads). |
| $I^t$ | Indices of all units (generators, storage and dispatchable or curtailable loads) available for dispatch in any contingency at time $t$. |
| $I^{tjk}$ | Indices of all units available for dispatch in post/contingency state $k$ of scenario $j$ at time $t$. |
| $p^{tijk}, q^{tijk}$ | Active/reactive injection for unit $i$ in post/contingency state $k$ of scenario $j$ at time $t$. |
| $C_P^{ti}(\cdot)$ | Cost function for active injection $i$ at time $t$. |
| $p_c^{ti}$ | Active power contract quantity for unit $i$ at time $t$. |
| $p_+^{tijk}, p_-^{tijk}$ | Upward/downward deviation from active power contract quantity for unit $i$ in post/contingency state $k$ of scenario $j$ at time $t$. |
| $C_{P+}^{ti}(\cdot), C_{P-}^{ti}(\cdot)$ | Cost for upward/downward deviation from active power contract quantity for unit $i$ at time $t$. |
| $r_+^{ti}, r_-^{ti}$ | Upward/downward active contingency reserve quantity provided by unit $i$ at time $t$. |
| $C_{R+}^{ti}(\cdot), C_{R-}^{ti}(\cdot)$ | Cost function for upward/downward contingency reserve purchased from unit $i$ at time $t$. |
| $\delta_+^{ti}, \delta_-^{ti}$ | Upward/downward load-following ramping reserves needed from unit $i$ at time $t$ for transition to time $t+1$. |
| $C_{\delta+}^{ti}(\cdot), C_{\delta-}^{ti}(\cdot)$ | Cost of upward/downward load-following ramp reserve for unit $i$ at time $t$. |
| $C_\delta^i(\cdot)$ | Quadratic, symmetric ramping cost on the difference between the dispatches for unit $i$ in adjacent periods. |
| $\theta^{tjk}, V^{tjk}, p^{tjk}, q^{tjk}$ | Vectors of voltage angles and magnitudes, active and reactive injections for power flow in post/contingency state $k$ of scenario $j$ at time $t$. |
| $g^{tjk}(\cdot)$ | Nonlinear AC power flow equations in post/contingency state $k$ of scenario $j$ at time $t$. |
| $h^{tjk}(\cdot)$ | Transmission, voltage and other limits in post/contingency state $k$ of scenario $j$ at time $t$. |

# Notation

$P^{tijk}_{\min}, P^{tijk}_{\max}$ Limits on active injection for unit $i$ in post/contingency state $k$ of scenario $j$ at time $t$.

$Q^{tijk}_{\min}, Q^{tijk}_{\max}$ Limits on reactive injection for unit $i$ in post/contingency state $k$ of scenario $j$ at time $t$.

$\delta^i_{\max+}, \delta^i_{\max-}$ Upward/downward load-following ramping reserve limits for unit $i$.

$\Delta^i_+, \Delta^i_-$ Upward/downward physical ramping limits for unit $i$ for transitions from base ($k = 0$) to contingency cases.

$s^{ti}_+, s^{ti}_-$ Upper/lower bounds on the energy stored in storage unit $i$ at the end of period $t$.

$S^{ti}_{\max}, S^{ti}_{\min}$ Stored energy max/min limits for storage unit $i$ at time $t$.

$S^i_0$ Initial stored energy (expected) in storage unit $i$.

$p^{tijk}_{\text{sc}}, p^{tijk}_{\text{sd}}$ Charge/discharge power injections of storage unit $i$ in post/contingency state $k$ of scenario $j$ at time $t$.

$C_{\text{sc}}, C_{\text{sd}}$ Vectors representing contributions to the value of expected leftover stored energy in terminal states from charging/discharging.

$\eta^i_{\text{in}}, \eta^i_{\text{out}}$ Charging/discharging (or pumping/generating) efficiencies for storage unit $i$.

$\eta^i_{\text{loss}}$ Fraction of stored energy lost per hour by storage unit $i$.

$\psi^{tjk}$ Probability of contingency $k$ in scenario $j$ at time $t$ ($\psi^{tj0}$ is the probability of no contingency, i.e. the base case, for scenario $j$ at time $t$).

$\alpha$ For contingency cases, the fraction of the time slice that is spent in the base case before the contingency occurs ($\alpha = 0$ means the entire period is spent in the contingency).

$\psi^{tjk}_\alpha$ Probability $\psi^{tjk}$ of contingency $k$ in scenario $j$ at time $t$ adjusted for $\alpha$.

$$\psi^{tjk}_\alpha = \begin{cases} \psi^{tj0} + \alpha \sum_{\kappa \in K^{tj} \neq 0} \psi^{tj\kappa}, & k = 0 \\ (1-\alpha)\psi^{tjk}, & \forall k \in K^{tj} \neq 0 \end{cases} \quad (1)$$

$\gamma^t$ Probability of making it to period $t$ without branching off the central path in a contingency in periods $1 \ldots t-1$.

$\phi^{tj_2j_1}$ Probability of transitioning to scenario $j_2$ in period $t$ given that we were at scenario $j_1$ in period $t-1$.

$u^{ti}$ Binary commitment state for unit $i$ in period $t$, 1 if unit is on-line, 0 otherwise.

$v^{ti}, w^{ti}$ Binary startup and shutdown states for unit $i$ in period $t$, 1 if unit has a startup/shutdown event in period $t$, 0 otherwise.

$\tau^+_i, \tau^-_i$ Minimum up and down times for unit $i$ in number of periods.

$C^{ti}_v, C^{ti}_w$ Startup and shutdown costs for unit $i$ at time $t$ in \$ per startup/shutdown.

# Objective Function

$$\min_x f(x) \qquad \text{where}$$

(1) active power dispatch and re-dispatch costs

(2) contingency reserve costs

(3) ramping wear & tear costs

$$f(x) = f_p(p, p_+, p_-) + f_r(r_+, r_-) + f_\delta(p)$$
$$+ f_{\text{lf}}(\delta_+, \delta_-) + f_s(p_{\text{sc}}, p_{\text{sd}}) + f_{\text{uc}}(v, w)$$

(4) load following ramp reserve costs

(5) cost/value of leftover stored energy in terminal states

(6) startup and shutdown costs

# Objective Function (1)-(3)

(1) cost of active power dispatch and re-dispatch

$$f_p(p, p_+, p_-) = \sum_{t \in T} \sum_{j \in J^t} \sum_{k \in K^{tj}} \psi_\alpha^{tjk} \sum_{i \in I^{tjk}} \left[ C_P^{ti}(p^{tijk}) + C_{P+}^{ti}(p_+^{tijk}) + C_{P-}^{ti}(p_-^{tijk}) \right]$$

(2) cost of contingency reserves

$$f_r(r_+, r_-) = \sum_{t \in T} \gamma^t \sum_{i \in I^t} \left[ C_{R+}^{ti}(r_+^{ti}) + C_{R-}^{ti}(r_-^{ti}) \right]$$

(3) cost of load-following ramping (wear & tear)

$$f_\delta(p) = \sum_{t \in T} \gamma^t \sum_{\substack{j_1 \in J^{t-1} \\ j_2 \in J^t}} \phi^{tj_2j_1} \sum_{i \in I^{tj_20}} C_\delta^i(p^{tij_20} - p^{(t-1)ij_10})$$

# Objective Function (4)-(6)

(4) cost of load-following ramp reserves

$$f_{\mathrm{lf}}(\delta_+, \delta_-) = \sum_{t \in T} \gamma^t \sum_{i \in I^t} \left[ C^{ti}_{\delta+}(\delta^{ti}_+) + C^{ti}_{\delta-}(\delta^{ti}_-) \right]$$

(5) cost (or value, since it is negative) of expected leftover stored energy in terminal states

$$f_s(p_{\mathrm{sc}}, p_{\mathrm{sd}}) = -(C^{\mathsf{T}}_{\mathrm{sc}} p_{\mathrm{sc}} + C^{\mathsf{T}}_{\mathrm{sd}} p_{\mathrm{sd}})$$

(6) startup and shutdown costs

$$f_{\mathrm{uc}}(v, w) = \sum_{t \in T} \gamma^t \sum_{i \in I^t} (C^{ti}_v v^{ti} + C^{ti}_w w^{ti})$$

# Standard OPF Constraints

All constraints, for all $t \in T$, all $j \in J^t$, all $k \in K^{tj}$, and all $i \in I^{tjk}$:

- nonlinear AC power balance equations

$$g^{tjk}(\theta^{tjk}, V^{tjk}, p^{tjk}, q^{tjk}) = 0$$

- nonlinear transmission flow limits, voltage limits, any other OPF inequality constraints

$$h^{tjk}(\theta^{tjk}, V^{tjk}, p^{tjk}, q^{tjk}) \leq 0$$

# Contingency Constraints

- reserve, redispatch and contract variables

$$
\begin{aligned}
0 \le p_+^{tijk} &\le r_+^{ti} \le R_{\max+}^{ti} \\
0 \le p_-^{tijk} &\le r_-^{ti} \le R_{\max-}^{ti} \\
p^{tijk} - p_c^{ti} &= p_+^{tijk} - p_-^{tijk}
\end{aligned}
$$

- ramping limits on transitions from base to contingency cases

$$
-\Delta_-^i \le p^{tijk} - p^{tij0} \le \Delta_+^i, \quad k \ne 0
$$

# Intertemporal Constraints

- load following ramping limits and reserves

$$
\begin{aligned}
0 \leq \delta_{+}^{ti} &\leq \delta_{\max+}^{ti} \\
0 \leq \delta_{-}^{ti} &\leq \delta_{\max-}^{ti} \\
p^{tij_20} - p^{(t-1)ij_10} &\leq \delta_{+}^{(t-1)i}, \quad j_1 \in J^{t-1}, j_2 \in J^t \\
p^{(t-1)ij_10} - p^{tij_20} &\leq \delta_{-}^{(t-1)i}, \quad j_1 \in J^{t-1}, j_2 \in J^t
\end{aligned}
$$

# Intertemporal Constraints

- storage

$$
\begin{aligned}
p^{tijk} &= p_{\mathrm{sc}}^{tijk} + p_{\mathrm{sd}}^{tijk} \\
p_{\mathrm{sc}}^{tijk} &\leq 0, \qquad p_{\mathrm{sd}}^{tijk} \geq 0 \\
s_{-}^{ti} &\geq S_{\mathrm{min}}^{ti}, \quad s_{+}^{ti} \leq S_{\mathrm{max}}^{ti} \\
s_{\Delta}^{tijk} &\equiv -\Delta(\eta_{\mathrm{in}}^{i} p_{\mathrm{sc}}^{tijk} + \frac{1}{\eta_{\mathrm{out}}^{i}} p_{\mathrm{sd}}^{tijk}) \\
s_{-}^{ti} &\leq s_{-}^{(t-1)i} + s_{\Delta}^{tij0} - \Delta \frac{\eta_{\mathrm{loss}}^{i}}{2} \left( s_{-}^{ti} + s_{-}^{(t-1)i} \right) \\
s_{+}^{ti} &\geq s_{+}^{(t-1)i} + s_{\Delta}^{tij0} - \Delta \frac{\eta_{\mathrm{loss}}^{i}}{2} \left( s_{+}^{ti} + s_{+}^{(t-1)i} \right) \\
S_{\mathrm{min}}^{ti} &\leq s_{-}^{(t-1)i} + \alpha s_{\Delta}^{tij0} + (1-\alpha) s_{\Delta}^{tijk}, \quad k \neq 0 \\
S_{\mathrm{max}}^{ti} &\geq s_{+}^{(t-1)i} + \alpha s_{\Delta}^{tij0} + (1-\alpha) s_{\Delta}^{tijk}, \quad k \neq 0
\end{aligned}
$$

# Unit Commitment

- injection limits and commitments

$$u^{ti} P^{tijk}_{\min} \leq p^{tijk} \leq u^{ti} P^{tijk}_{\max}$$
$$u^{ti} Q^{tijk}_{\min} \leq q^{tijk} \leq u^{ti} Q^{tijk}_{\max}$$

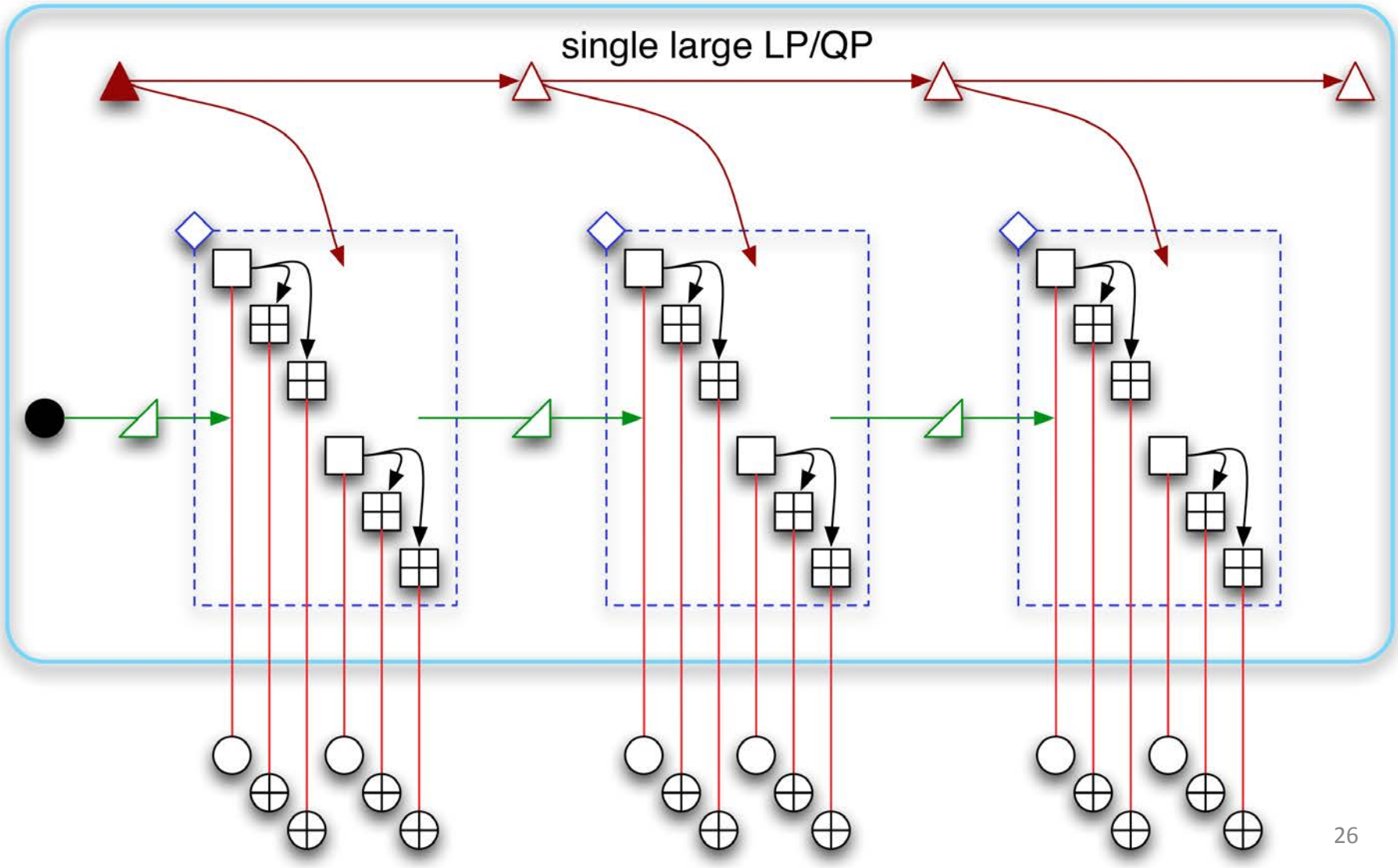
- startup and shutdown events

$$u^{ti} - u^{(t-1)i} = v^{ti} - w^{ti}$$

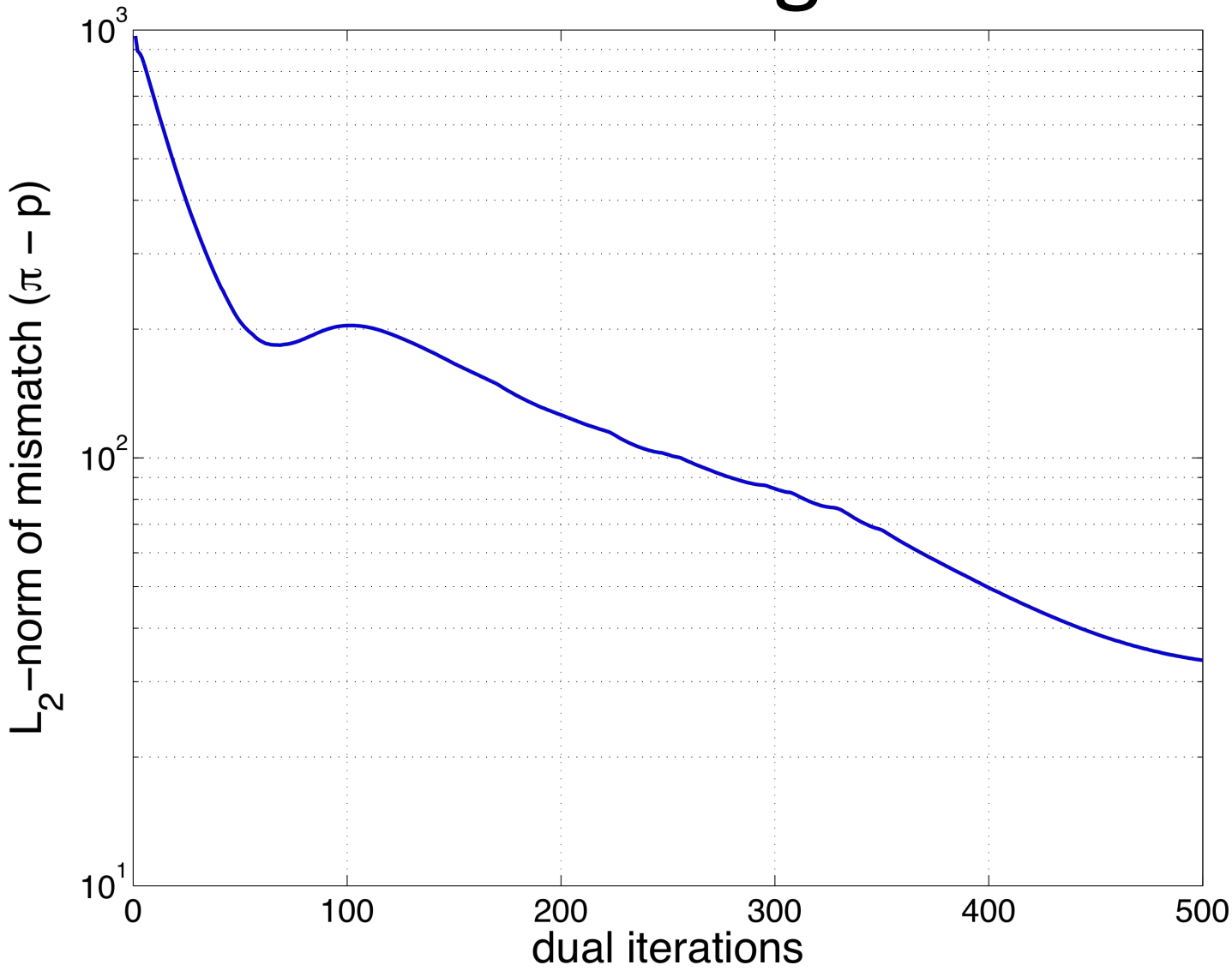
- minimum up and down times

$$\sum_{y=t-\tau_i^+}^{t} v^{yi} \leq u^{ti}, \qquad \sum_{y=t-\tau_i^-}^{t} w^{yi} \leq 1 - u^{ti}$$

