Cornell University

PSERC

Development and Testing of New Tools

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

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U.S. DEPARTMENT OF ENERGY

CERTS
Consortium for Electric Reliability Technology Solutions

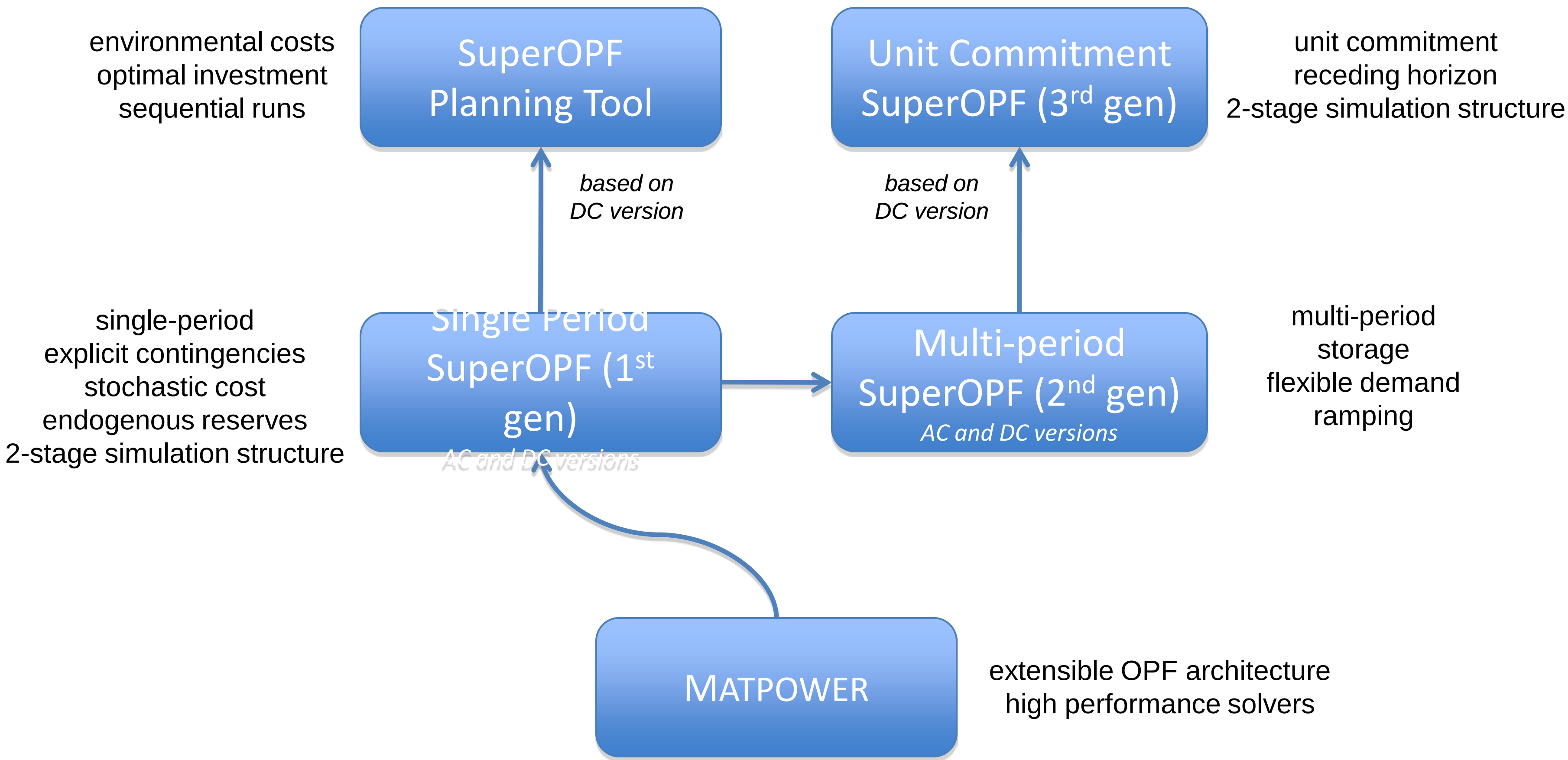
Other Contributors

- Input scenario creation and analysis
  - **C. Lindsay Anderson** (Cornell)
  - **Amandeep Gupta** (Cornell)
  - **Jung Mo** (Cornell)
  - Tim Mount (Cornell)
  - Laurie Tupper (Cornell)
- Simulation environment and testing
  - **Daniel Muñoz-Álvarez** (Cornell)
  - Wooyoung Jeon (Cornell)
  - **Alberto Lamadrid** (Lehigh)
- MATPOWER
  - Shrirang Abhyankar (Argonne)
  - Alexander J. Flueck (IIT)
  - Daniel Molzahn (U Wisc/Madison)
  - MATPOWER user base (worldwide)

Outline

- Overview of Tools
- MATPOWER
- SuperOPF Planning Tool
- Multiperiod SuperOPF *(2nd gen)*
  - *especially storage model*
- Simulation Environment
- Unit Commitment SuperOPF *(3rd gen)*
- Discussion of UC SuperOPF Implemenation Preliminary Results

Project Overview



MATPOWER

Free, open-source power system simulation environment with extensible OPF and interfaces to state-of-the-art solvers.

- bug fixes, performance enhancements, general maintenance
- used worldwide in teaching, research, consulting
- momentum growing
- 37,000 downloads of version 4.x
- 12,000 of those in the last year
- growing user support needs
- serves as foundation for all tools in this project

MATPOWER

Near term (few months) plans, new release including …

- accumulated enhancements, fixes since v4.1
- contributed code:
  - continuation power flow
    - contributed by Shrirang Abhyankar (Argonne), Alex Flueck, (IIT)
  - applications of SDP (semi-definite programming) relaxations to the OPF
    - contributed by Dan Molzahn (U of Wisc/Madison)
    - solver for SDP relaxation of OPF problem
    - sufficient condition for global optimality of specified OPF solution
    - sufficient conditions for insolvability of the power flow equations

MATPOWER

Longer term (over next year) …

- integrate 3rd generation SuperOPF into a new MATPOWER release
- assured wide distribution
- significant boost for other researchers
- increased visibility and opportunities for feedback
- LOTS of cleanup and documentation work required to make this work

SuperOPF Planning Tool

- used extensively by R & M Project 2E: "Mapping Energy Futures: SuperOPF Planning Tool" *(Bill Schulze)*
- based on 1^{st} gen (single-period) SuperOPF
  - coupled DC OPF of multiple scenarios
  - tied together by capacities that reflect investment/retirement
  - additional constraints, e.g. regional build limits

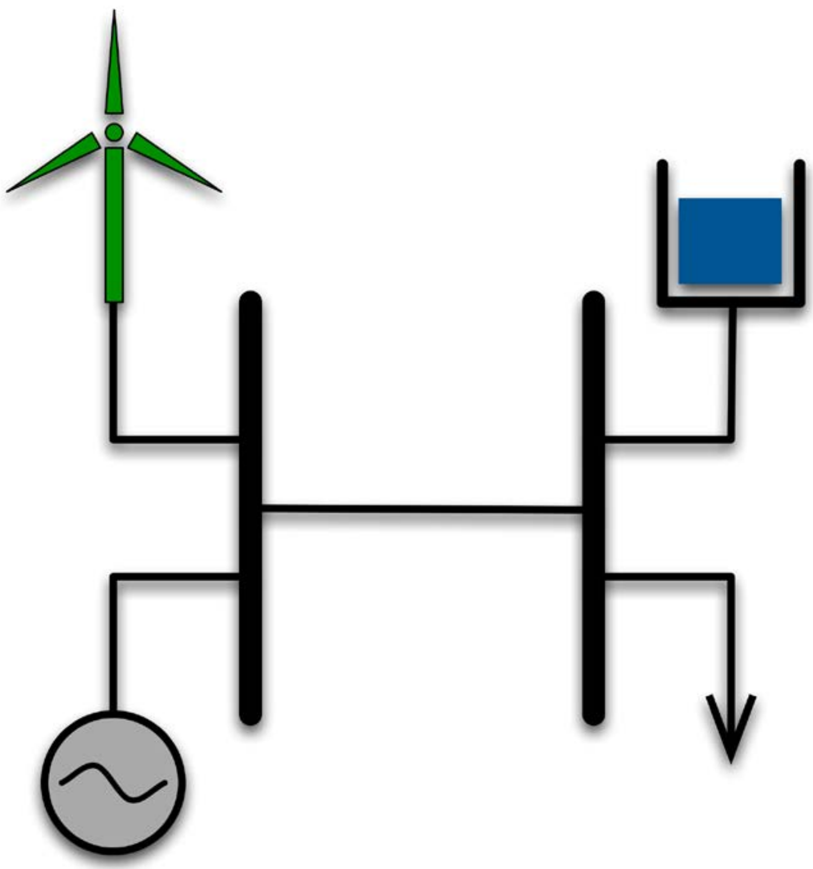
SuperOPF Planning Tool

- modified formulation
  - added ability to specify scenario-specific availability factors
  - improved ability to model wind and solar
  - greatly improved performance
  - via techniques to improve problem robustness enabling us to exploit the speed and scalability of interior point solvers
- current problem size
  - Eastern Interconnect with 73 representative hours
  - over 7 million variables, almost 19 million constraints
- looking toward integration of binary variables

Multi-period SuperOPF (2^{nd} gen)

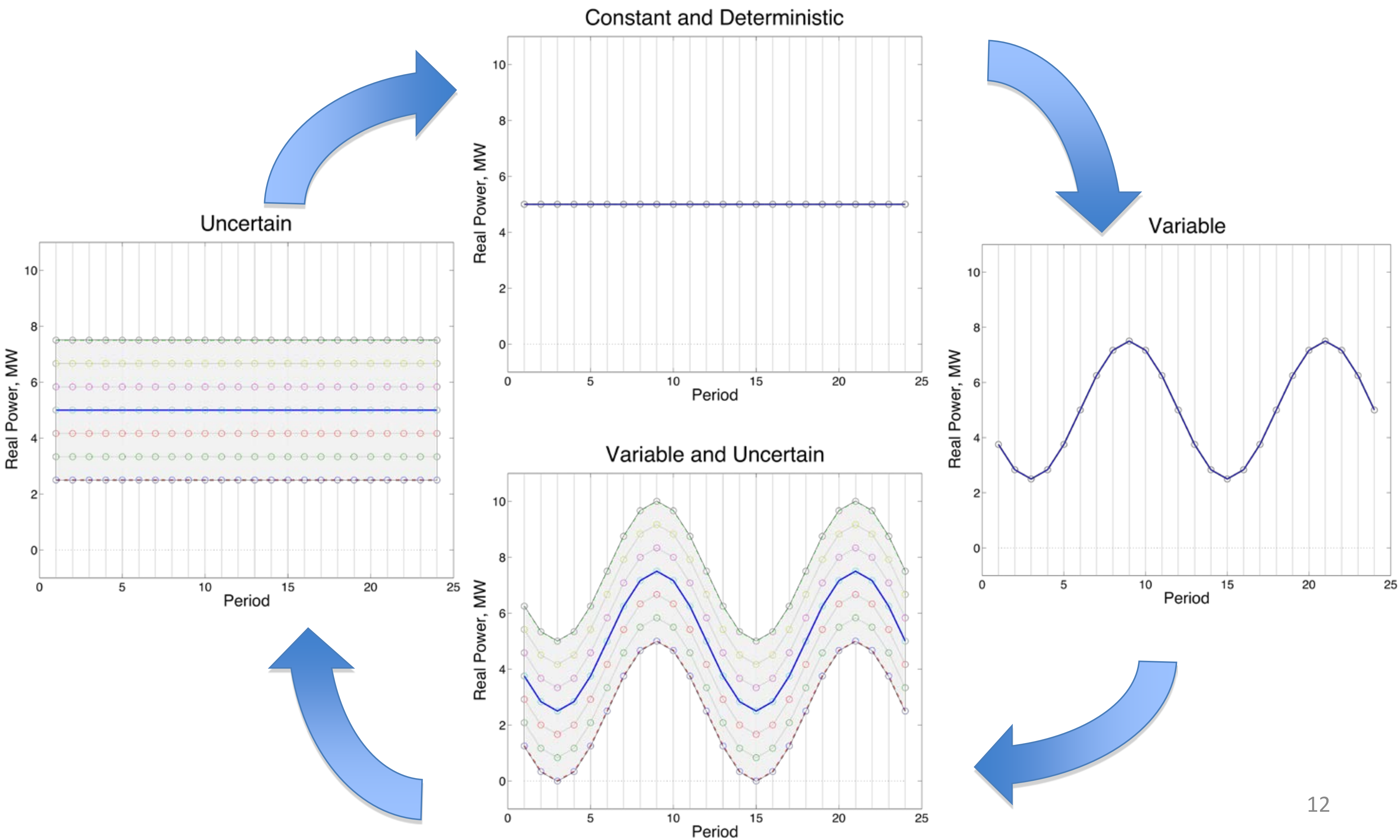
- used extensively by R & M Project 2A: Evaluating Effects of Managing Controllable Demand & DER *(Tim Mount)*
- coupled OPF scenarios (wind and outage scenarios for multi-period horizon)
- linked within a period by reserve and redispatch vars/costs/constraints
- linked through time by storage and ramping vars/costs/constraints
- transitions from period-to-period, state-to-state governed by transition probability matrices
- implications
  - not tracking individual trajectories, only bounds on a “central path” (e.g. load following ramp)
  - not tracking actual amounts of stored energy, only storage state bounds for “central path”

Toy System for Illustration



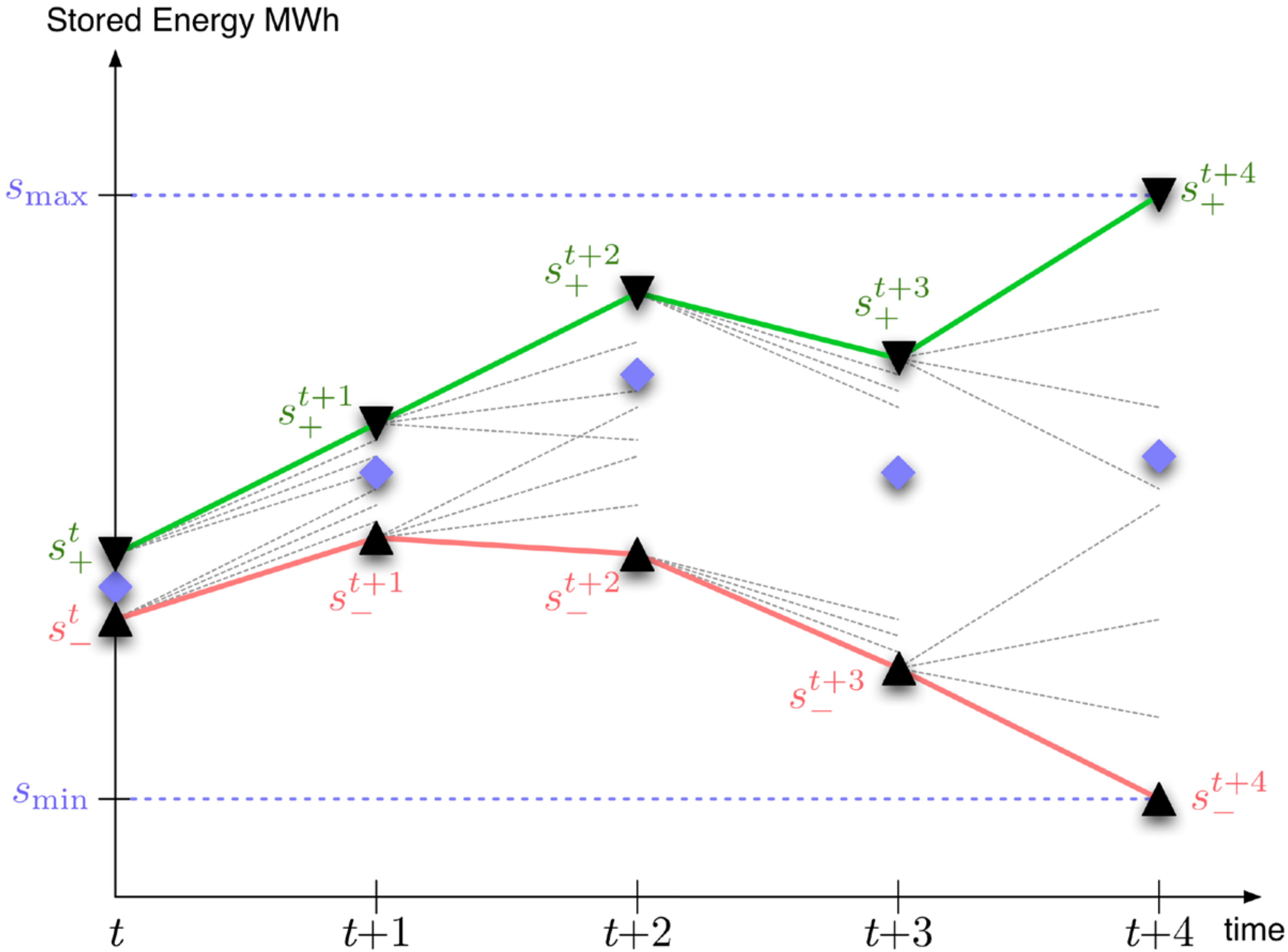
- conventional gen with quadratic cost
- constant deterministic load
- 100% efficient grid-level storage unit
- wind generator with normally distributed output, with 2 parameters:
  - variability
  - uncertainty

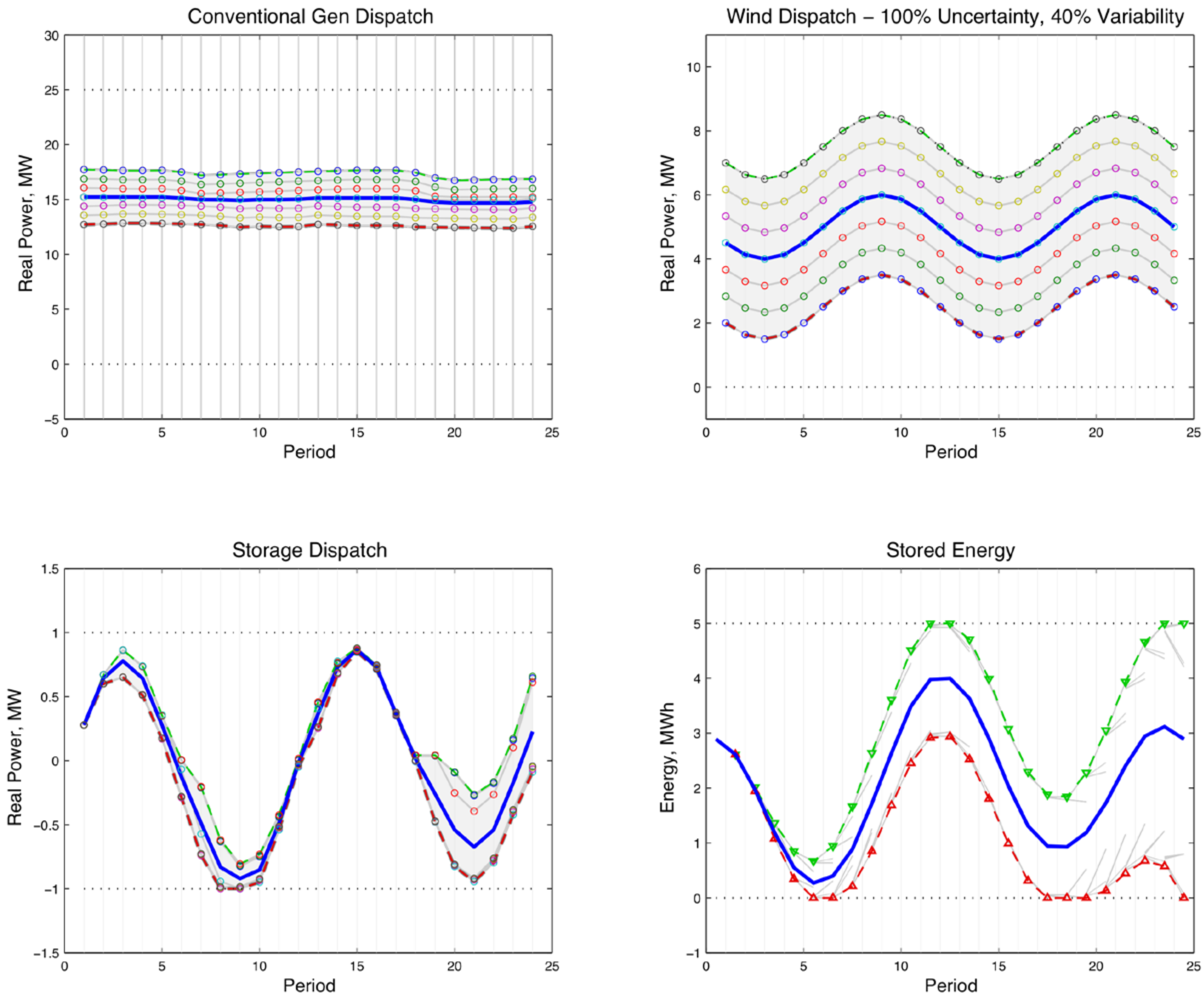
Uncertainty & Variability

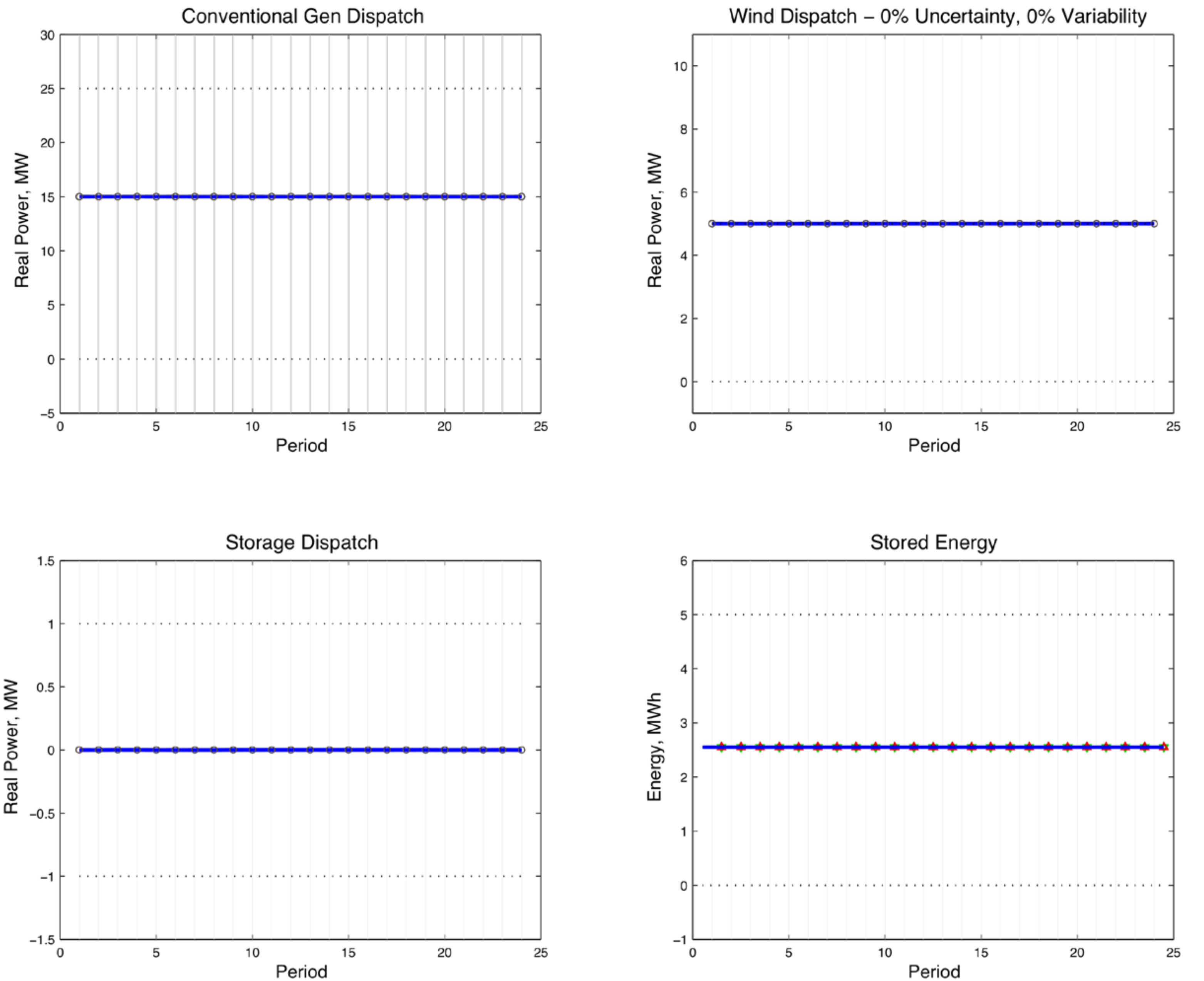


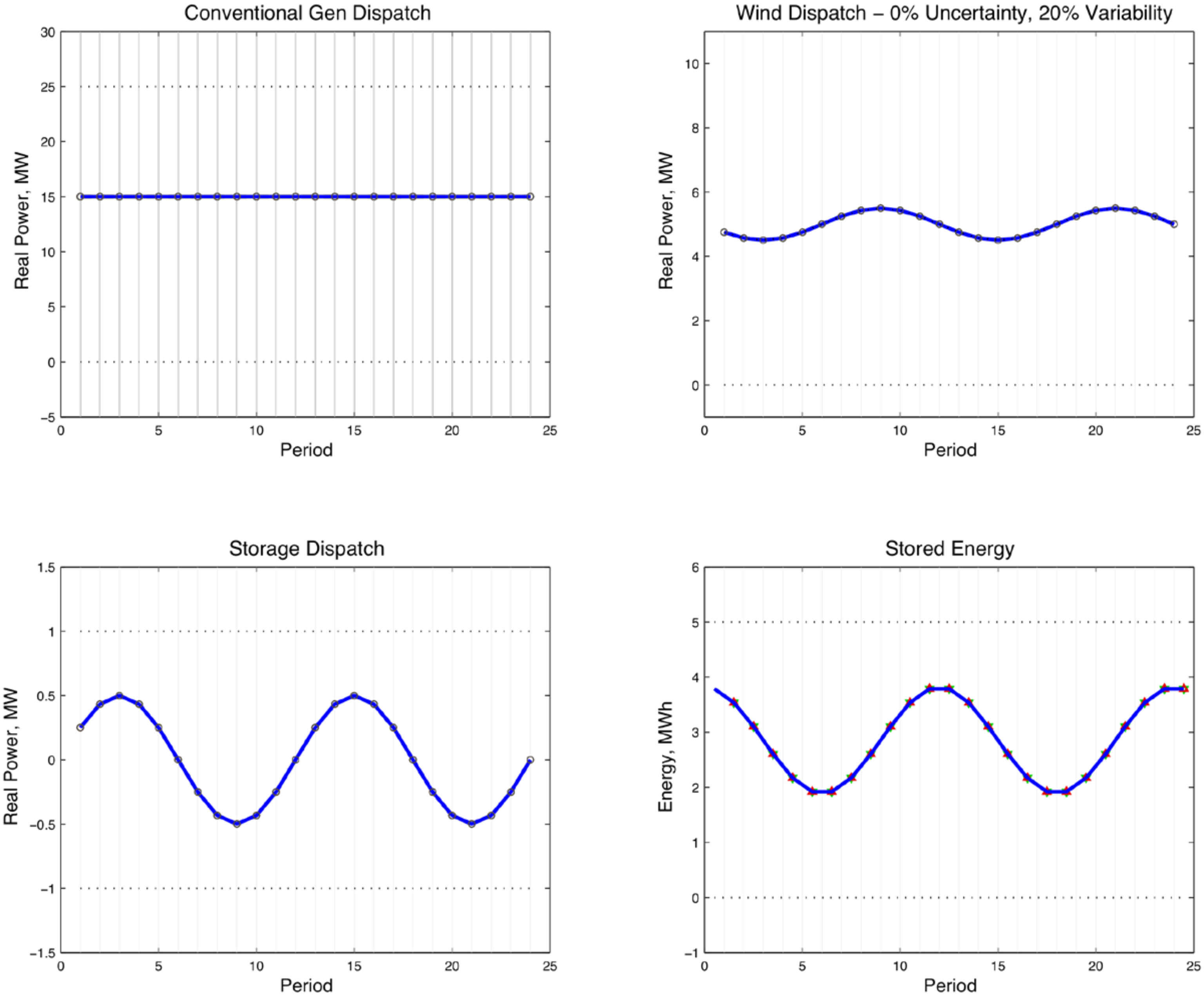
Example of Tradeoff of Storage Usage

time arbitrage vs. uncertainty mitigation




Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 40% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 0% Uncertainty, 0% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 0% Uncertainty, 20% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
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Stored Energy
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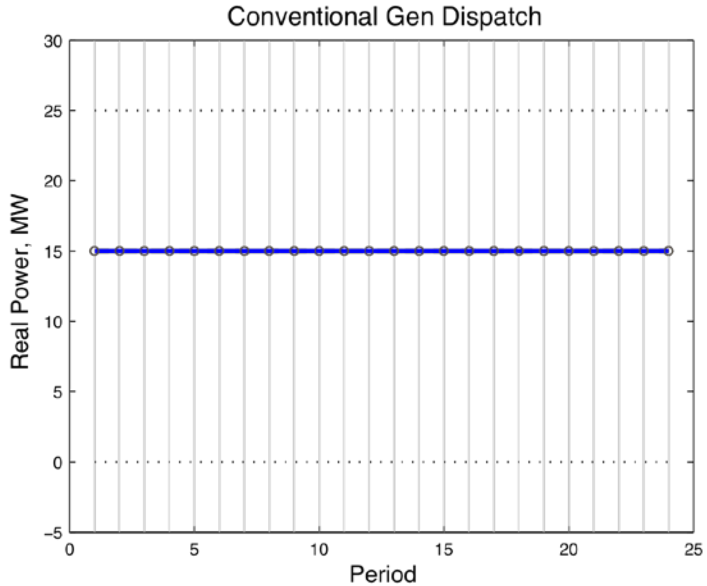
Conventional Gen Dispatch
Real Power, MW
Period
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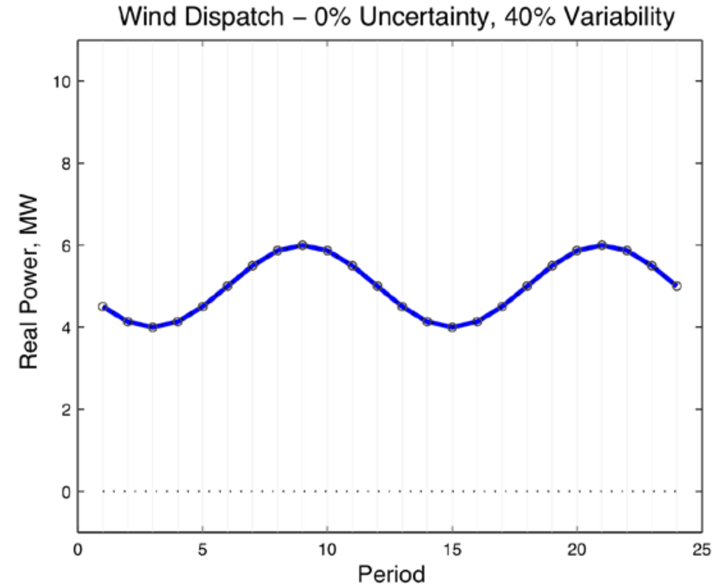
Wind Dispatch – 0% Uncertainty, 40% Variability
Real Power, MW
Period
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8
6
4
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10
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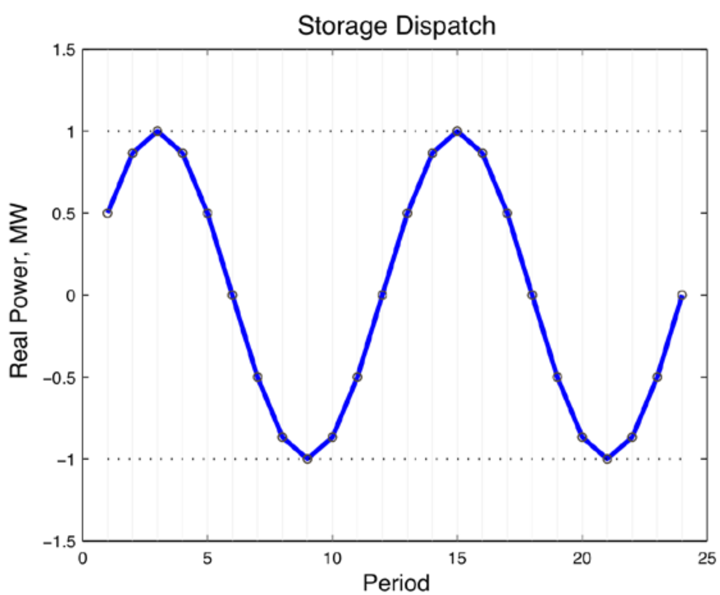
20
25


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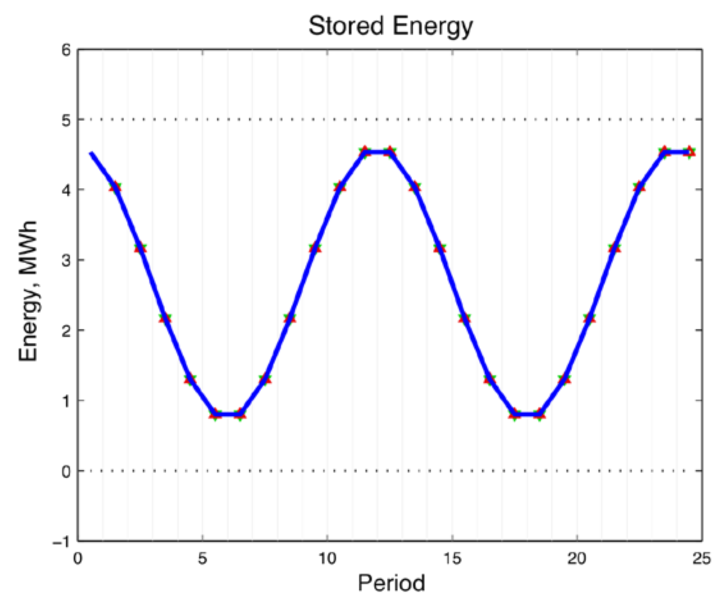
20
25


Stored Energy
Energy, MWh
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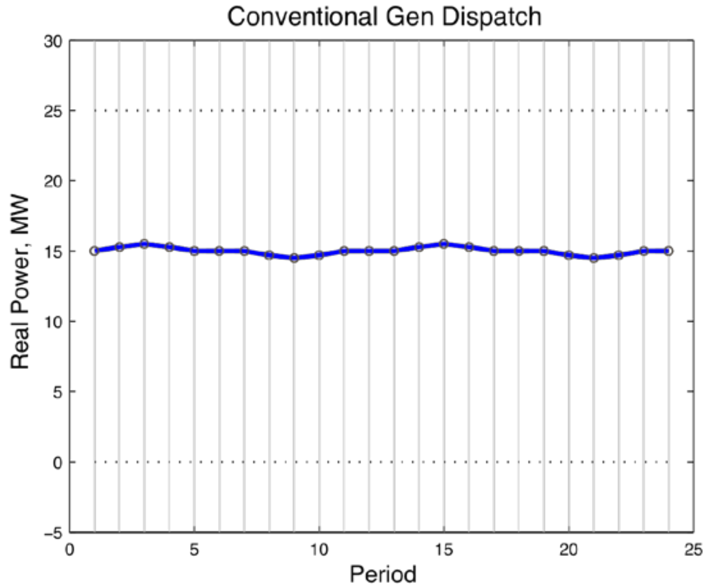
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−5
Real Power, MW
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20
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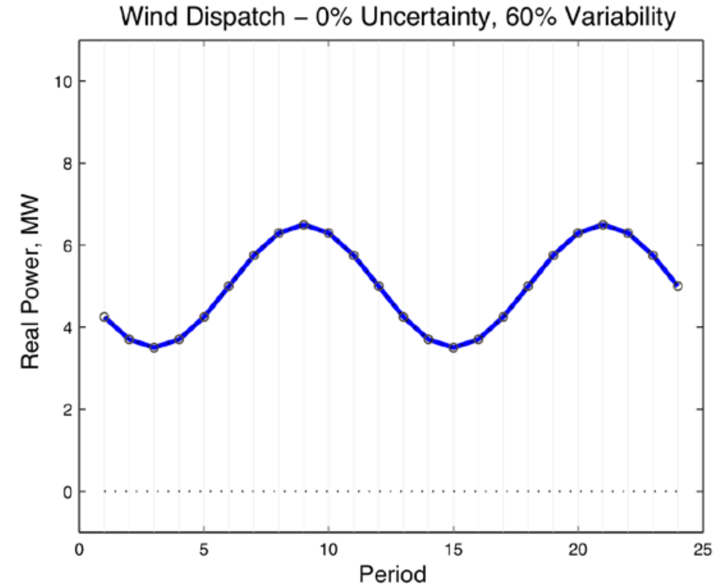
Period


Wind Dispatch – 0% Uncertainty, 60% Variability
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8
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4
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0
Real Power, MW
0
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15
20
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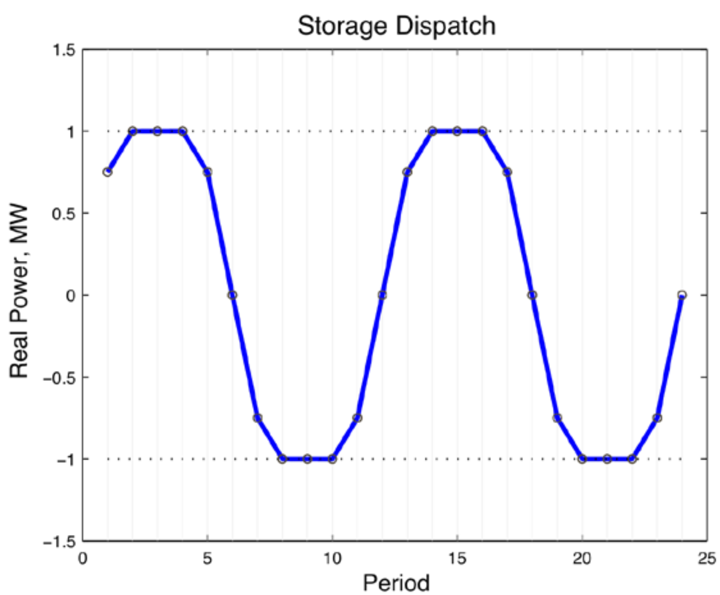
Period


Storage Dispatch
1.5
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0.5
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−0.5
−1
−1.5
Real Power, MW
0
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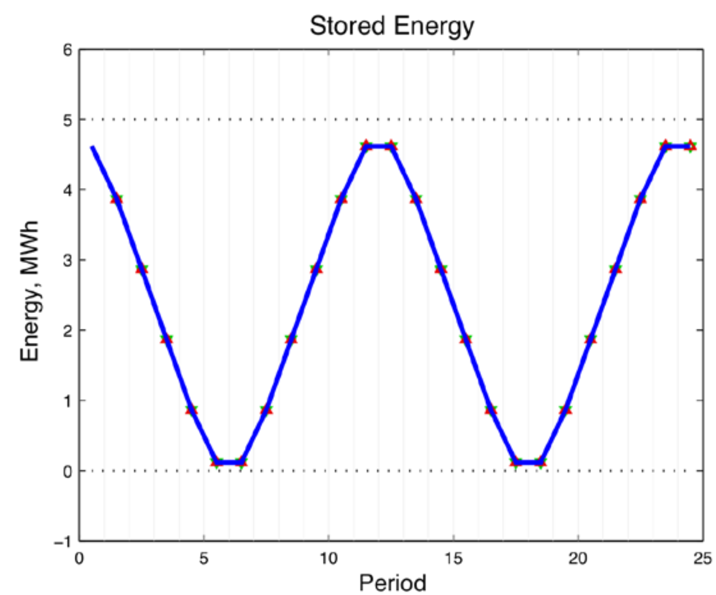
Period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Energy, MWh
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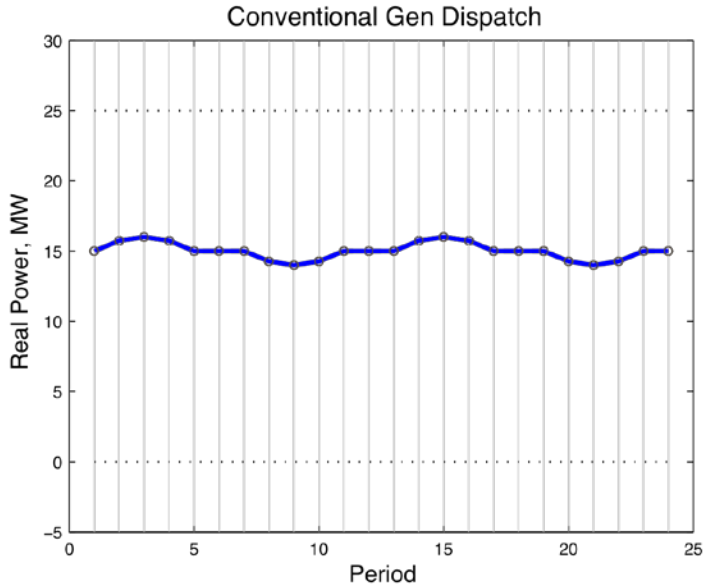
Period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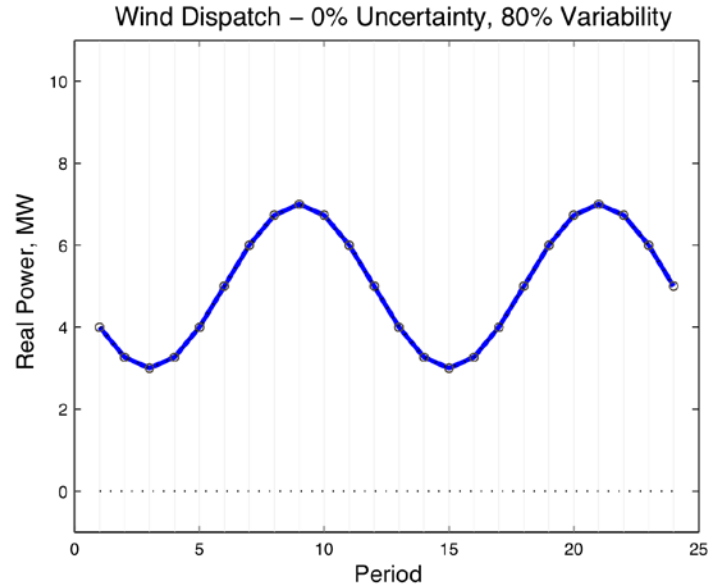
Wind Dispatch – 0% Uncertainty, 80% Variability
Real Power, MW
Period
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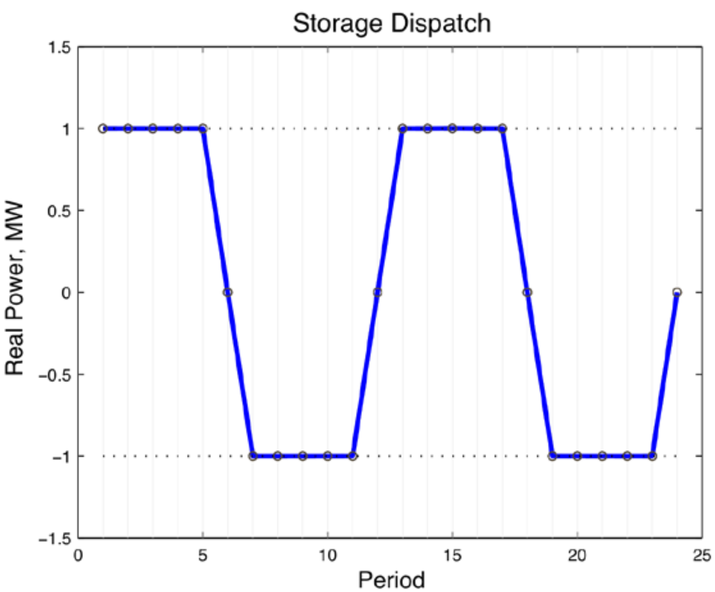
Storage Dispatch
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−0.5
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−1.5
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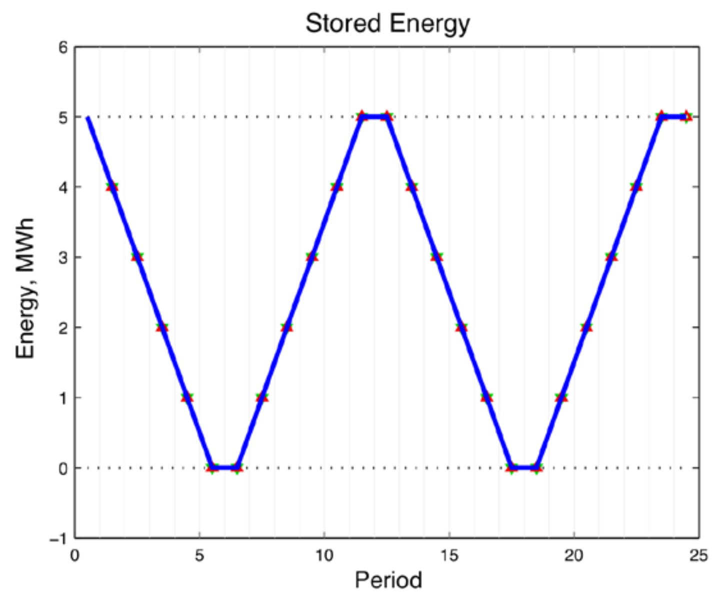
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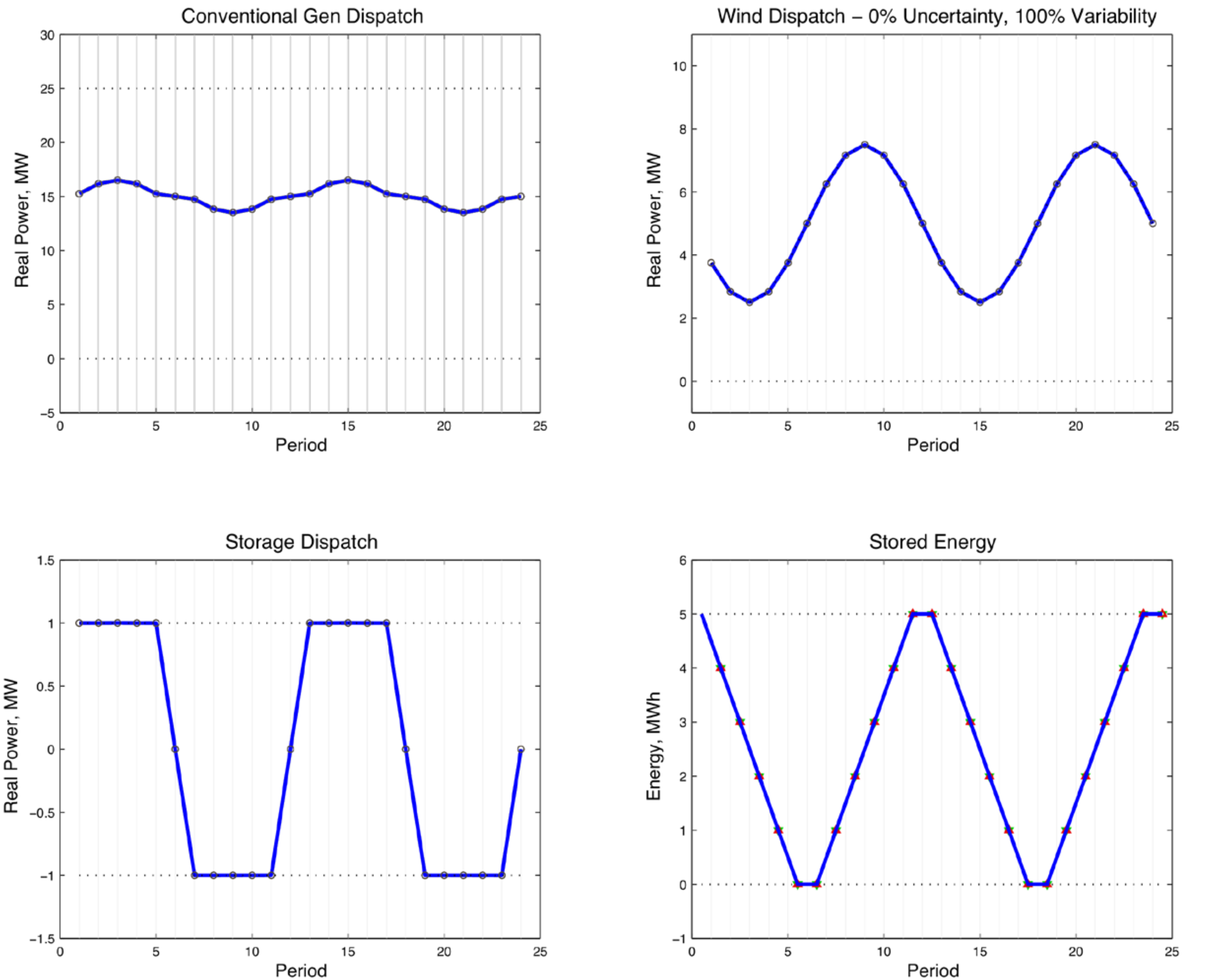
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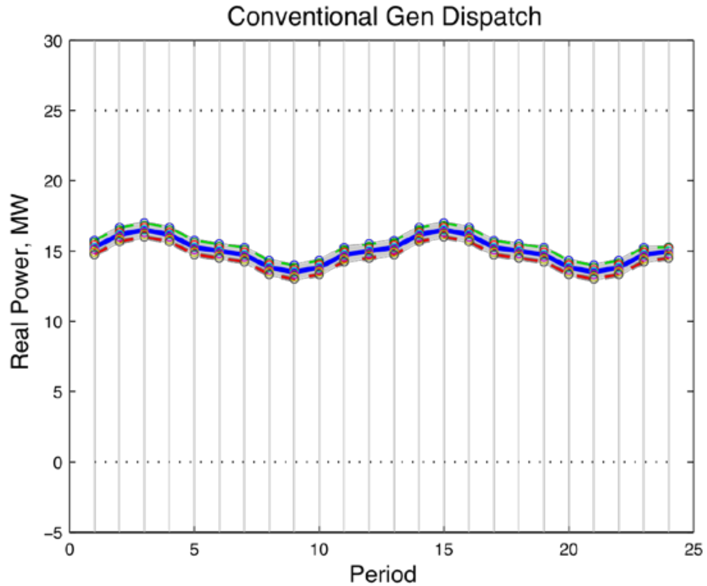
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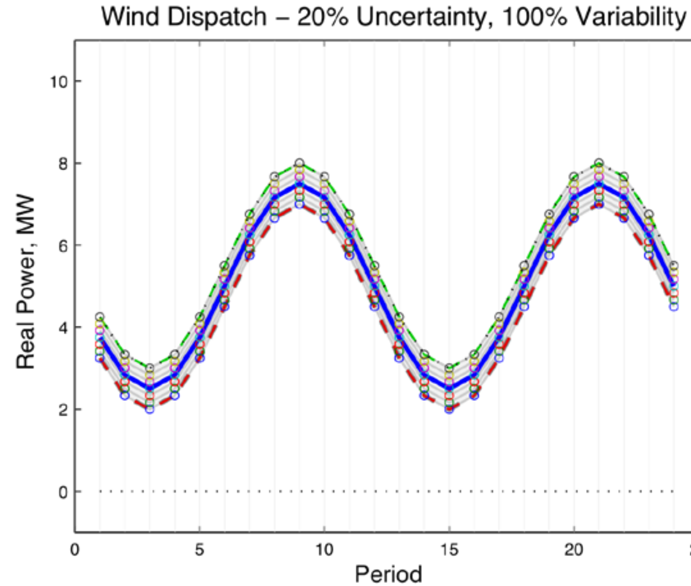
Wind Dispatch – 20% Uncertainty, 100% Variability
Real Power, MW
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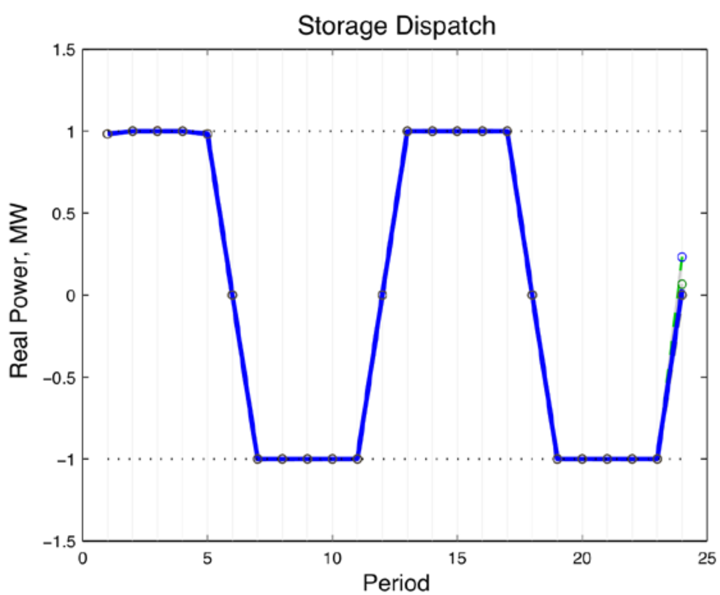
Storage Dispatch
Real Power, MW
Period
1.5
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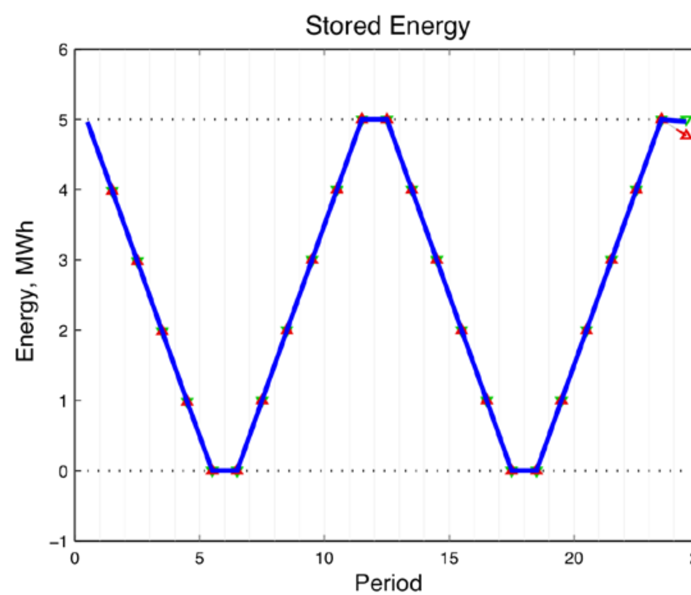
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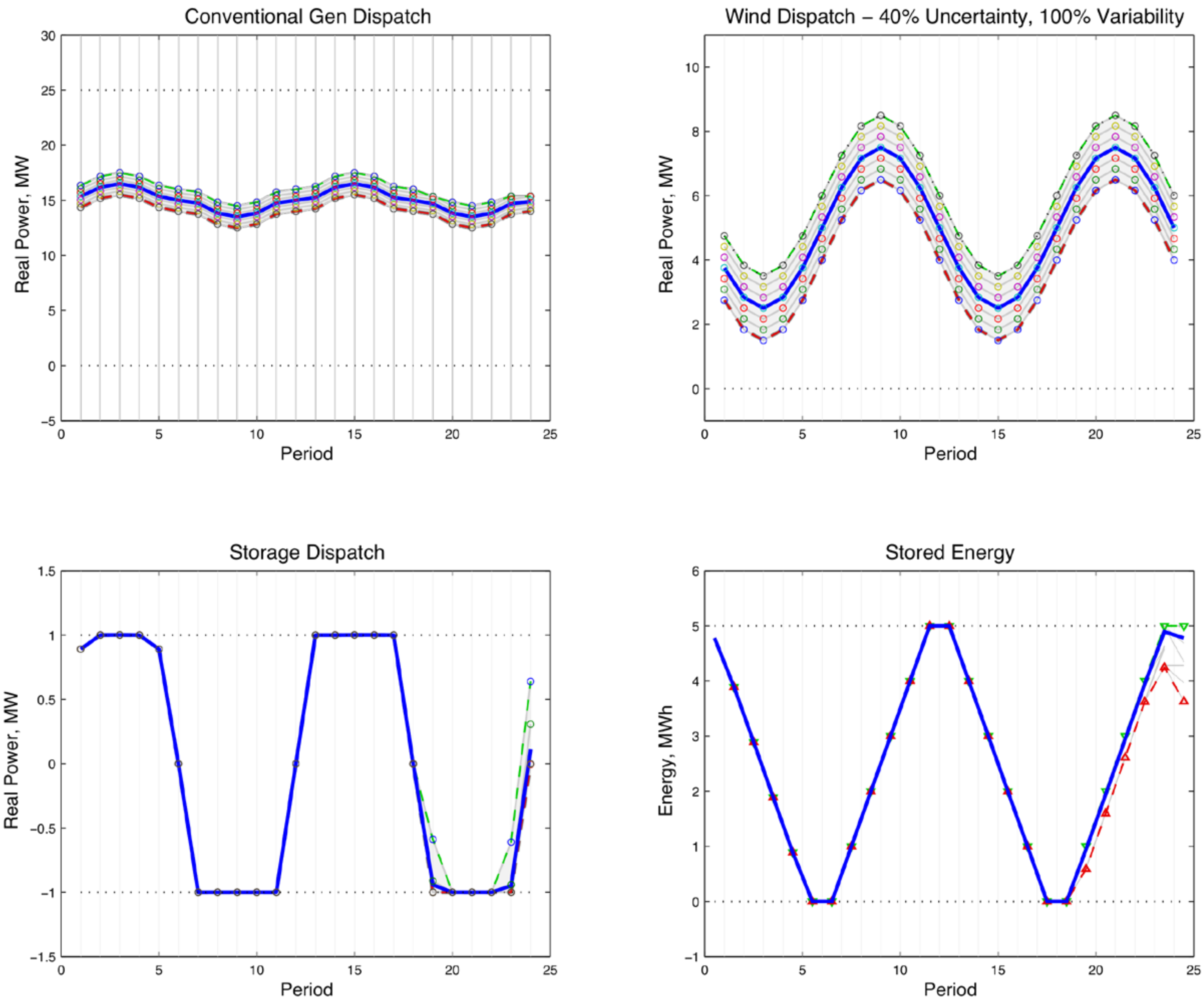
Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 40% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
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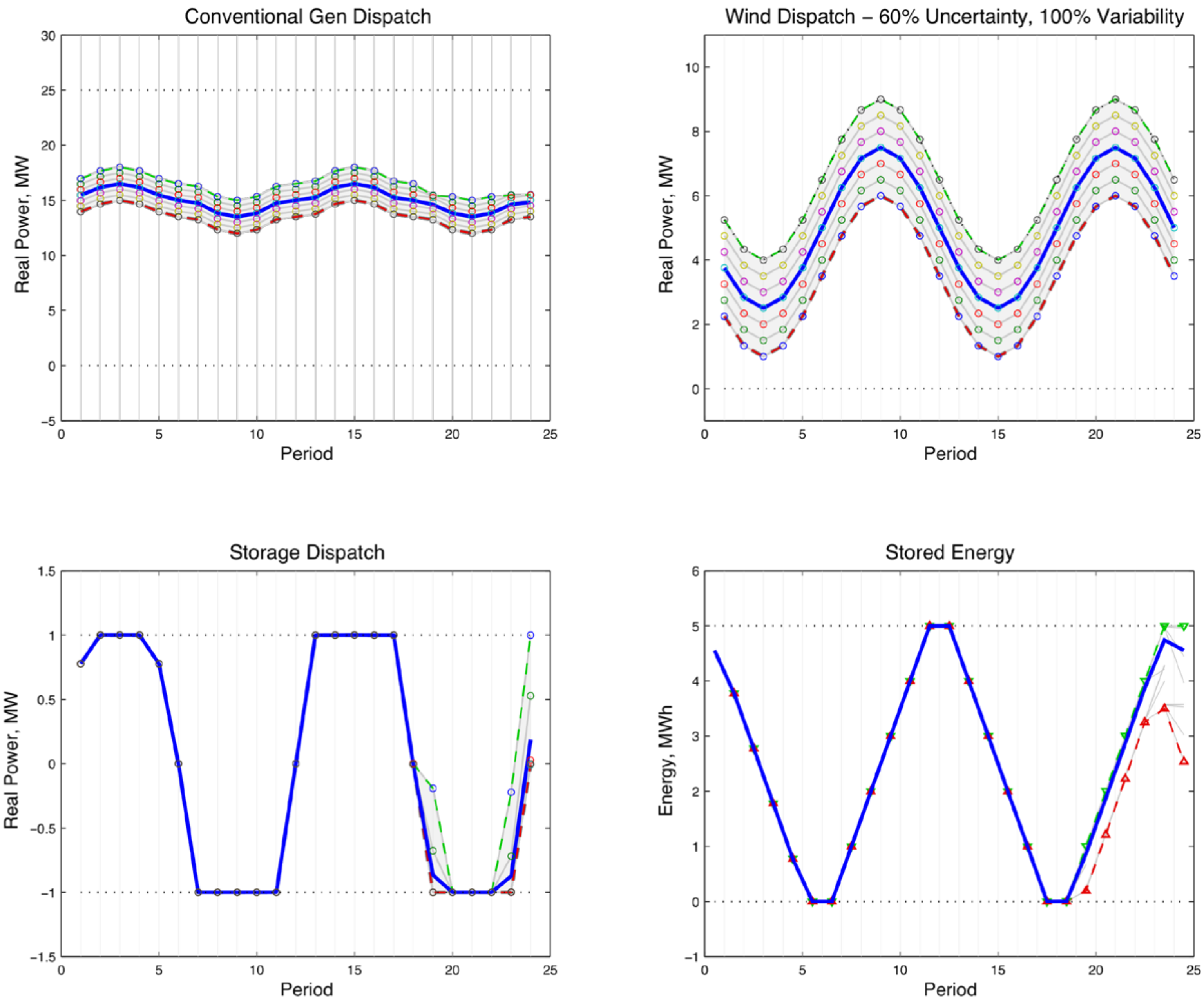
Period


Conventional Gen Dispatch
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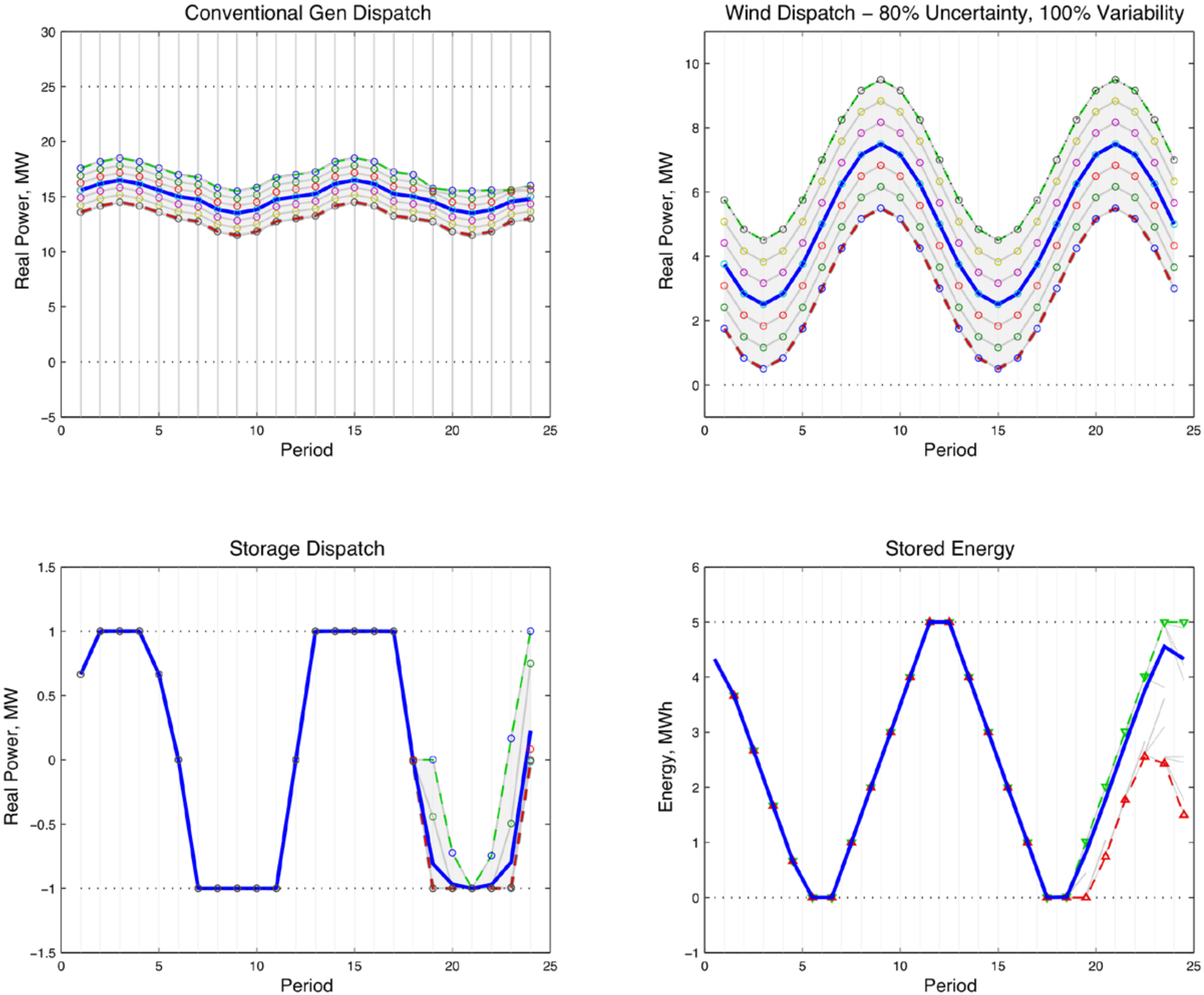
Period
Wind Dispatch – 60% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period