# Decomposition of Continuous Sub-problem



# Slow Convergence



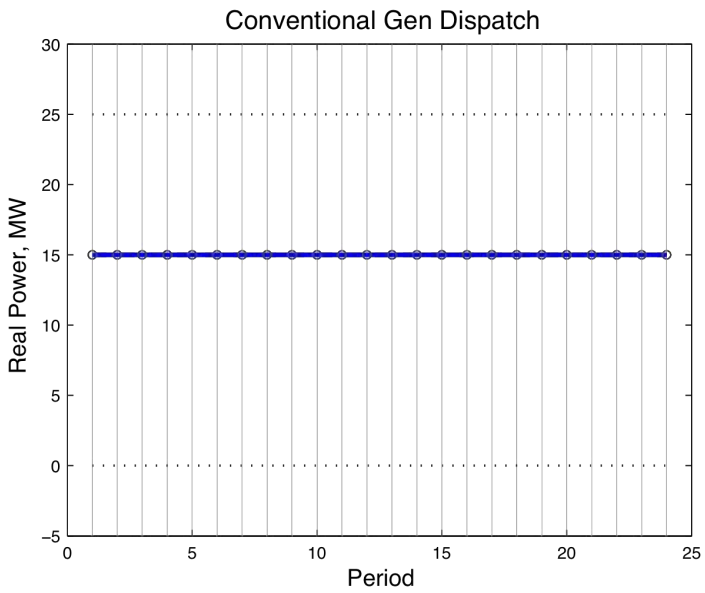
# DC Network Example

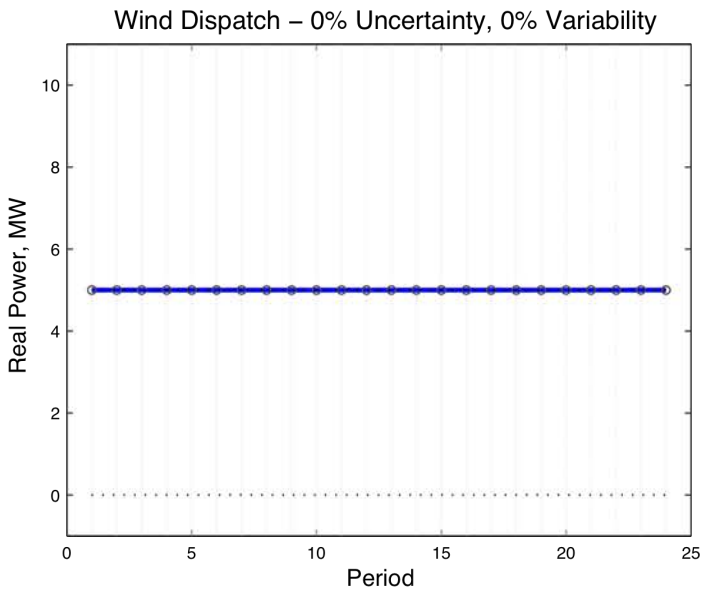
| number of … | |
|---|---|
| buses | 118 |
| conventional generators | 37 |
| wind farms | 11 |
| grid-level storage units | 4 |
| curtailable loads | 99 |
| periods in horizon, $\|T\|$ | 24 |
| scenarios per period, $\|J^t\|$ | 4 |
| contingencies per scenario, $\|K^{tj}\| - 1$ | 7 |
| variables in resulting QP | 462,686 |
| constraints in resulting QP | 819,812 |

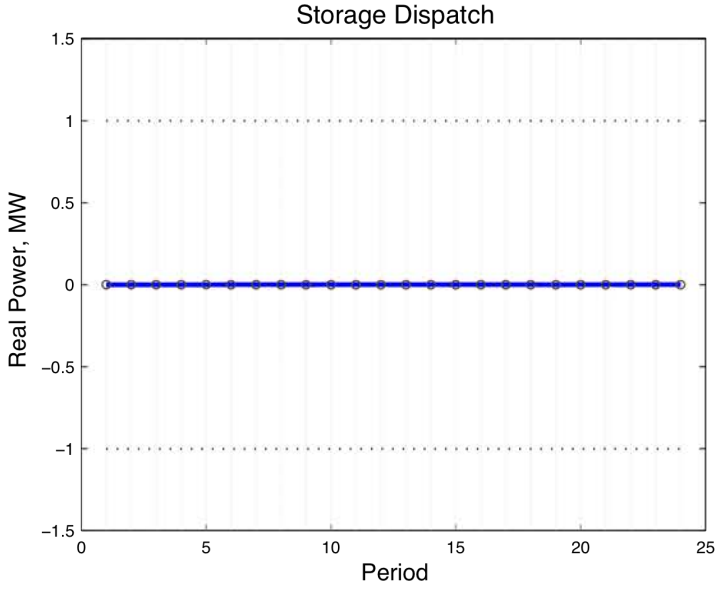
Roughly equivalent to a 90,000 bus OPF + additional vars/constraints.
Solves in under 20 minutes on a Mac Pro (no special tuning).

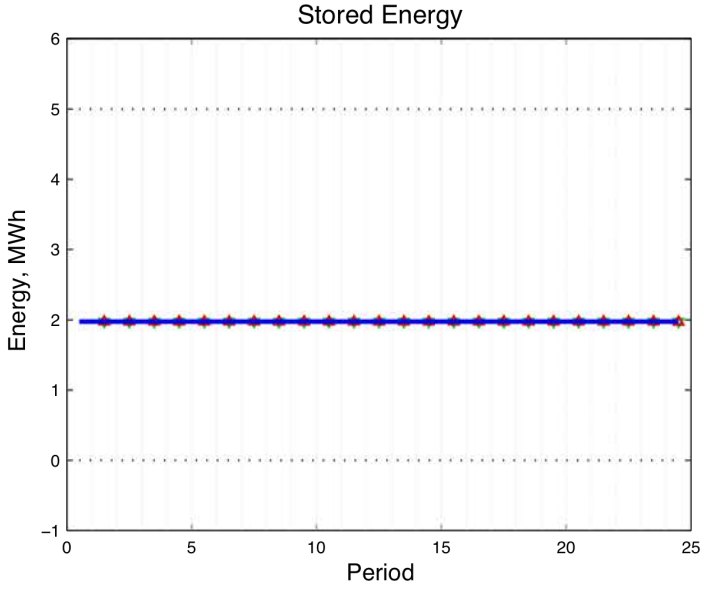
# Storage Usage Tradeoff Example

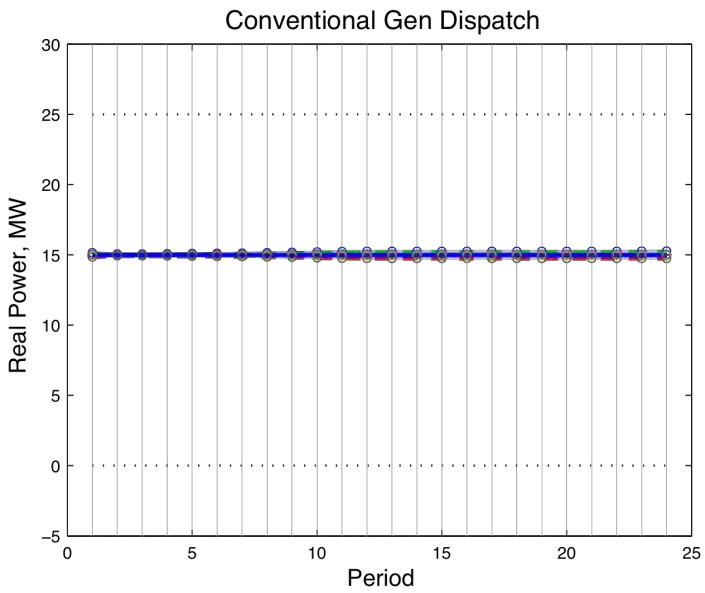
- time arbitrage vs. uncertainty mitigation
- based on example system with:
  - conventional gen with quadratic cost
  - constant deterministic demand
  - 100% efficient grid level storage unit (e.g. battery)
  - normally distributed wind generation with 2 parameters that are varied over a range (0-100%):
    - uncertainty – variance of distribution
    - variability – change in mean of distribution from period to period