Conventional Gen Dispatch
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Period
Wind Dispatch – 80% Uncertainty, 100% Variability
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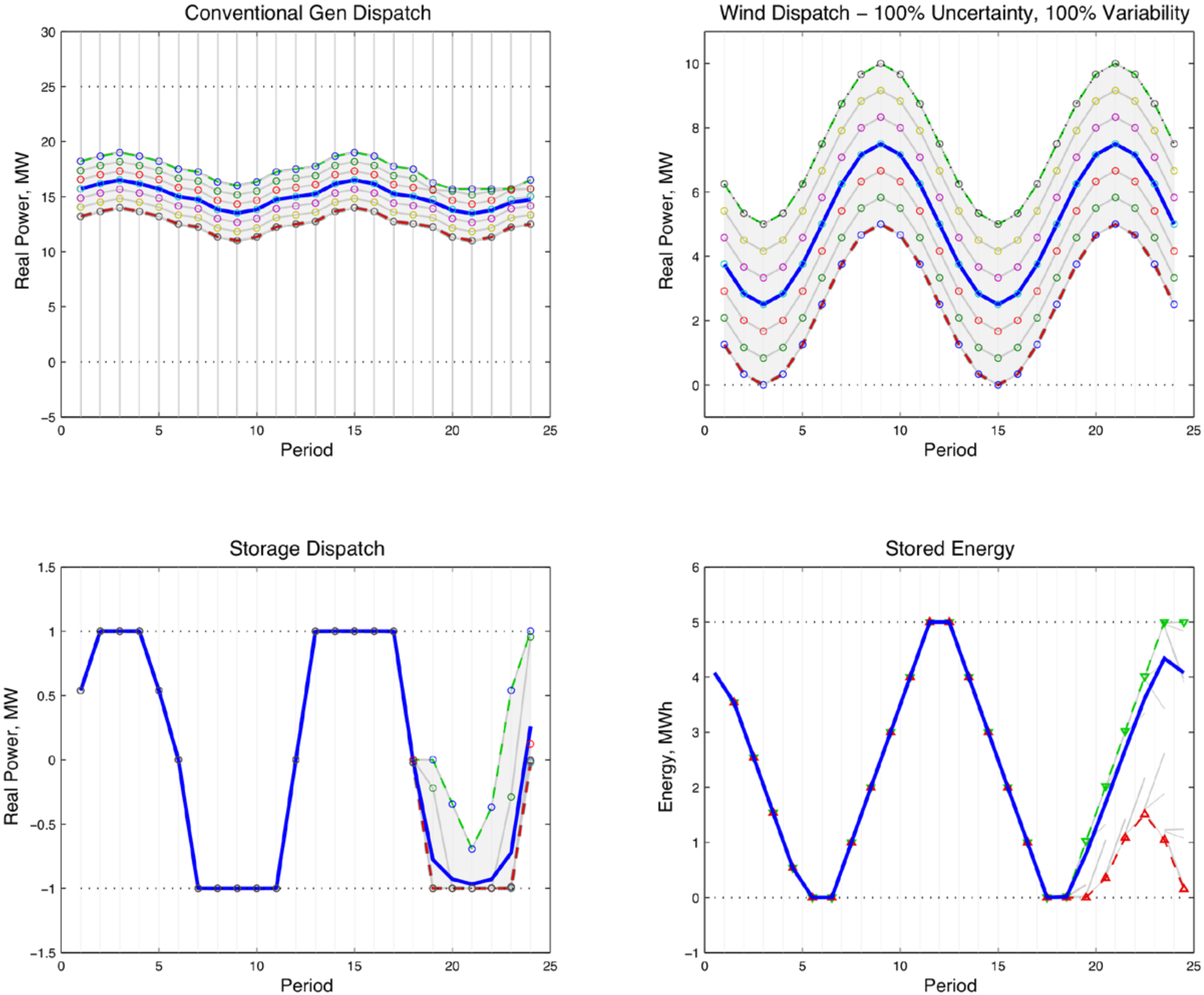
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period



Conventional Gen Dispatch
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Period
Wind Dispatch – 100% Uncertainty, 100% Variability
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Real Power, MW
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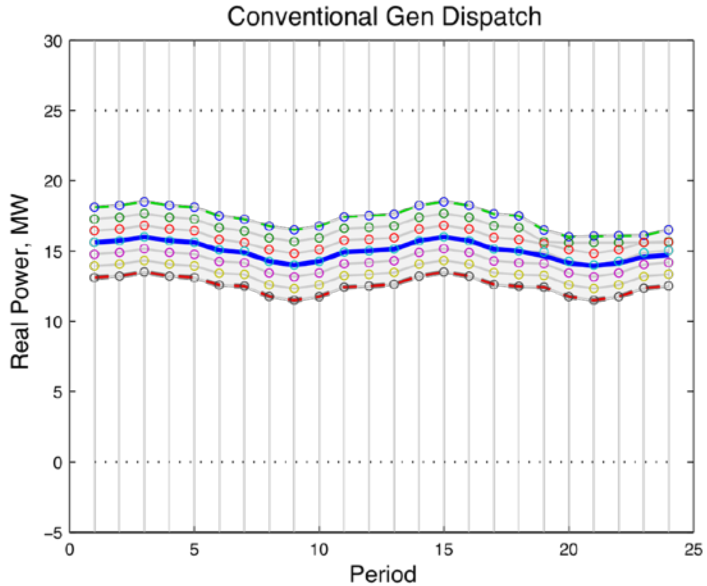
Energy, MWh
Period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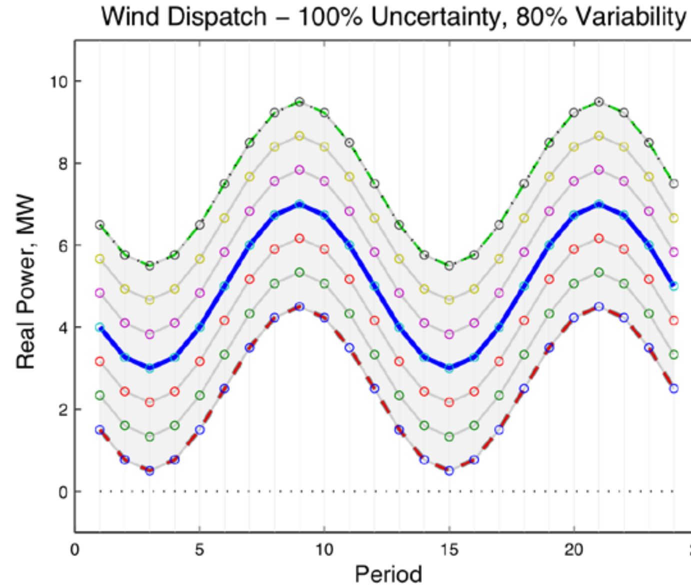
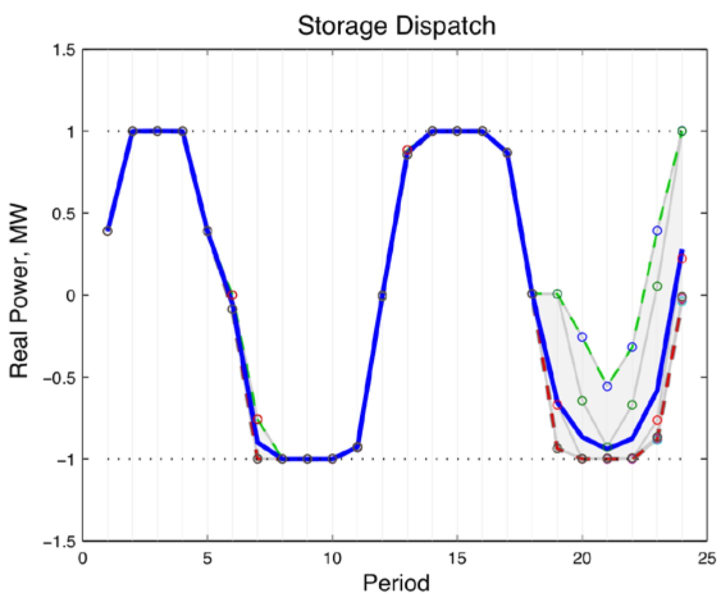

Wind Dispatch – 100% Uncertainty, 80% Variability
Real Power, MW
Period


Storage Dispatch
Real Power, MW
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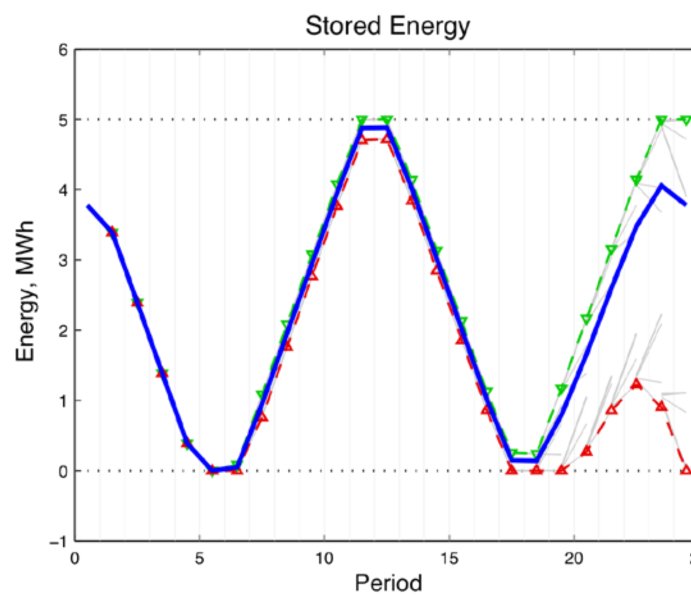
Stored Energy
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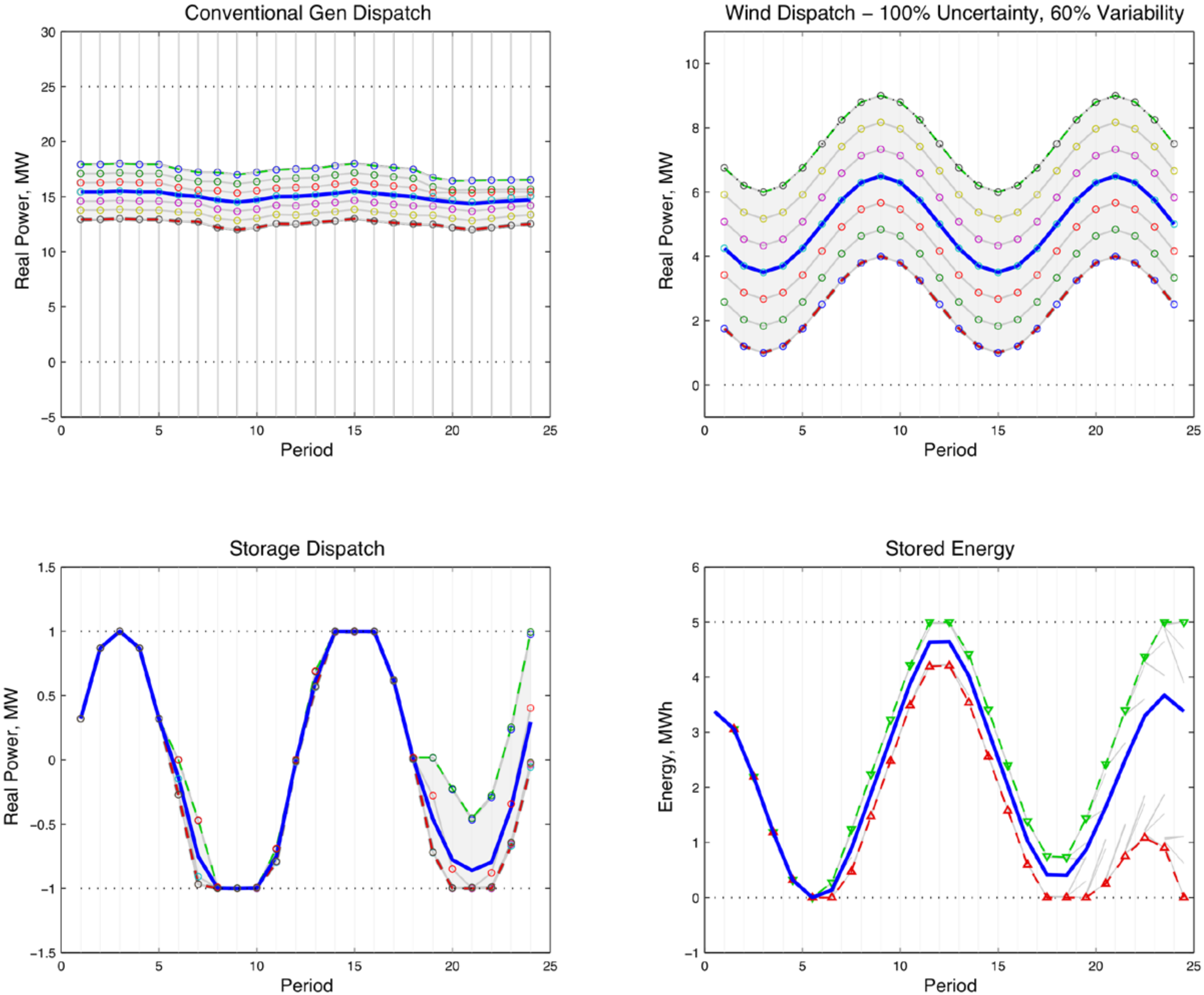
Period


Conventional Gen Dispatch
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Period
Wind Dispatch – 100% Uncertainty, 60% Variability
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Period
Storage Dispatch
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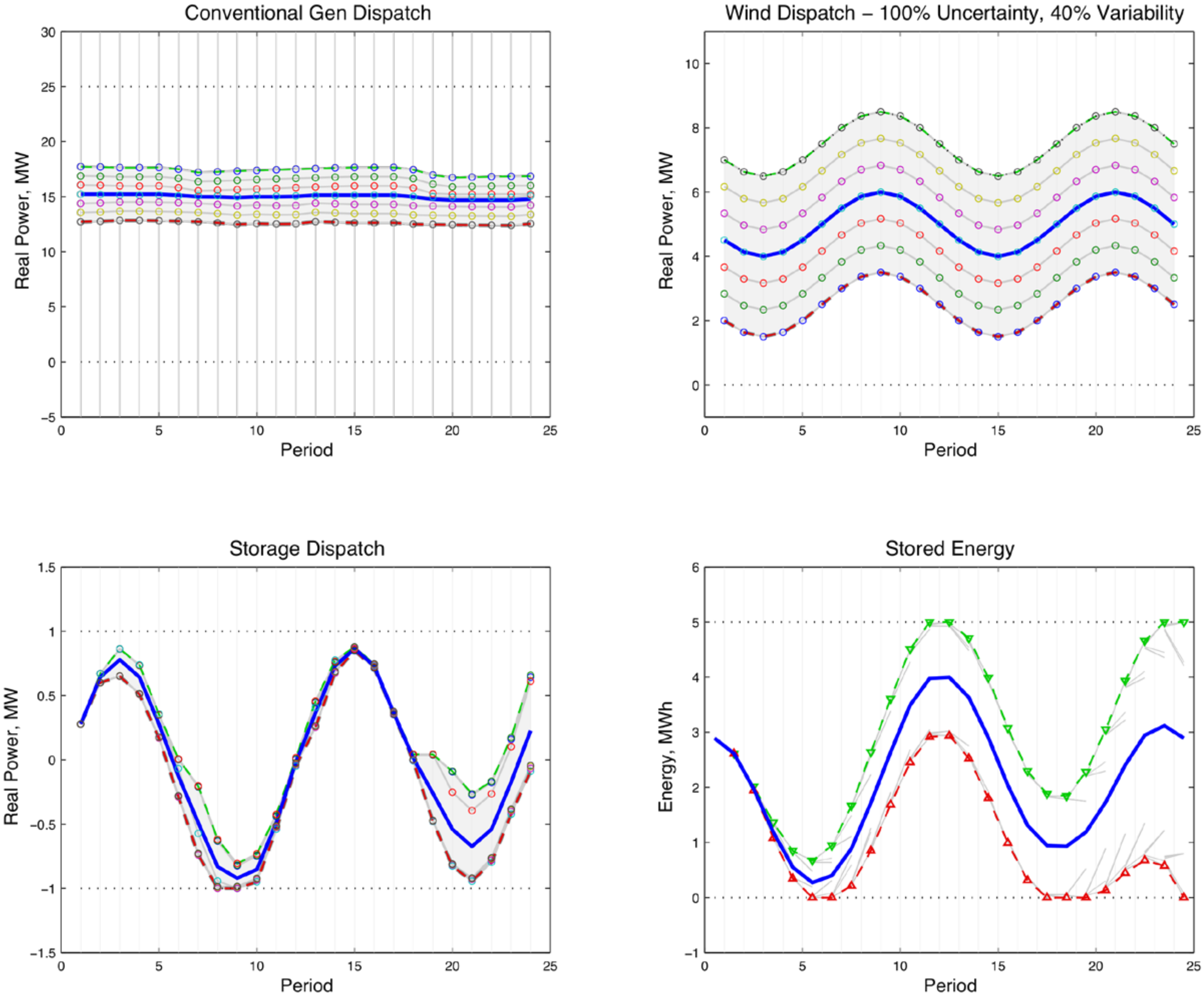
Period



Conventional Gen Dispatch
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Period
Wind Dispatch – 100% Uncertainty, 40% Variability
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Period
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Real Power, MW
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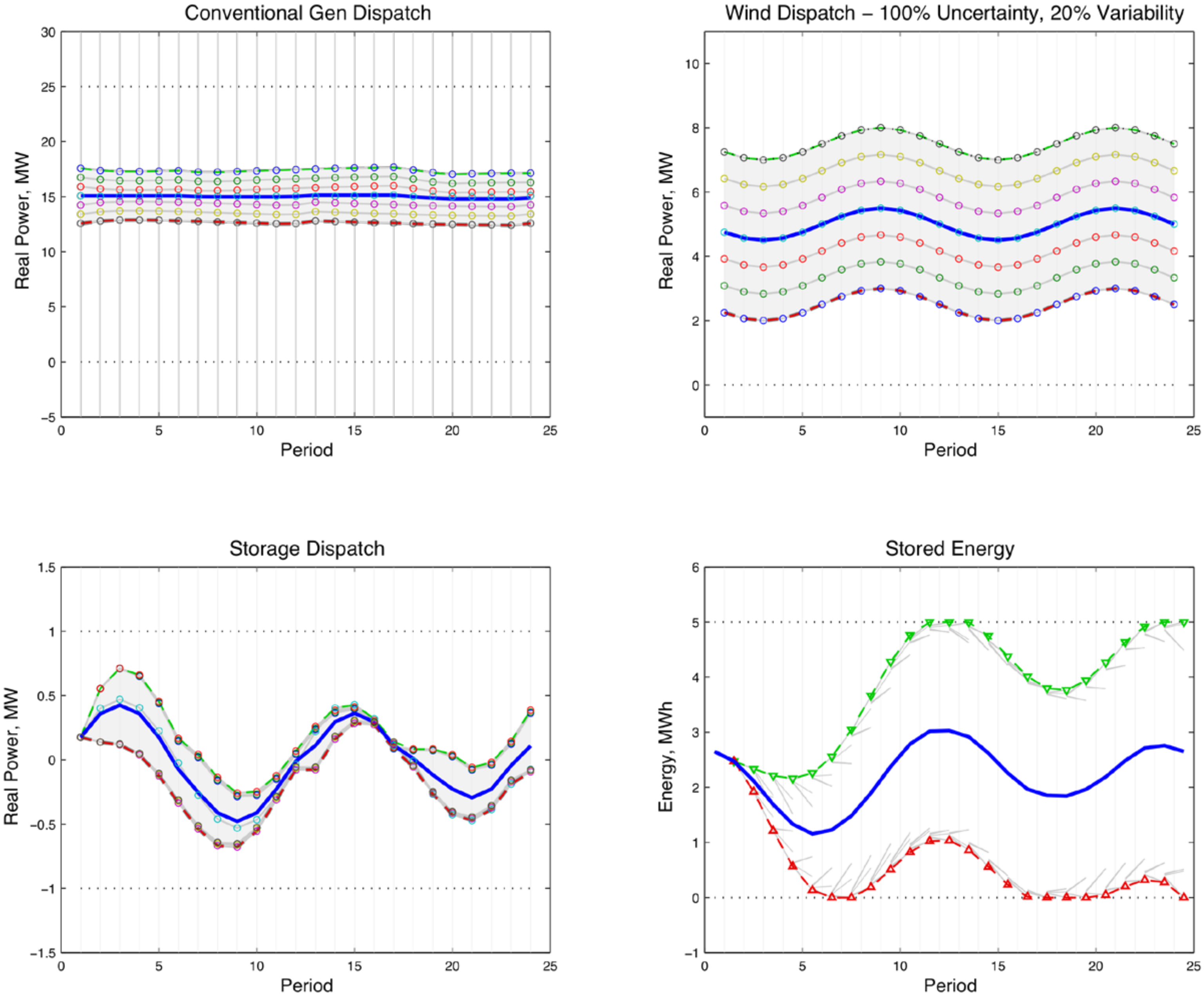
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Wind Dispatch – 100% Uncertainty, 20% Variability
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Real Power, MW
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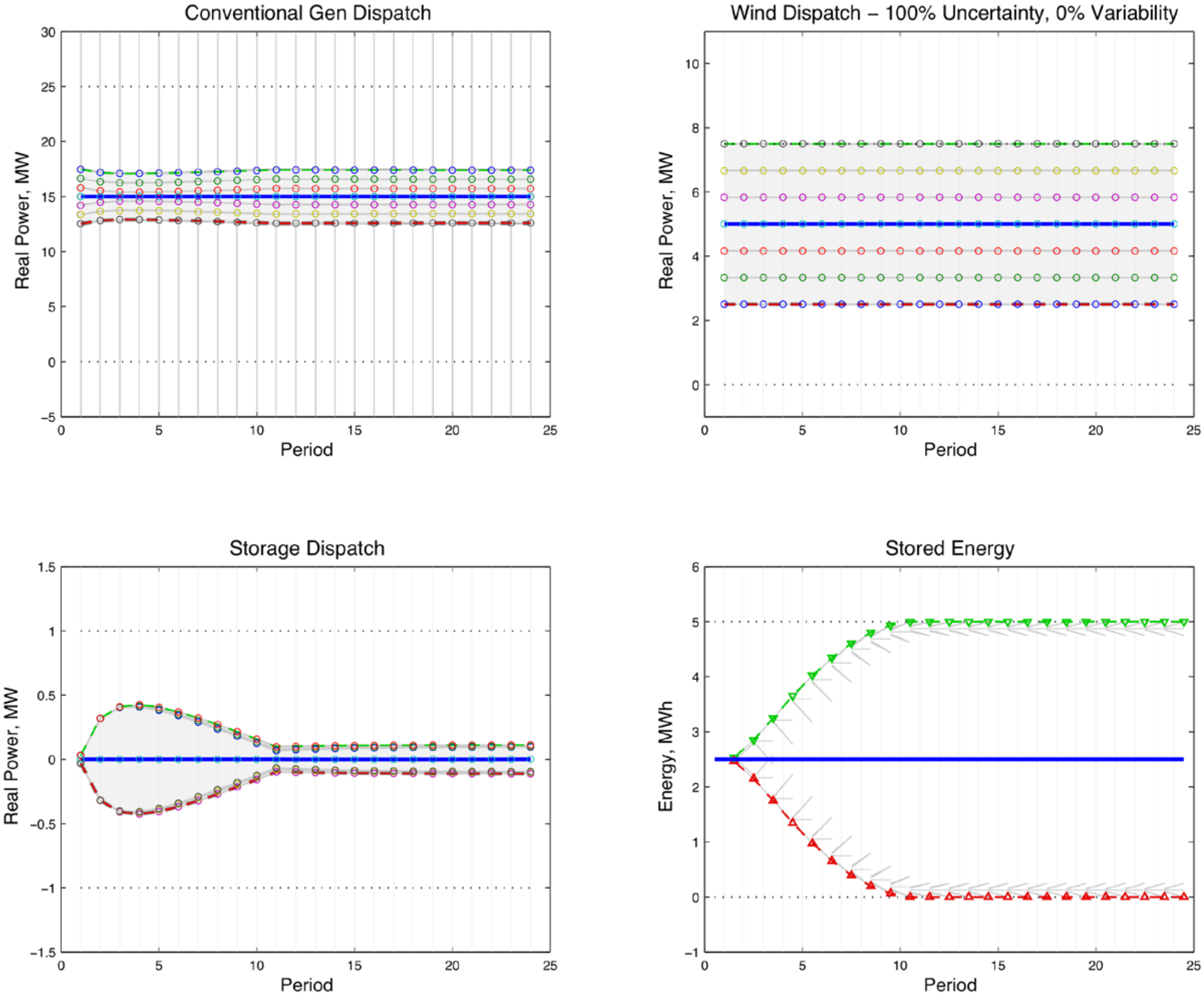
Energy, MWh
Period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Wind Dispatch – 100% Uncertainty, 0% Variability
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Storage Dispatch
Real Power, MW
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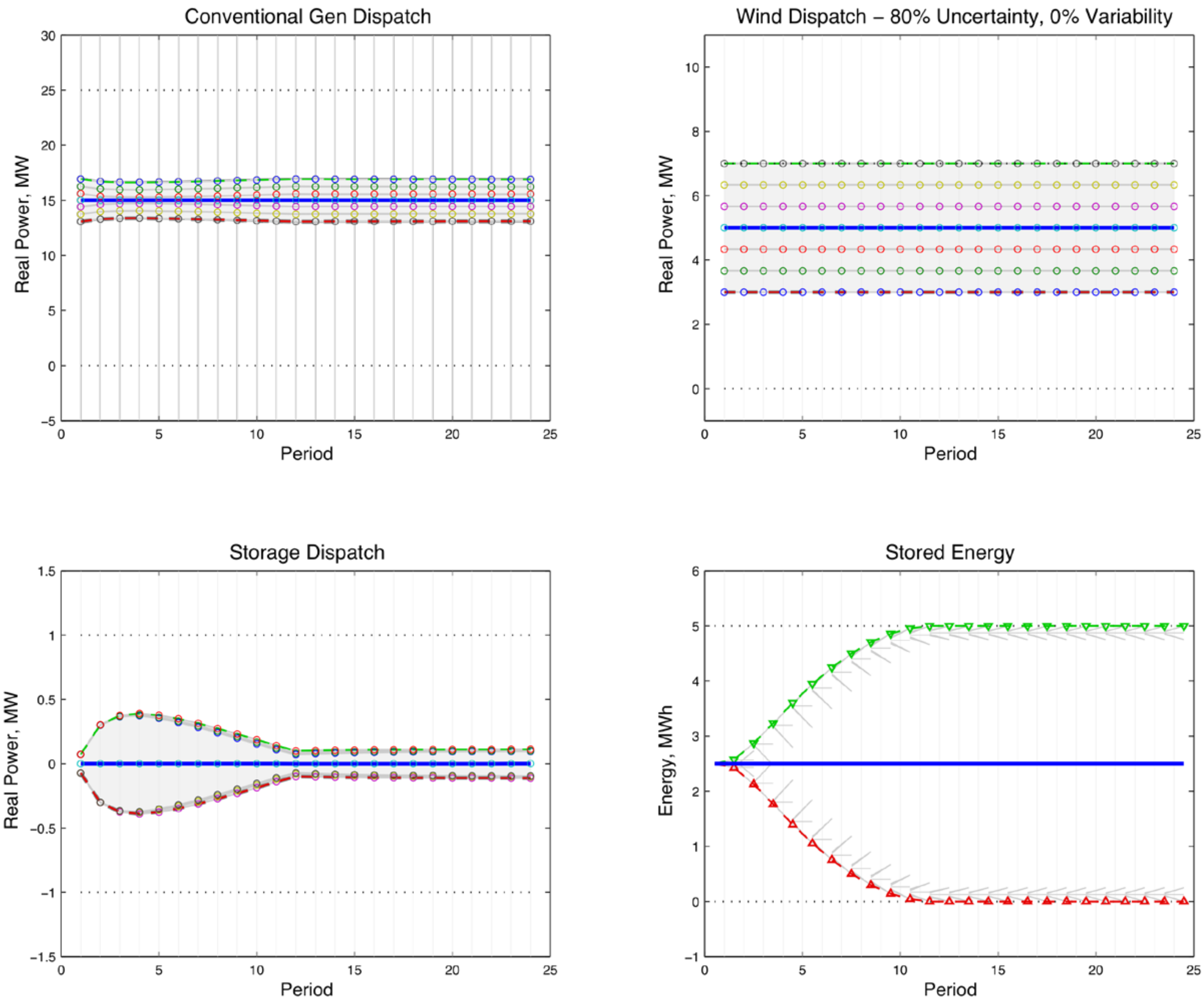
Stored Energy
Energy, MWh
Period



Conventional Gen Dispatch
Real Power, MW
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Period
Wind Dispatch – 80% Uncertainty, 0% Variability
Real Power, MW
10
8
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25
Period
Storage Dispatch
Real Power, MW
1.5
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Period
Stored Energy
Energy, MWh
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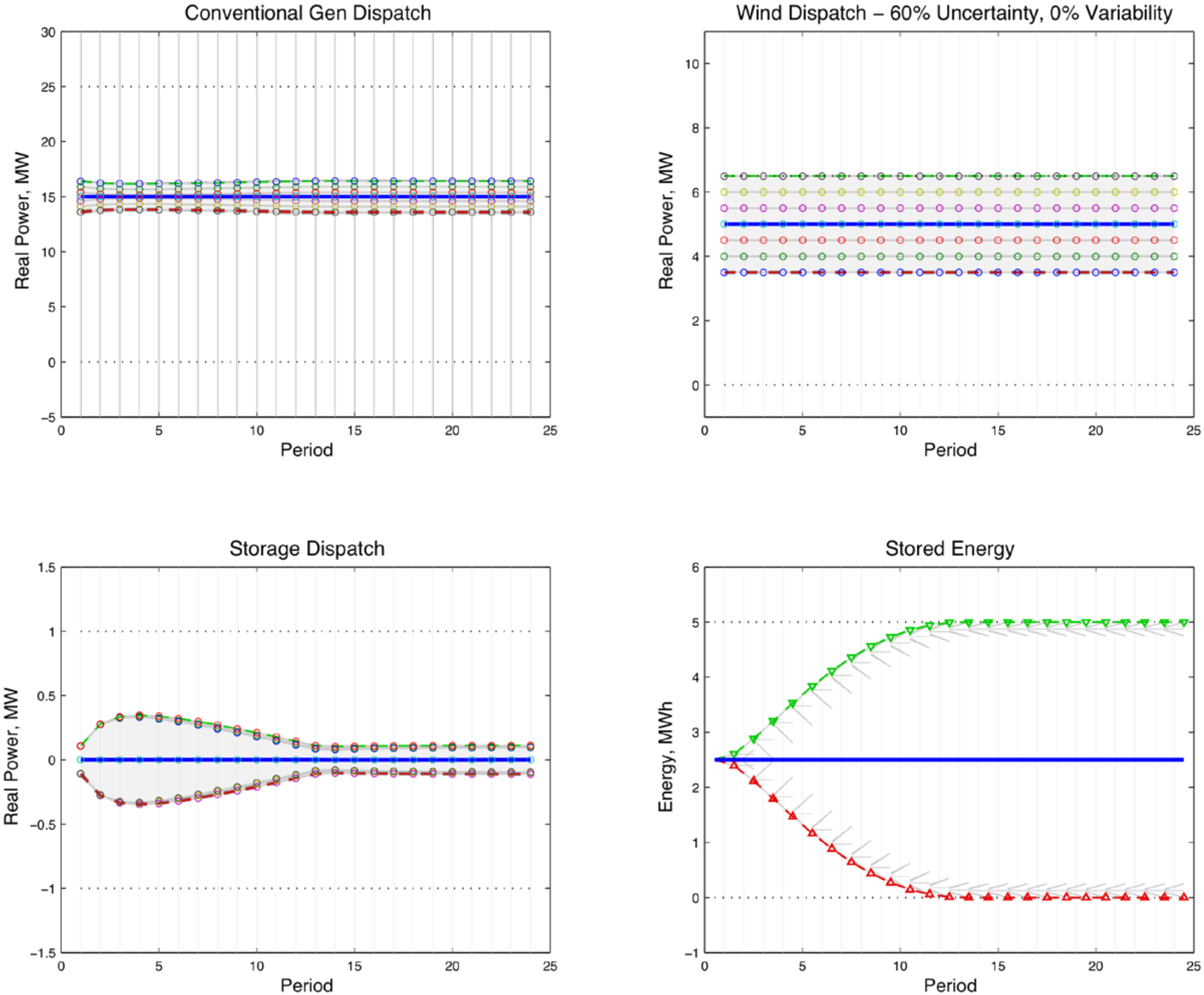
Period


Conventional Gen Dispatch
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Period
Wind Dispatch – 60% Uncertainty, 0% Variability
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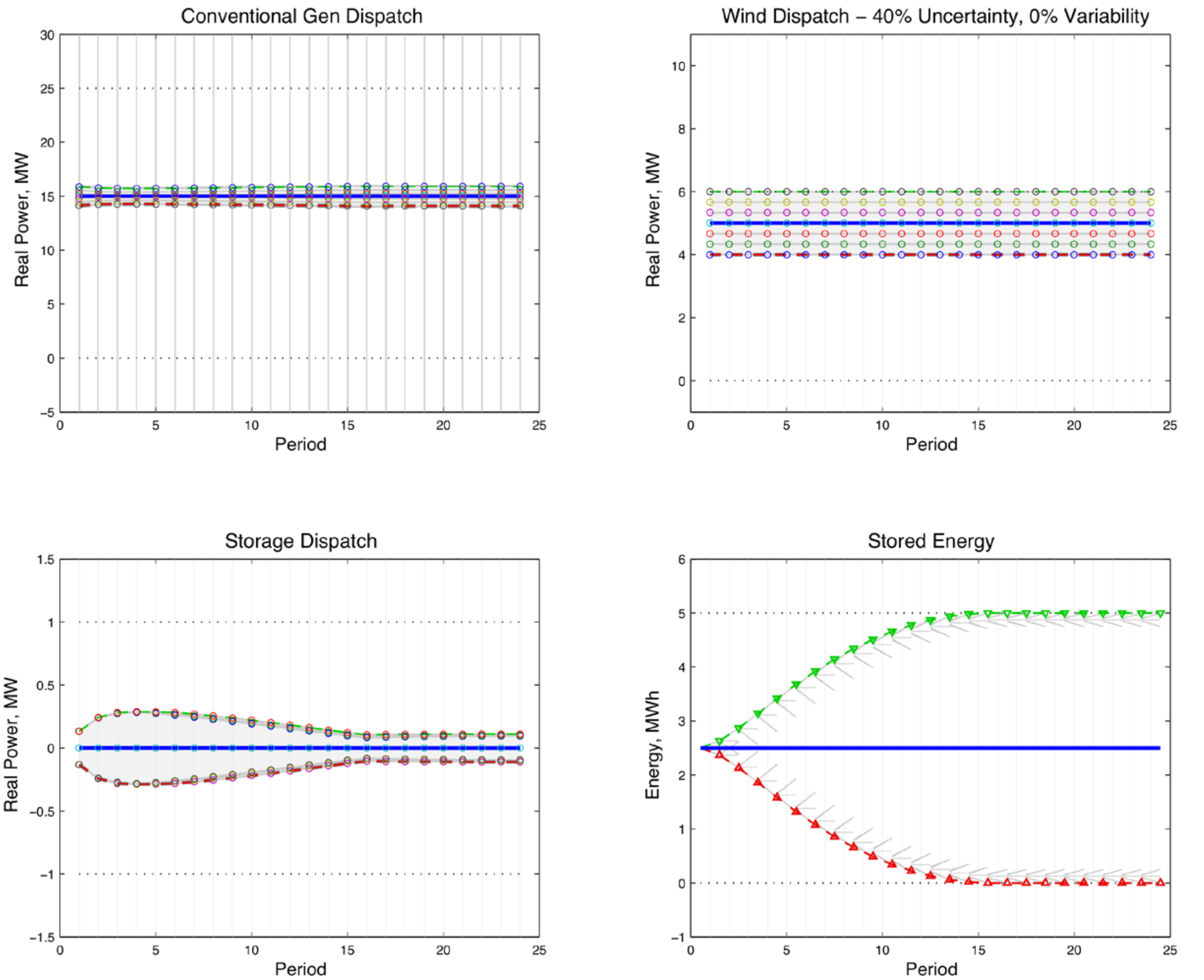
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period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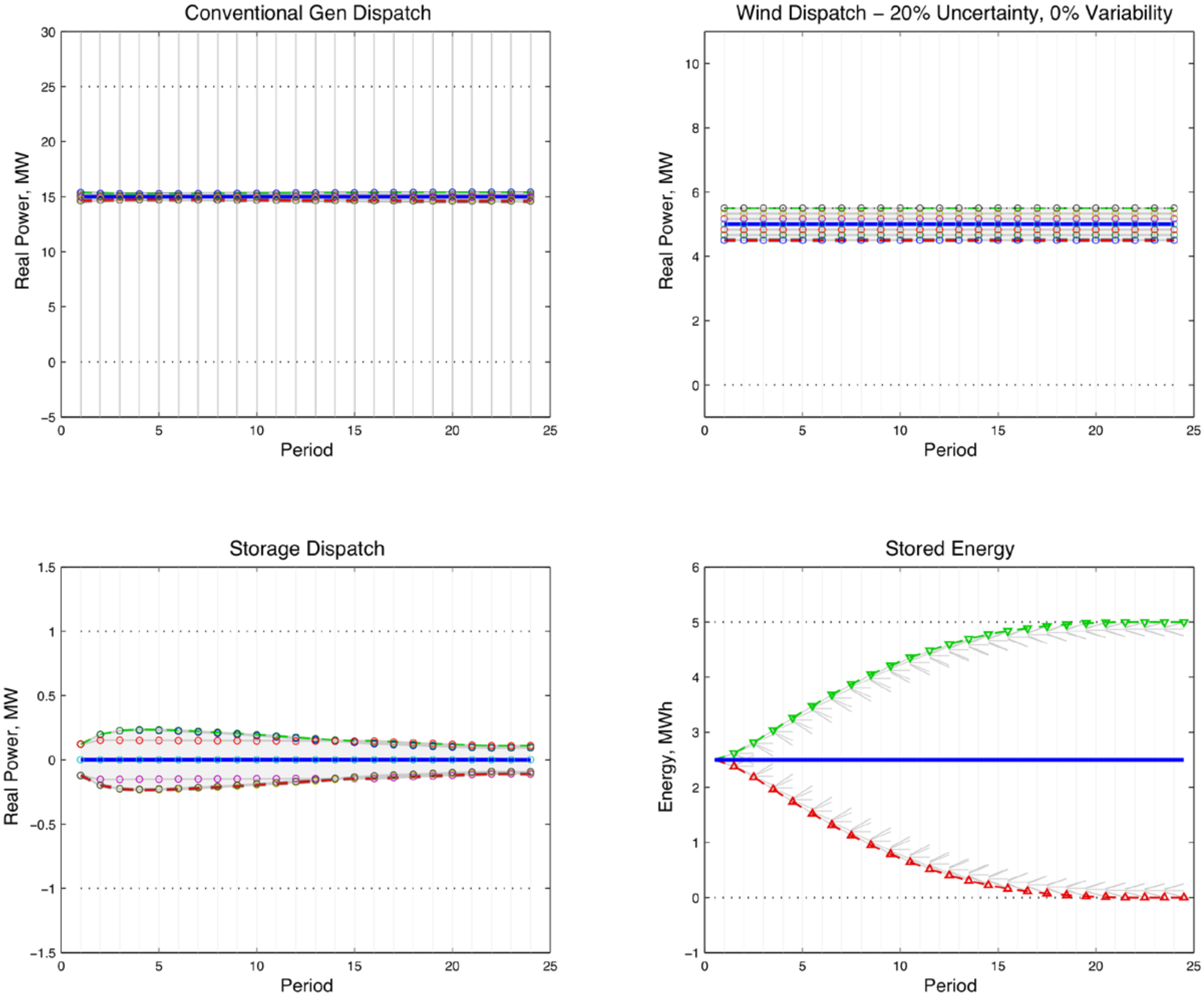
Real Power, MW
Period
Wind Dispatch – 40% Uncertainty, 0% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period


Conventional Gen Dispatch
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Period
Wind Dispatch – 20% Uncertainty, 0% Variability
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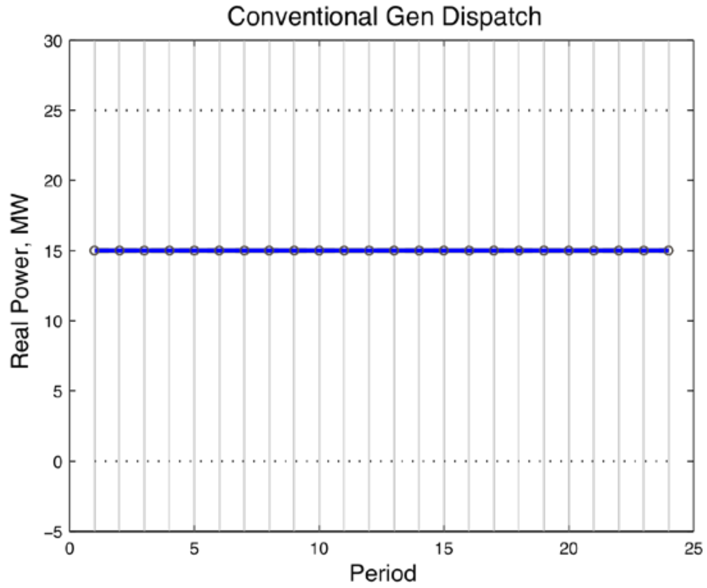
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy
Energy, MWh
Period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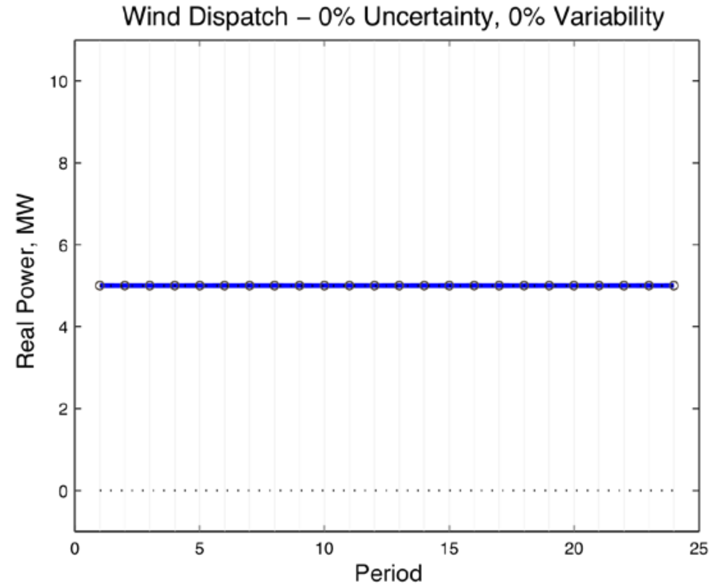
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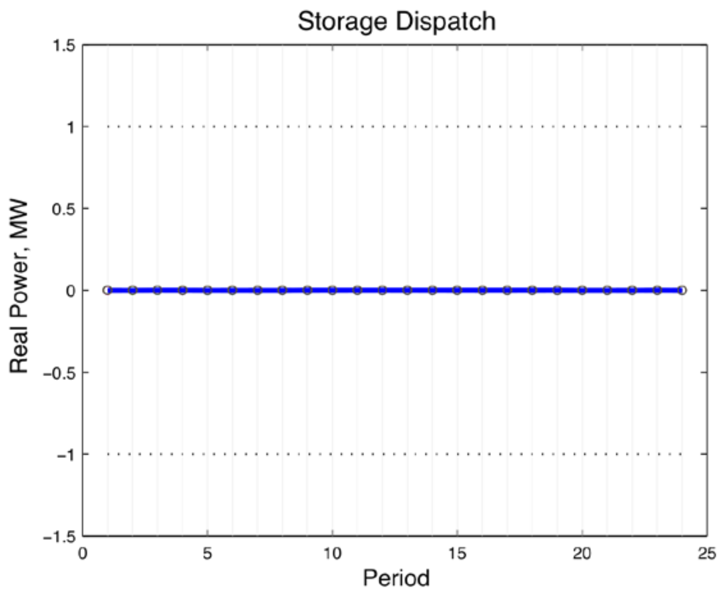
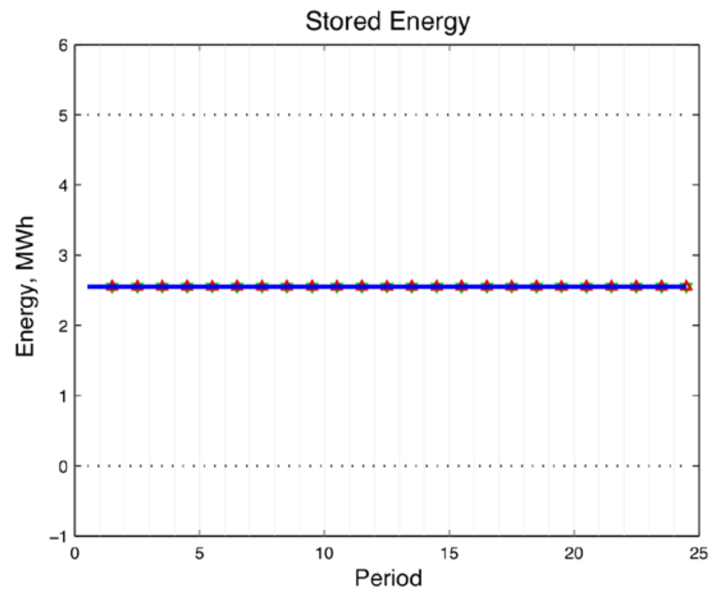
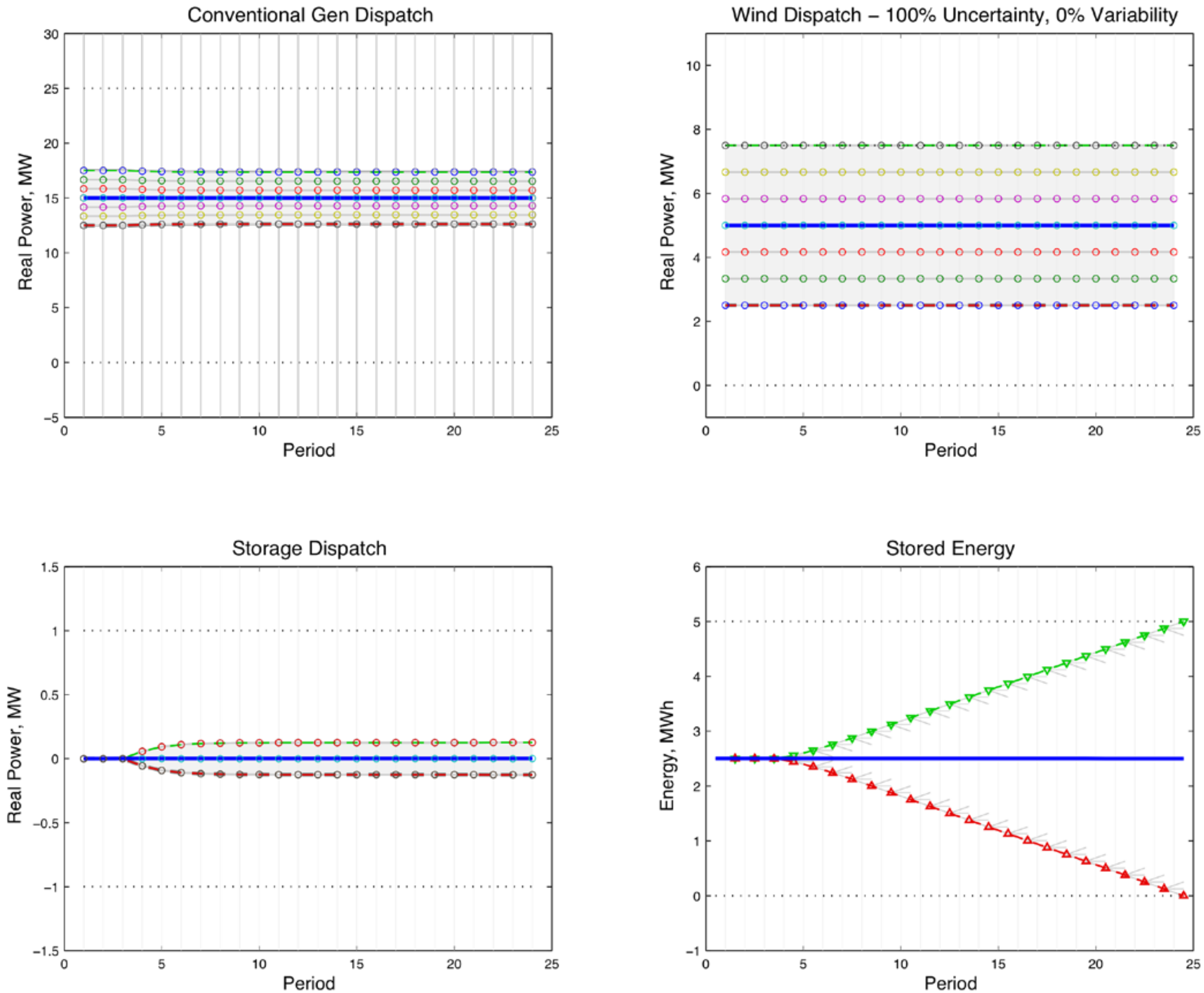
Real Power, MW
Period