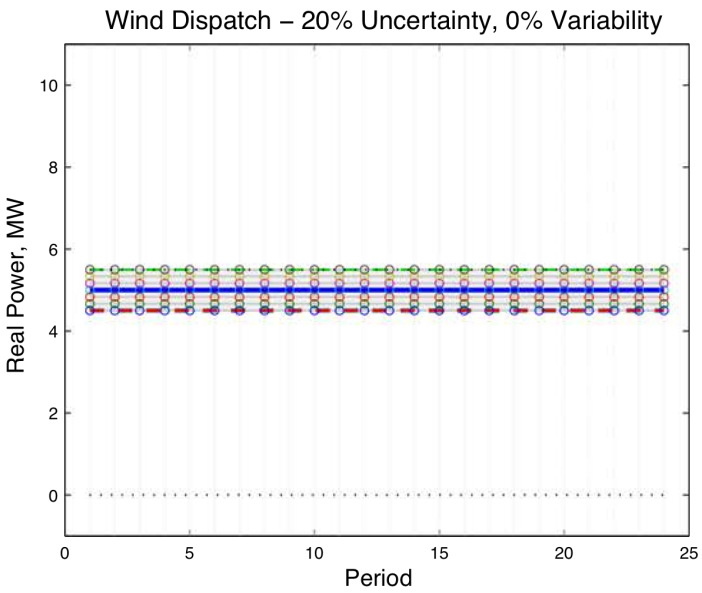

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

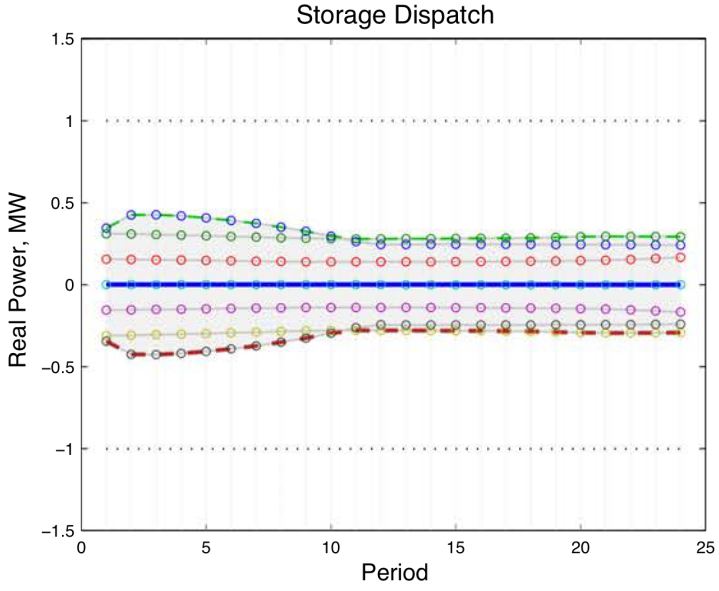

Wind Dispatch – 0% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

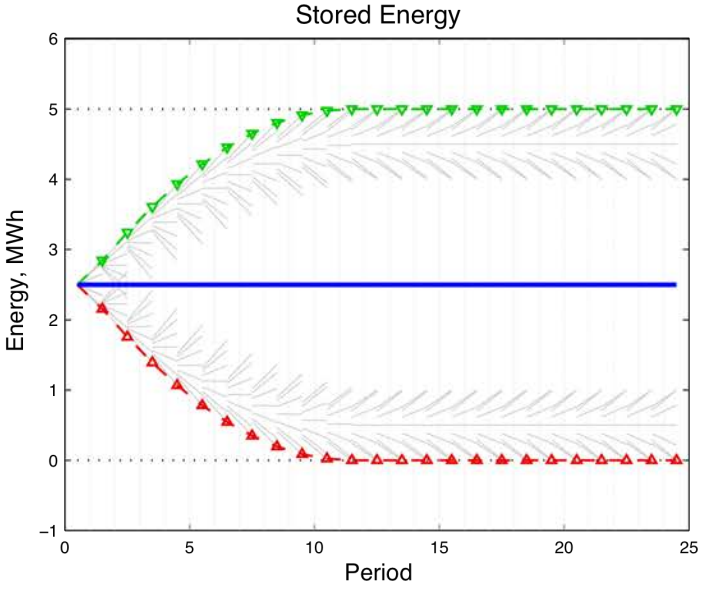

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

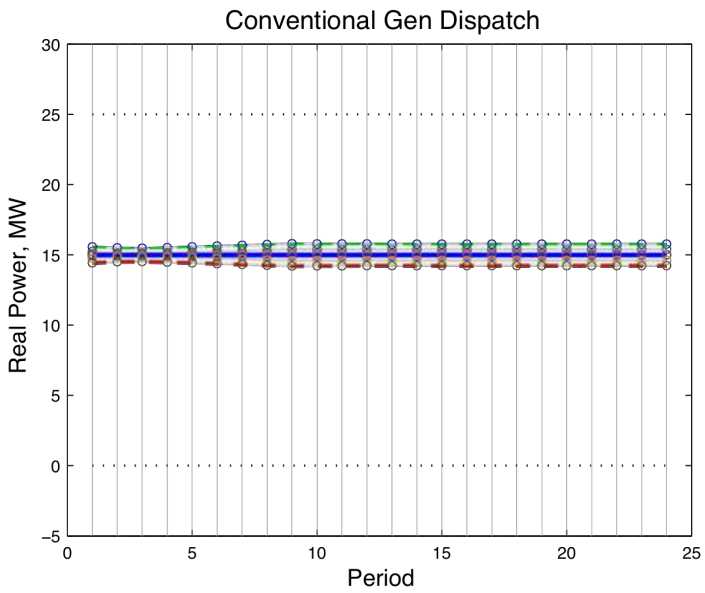

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

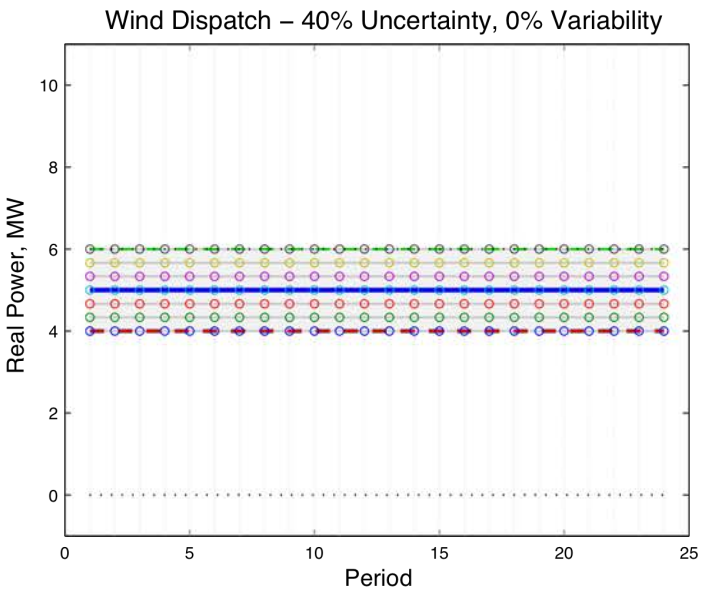

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

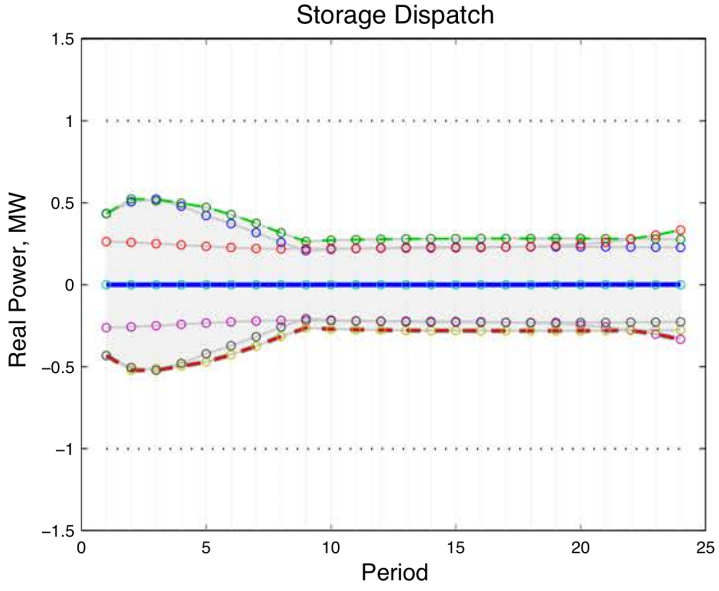

Wind Dispatch – 20% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

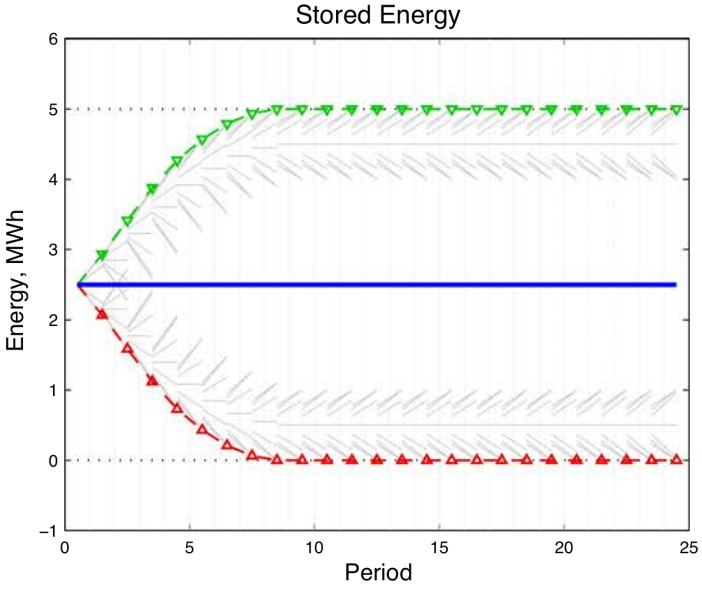

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

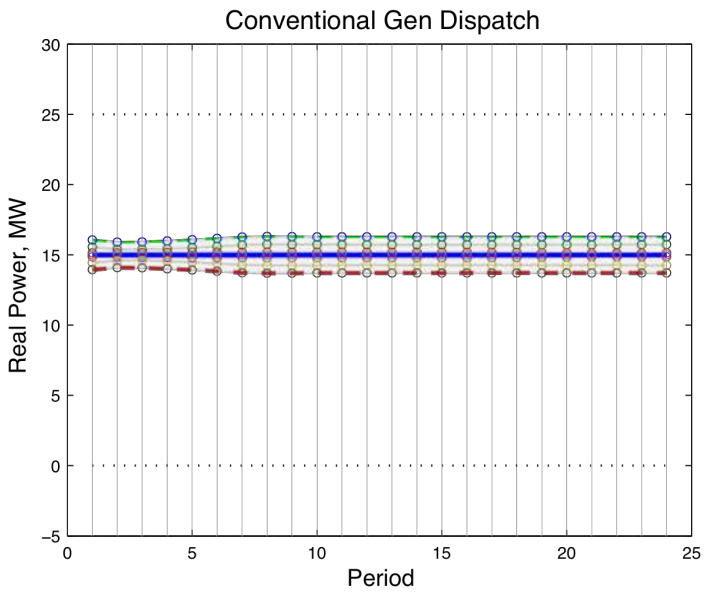

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

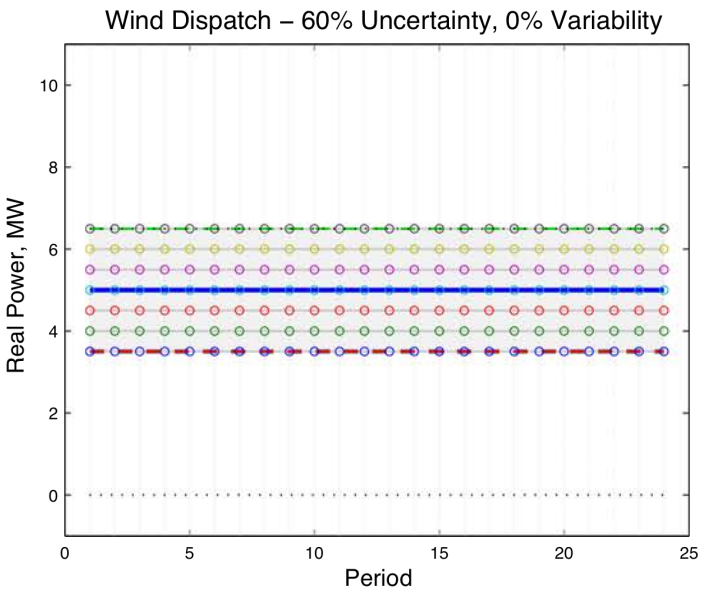

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

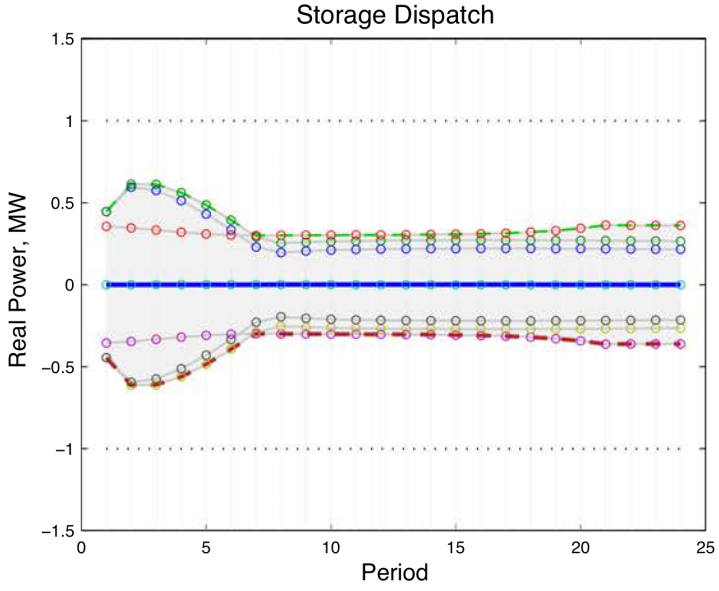

Wind Dispatch – 40% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

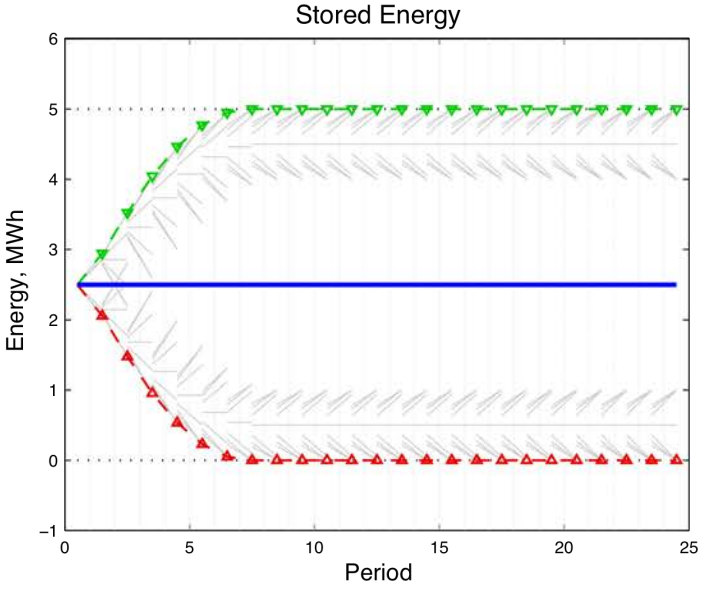

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

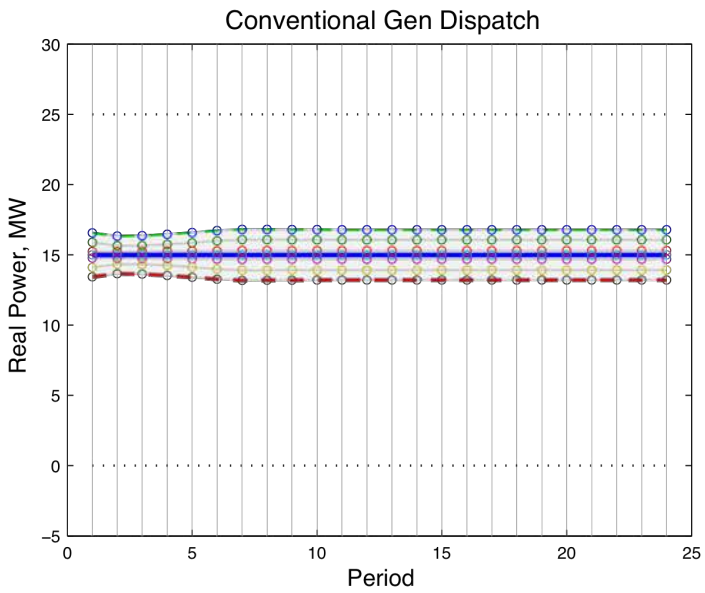

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

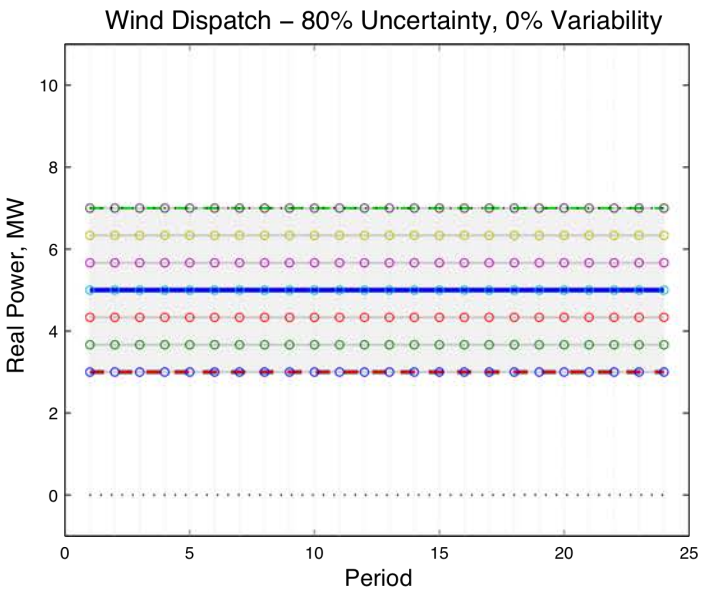

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

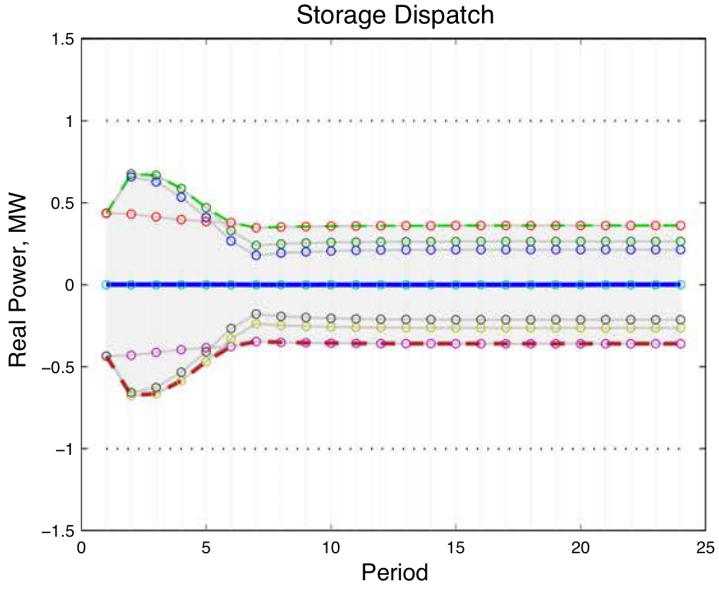

Wind Dispatch – 60% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

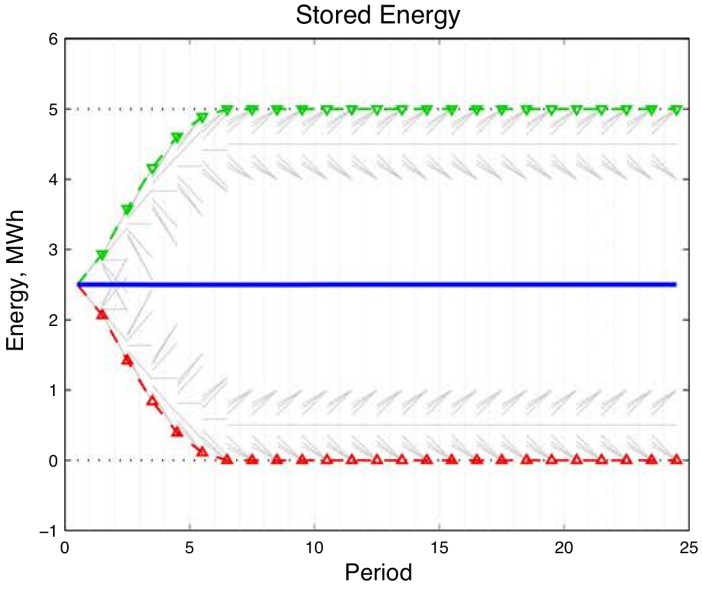

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

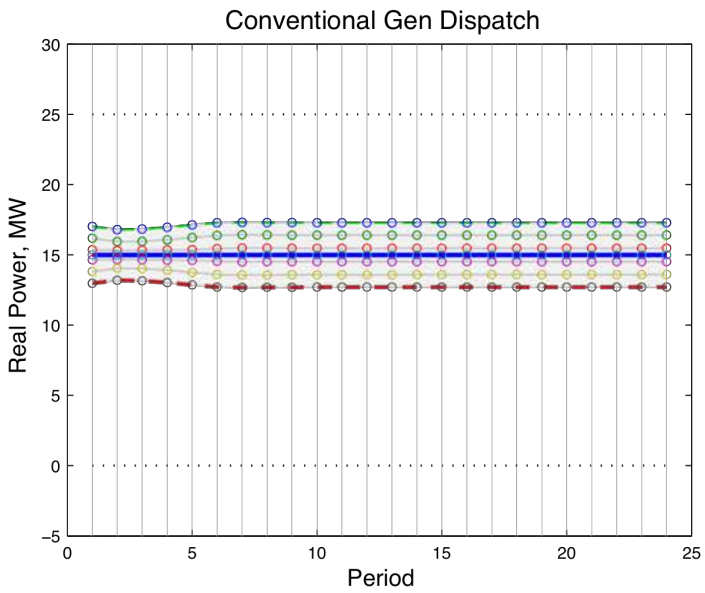

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

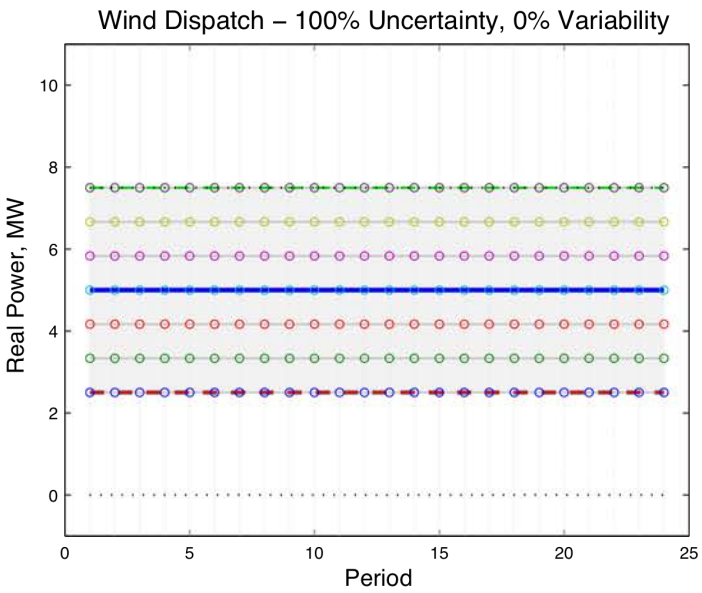

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

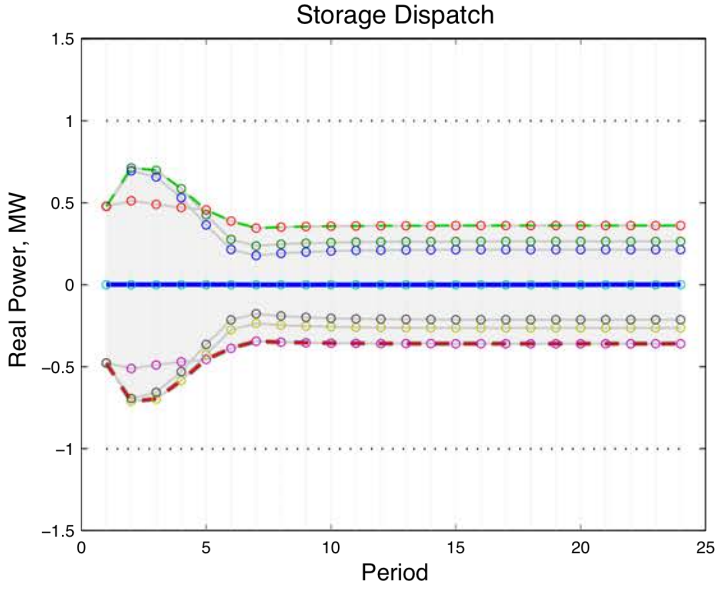

Wind Dispatch – 80% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

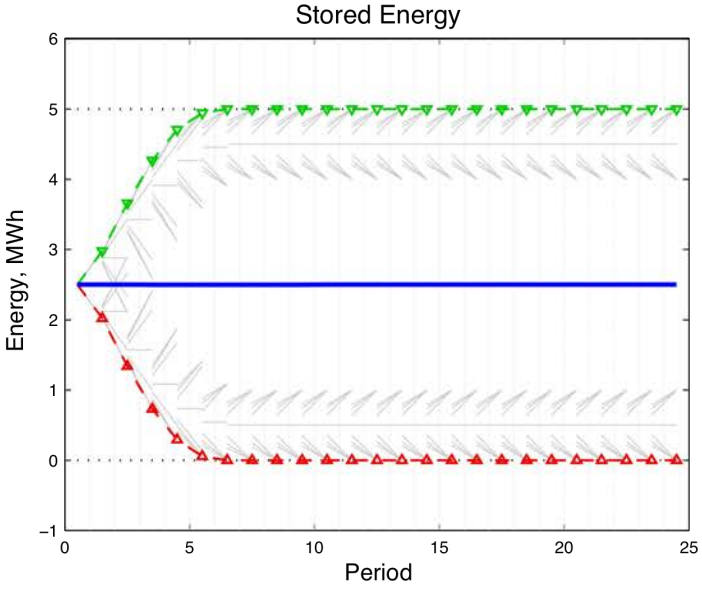

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

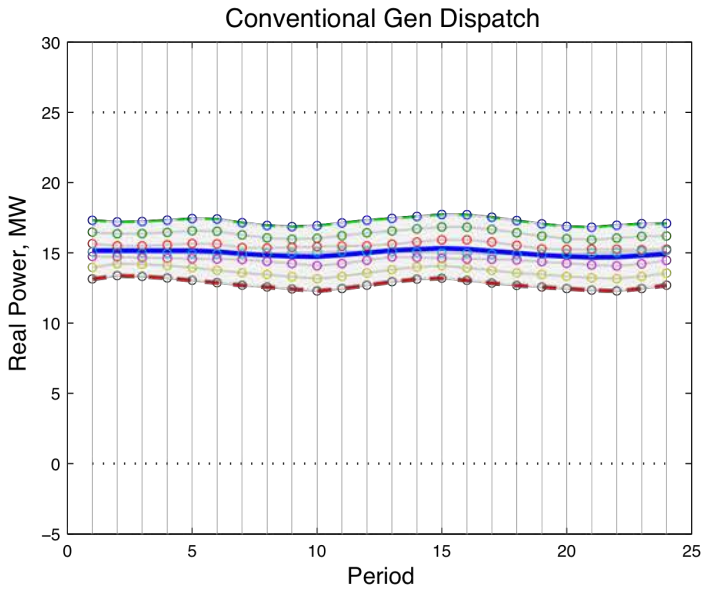

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

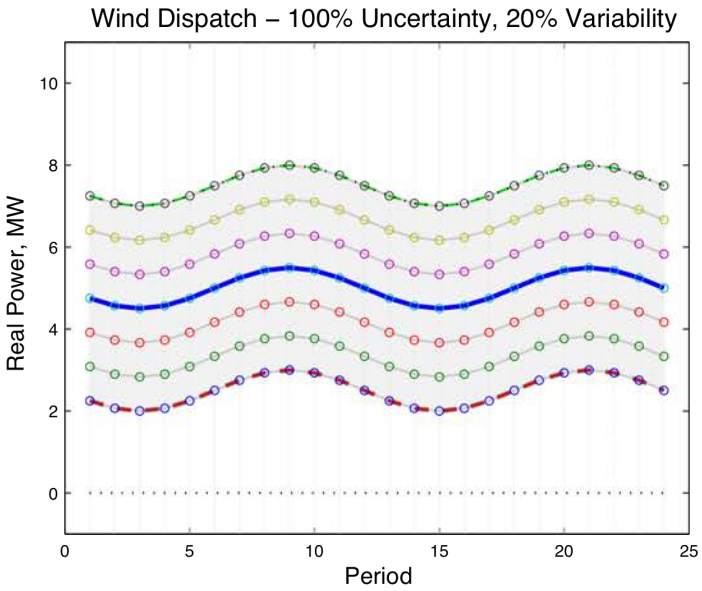

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

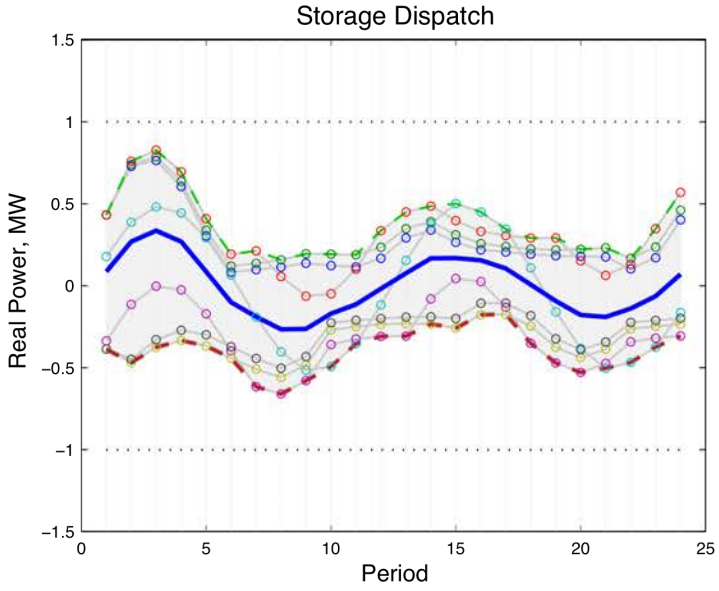

Wind Dispatch – 100% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

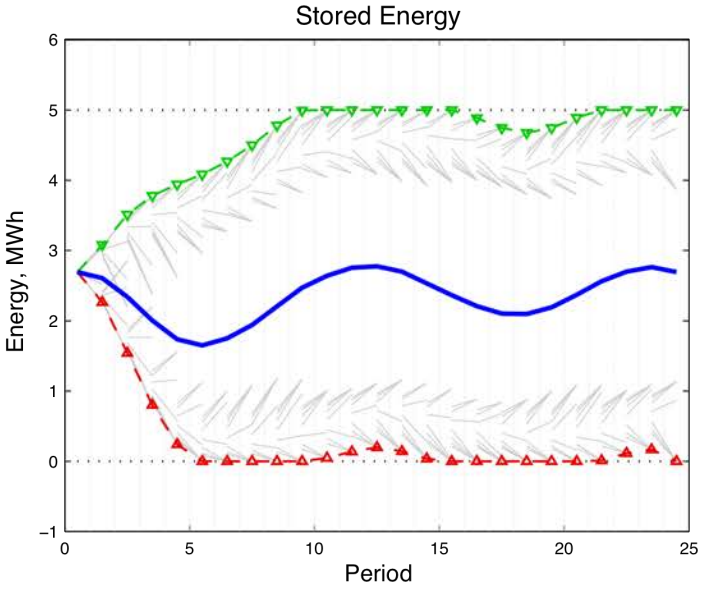

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

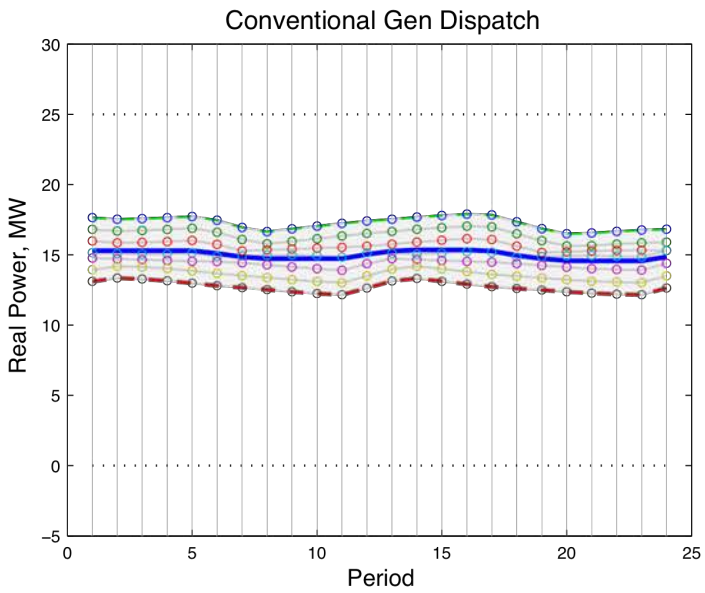

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

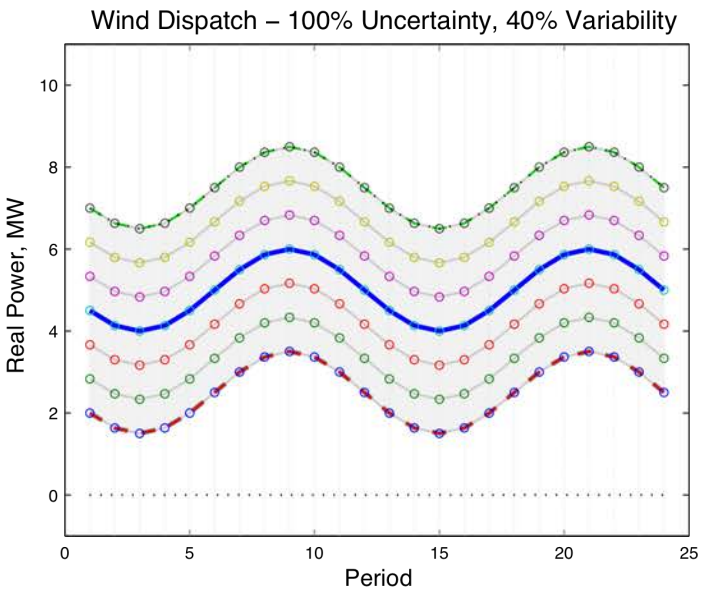

Conventional Gen Dispatch
Real Power, MW
Period

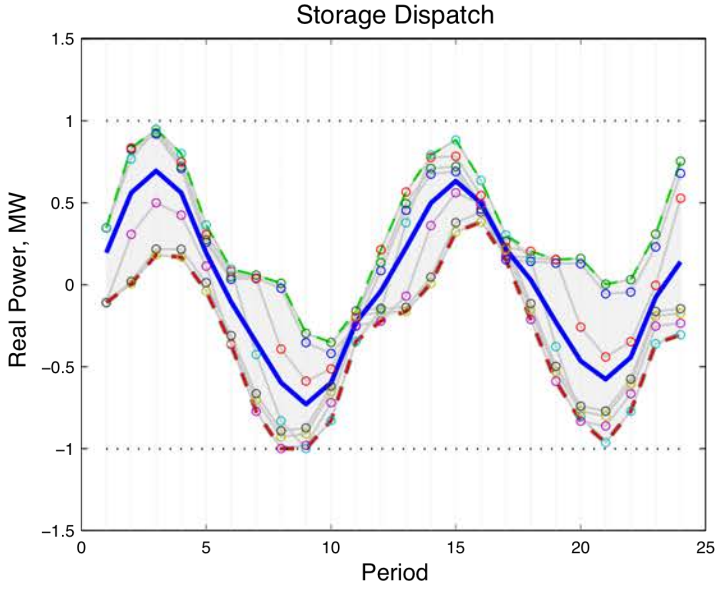

Wind Dispatch – 100% Uncertainty, 20% Variability
Real Power, MW
Period

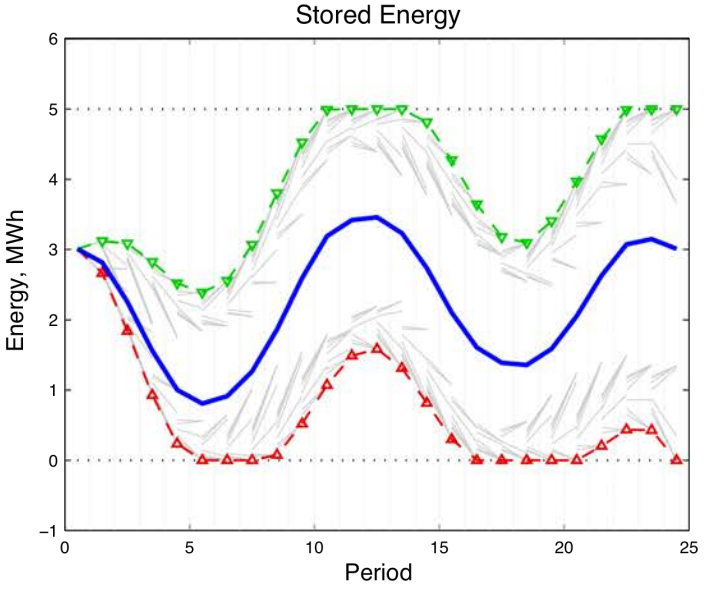

Storage Dispatch
Real Power, MW
Period

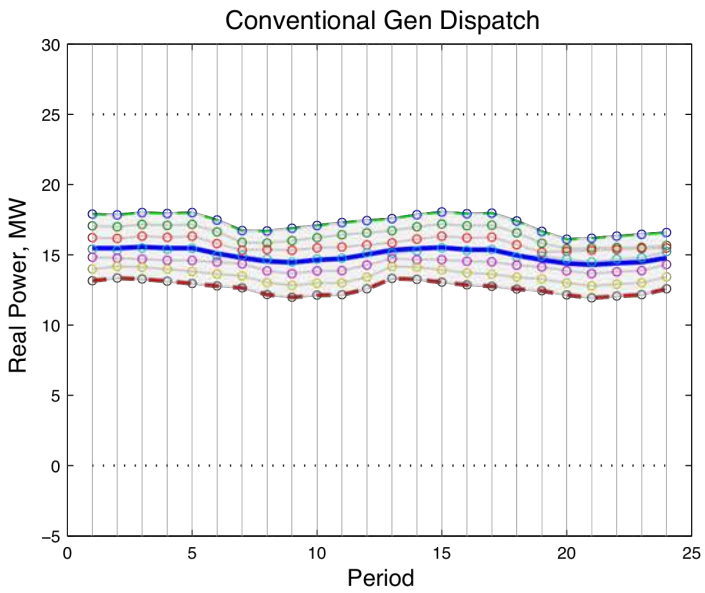

Stored Energy
Energy, MWh
Period

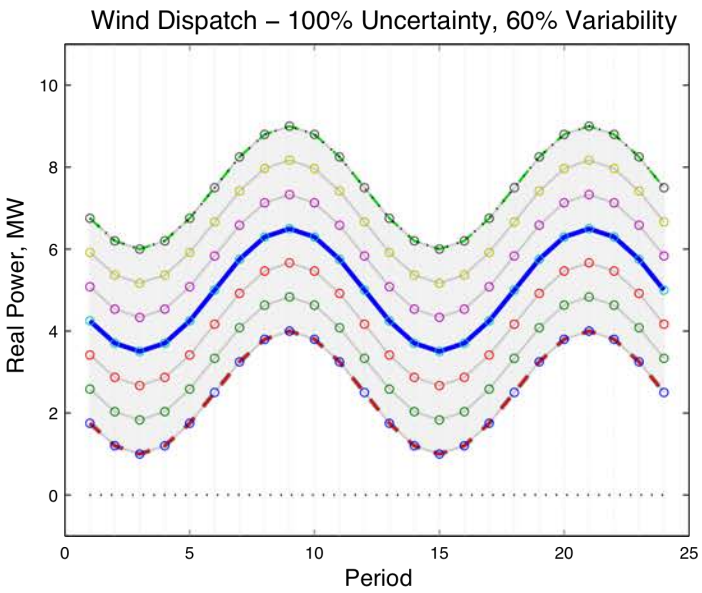

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

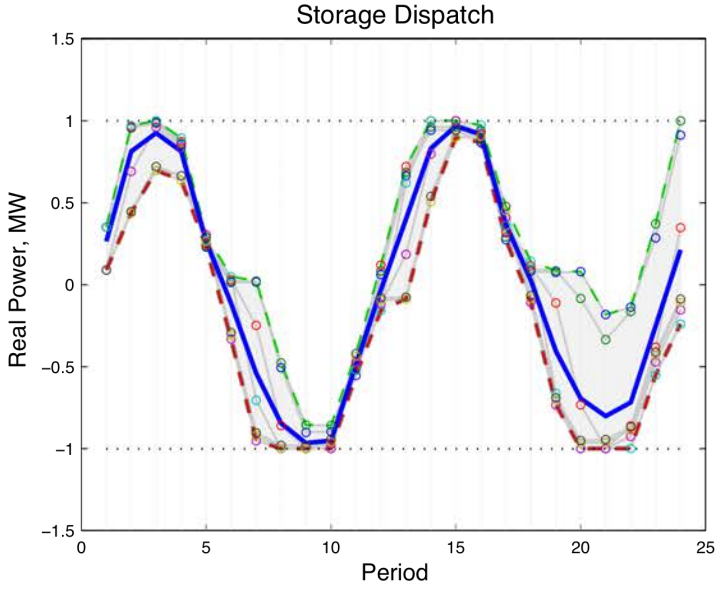

Wind Dispatch – 100% Uncertainty, 40% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