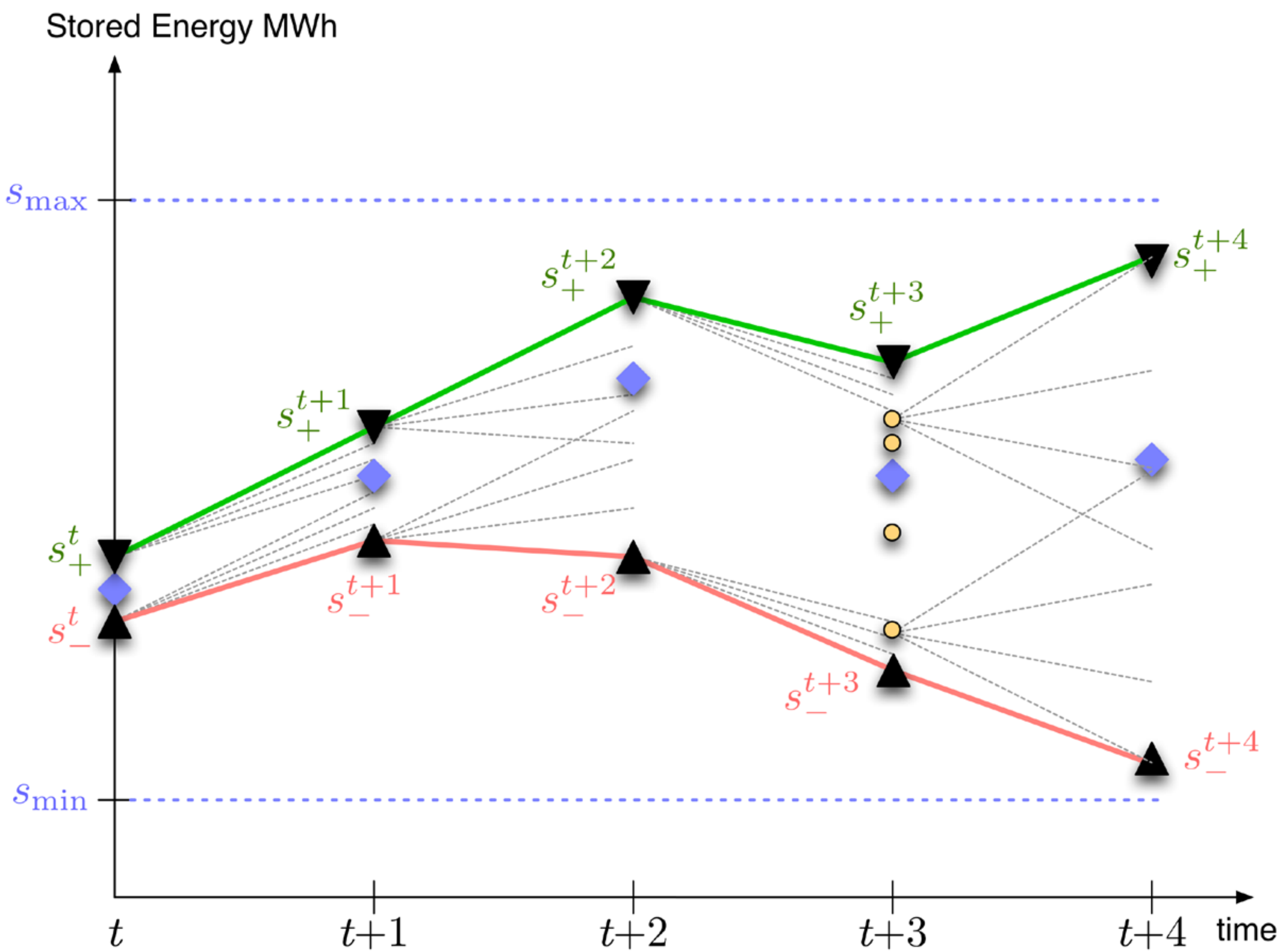

Storage Dispatch
Real Power, MW
Period

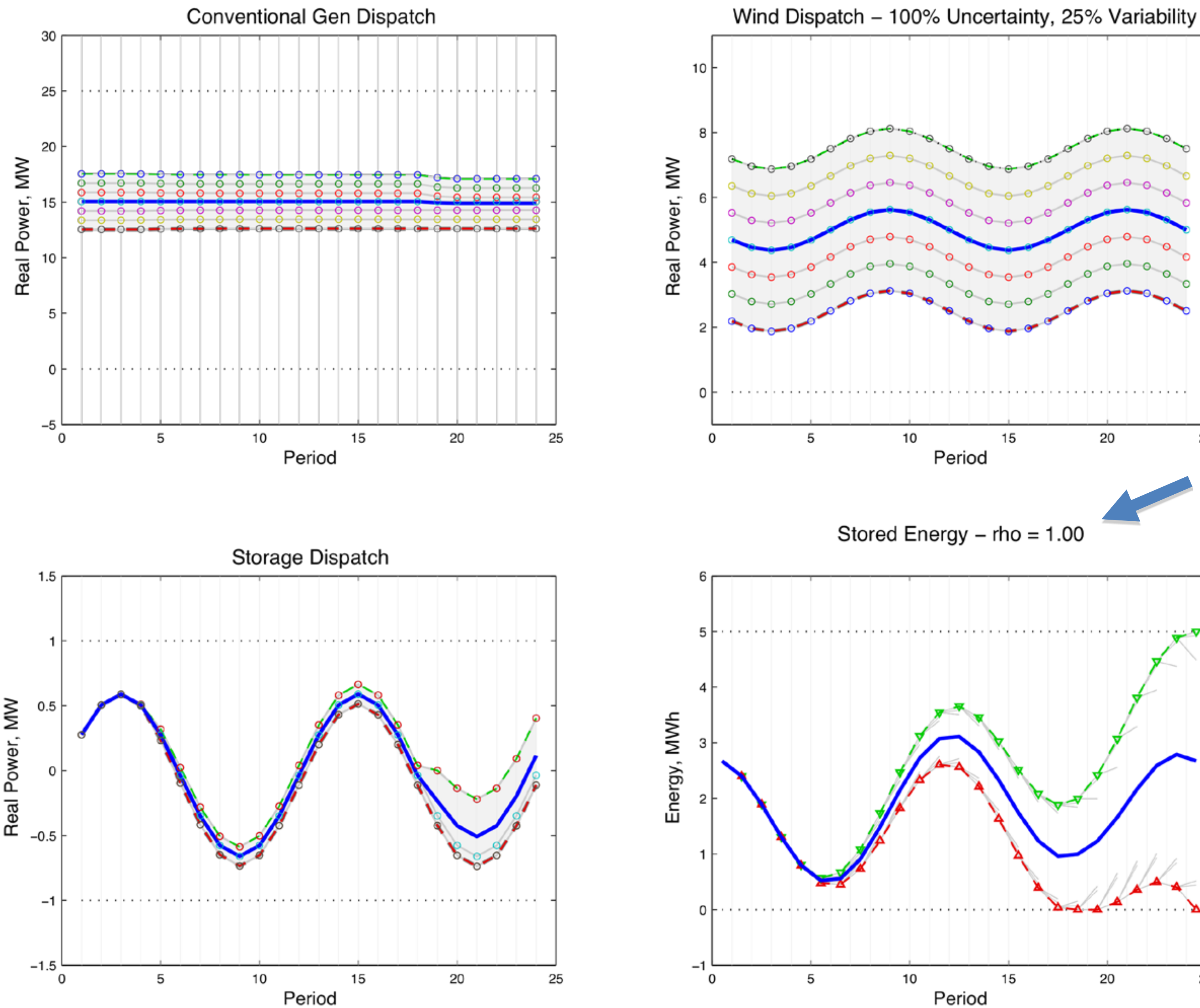

Stored Energy
Energy, MWh
Period

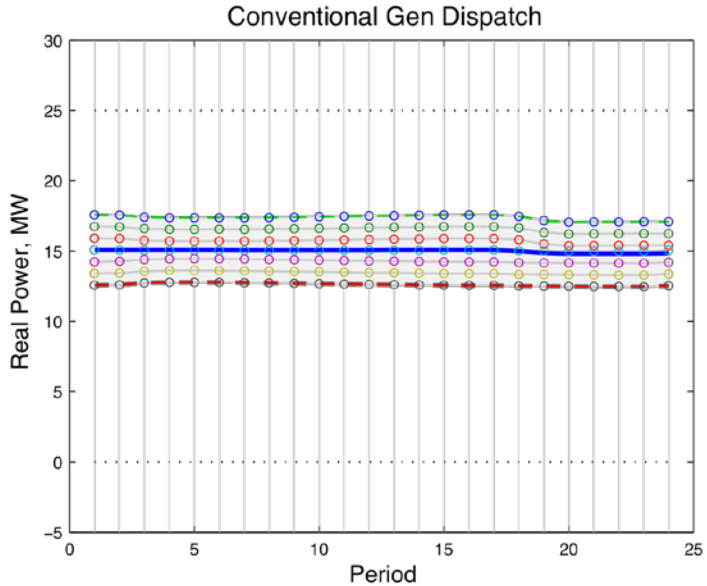
Worst Case Storage Constraint Problem

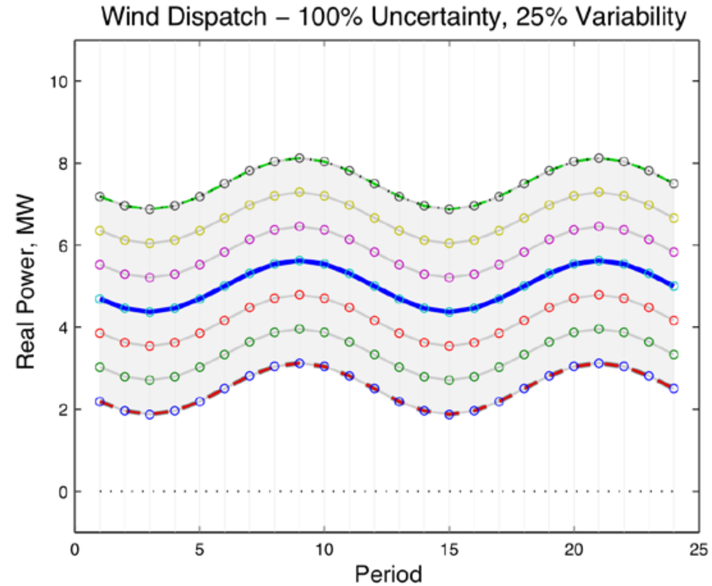


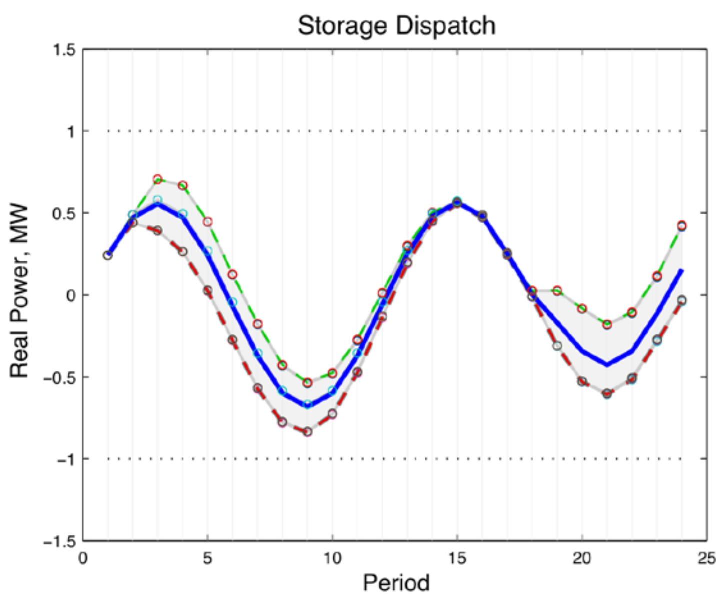
Relaxing Worst Case Storage Constraints

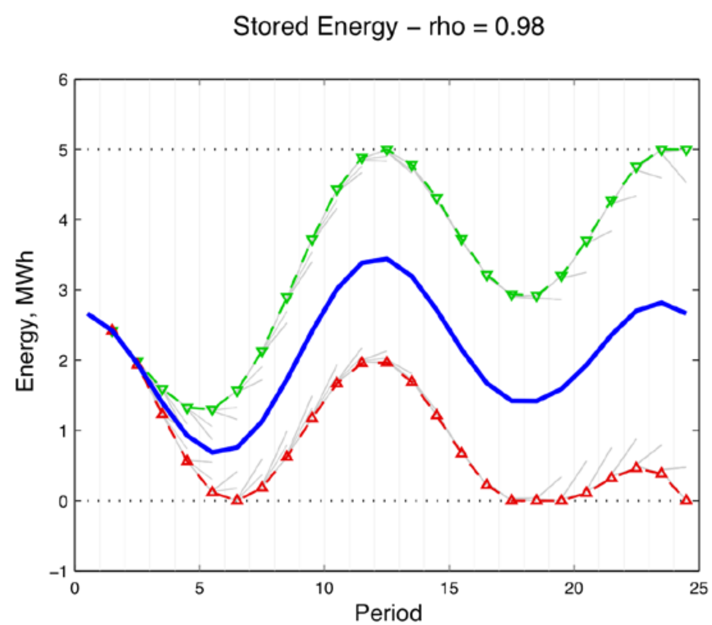


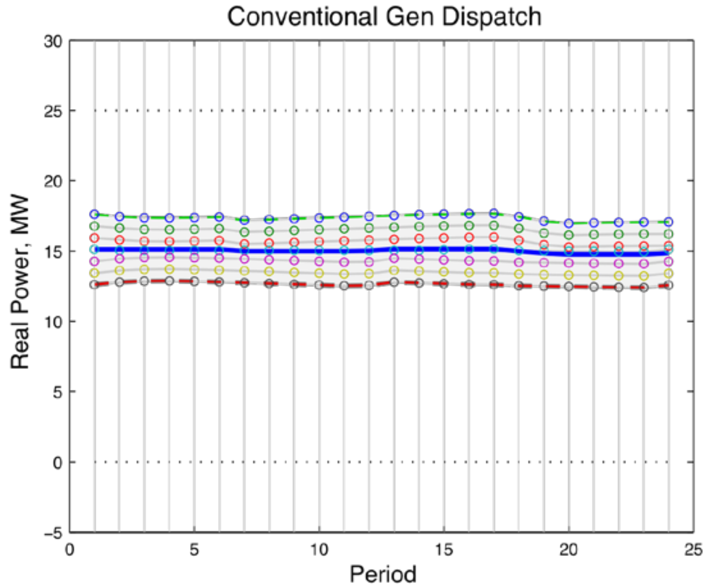

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 1.00
Energy, MWh
Period

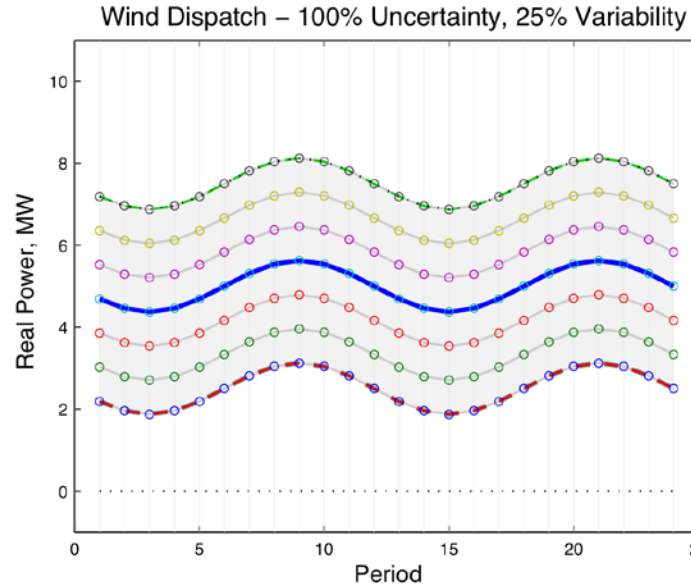

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

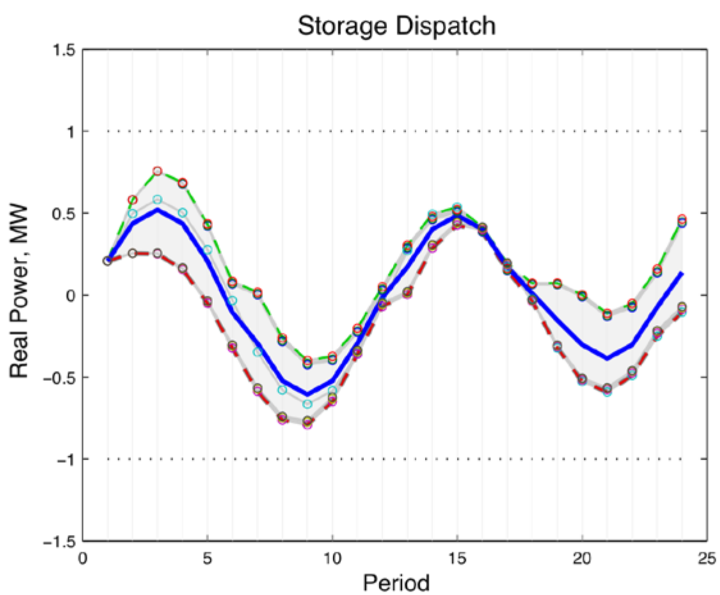

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

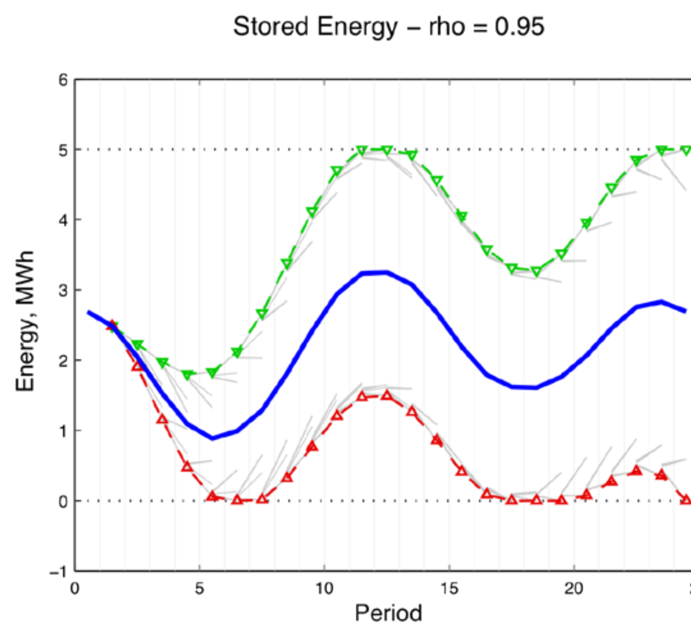

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

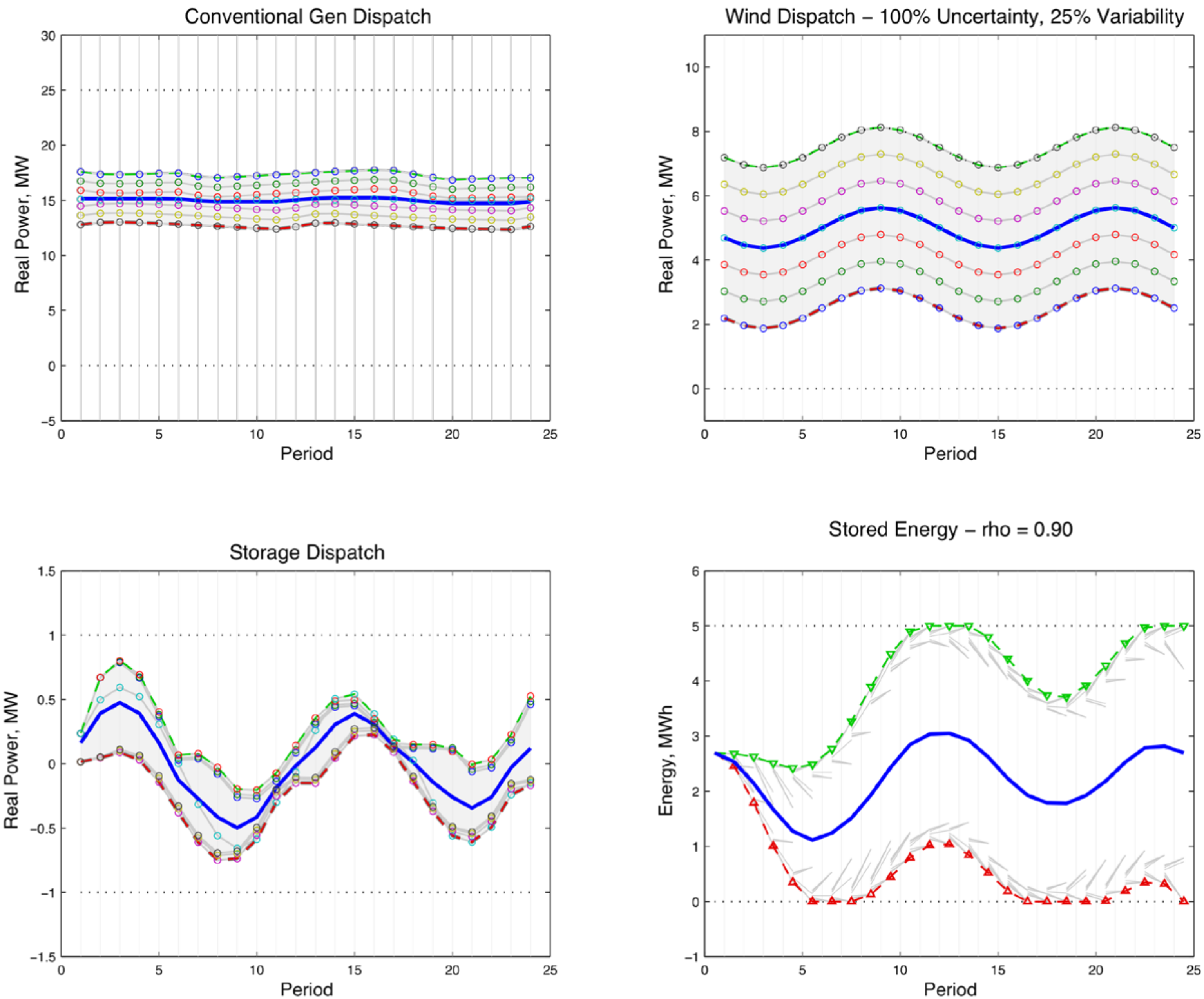

Stored Energy – rho = 0.98
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


Conventional Gen Dispatch
Real Power, MW
Period

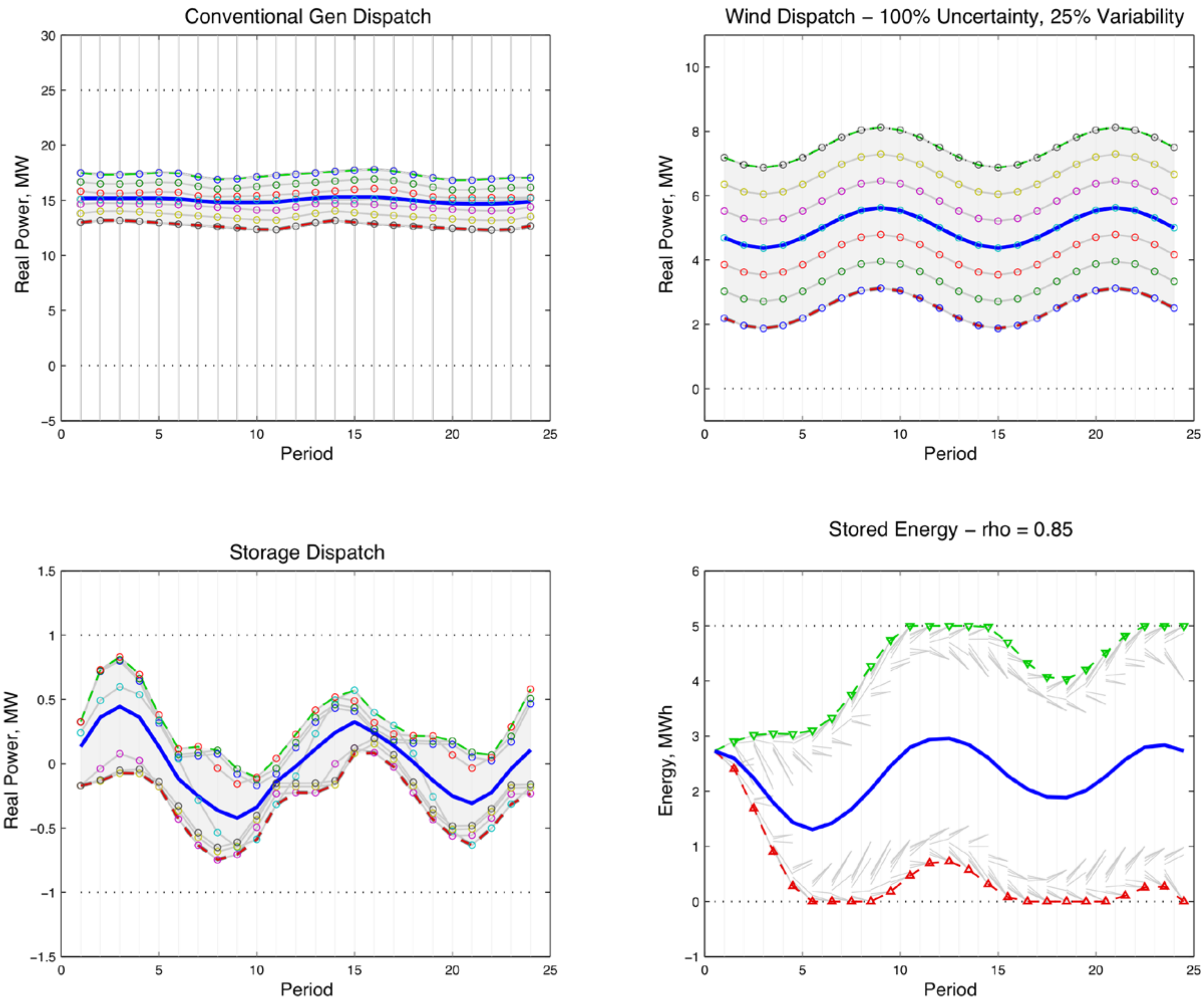

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period

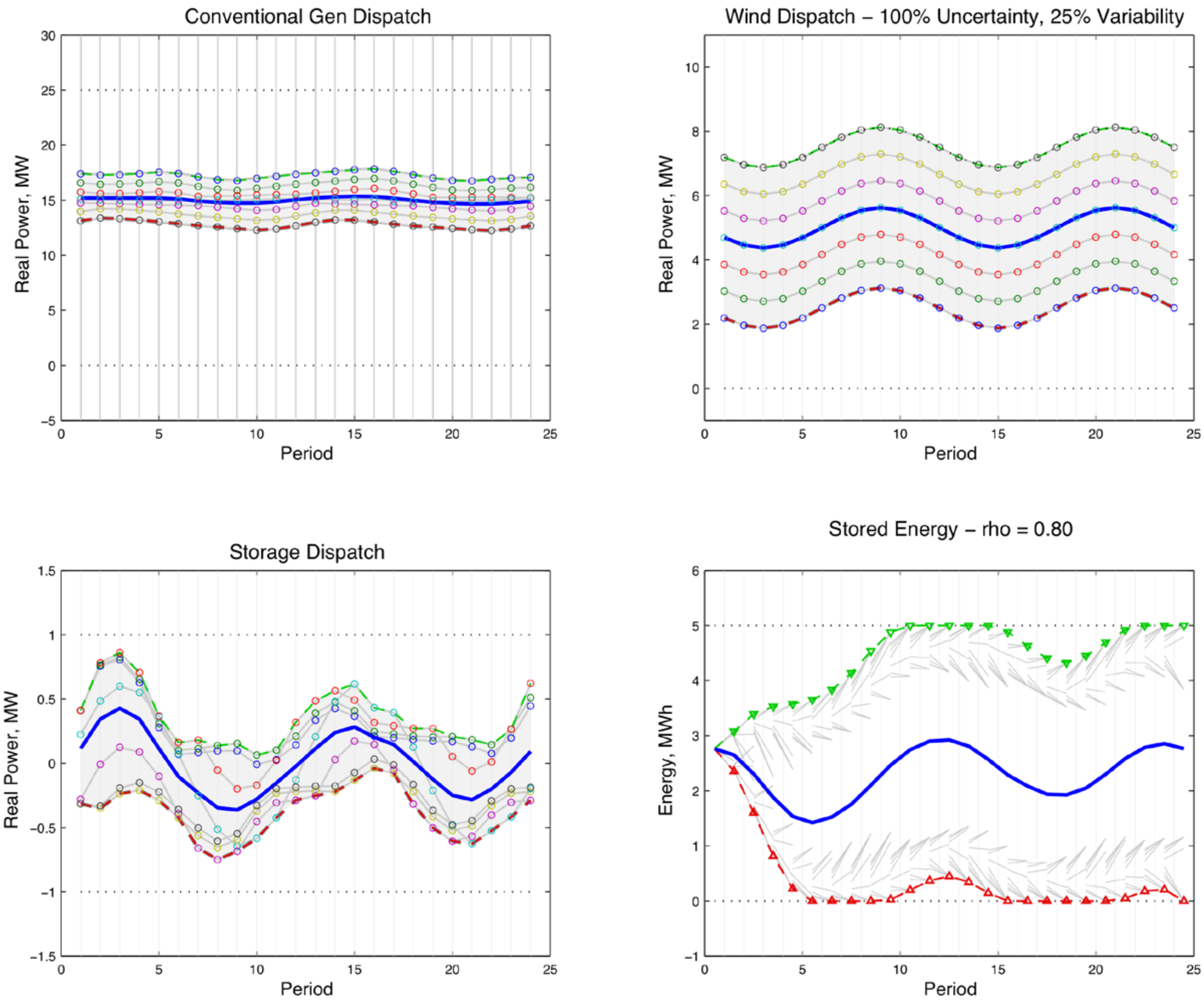

Storage Dispatch
Real Power, MW
Period

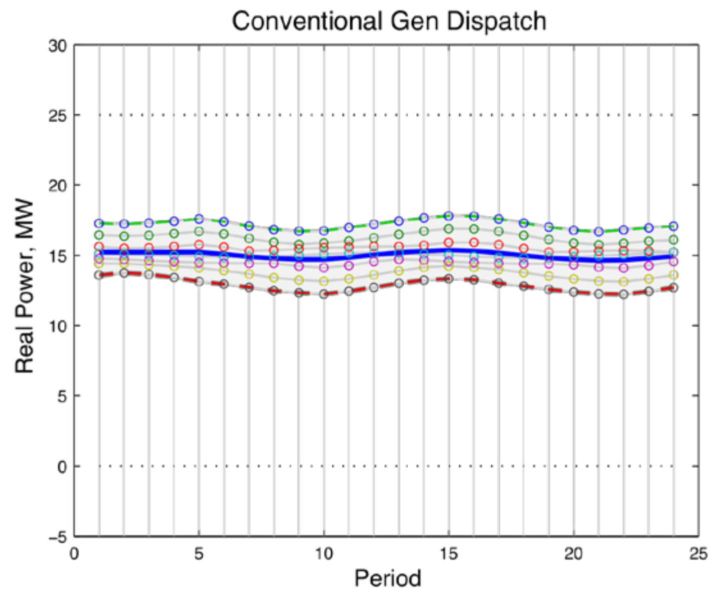

Stored Energy – rho = 0.95
Energy, MWh
Period

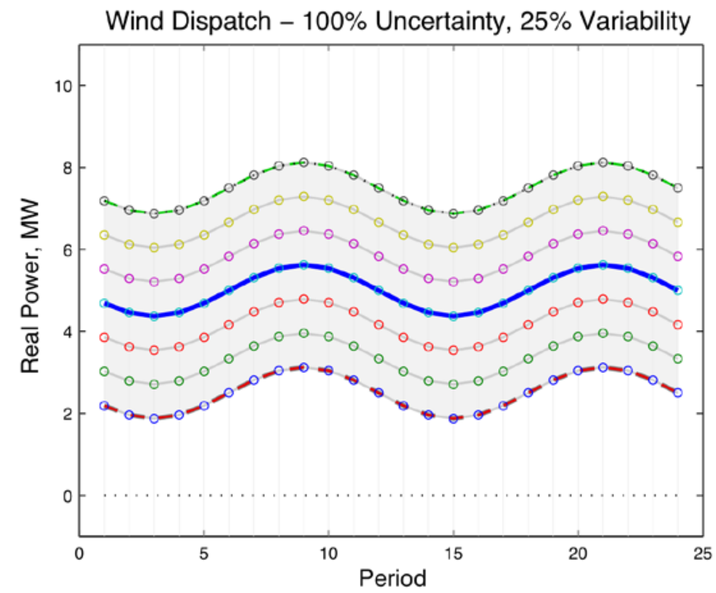


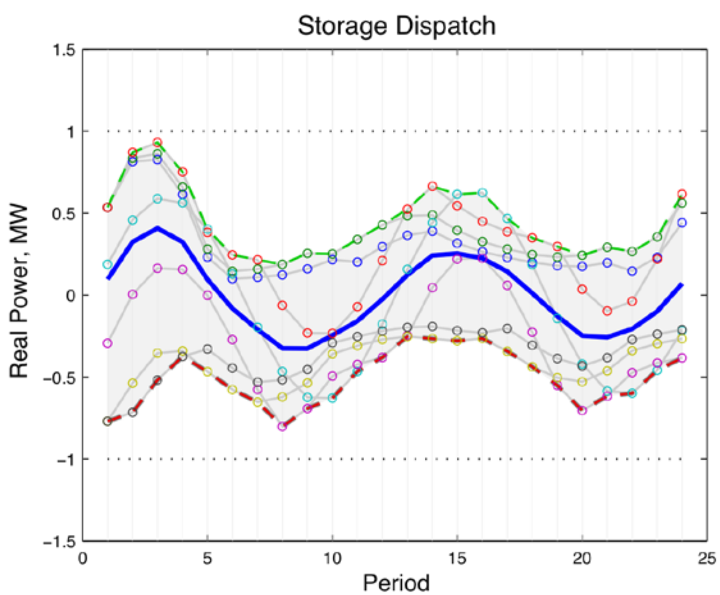
Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 0.90
Energy, MWh
Period

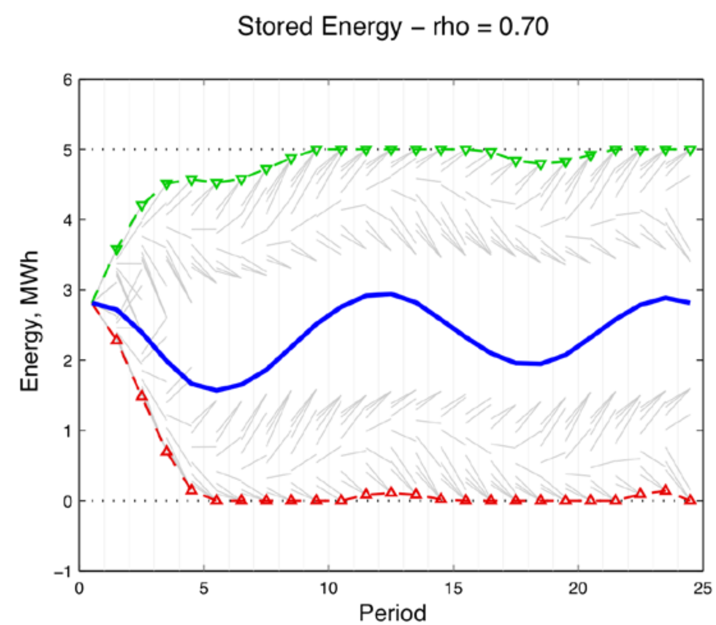

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 0.85
Energy, MWh
Period

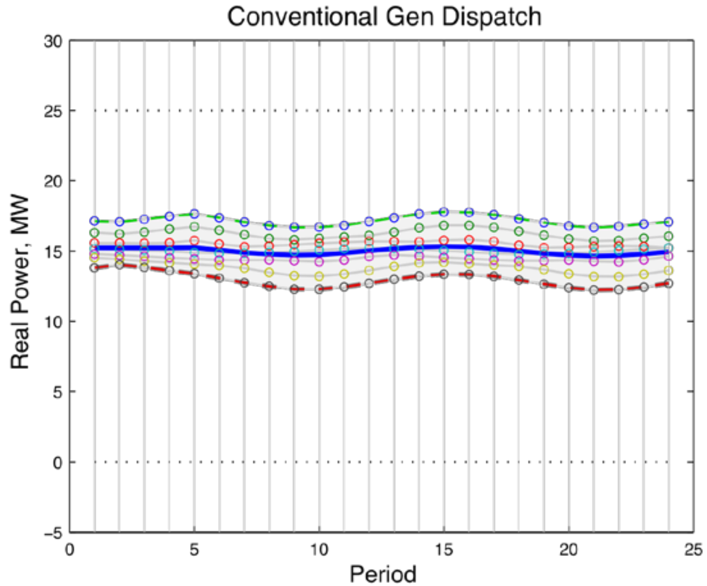

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 0.80
Energy, MWh
Period

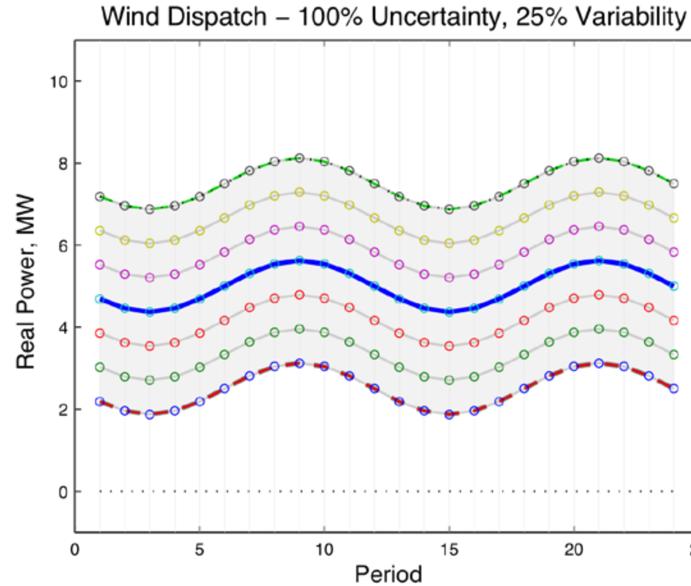

Conventional Gen Dispatch
Real Power, MW
Period

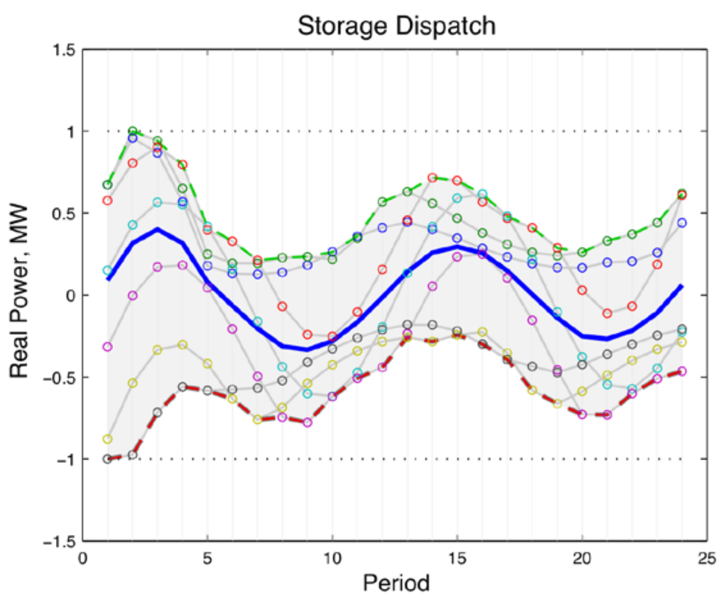

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period

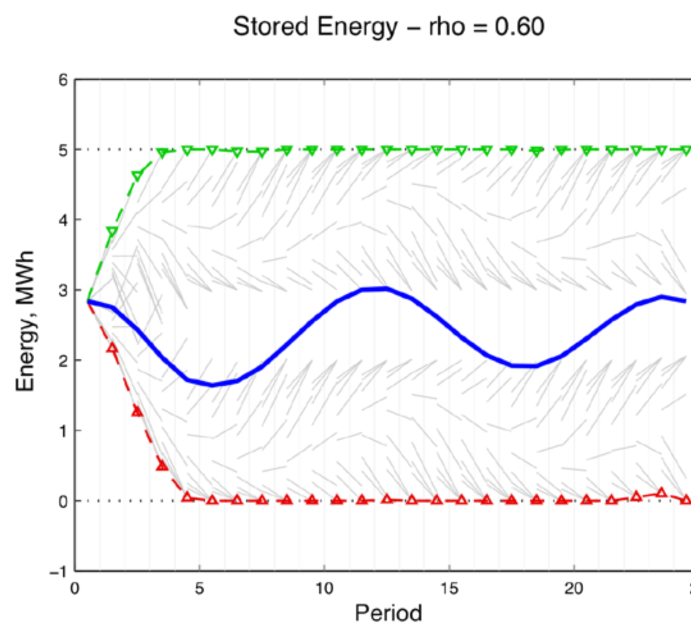

Storage Dispatch
Real Power, MW
Period

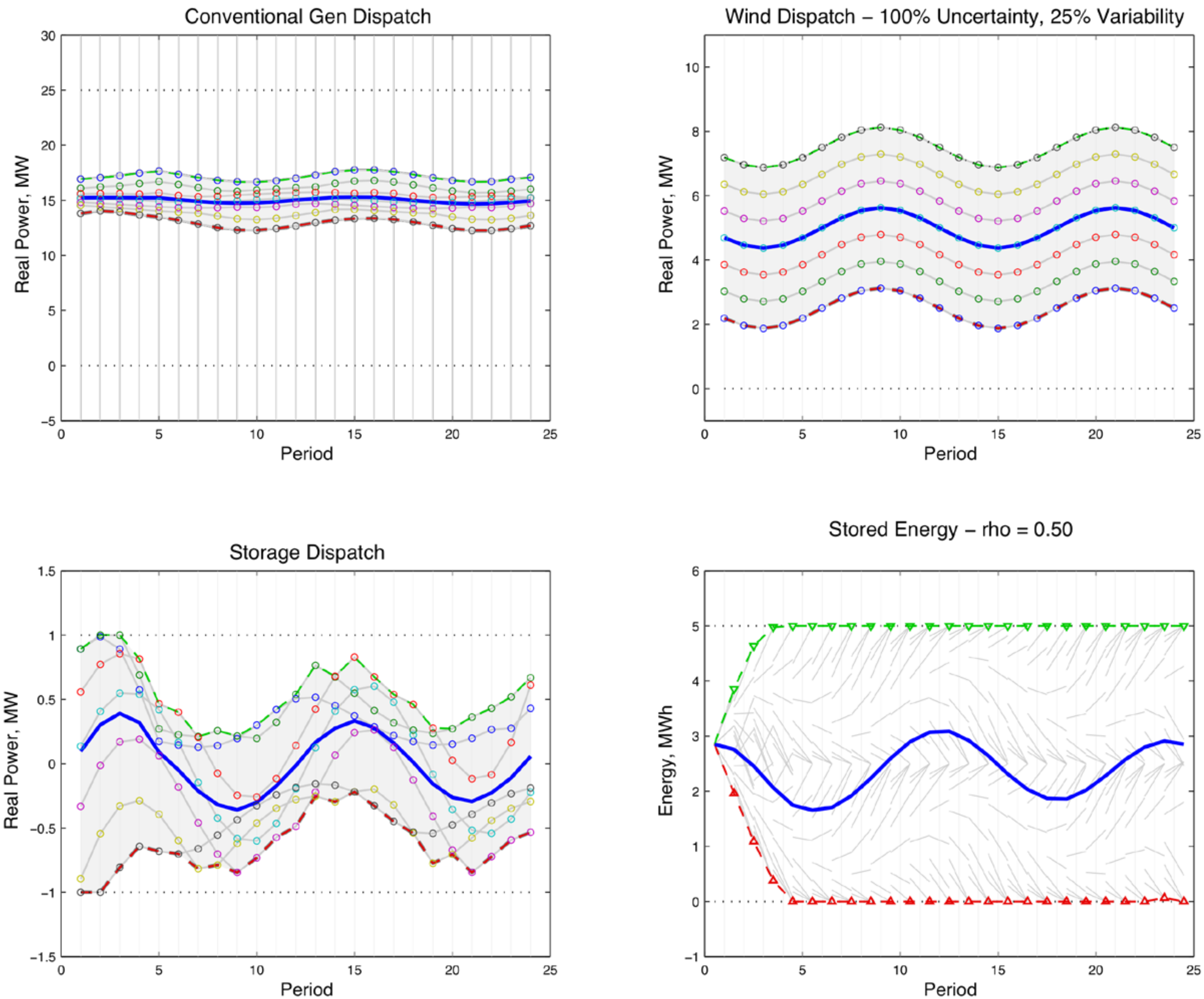

Stored Energy – rho = 0.70
Energy, MWh
Period

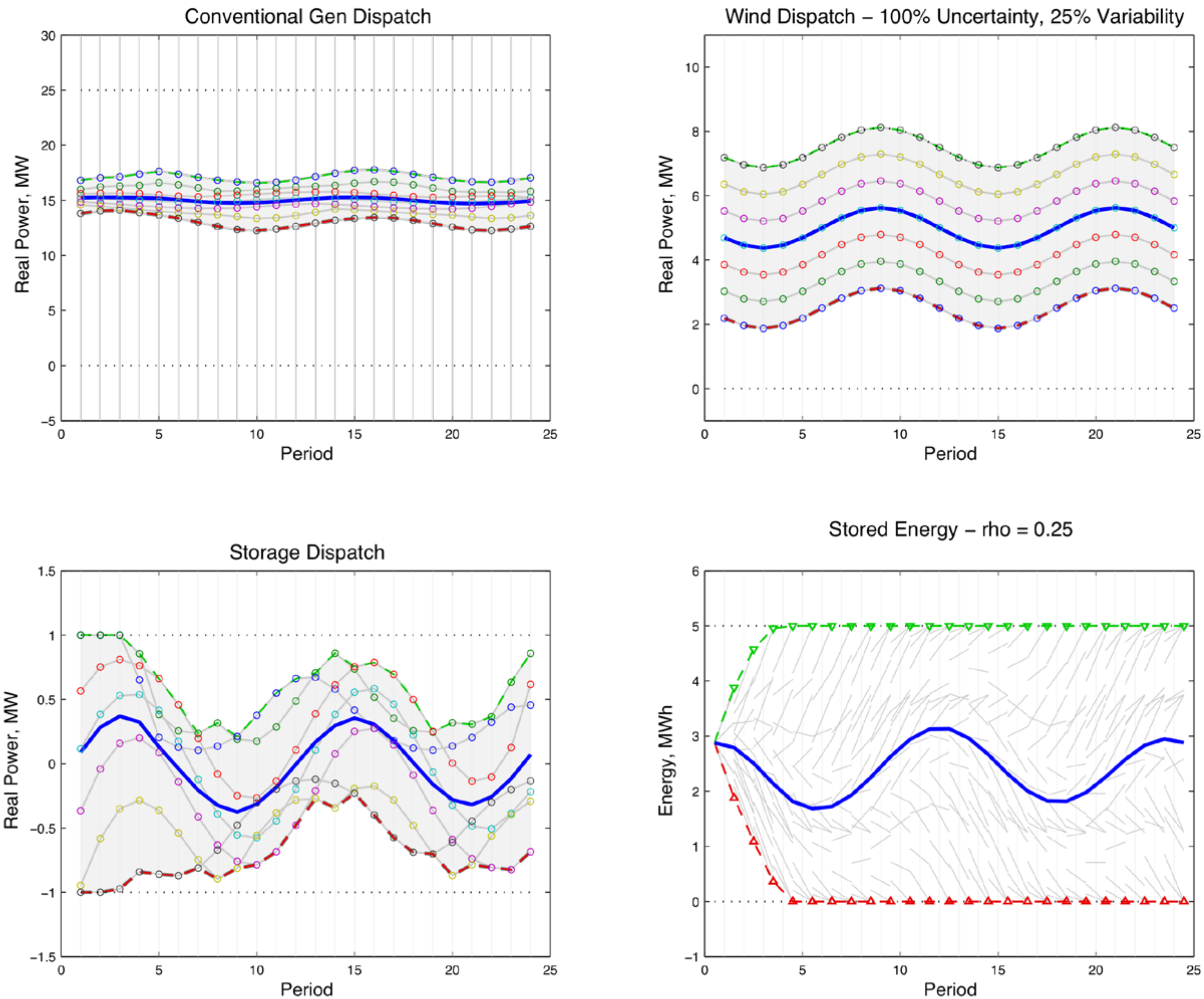

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

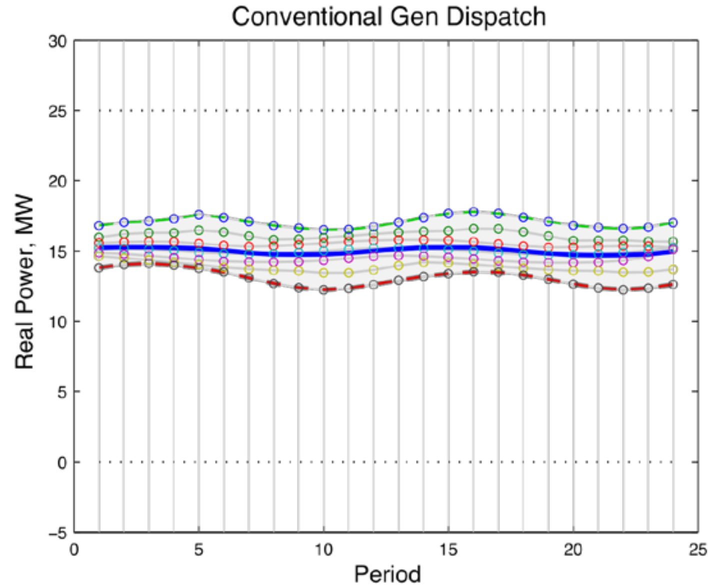

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

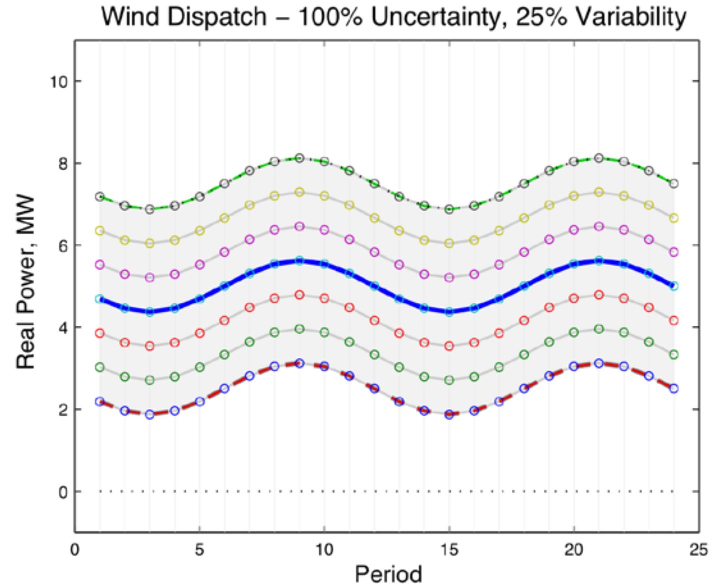

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

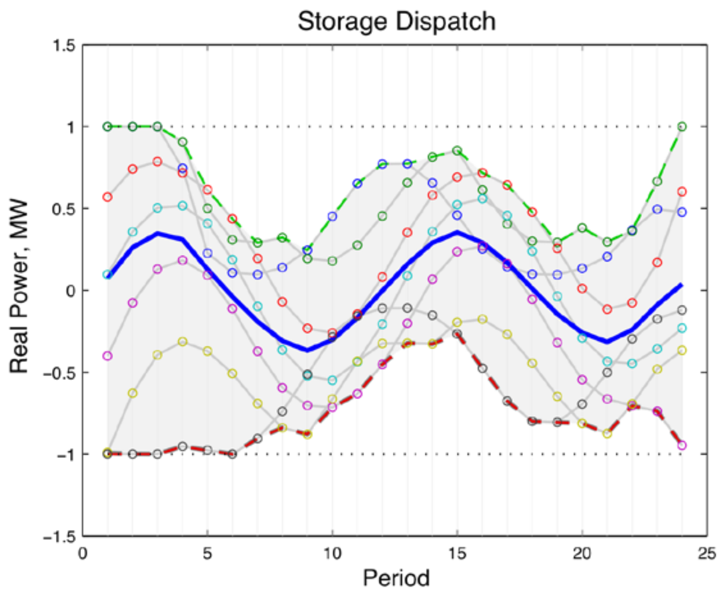

Stored Energy – rho = 0.60
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

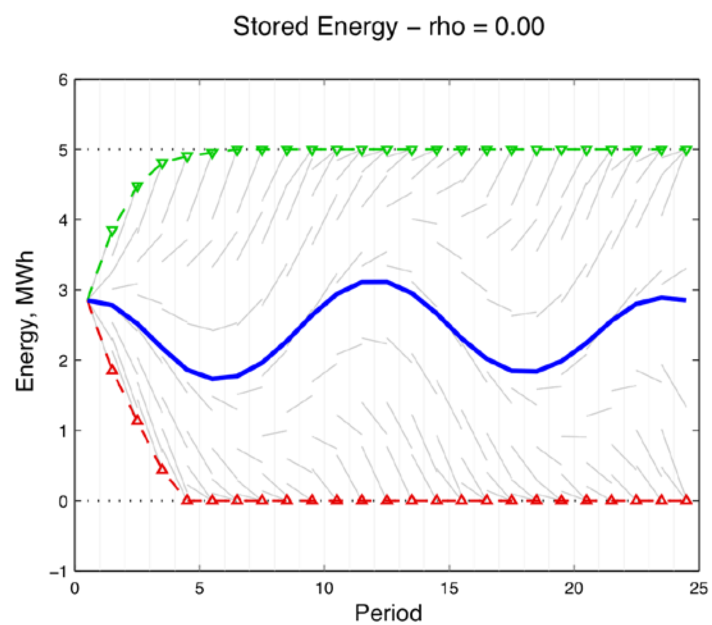

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 0.50
Energy, MWh
Period


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – rho = 0.25
Energy, MWh
Period