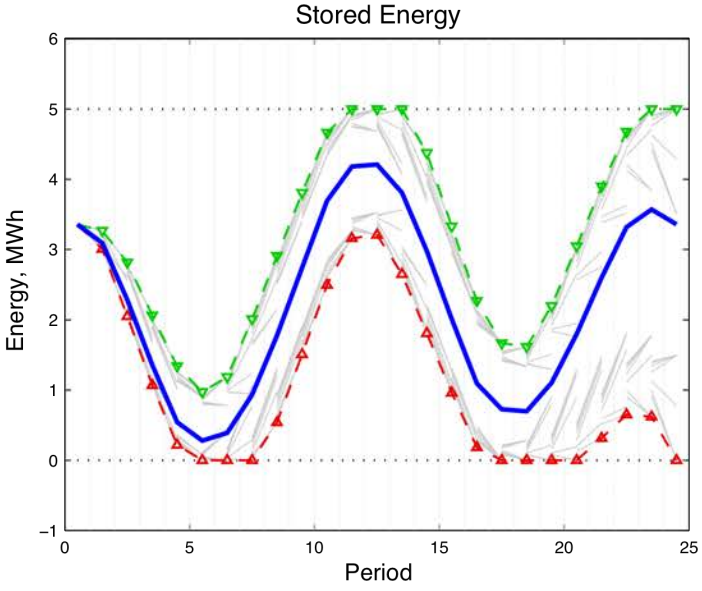

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

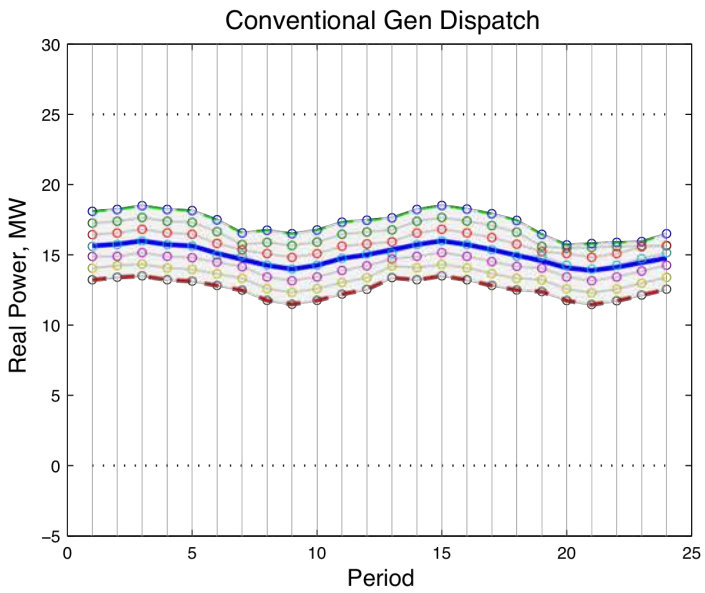

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

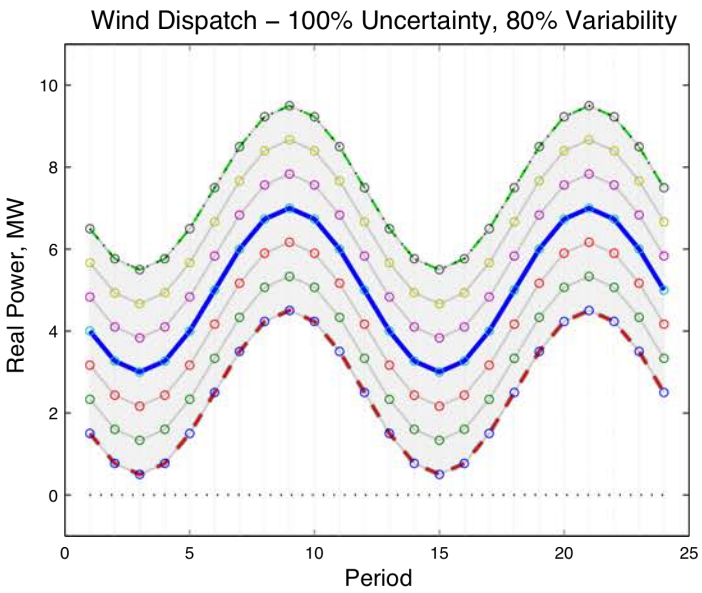

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25


Wind Dispatch – 100% Uncertainty, 60% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25


Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25


Wind Dispatch – 100% Uncertainty, 80% Variability
Real Power, MW
Period
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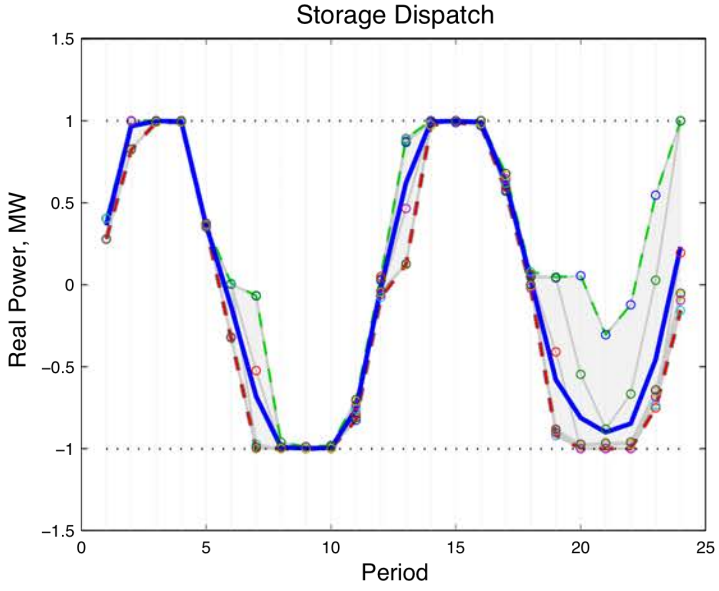
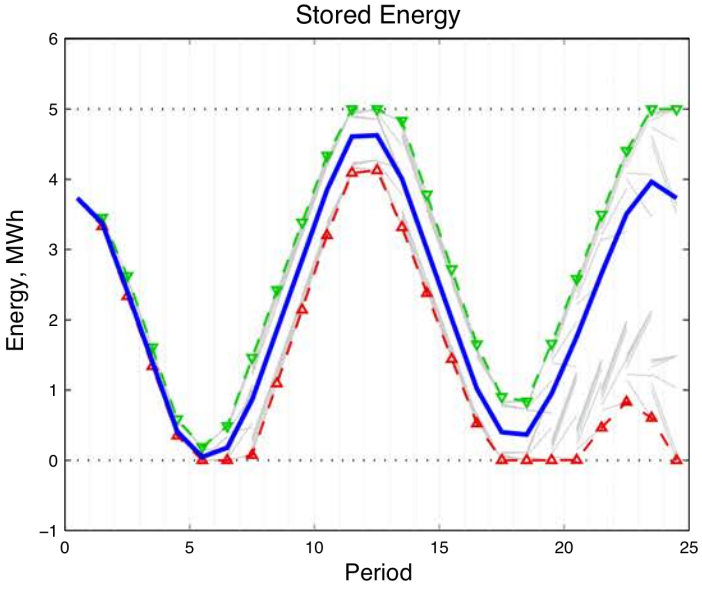
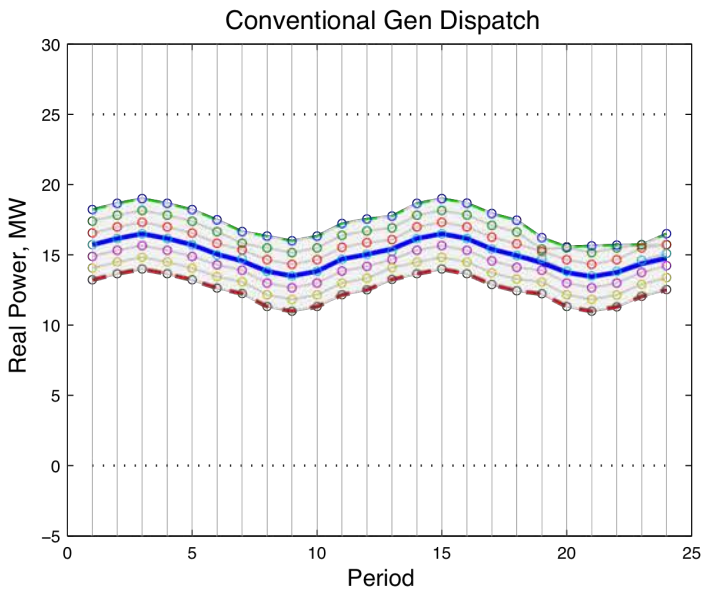
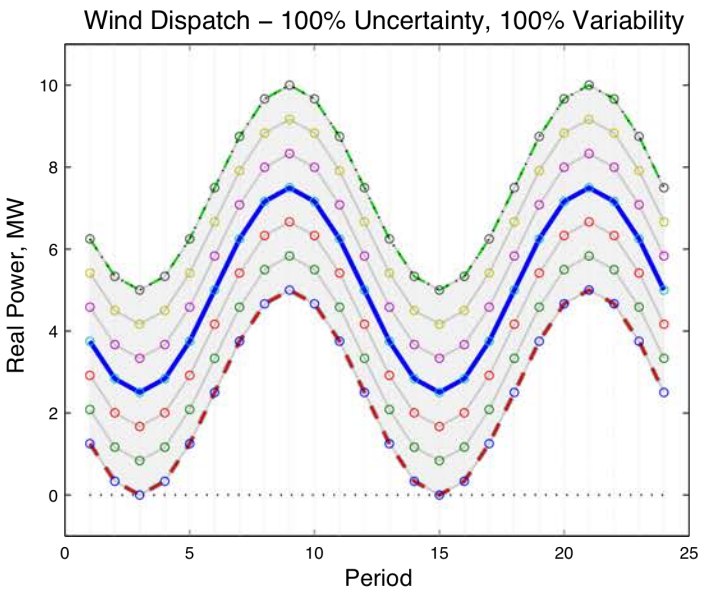
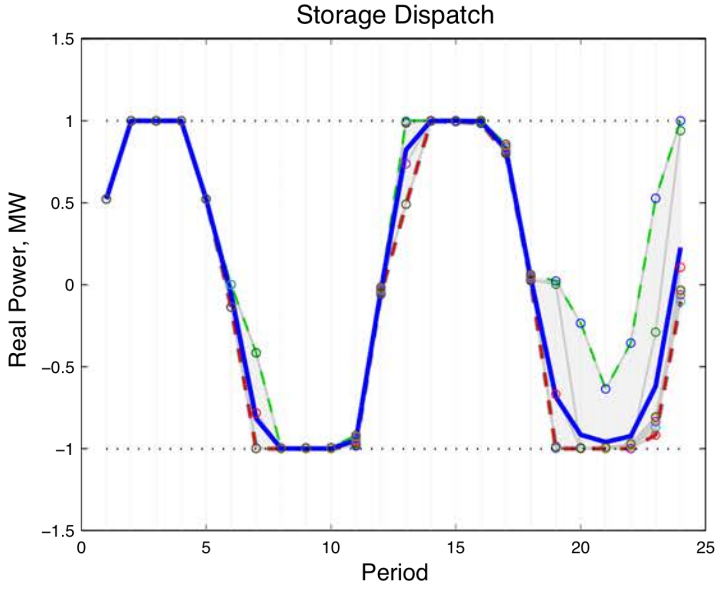
6
4
2
0
0
5
10
15
20
25


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25


Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25


Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
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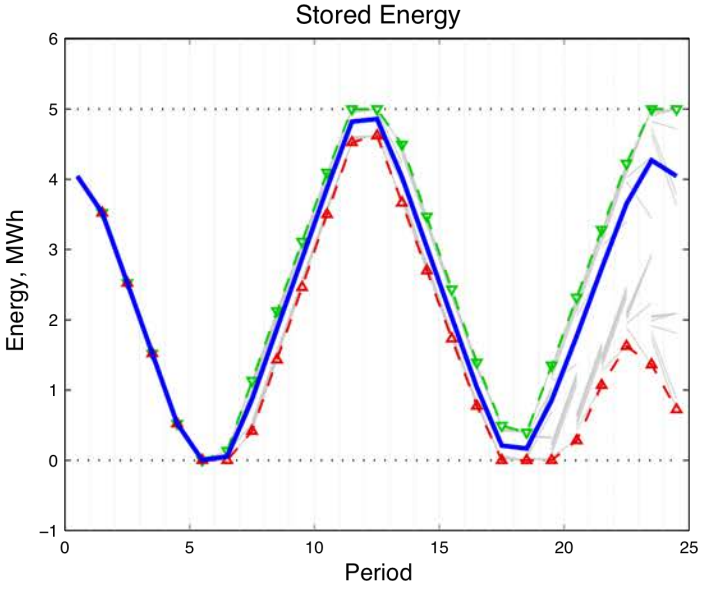
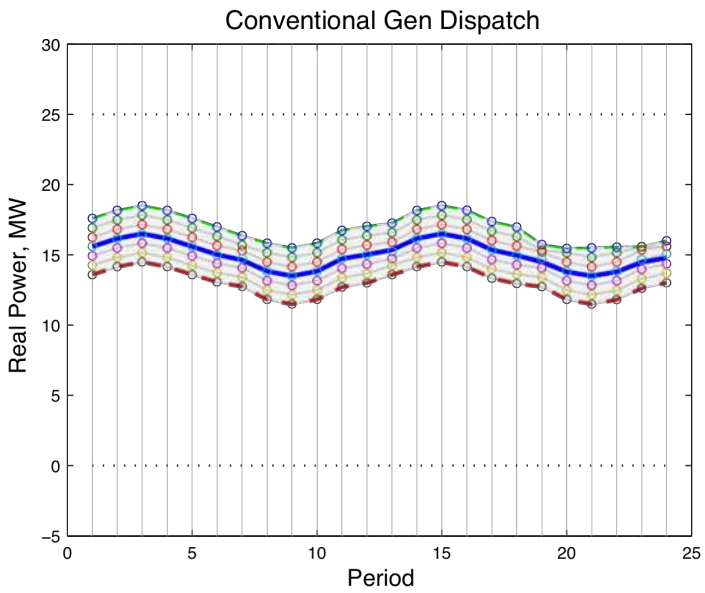
20
25


Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
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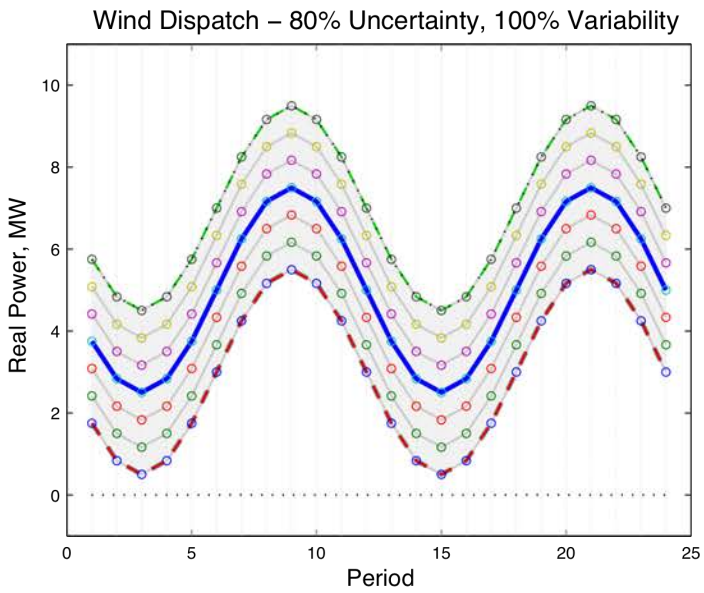
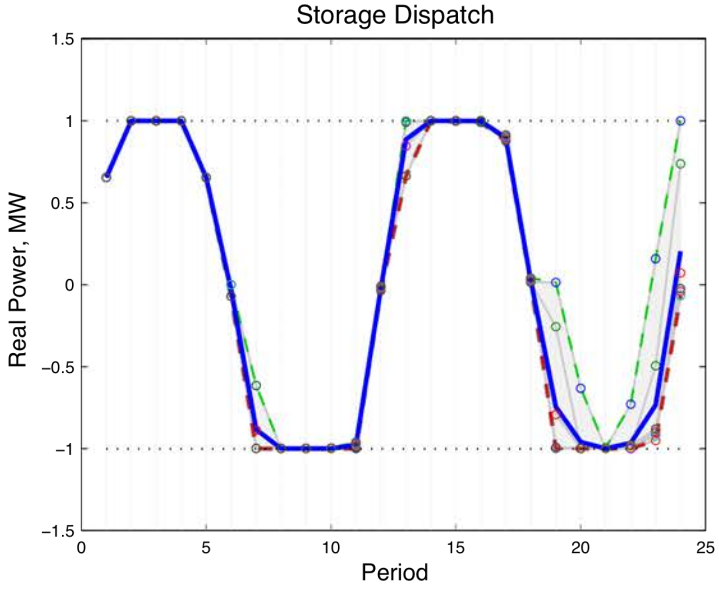
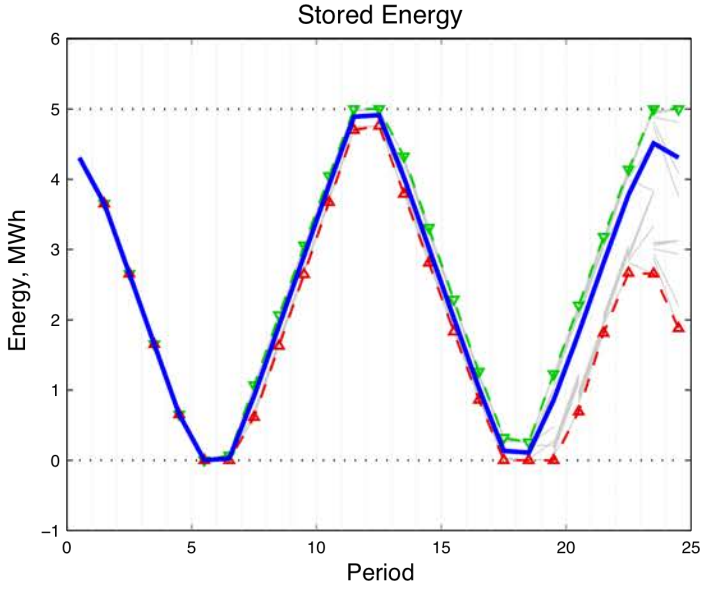
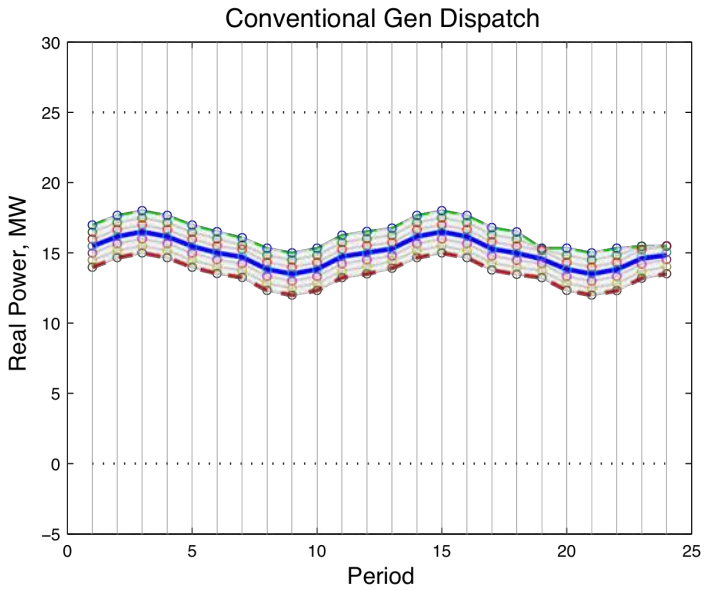
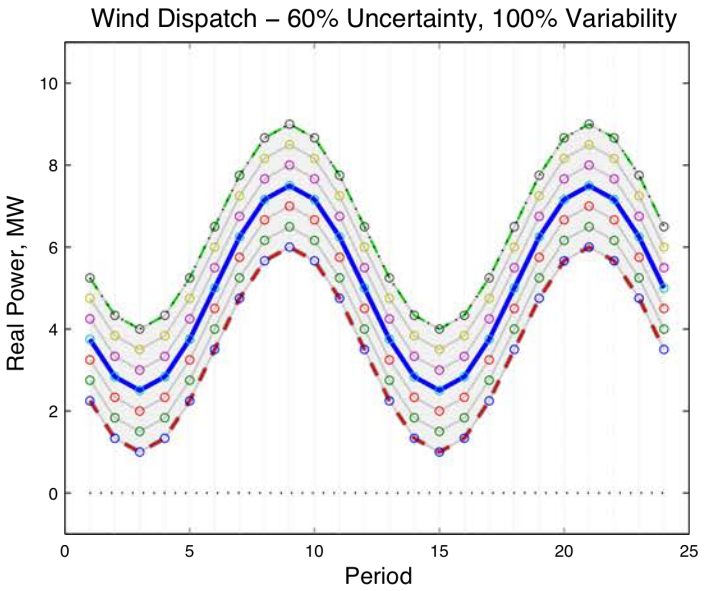
10
15
20
25