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

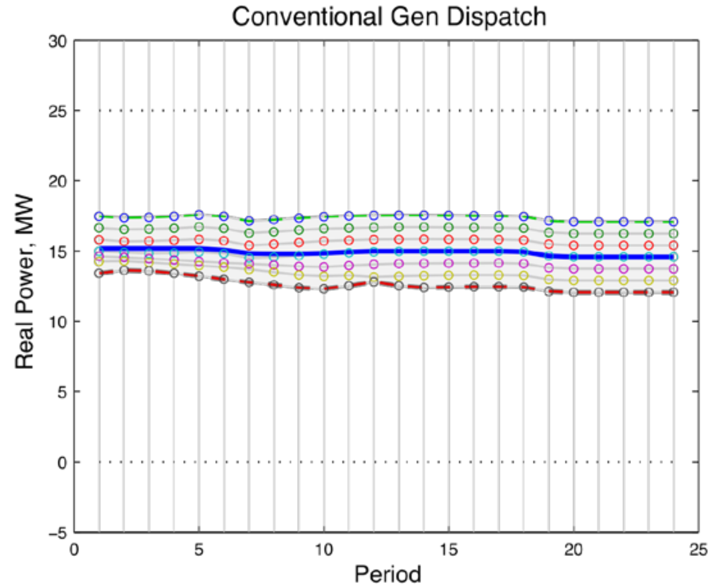

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

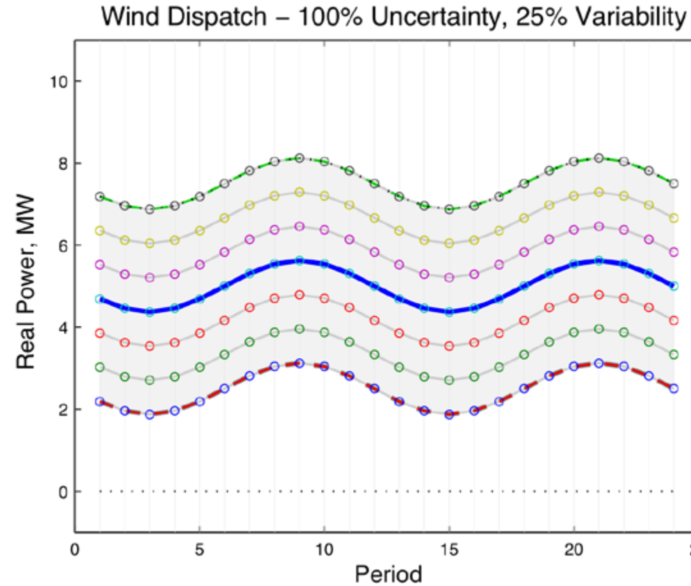

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

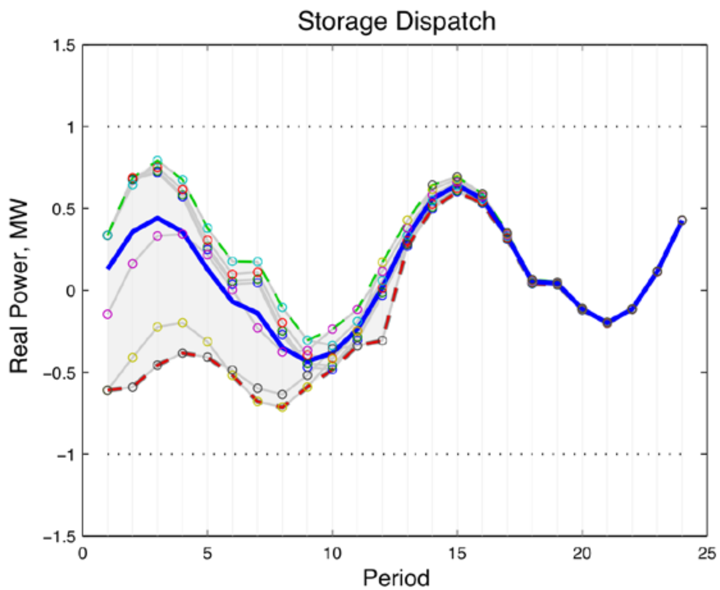

Stored Energy – rho = 0.00
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

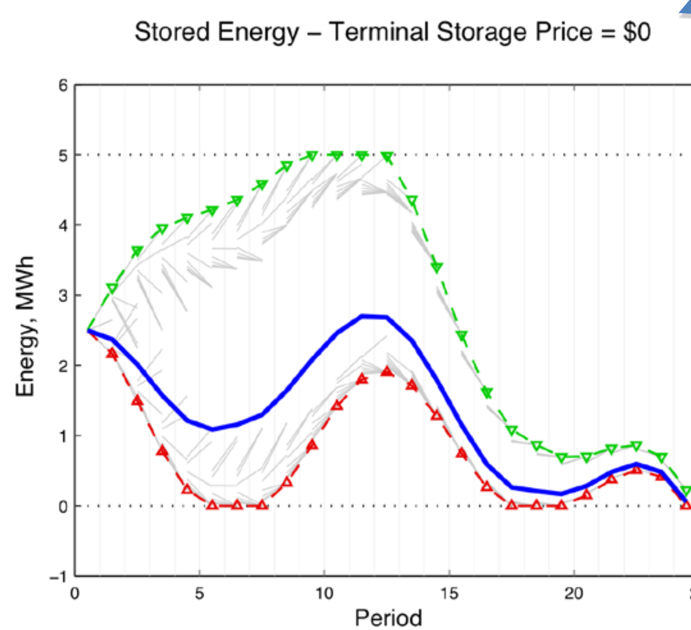
Value of Leftover Storage in Terminal States

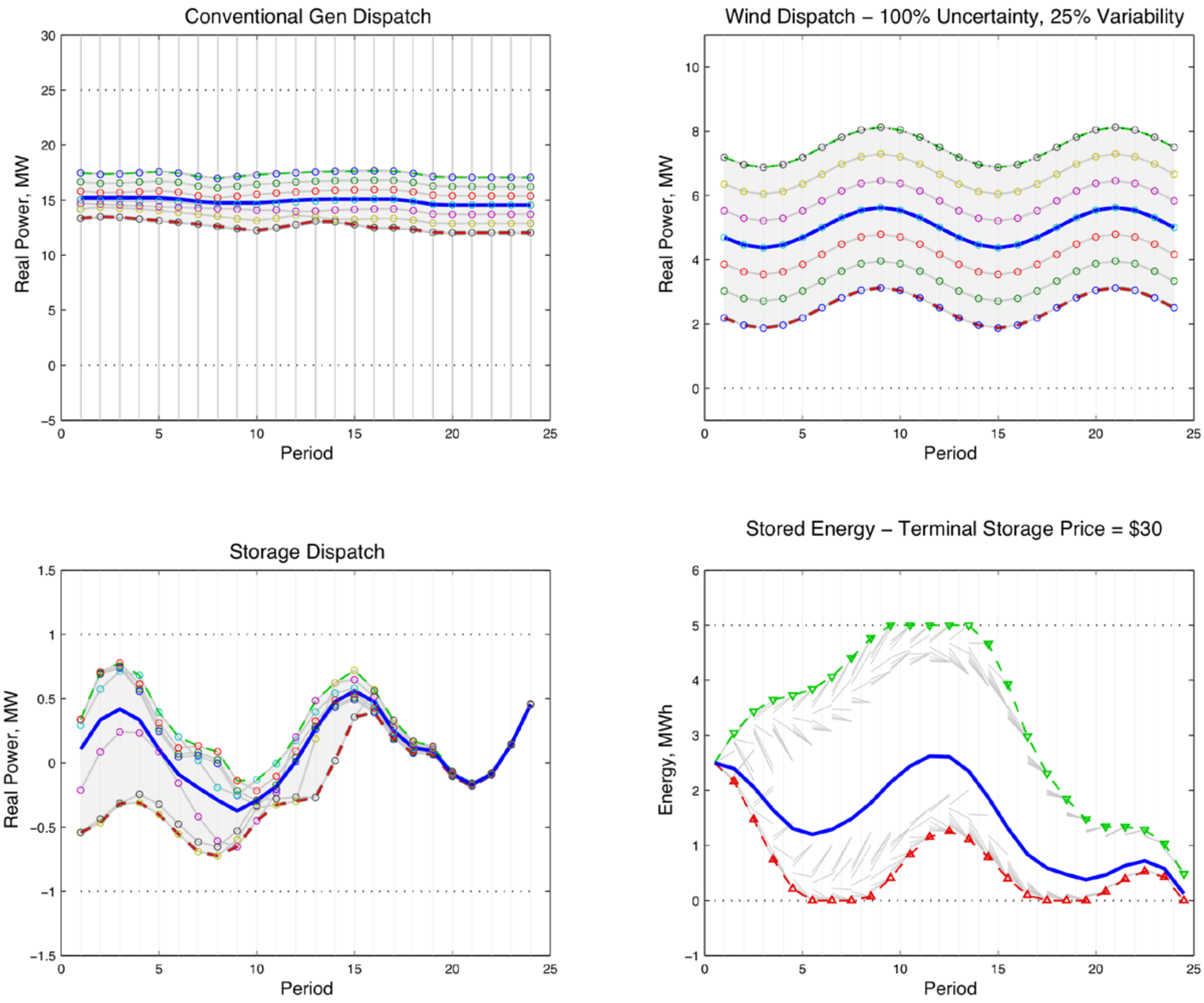
- 5 price model, allowing to specify a unique value for each of the following 5 types of contributions to the total expected value of leftover stored energy:
  - charging or discharging in non-terminal states
  - charging in terminal end-of-horizon base states
  - discharging in terminal end-of-horizon base states
  - charging in terminal contingency states
  - discharging in terminal contingency states
- optional cyclic storage constraint
  - initial stored energy is a variable, constrained to equal expected final stored energy
- optional target constraint for expected stored energy

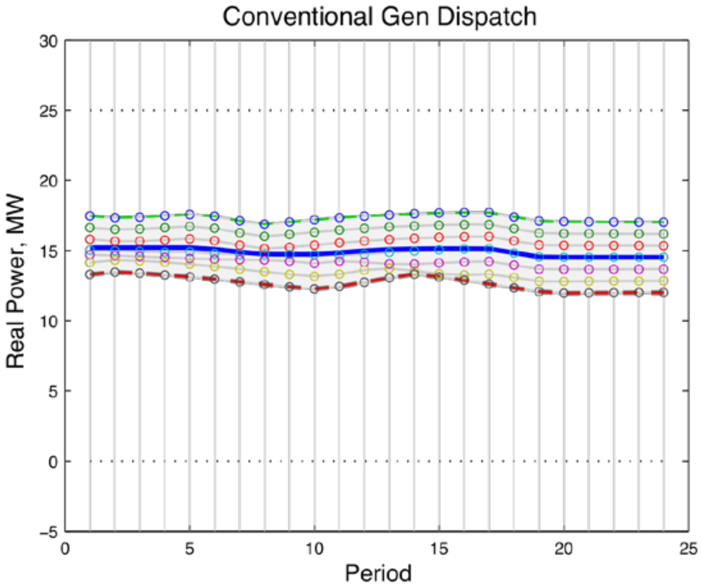

Conventional Gen Dispatch
Real Power, MW
Period

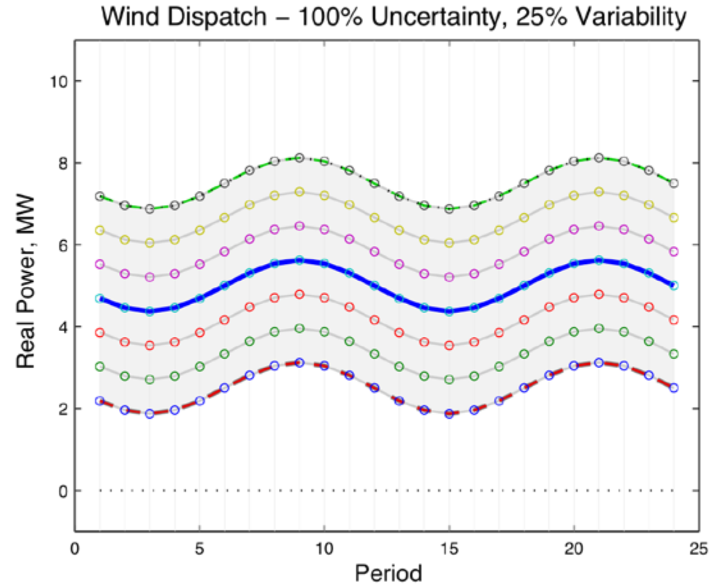

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period

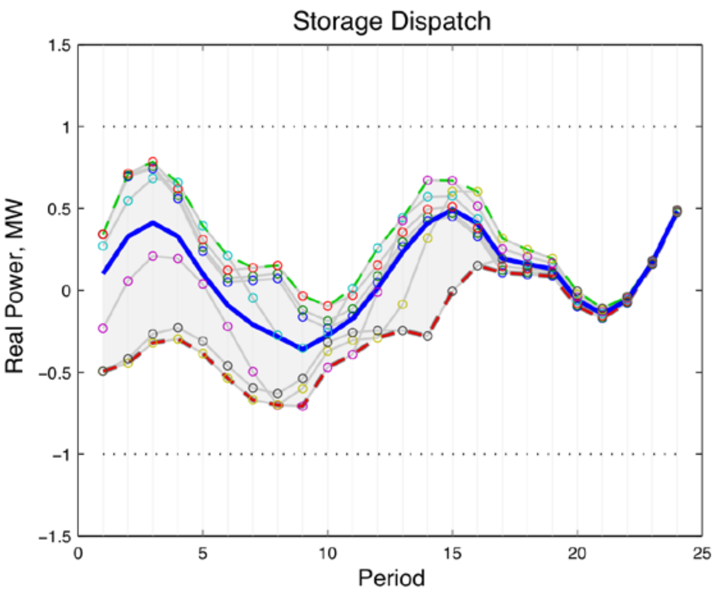

Storage Dispatch
Real Power, MW
Period

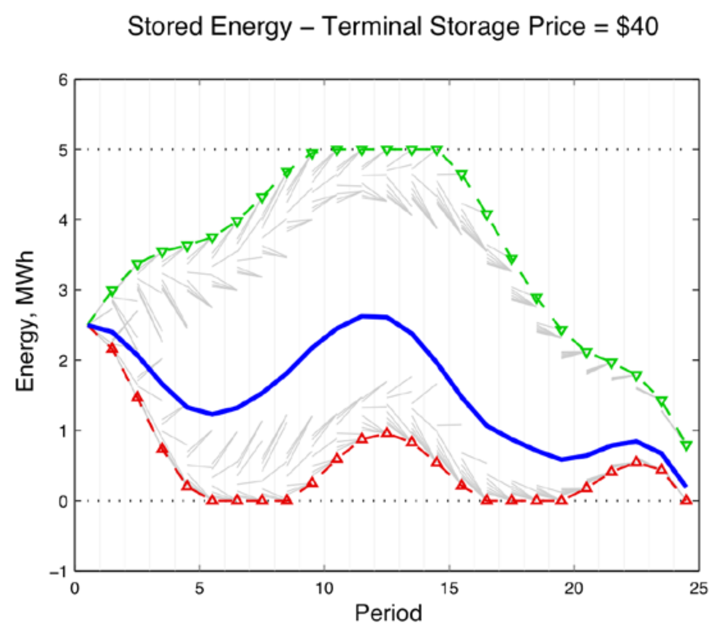

Stored Energy – Terminal Storage Price = $0
Energy, MWh
Period

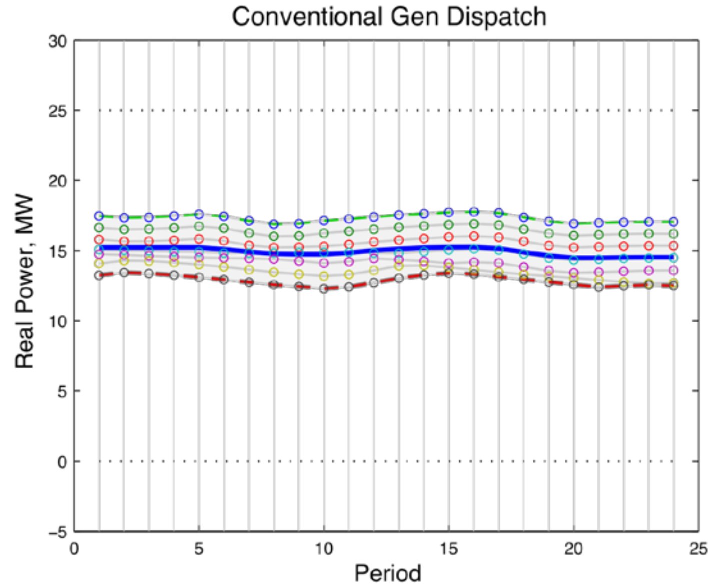

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Terminal Storage Price = $30
Energy, MWh
Period

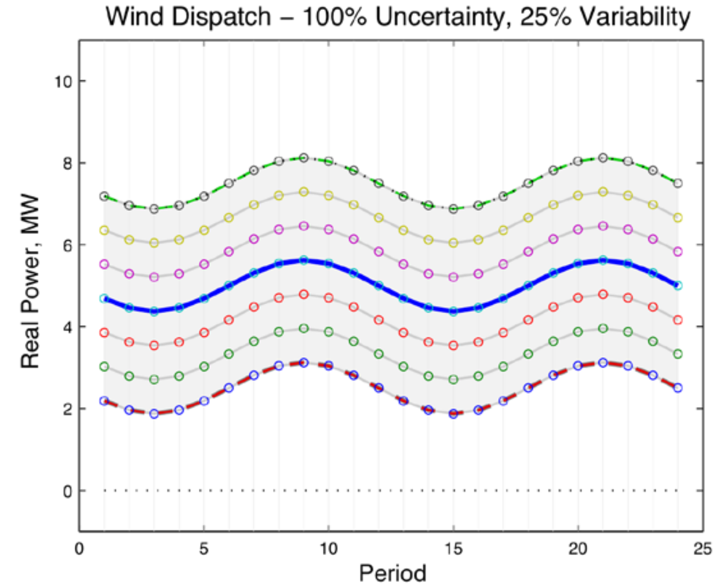

Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25

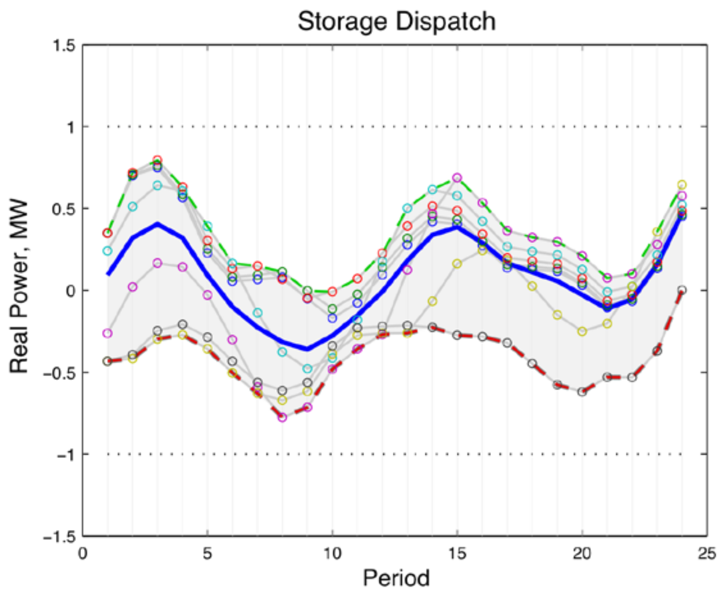

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

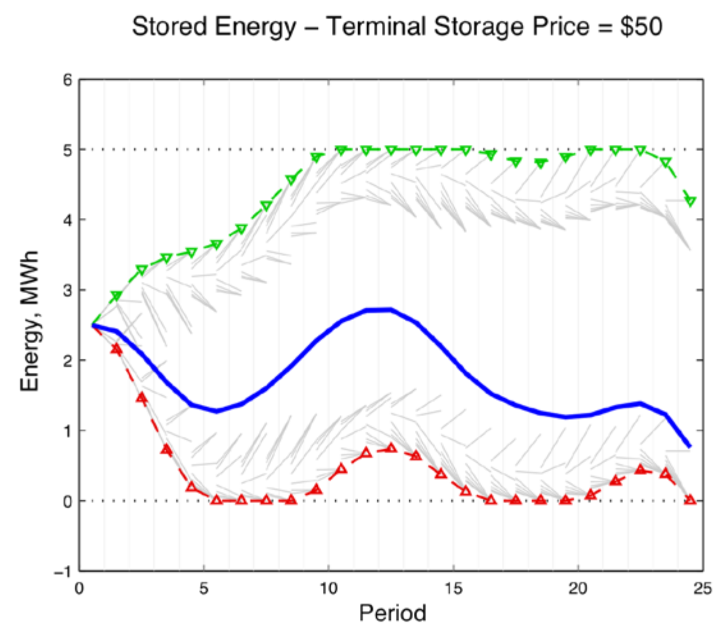

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

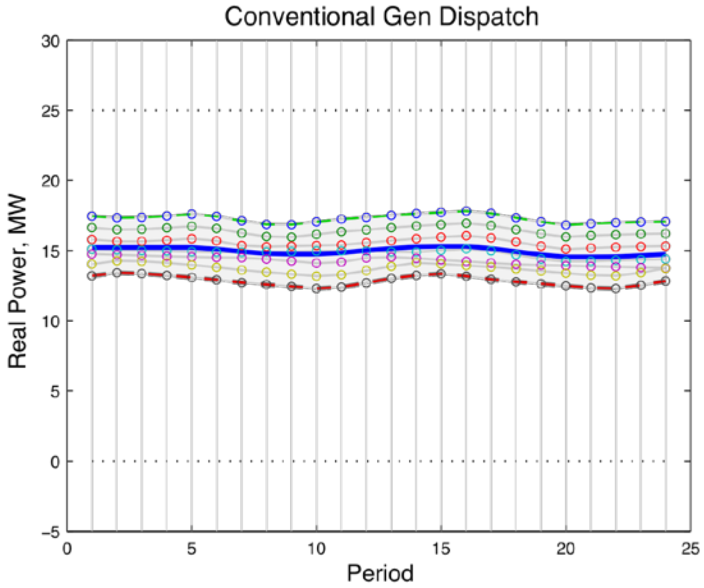

Stored Energy – Terminal Storage Price = $40
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

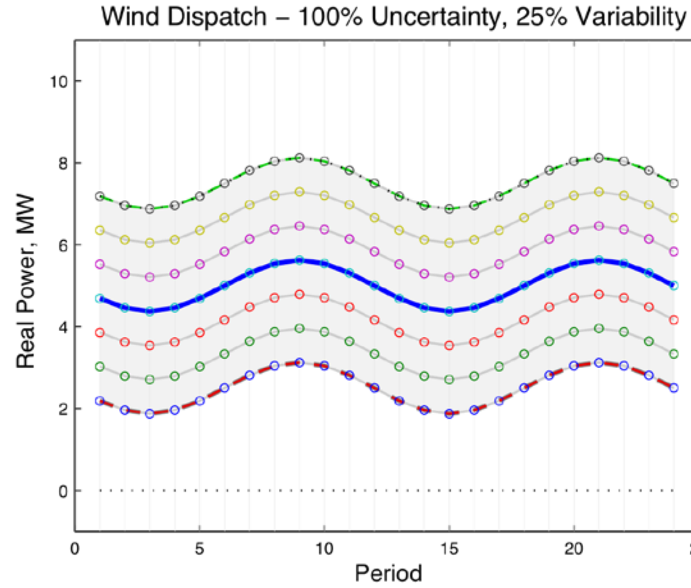

Conventional Gen Dispatch
Real Power, MW
30
25
20
15
10
5
0
−5
0
5
10
15
20
25
Period

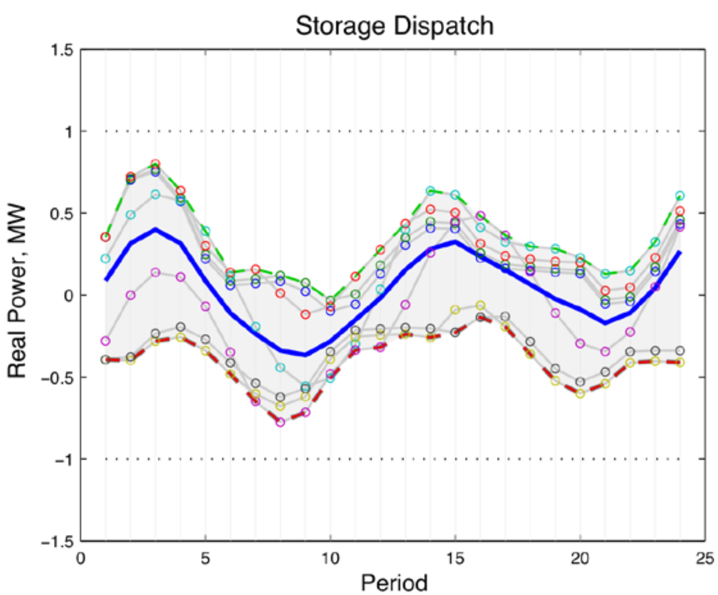

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
10
8
6
4
2
0
0
5
10
15
20
25
Period

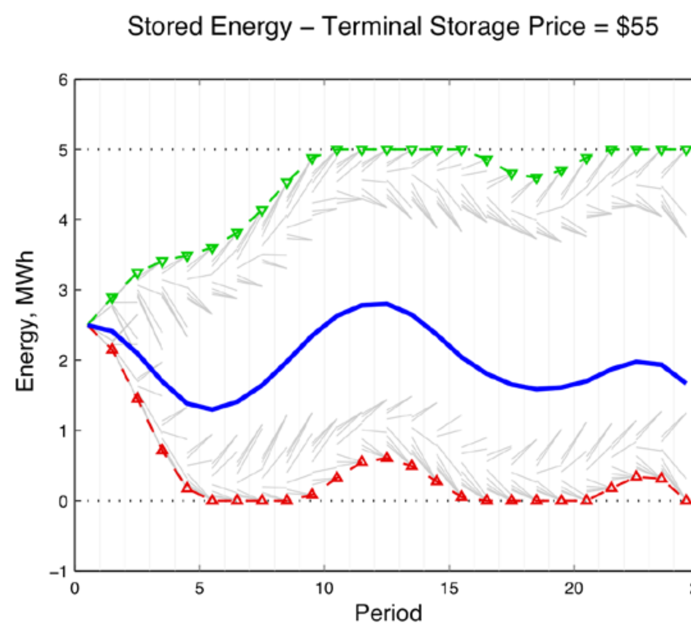

Storage Dispatch
Real Power, MW
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25
Period

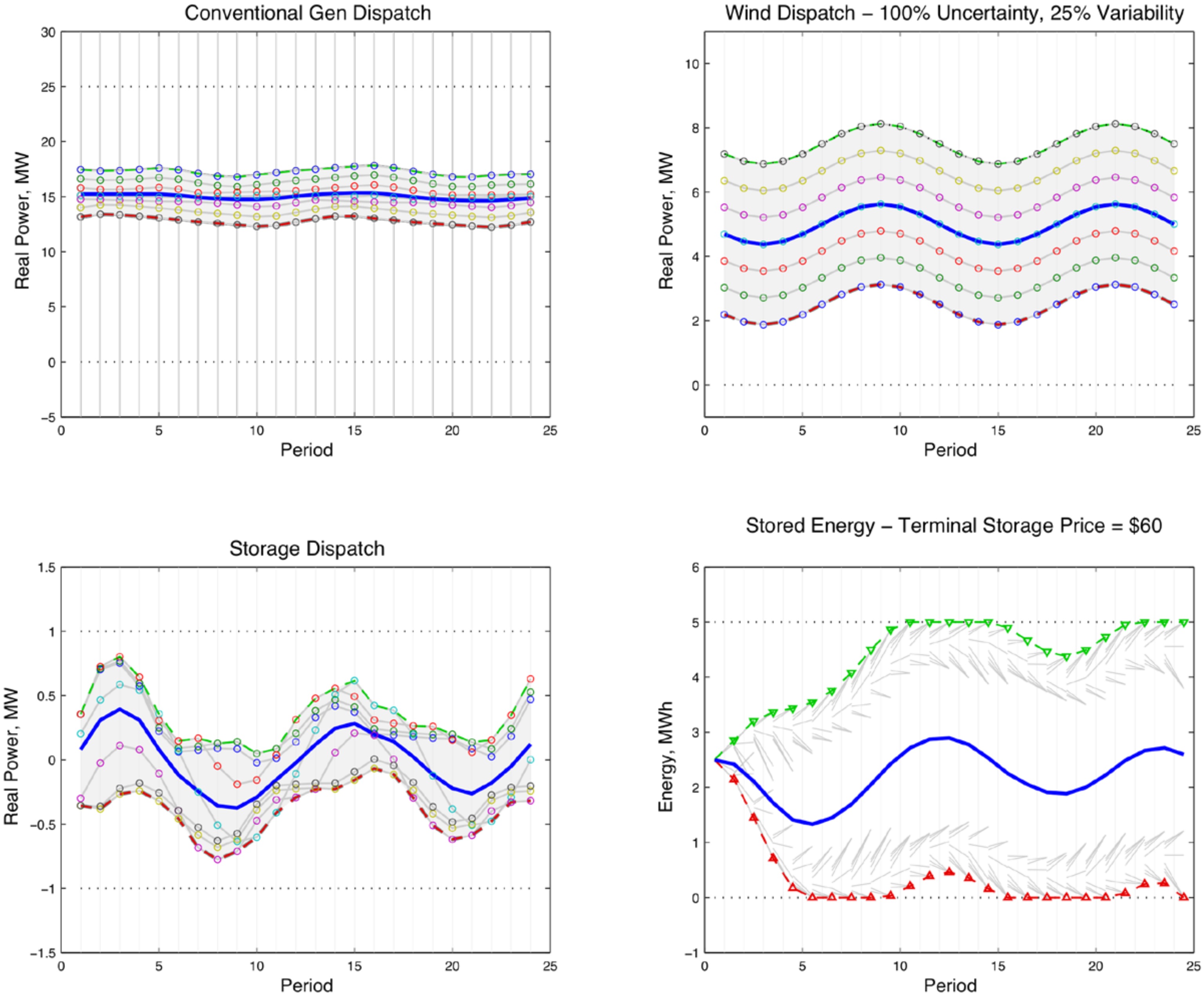

Stored Energy – Terminal Storage Price = $50
Energy, MWh
6
5
4
3
2
1
0
−1
0
5
10
15
20
25
Period


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

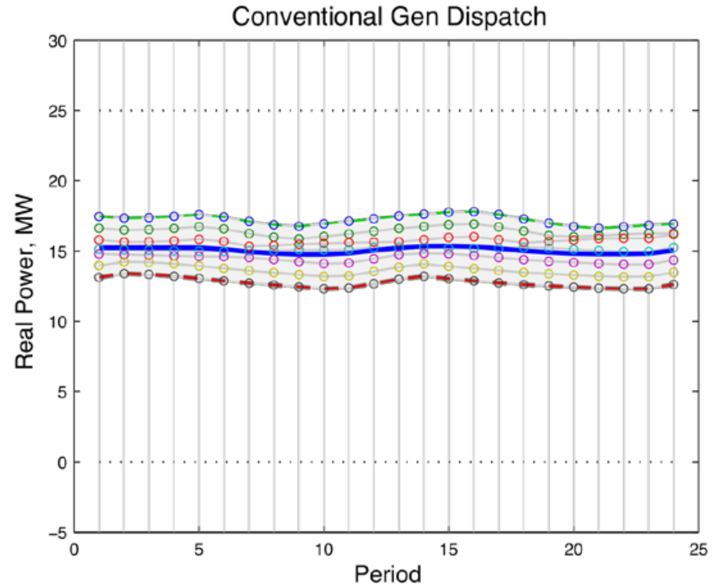

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
10
8
6
4
2
0
0
5
10
15
20
25
Period