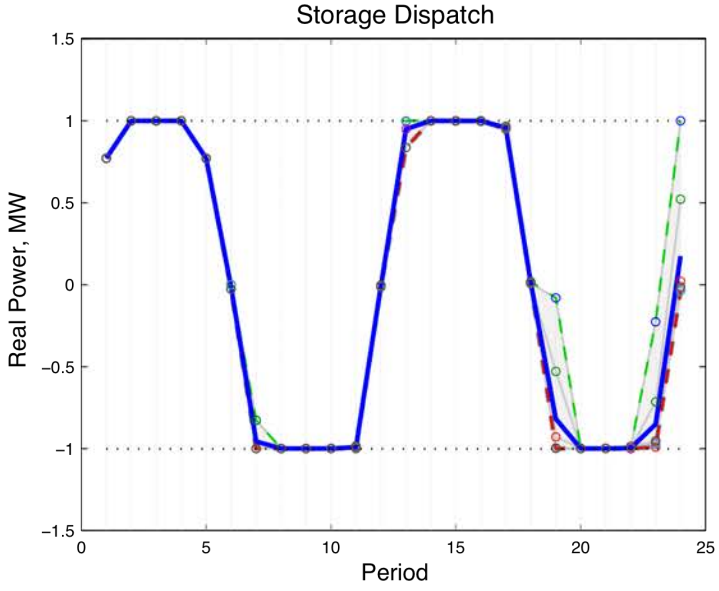

Wind Dispatch – 80% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

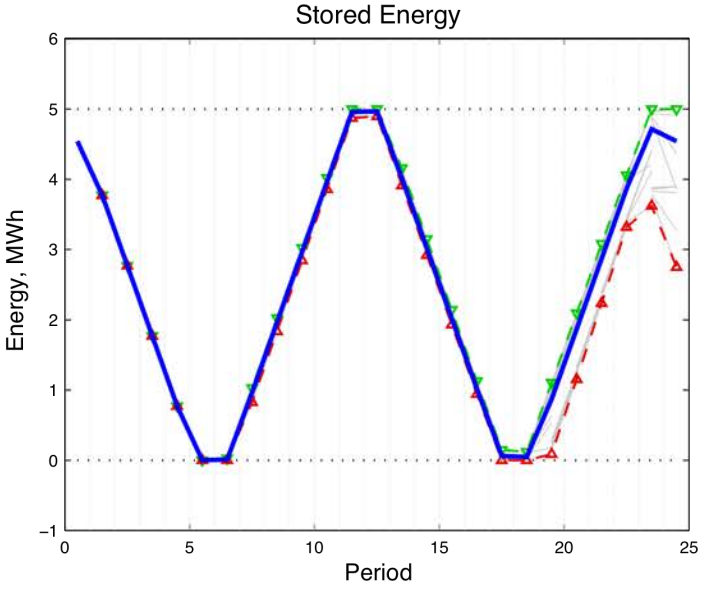

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

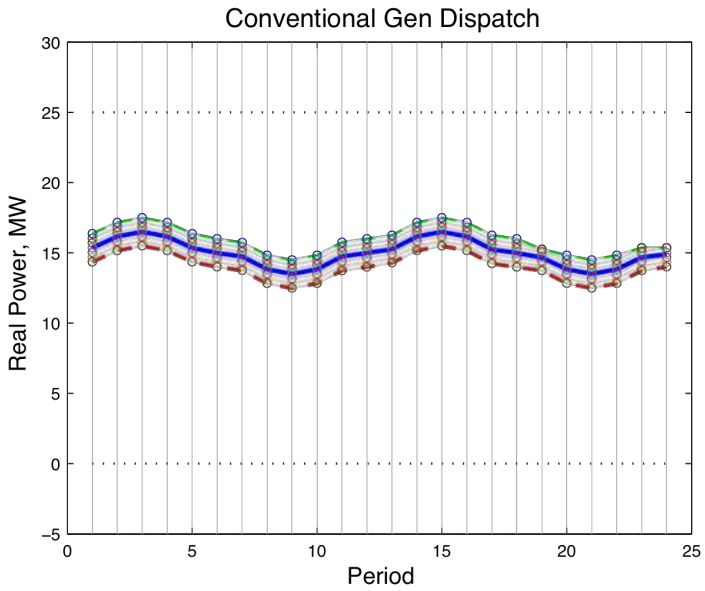

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

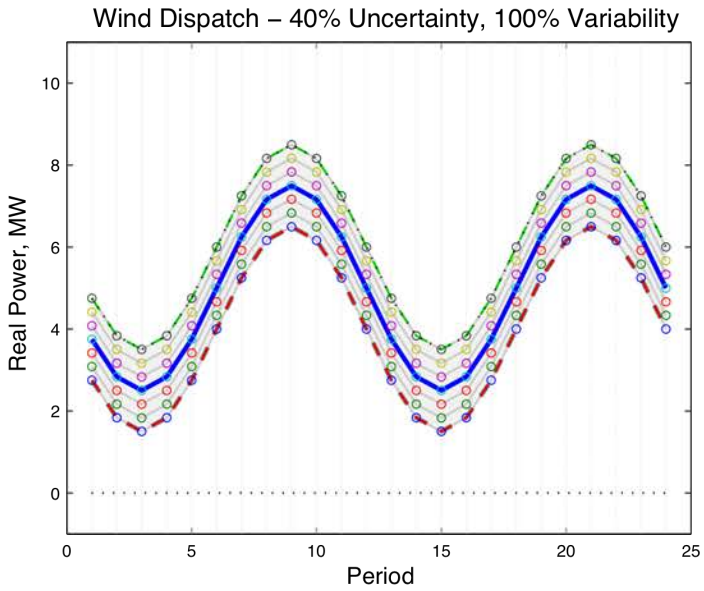

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

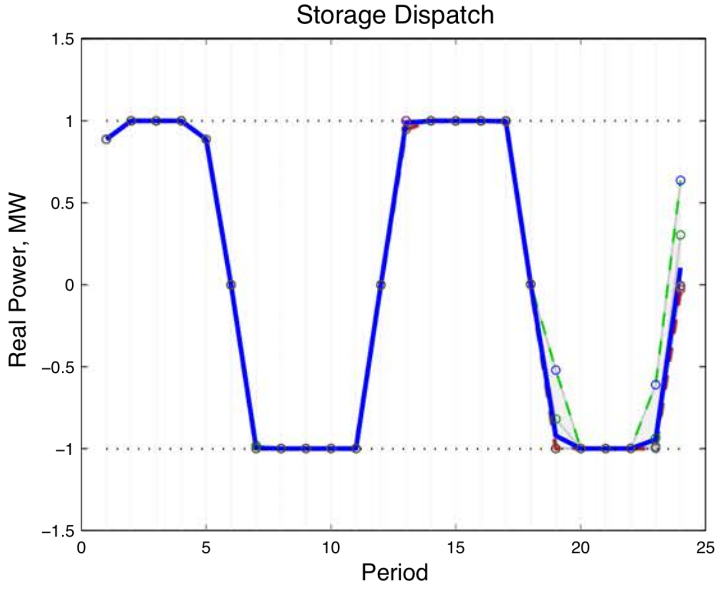

Wind Dispatch – 60% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

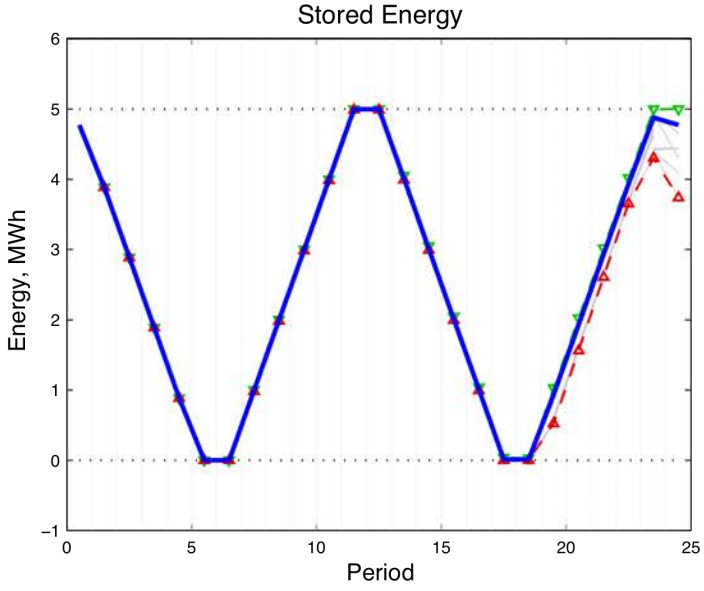

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

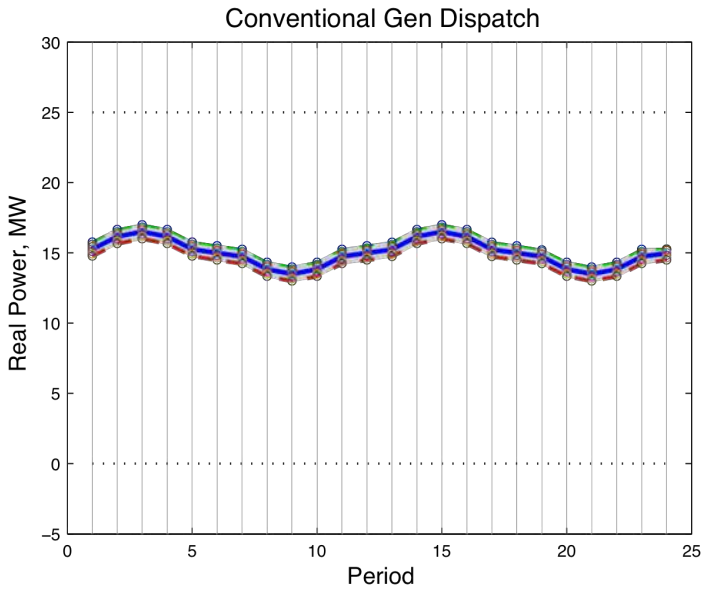

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

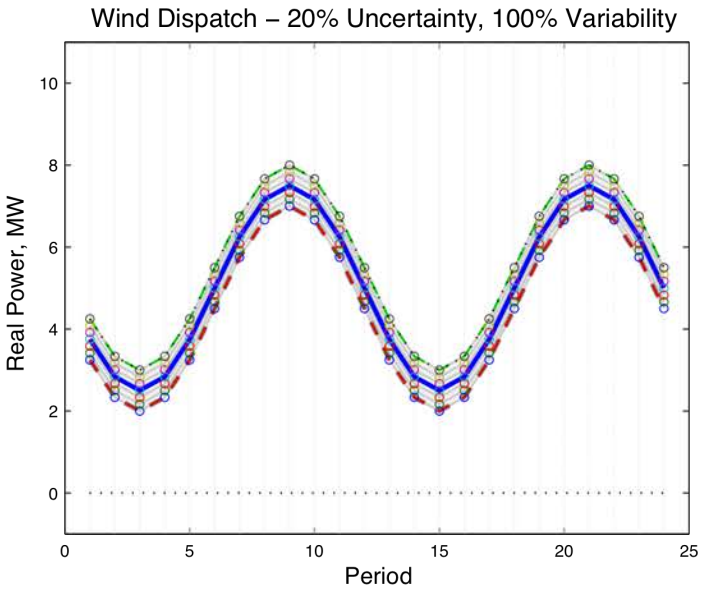

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

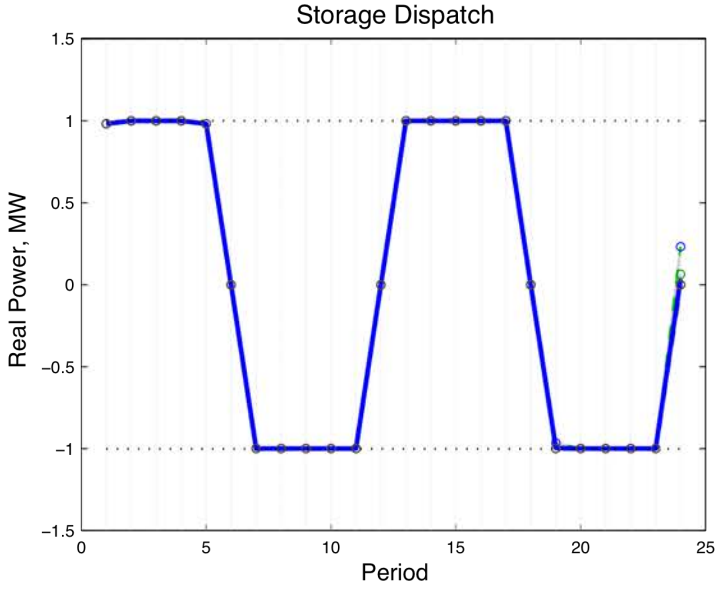

Wind Dispatch – 40% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

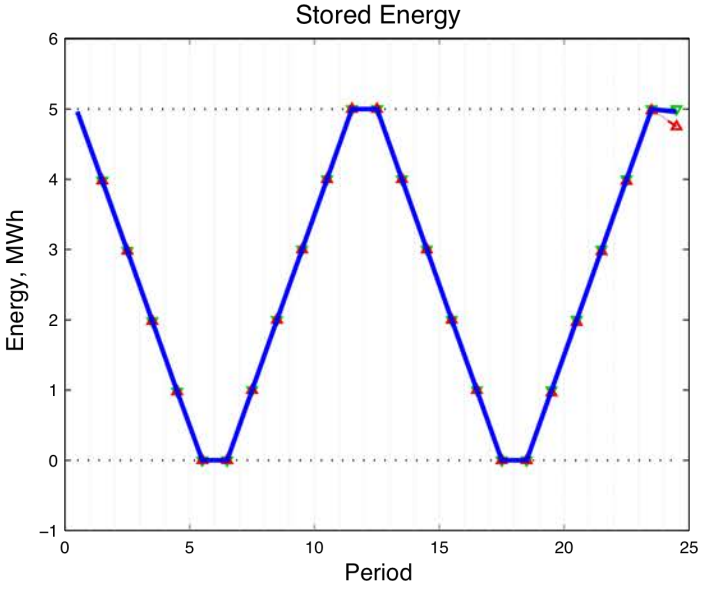

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

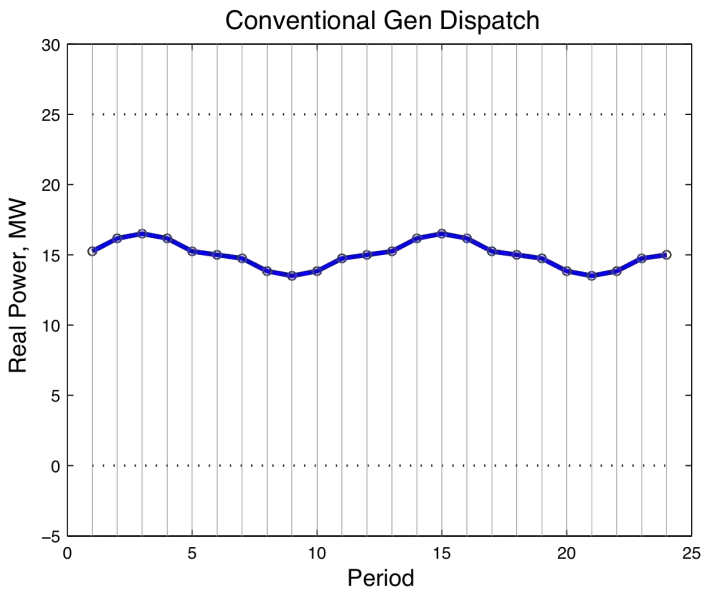

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

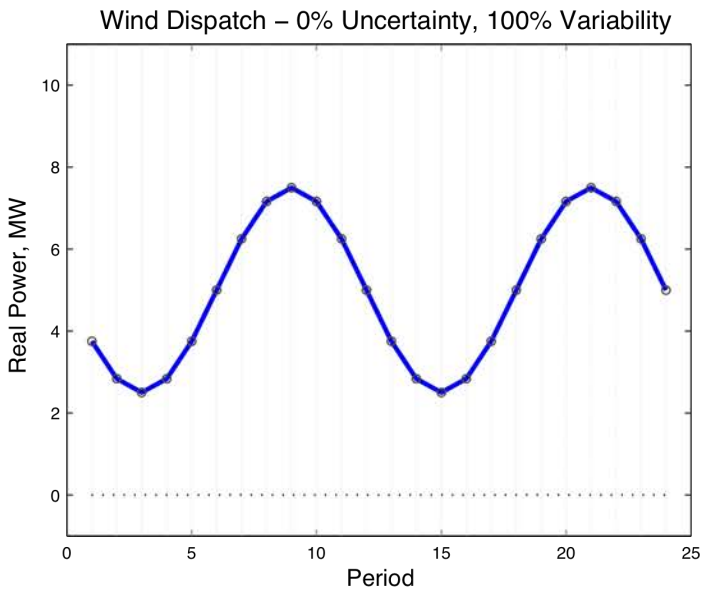

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

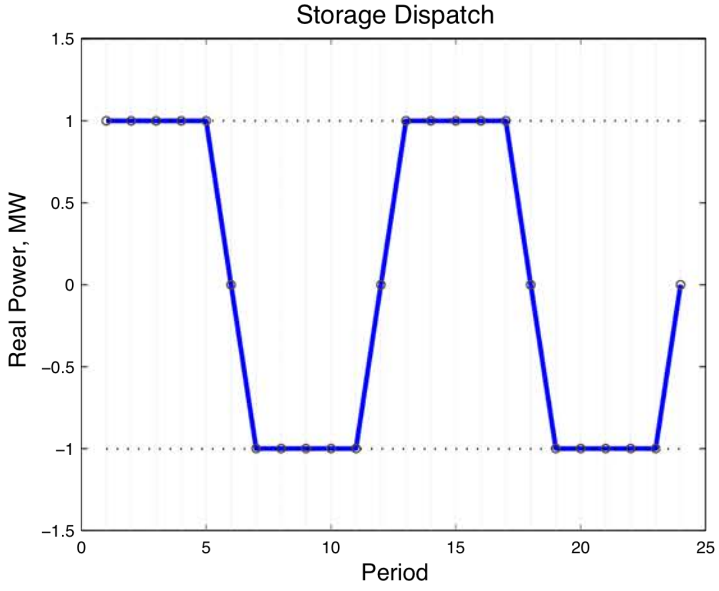

Wind Dispatch – 20% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

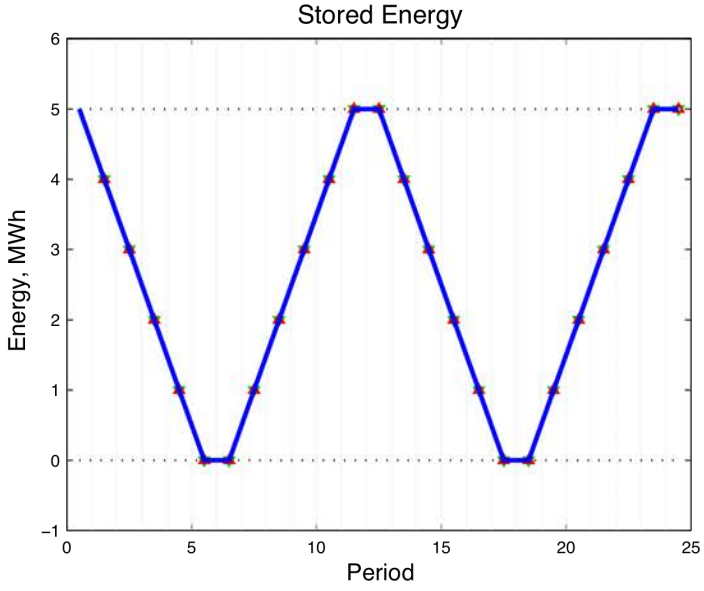

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

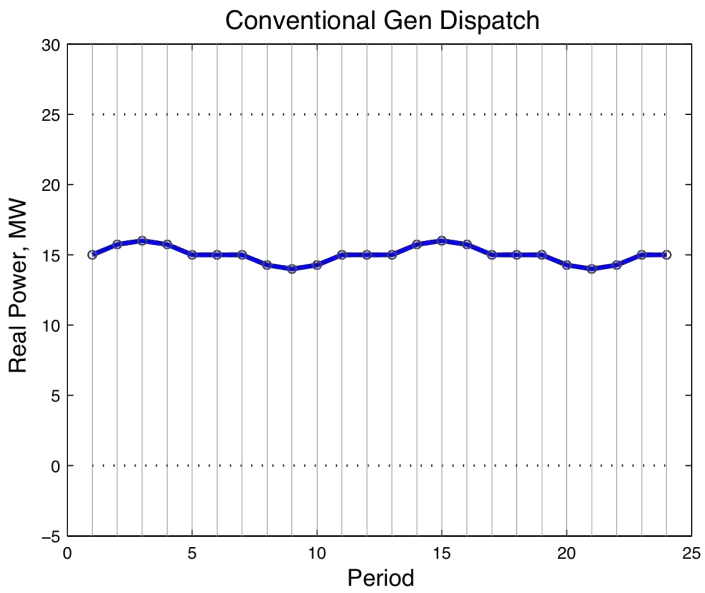

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

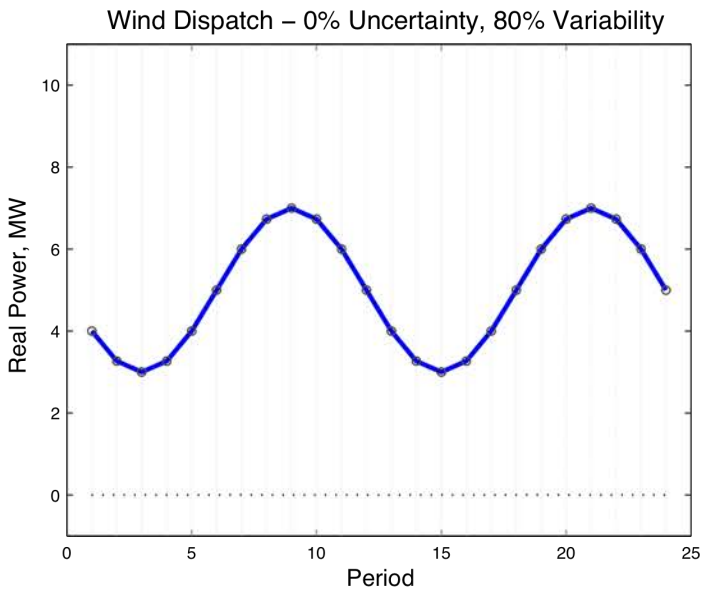

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

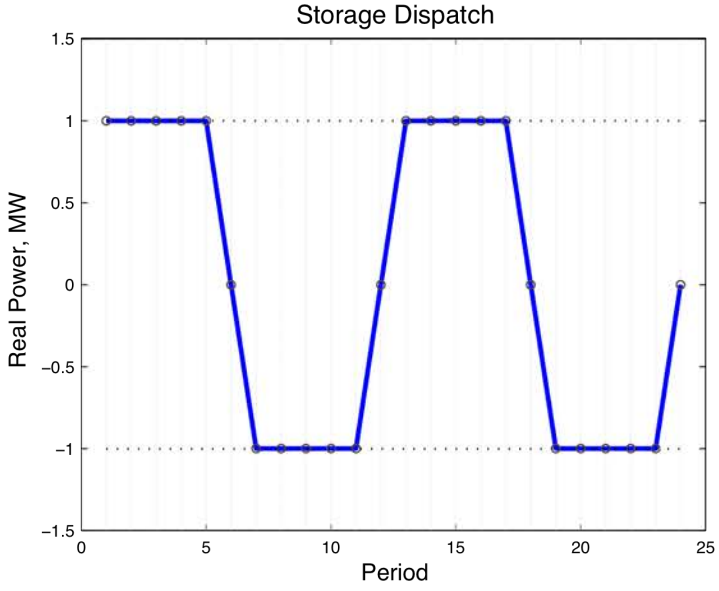

Wind Dispatch – 0% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

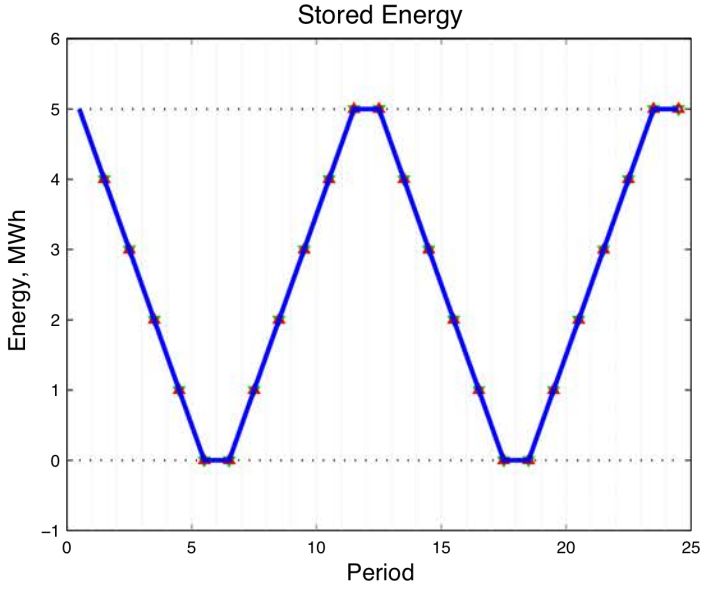

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

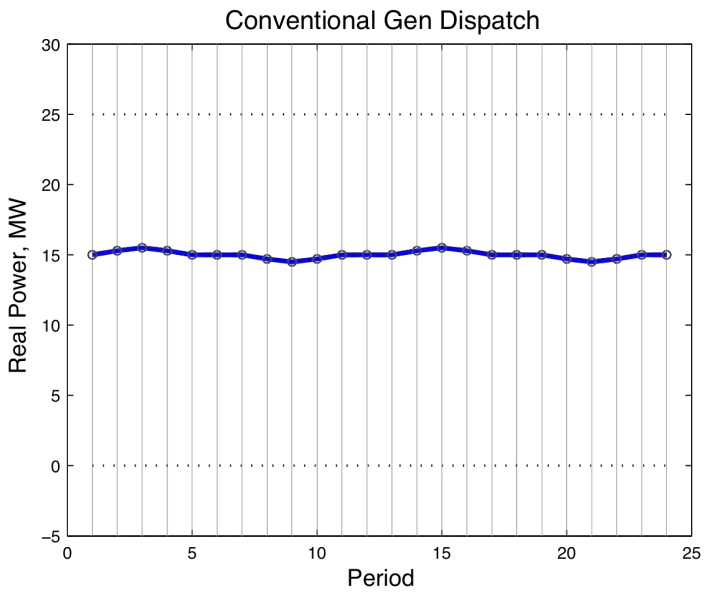

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

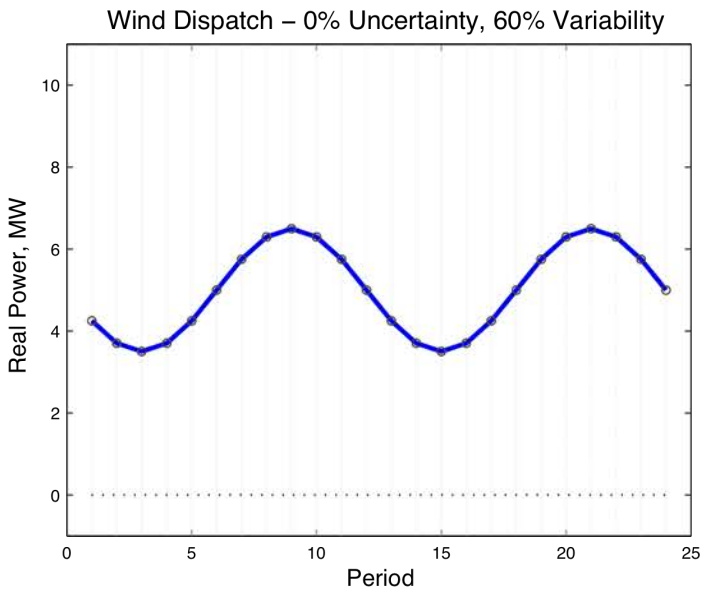

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

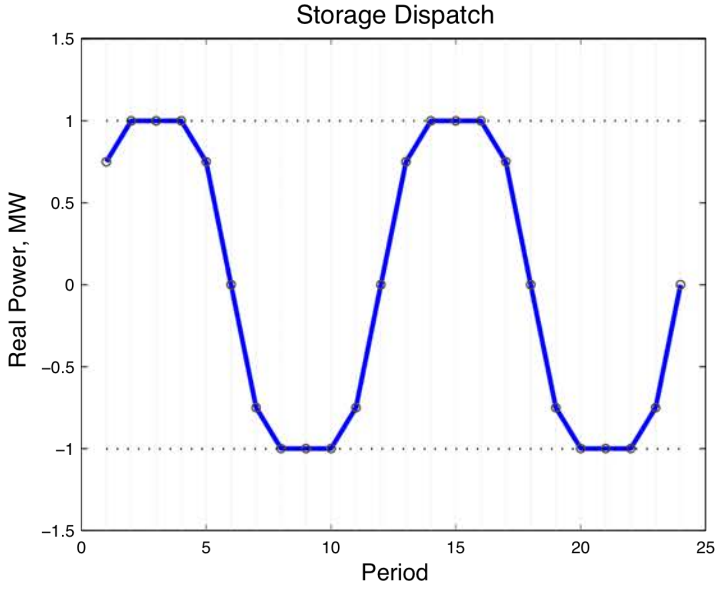

Wind Dispatch – 0% Uncertainty, 80% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