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

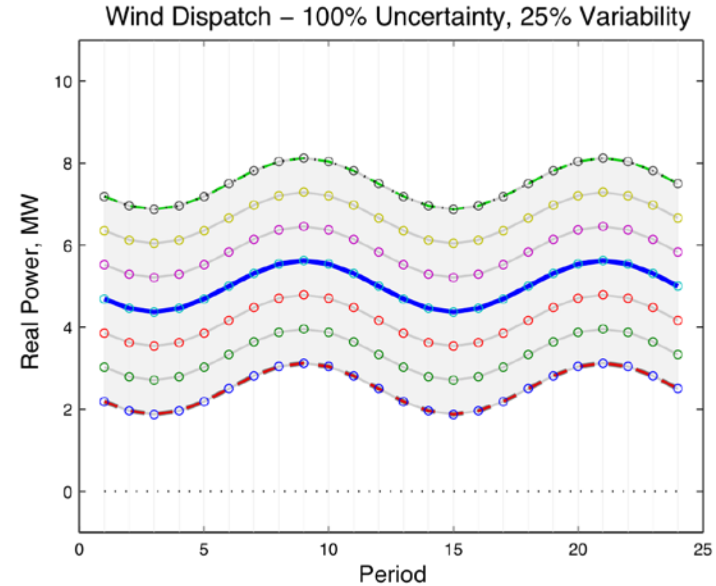

Stored Energy – Terminal Storage Price = $55
Energy, MWh
6
5
4
3
2
1
0
−1
0
5
10
15
20
25
Period



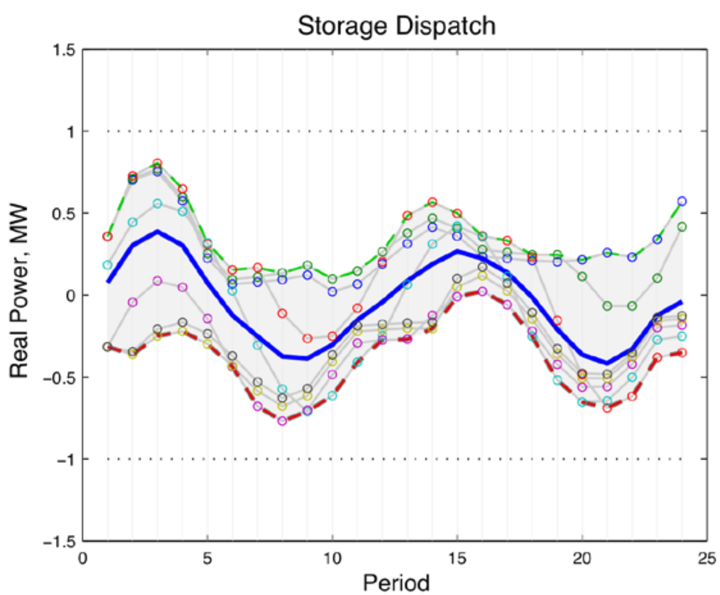
Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Terminal Storage Price = $60
Energy, MWh
Period



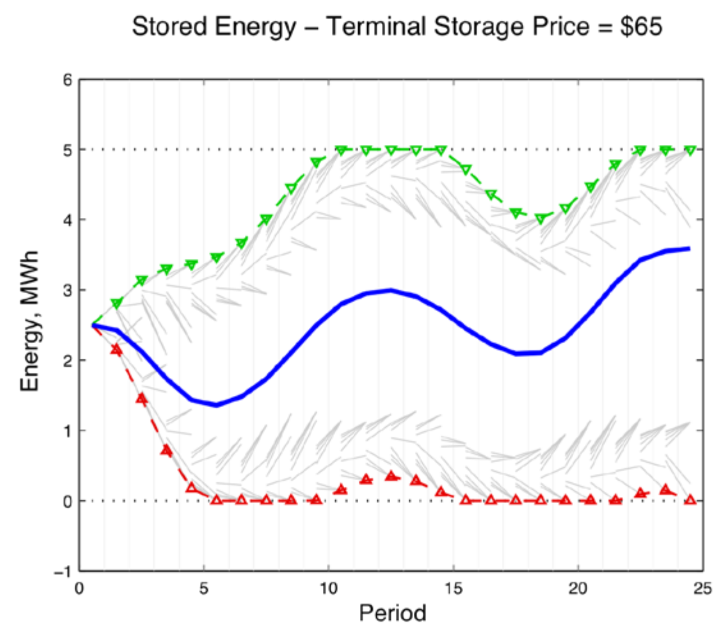
Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25



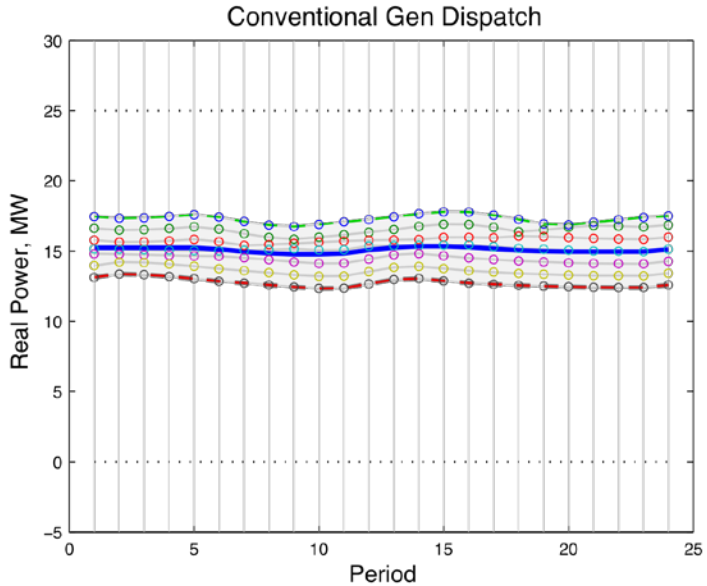
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

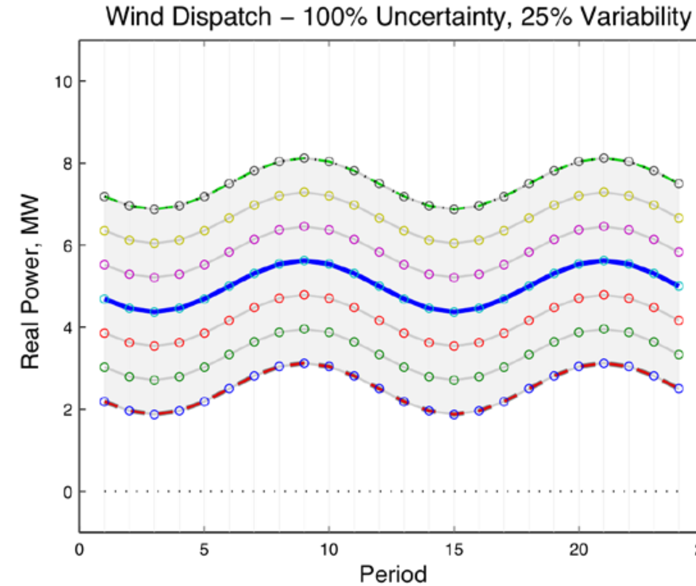


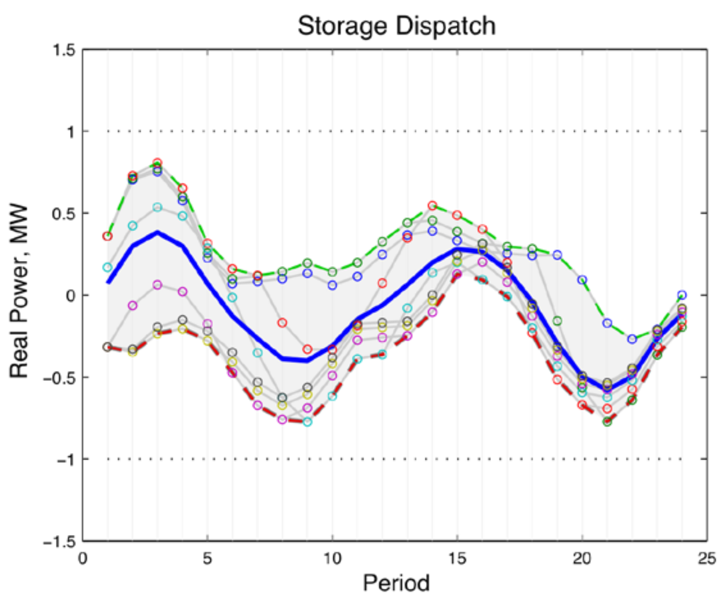
Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

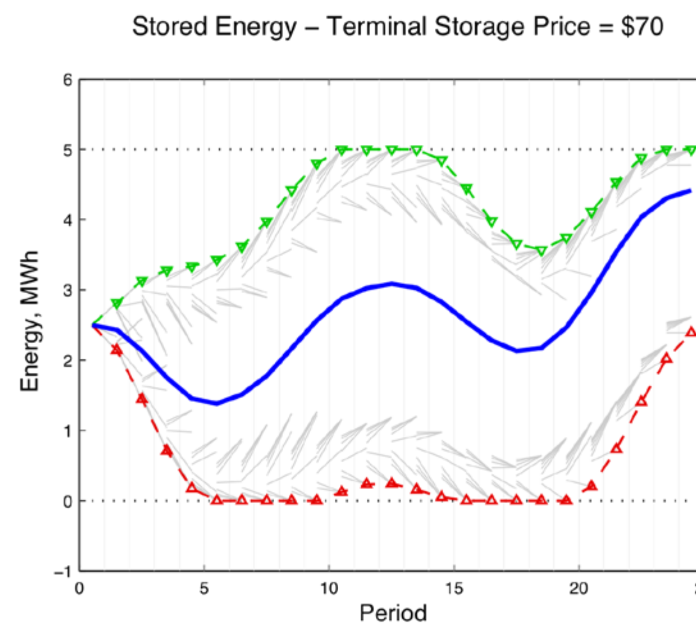


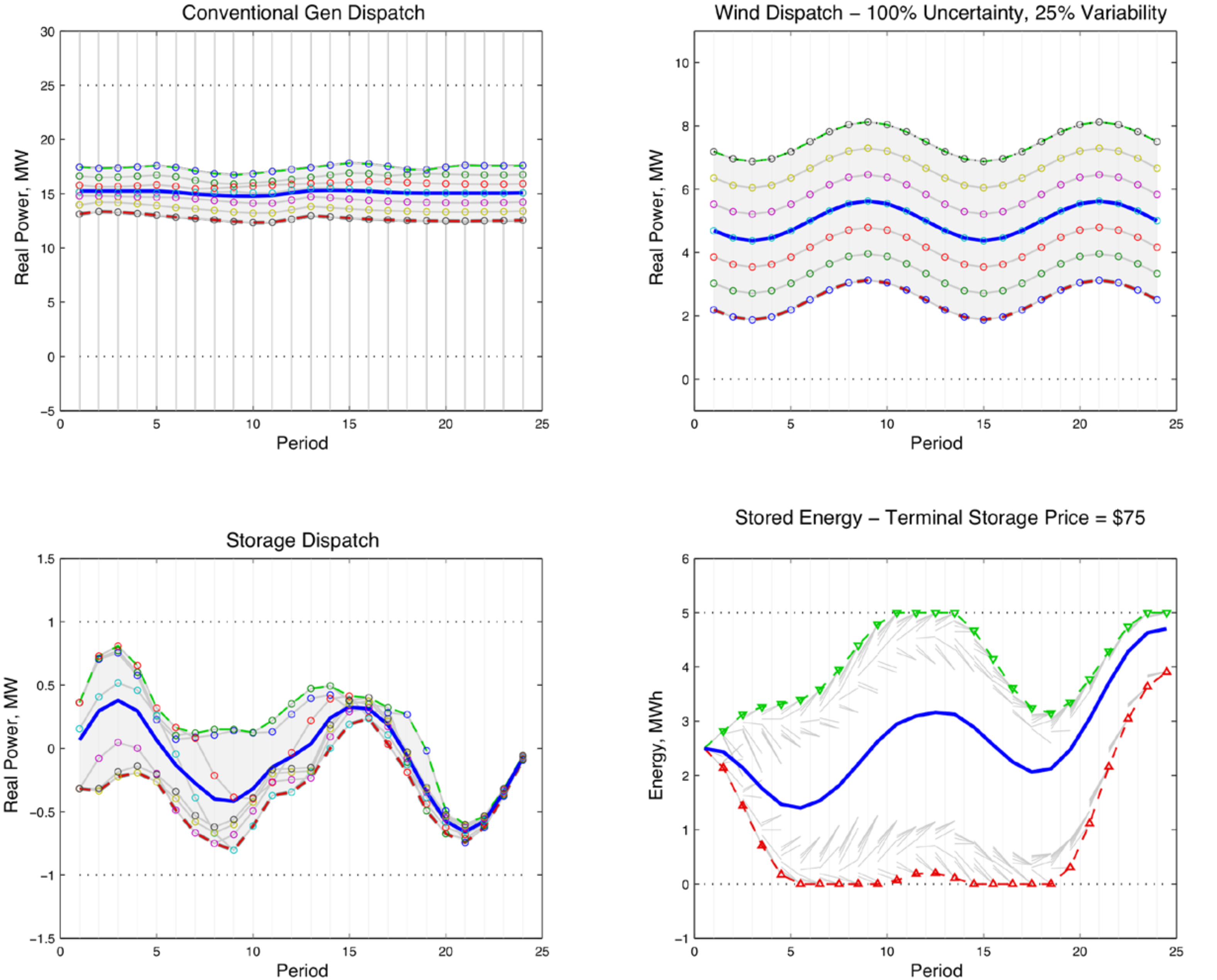
Stored Energy – Terminal Storage Price = $65
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25


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

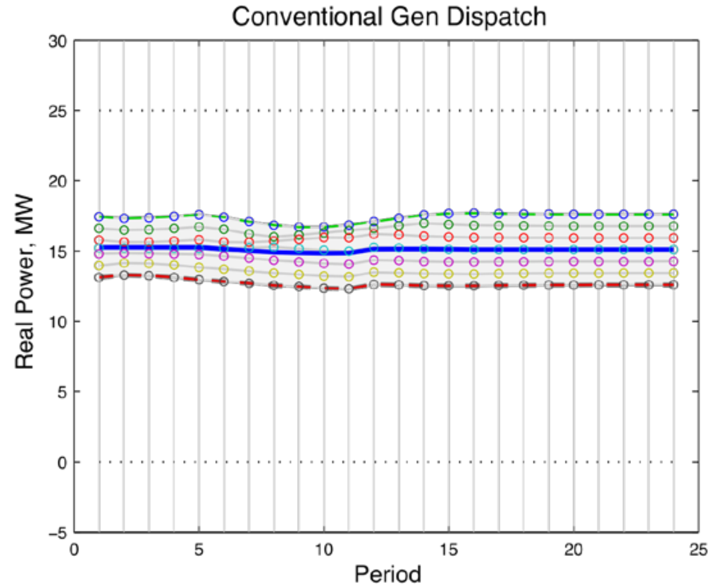

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

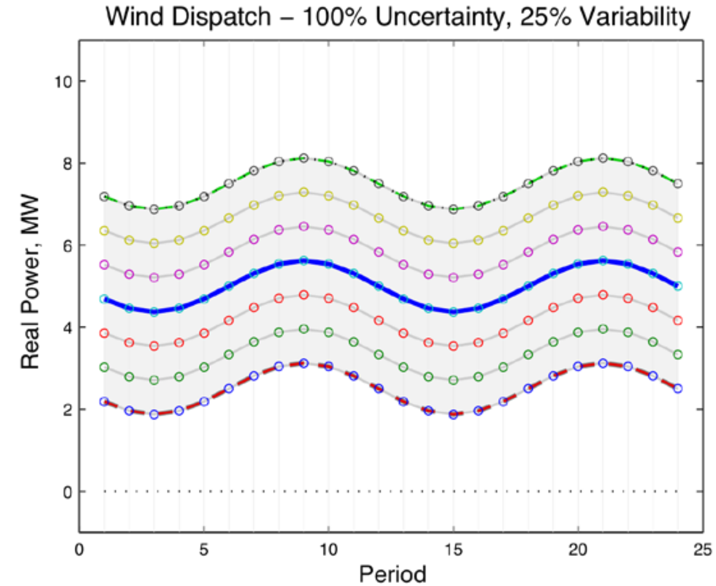

Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

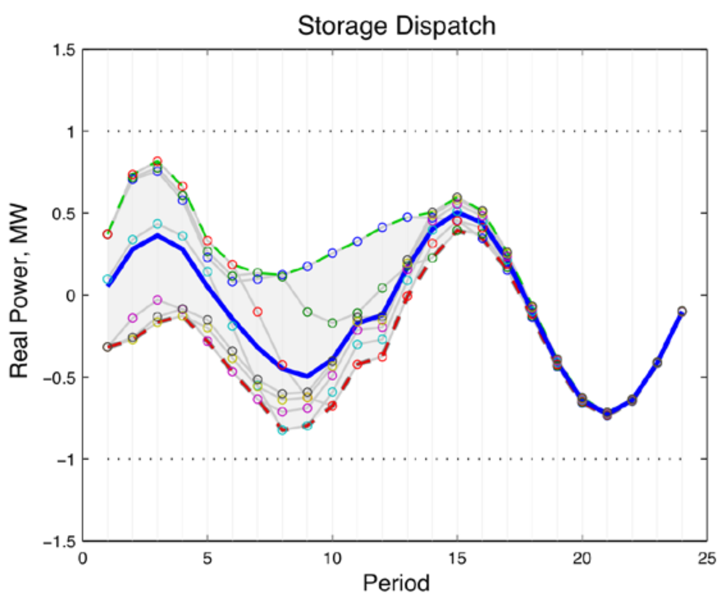

Stored Energy – Terminal Storage Price = $70
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

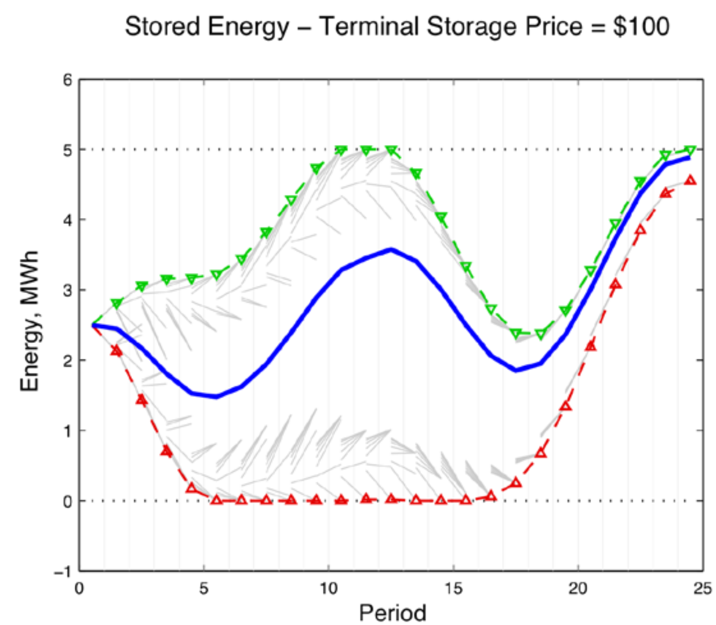


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Terminal Storage Price = $75
Energy, MWh
Period


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

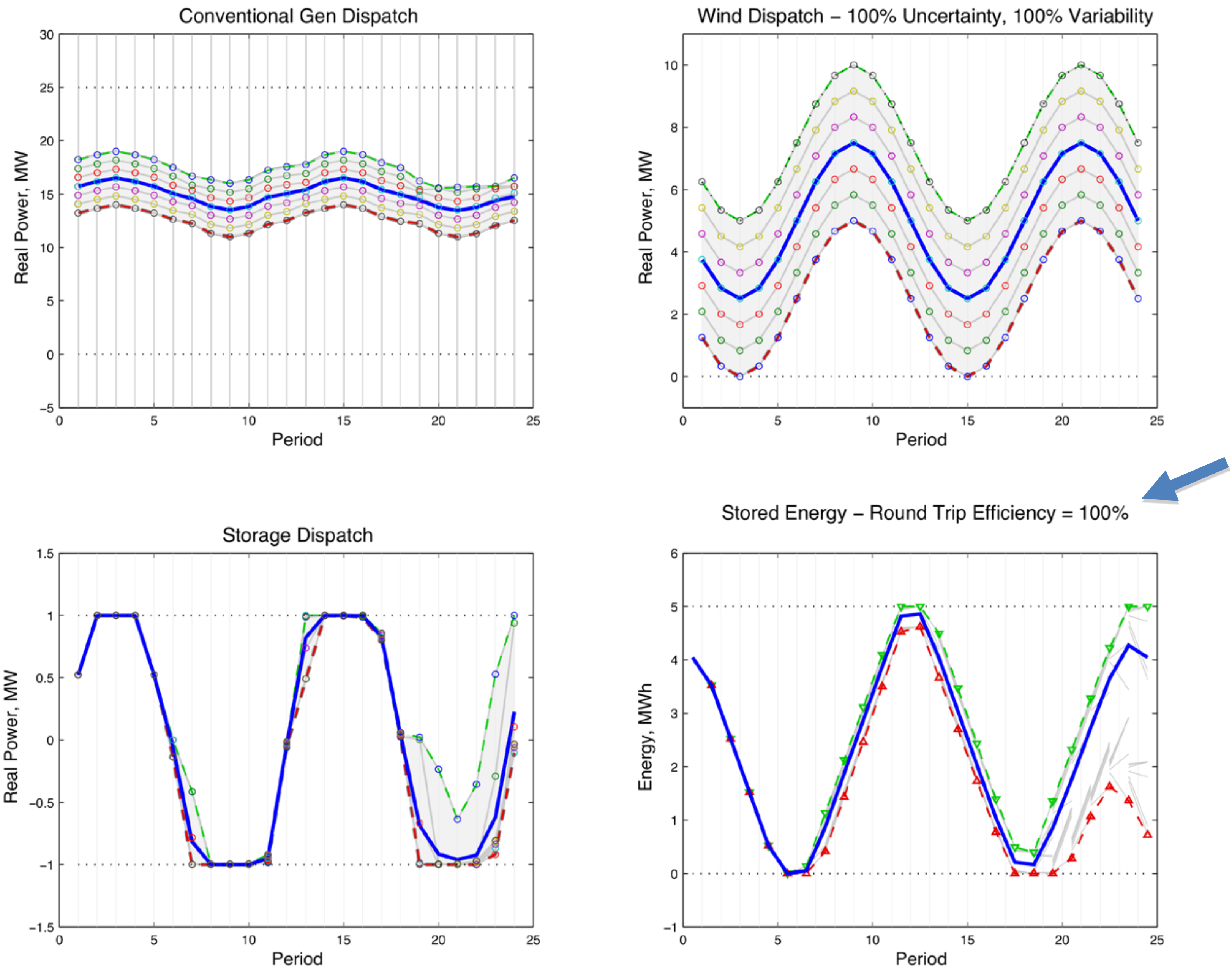

Wind Dispatch – 100% Uncertainty, 25% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25


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

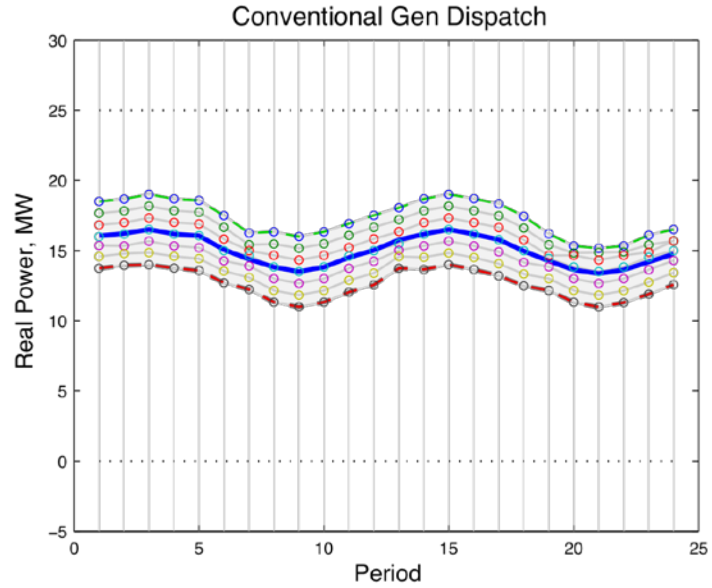

Stored Energy – Terminal Storage Price = $100
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

Storage Efficiency

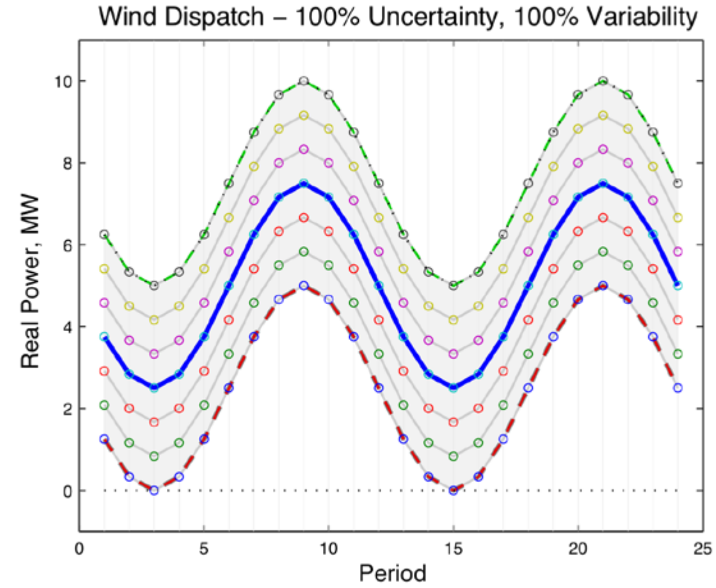
- input efficiency
- output efficiency
- losses



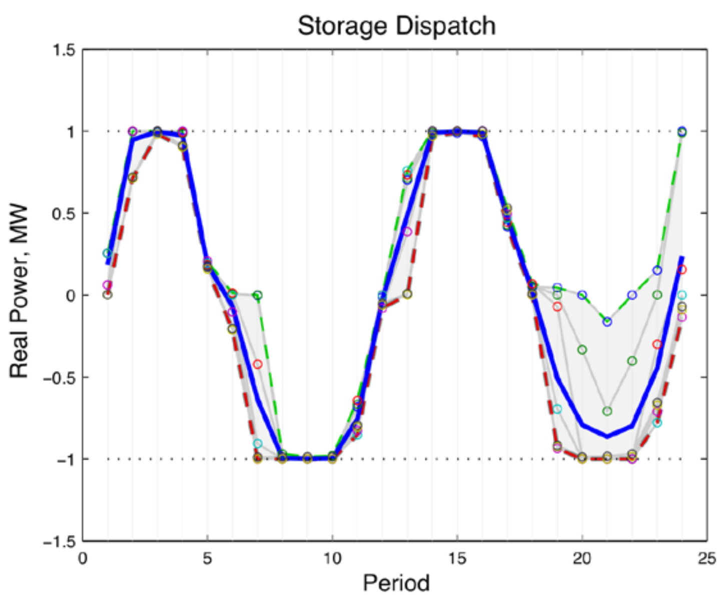
Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 100%
Energy, MWh
Period



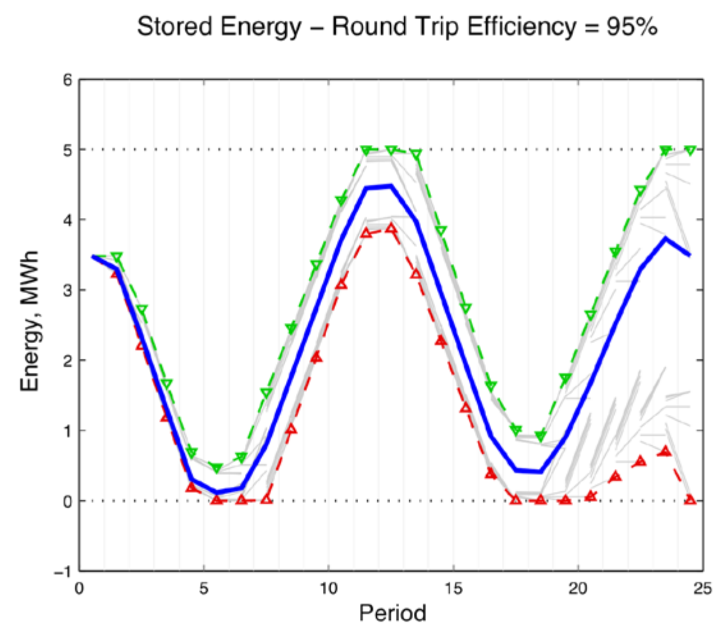
Conventional Gen Dispatch
Real Power, MW
Period
30
25
20
15
10
5
0
−5
0
5
10
15
20
25



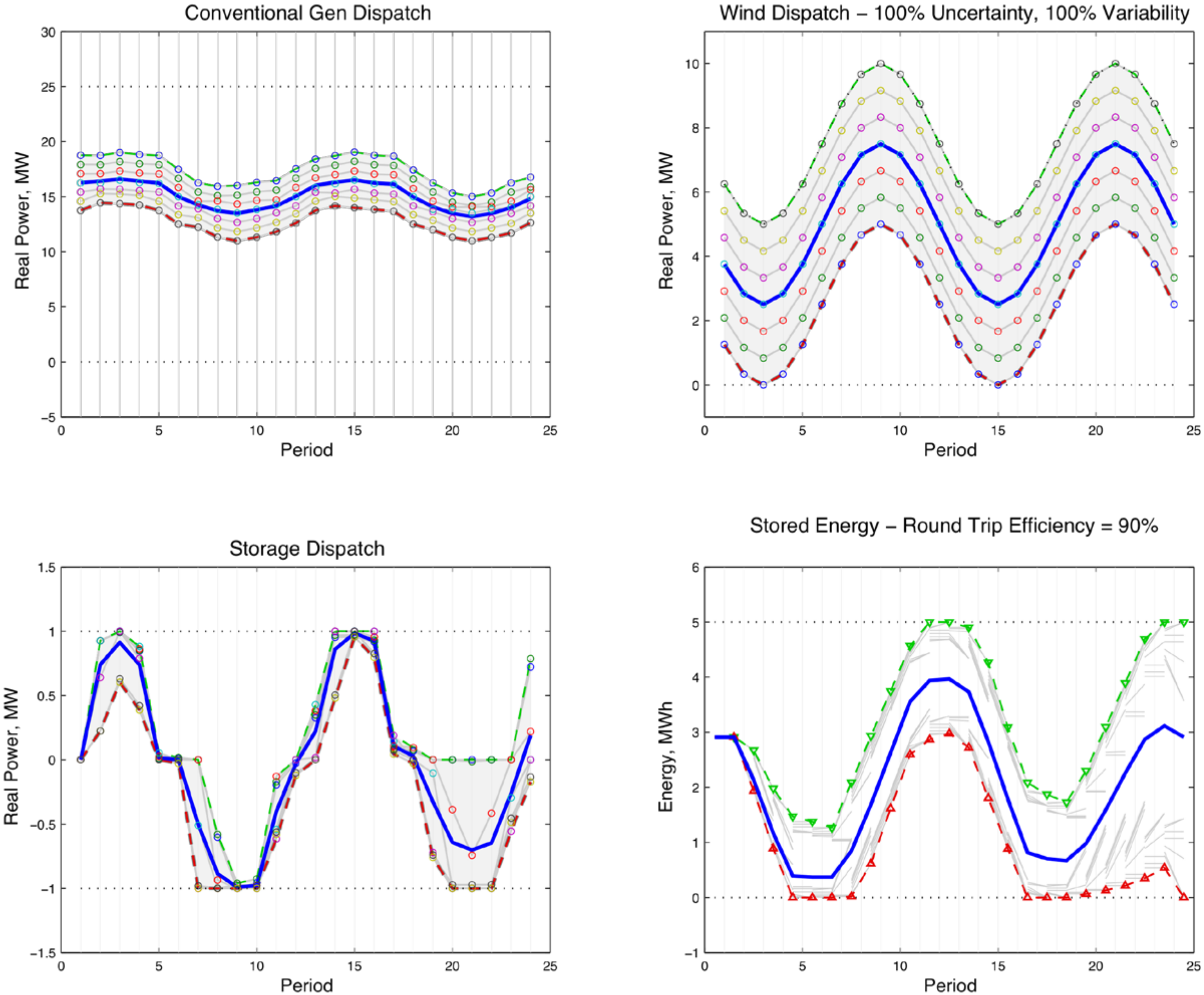
Wind Dispatch − 100% Uncertainty, 100% Variability
Real Power, MW
Period
10
8
6
4
2
0
0
5
10
15
20
25