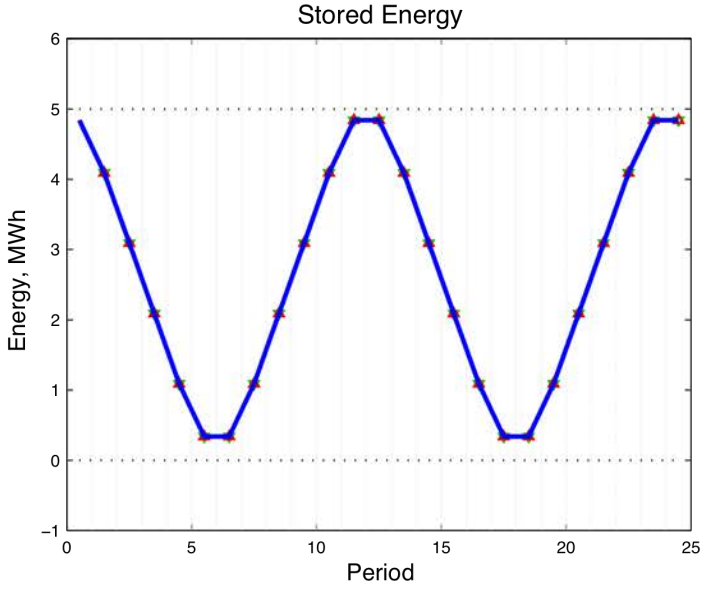

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

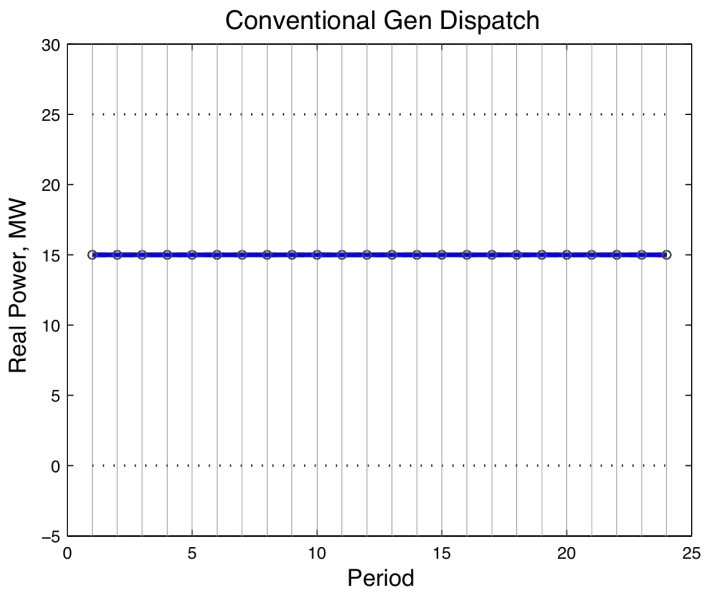

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

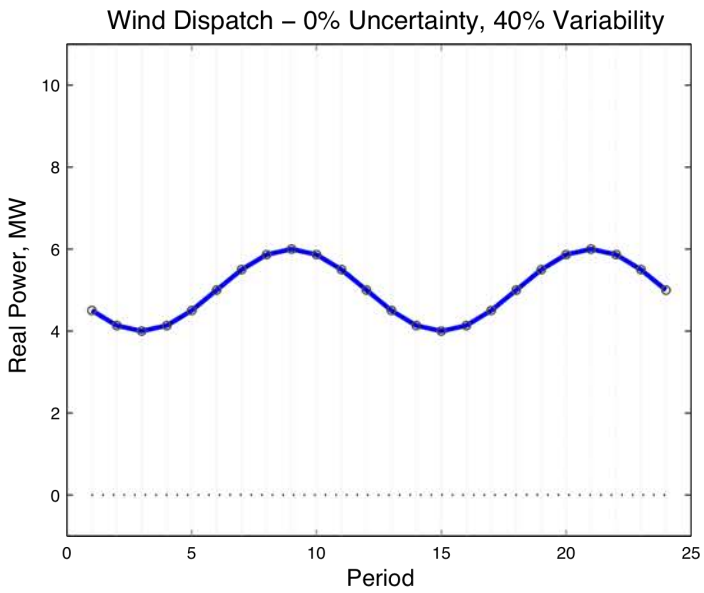

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

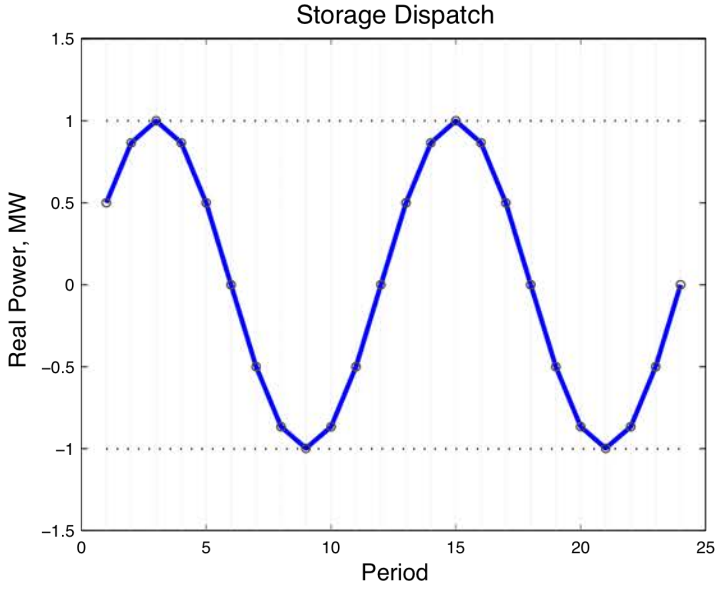

Wind Dispatch – 0% Uncertainty, 60% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

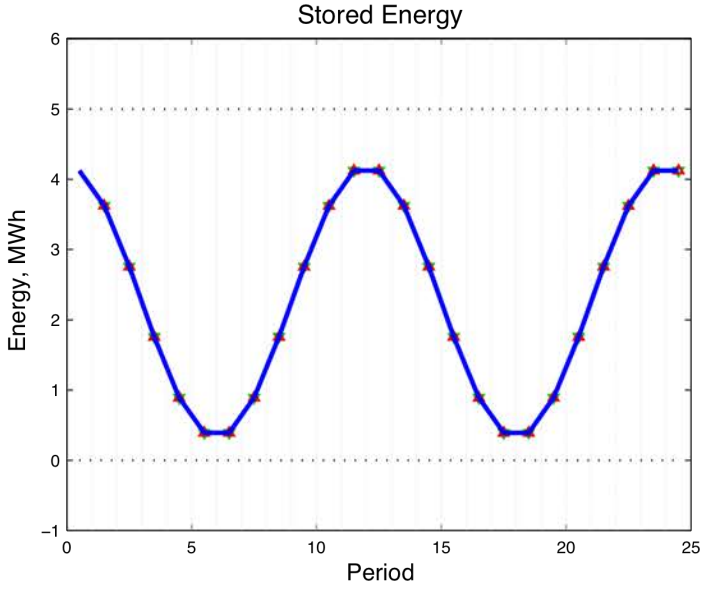

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

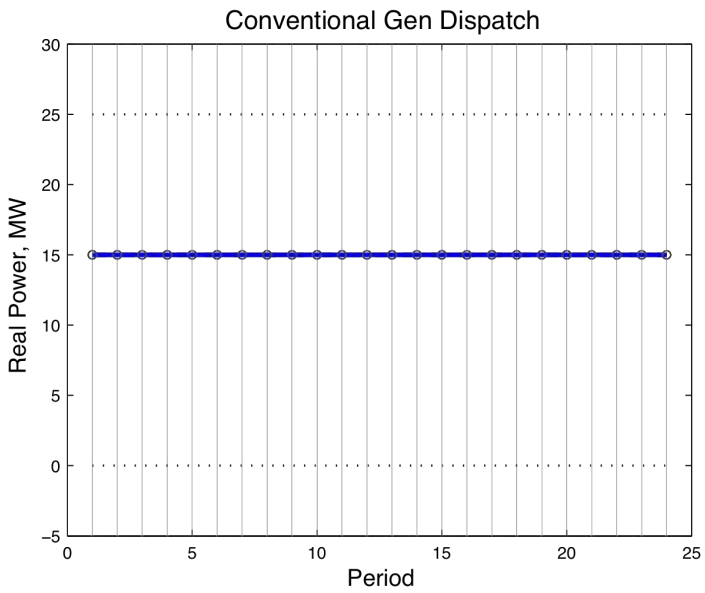

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

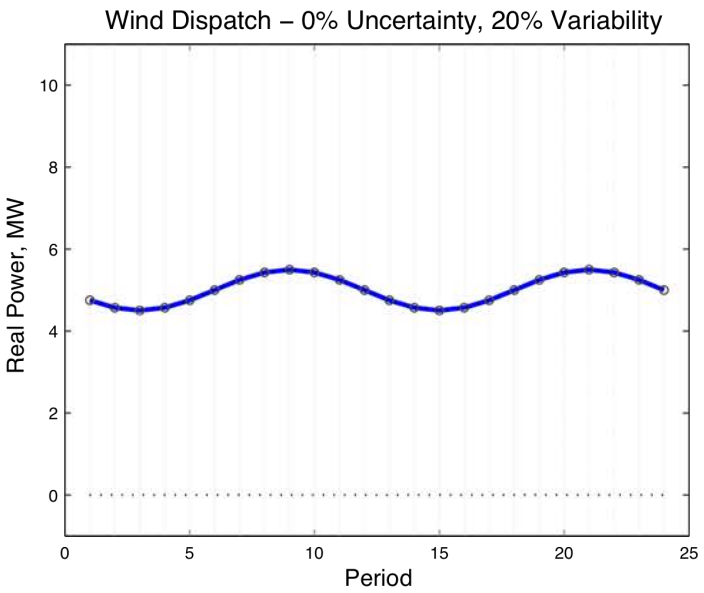

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

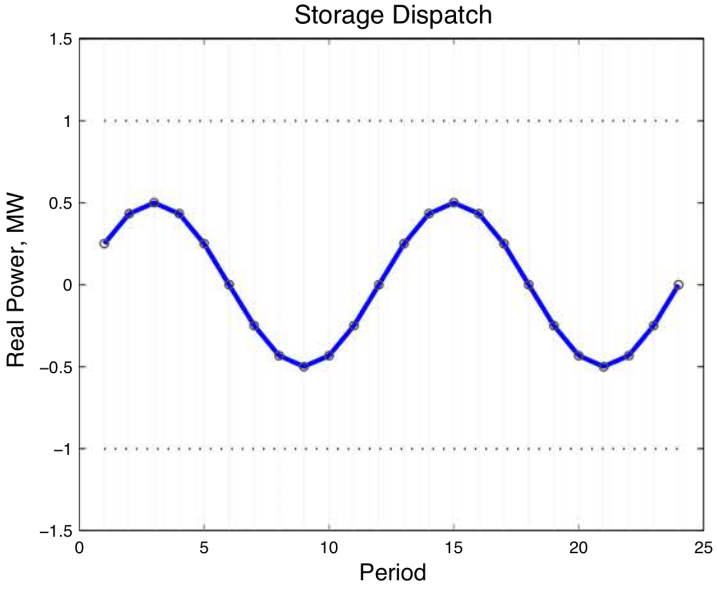

Wind Dispatch – 0% Uncertainty, 40% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

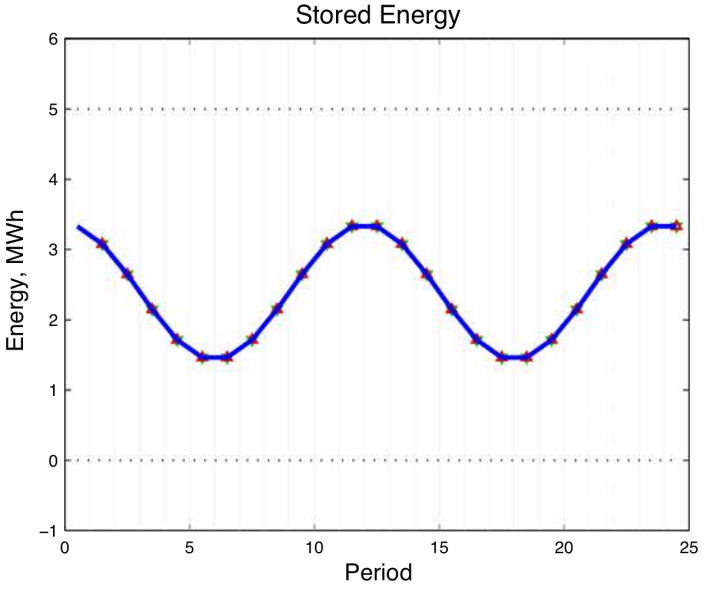

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

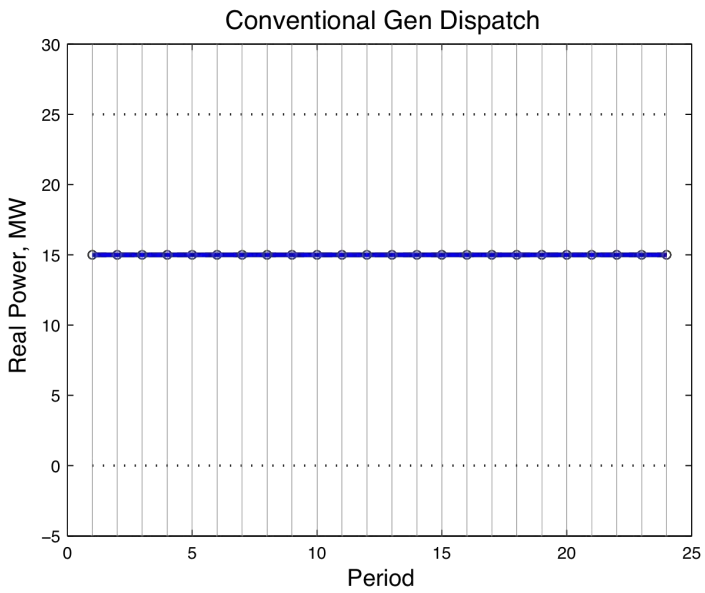

Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25


Wind Dispatch – 0% Uncertainty, 20% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25


Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
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10
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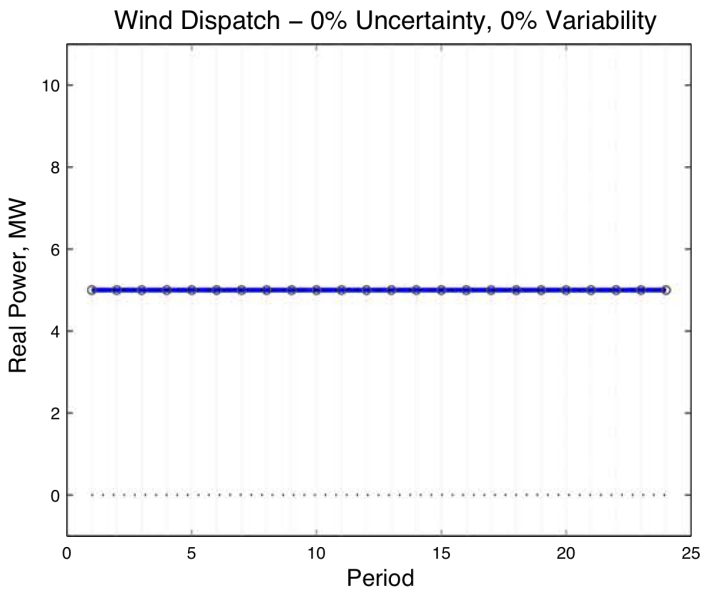
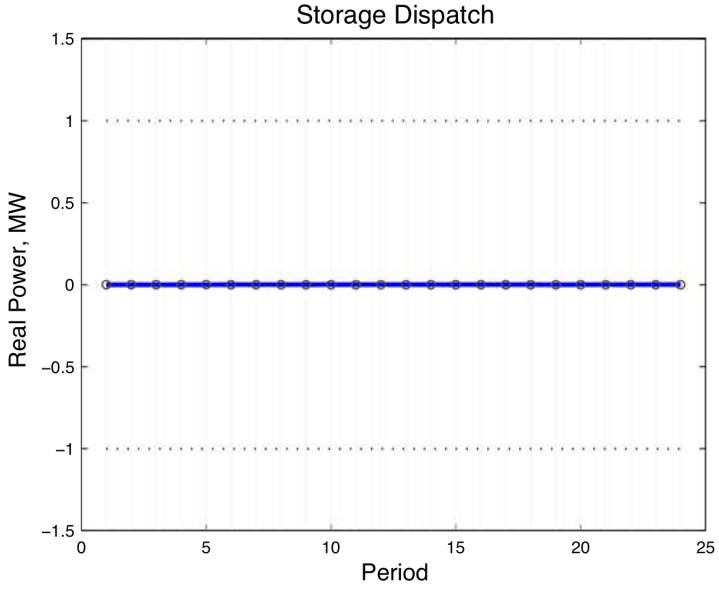
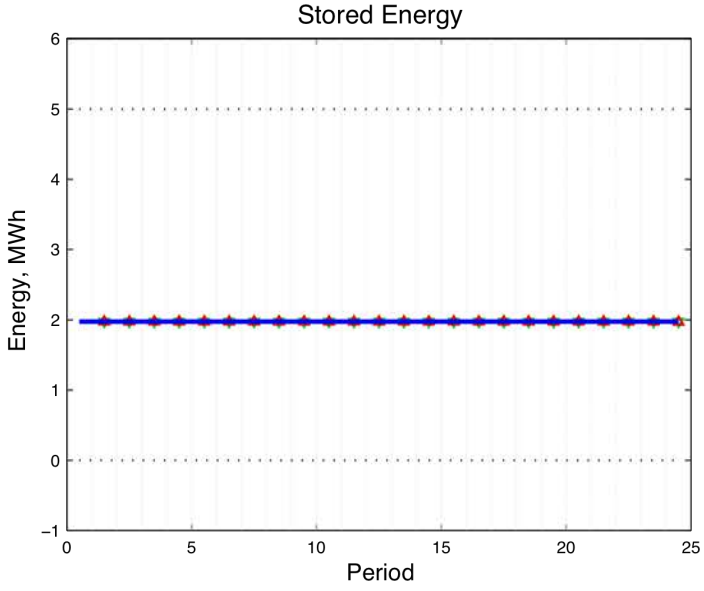
20
25


Wind Dispatch – 0% Uncertainty, 0% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25


Stored Energy
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

# Questions?