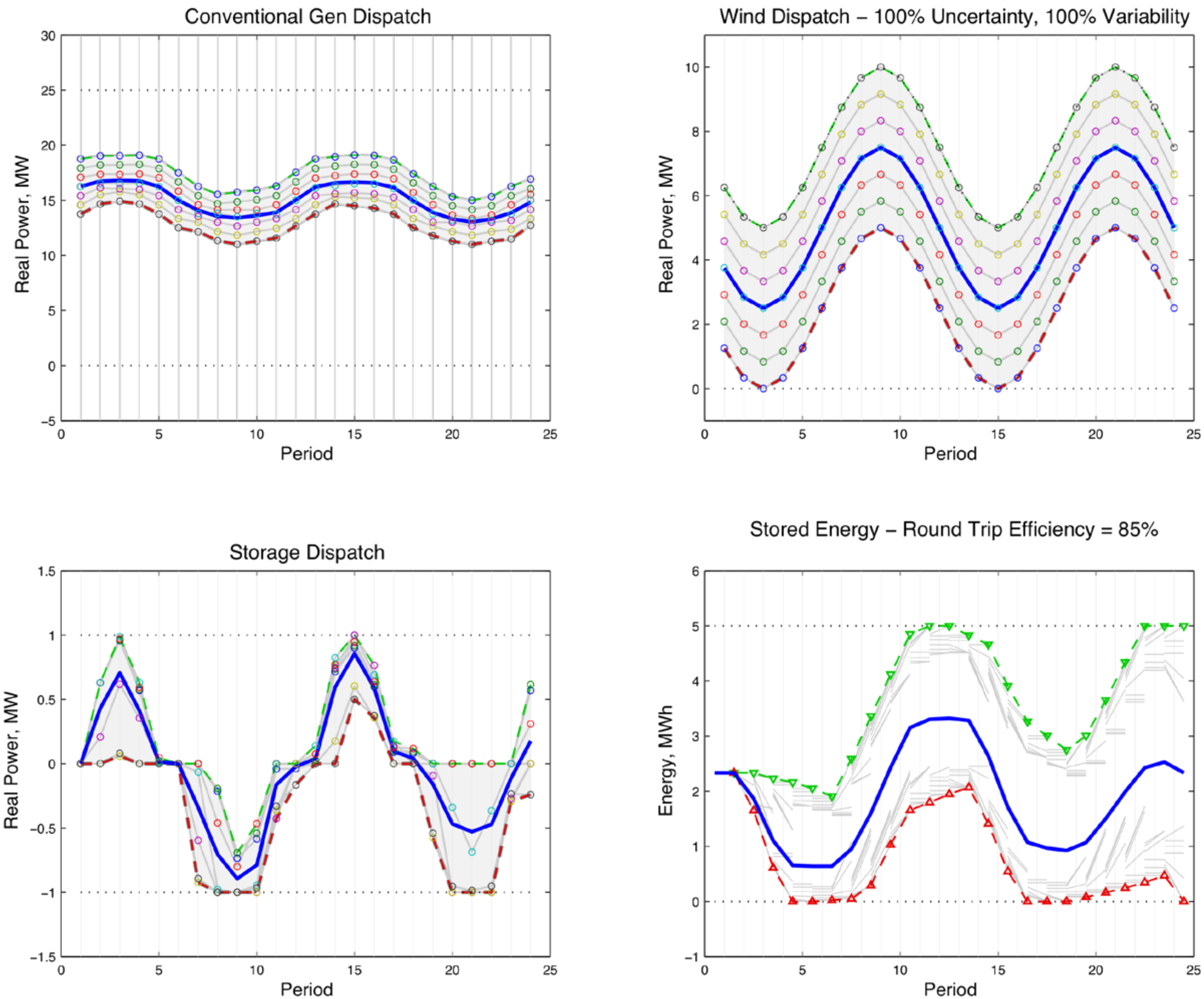


Storage Dispatch
Real Power, MW
Period
1.5
1
0.5
0
−0.5
−1
−1.5
0
5
10
15
20
25

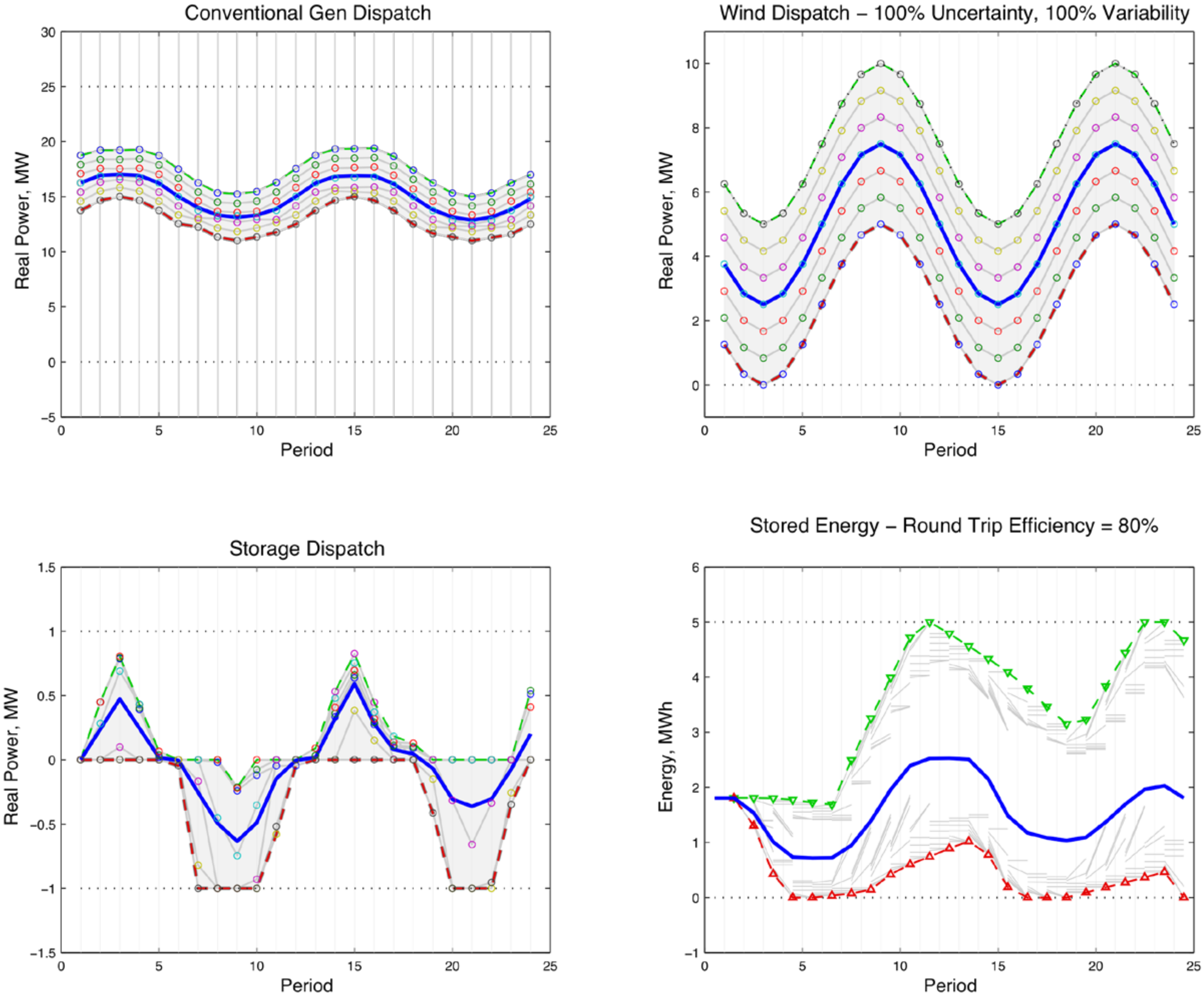


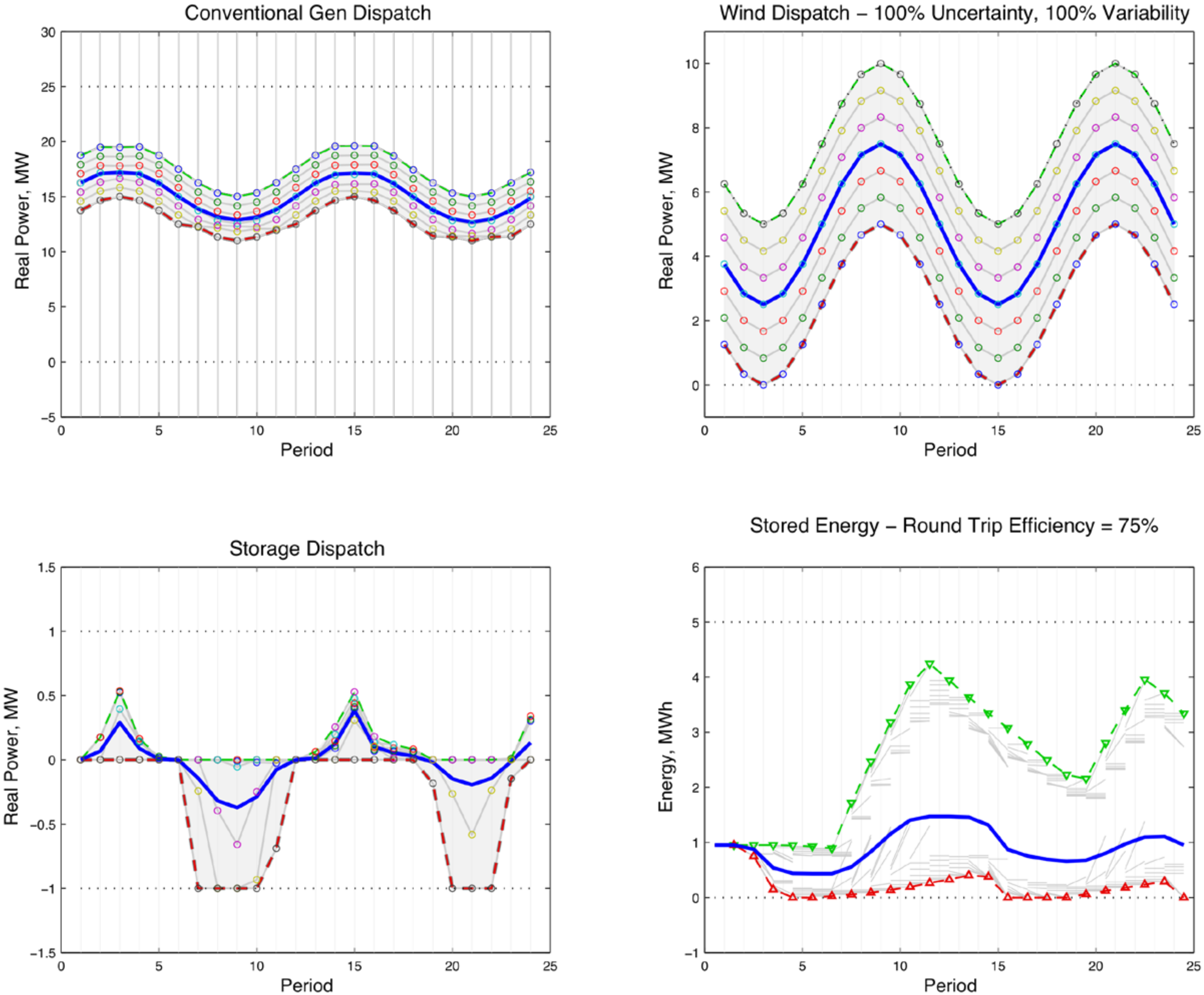
Stored Energy − Round Trip Efficiency = 95%
Energy, MWh
Period
6
5
4
3
2
1
0
−1
0
5
10
15
20
25

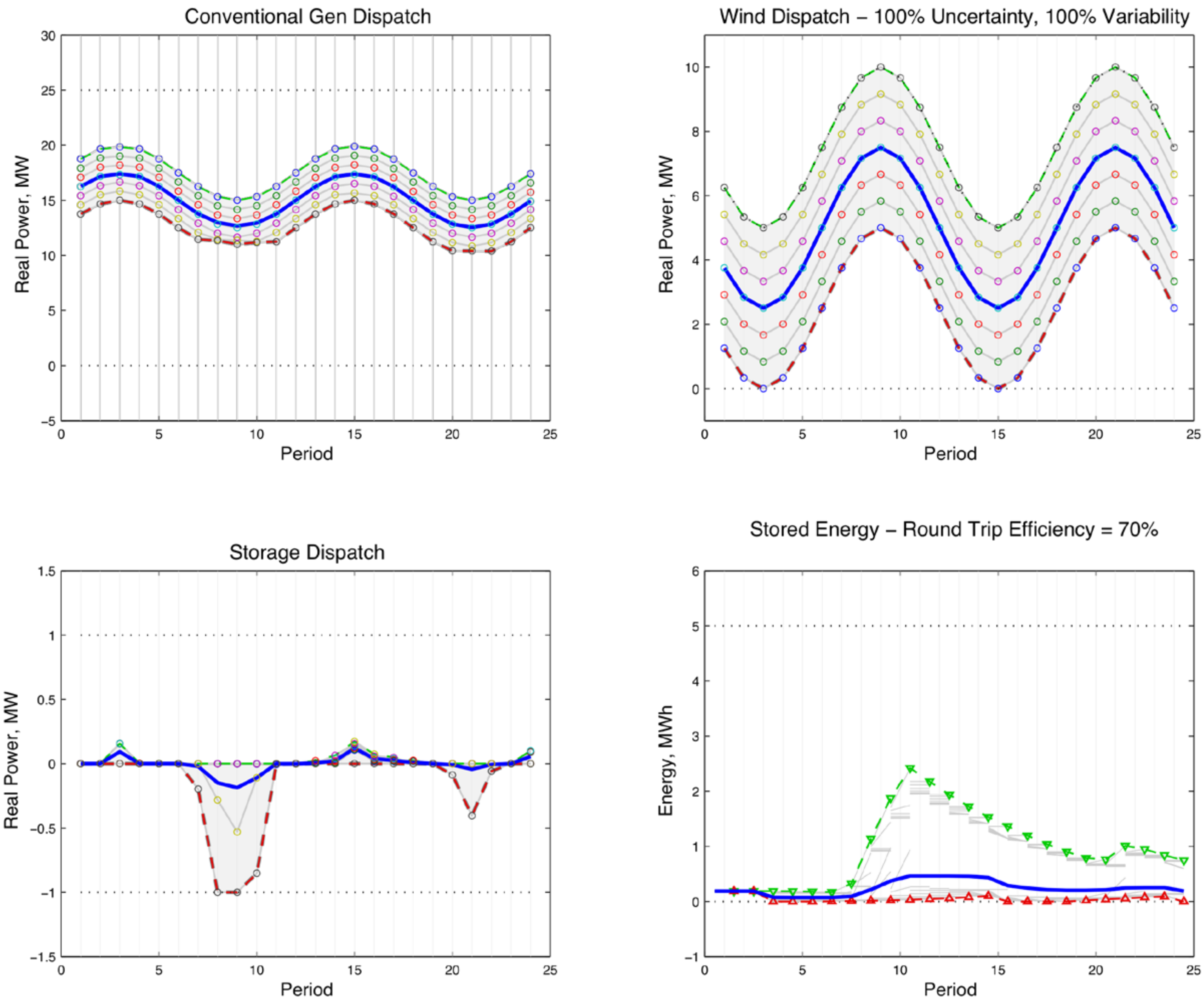

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 90%
Energy, MWh
Period

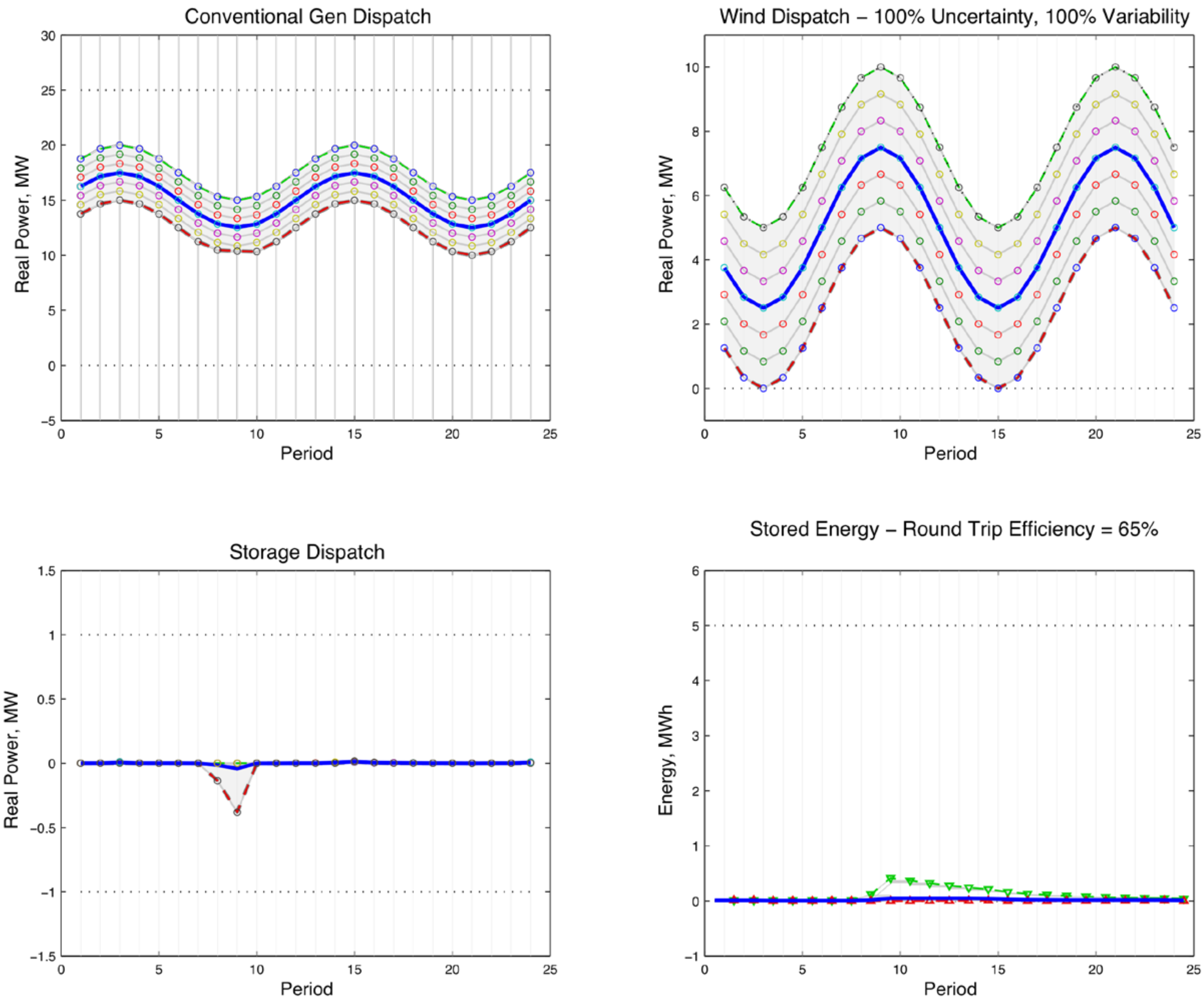


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 85%
Energy, MWh
Period

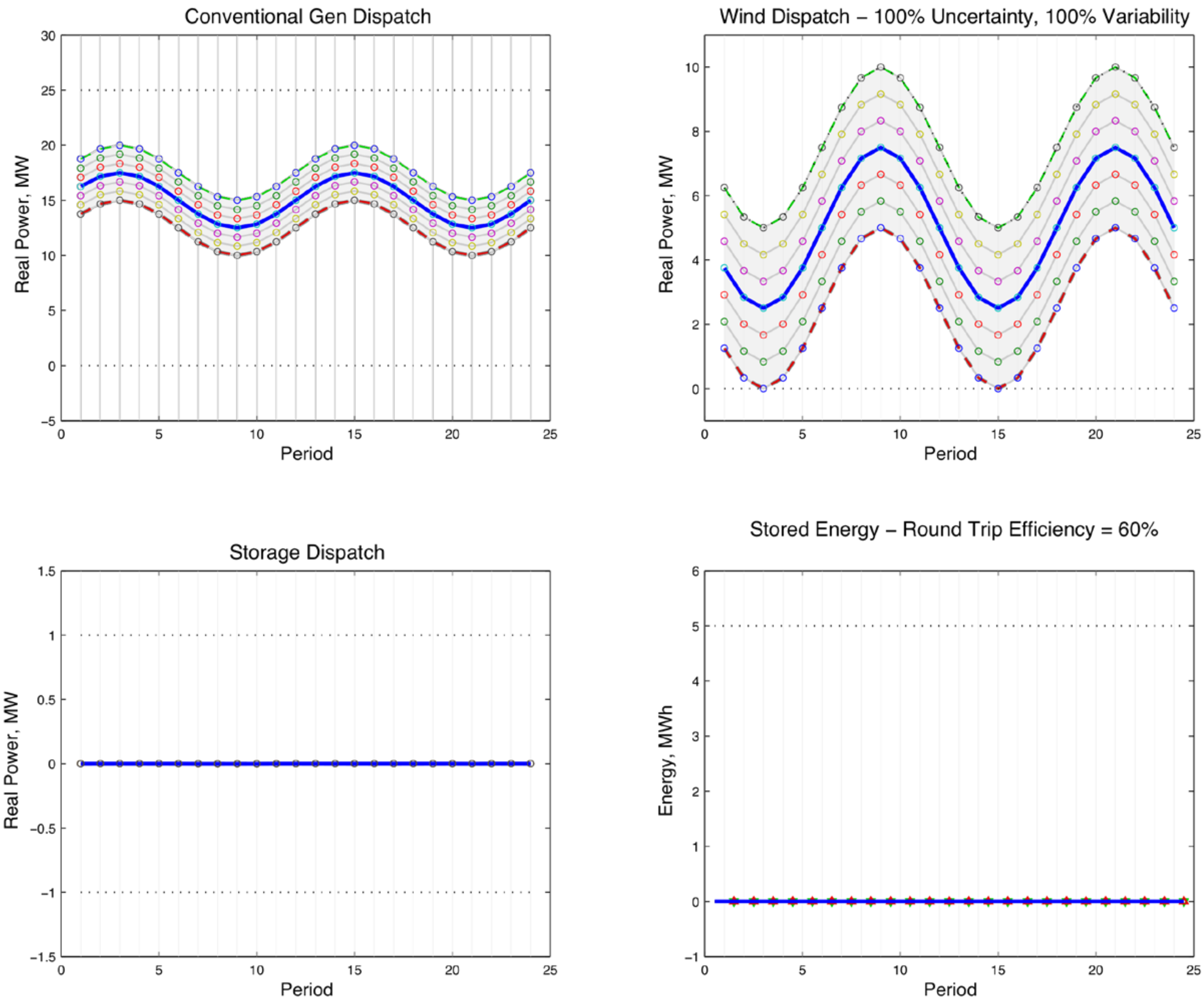

Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 80%
Energy, MWh
Period


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 75%
Energy, MWh
Period


Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 70%
Energy, MWh
Period



Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 65%
Energy, MWh
Period

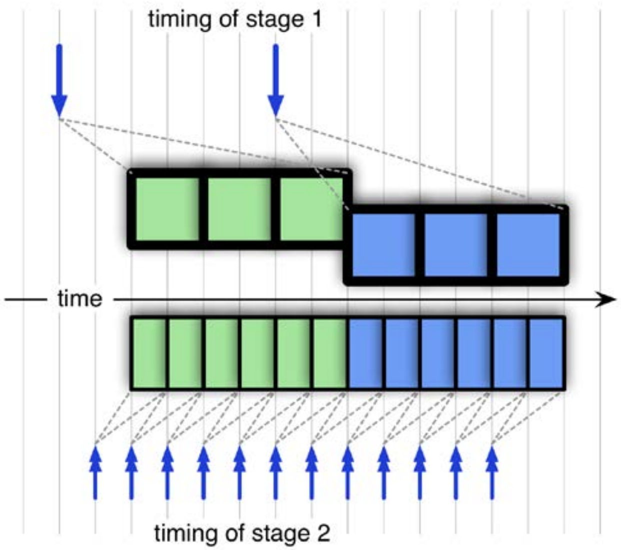


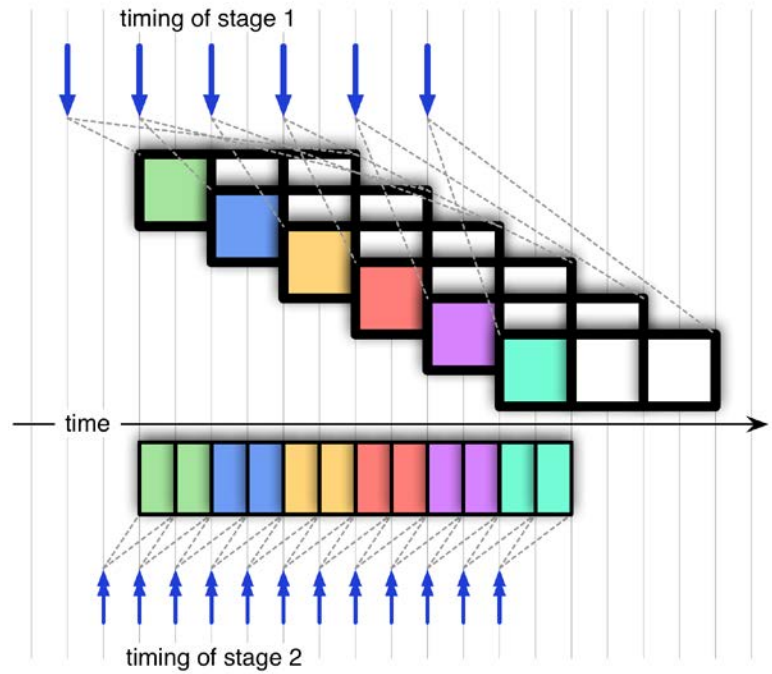
Conventional Gen Dispatch
Real Power, MW
Period
Wind Dispatch – 100% Uncertainty, 100% Variability
Real Power, MW
Period
Storage Dispatch
Real Power, MW
Period
Stored Energy – Round Trip Efficiency = 60%
Energy, MWh
Period

Simulation Environment

- multi-period SuperOPF (2nd/3rd gen)
- two stage structure
  - stage 1 – day-ahead / hour-ahead
    - multiperiod – determines contracts for energy, reserve/ramping capacity and unit commitment
    - computes 24-hour plan
  - stage 2 – real-time / balancing
    - determines balancing energy, real-time prices
    - executes based on the plan and resolved uncertainties

Day-at-a-Time vs. Receding Horizon





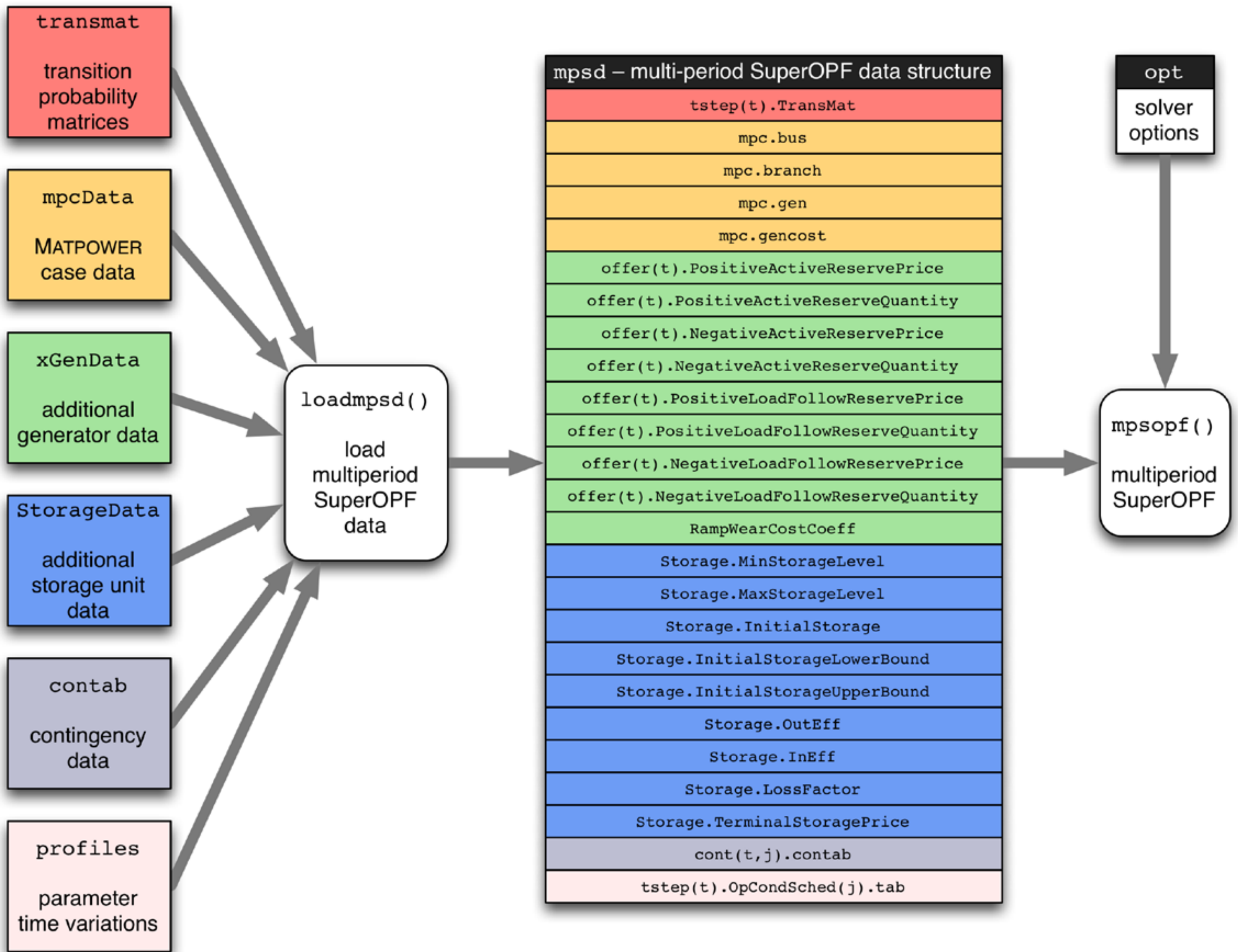
Traditional Approach – Stage 1 runs *once-per-day*, finds hourly solution for *full day*; stage 2 runs intra-hour, finds single period solution subject to *day-ahead* contracts.

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.

Stage 1 Requires Input Scenarios

- Uncertainty characteristics must reflect increased accuracy of shorter term forecasts
- Previous approach
  - generate simulated forecast for entire wind/load data sets
  - select forecasts "similar" to planning day
  - cluster to generate scenarios for each hour and transition probabilities
  - Issues
  - not enough "similar" days
  - even "similar" days don't have shared starting point (current operating state)
  - resulting scenarios do not adequately cover tails
- New approach
  - estimate models for temperature, load and wind
  - use model to generate many potential realizations of planning day based on common history
  - cluster to generate scenarios for each hour and transition probabilities
    - with new techniques for incorporating outliers and scenarios with specific behaviors

Input Data File Standards



Unit Commitment SuperOPF (3rd gen)

Same as 2nd gen Multi-period SuperOPF, with addition of …

- integer unit commitment decisions
- startup/shutdown costs
- minimum up/down times

Implementation is Flexible

Can be used to solve DC versions of:

- standard deterministic OPF
- single period secure, stochastic OPF *(1st gen SuperOPF)*
- multiperiod deterministic OPF (with ramping, storage)
- multiperiod secure, stochastic OPF *(2nd gen SuperOPF)*
- deterministic UC w/economic dispatch
- deterministic UC w/OPF constraints
- secure, stochastic UC with individual trajectories
- secure, stochastic UC with full transition probabilities

Plan to integrate into upcoming version of MATPOWER for wide distribution.

References

- Two papers
  - Carlos E. Murillo-Sánchez, Ray D. Zimmerman, C. Lindsay Anderson and Robert J. Thomas, "A Stochastic, Contingency-Based Security-Constrained Optimal Power Flow for the Procurement of Energy and Distributed Reserve", *Decision Support Systems*, 2013, http://dx.doi.org/10.1016/j.dss.2013.04.006.
  - Carlos E. Murillo-Sánchez, Ray D. Zimmerman, C. Lindsay Anderson and Robert J. Thomas, "Secure Planning and Operations of Systems with Stochastic Sources, Energy Storage and Active Demand", *accepted for the Special Issue of IEEE Transactions on Smart Grid on "Optimization Methods and Algorithms Applied to Smart Grid"*
- Presentation at FERC Software Conference "Increasing Real-time and Day-ahead Market Efficiency Through Improved Software"
  - http://www.ferc.gov/industries/electric/indus-act/market-planning/2013-conference.asp

Discussion of UC SuperOPF Implementation and Preliminary Results

Carlos E. Murillo-Sánchez

Traditional MIP UC formulation

$$u^{ti} P_{\min}^{tijk} \leq p^{tijk} \leq u^{ti} P_{\max}^{tijk}$$

$$u^{ti} Q_{\min}^{tijk} \leq q^{tijk} \leq u^{ti} Q_{\max}^{tijk}$$

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

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

- In practice, only u variables need to be defined as binary.
- A u variable shuts down all injections related to a given generator in a given time slice (all scenarios, all contingencies and base cases).
- On input, a unit can have “available for commitment decision”, “forced on” or “forced off” status.
- However, a number of issues must be addressed for incorporation into the SuperOPF framework.

The lighter issues

- Several changes introduced in the code so that all required injections are represented.
- Forced-off injections trigger superfluous contingencies filters and pruning occurs.

The issue of structure

- The SuperOPF tree can be thought of as a probability tree with recombination of scenarios in the central path.
- A contingency might be defined in which one of the generators available for the commitment decision goes offline.
- If $u=0$, that contingency is superfluous and the base case in the corresponding scenario should assimilate that contingency's probability.
- Indeed, $u=0$ or $u=1$ changes the structure of the probability tree and the corresponding probability weights in the cost function!
- Can adopt a cost formulation that switches on or off certain cost segments (for linear or piecewise linear costs), but it is messy and introduces u's in the cost in a complicated manner (otherwise each u simply triggers the fixed part of the corresponding operation cost into the objective) .

A simplification

- Ignore the issue of structural change in probability tree; ok if probabilities of injection outages are small.
- Then, if $u=0$, the contingency for which the generator in question is ousted generates a power flow that is identical to that of the base case, so no reserve requirements will be set by the superfluous contingency flow.
- If $u=1$ all is fine.
- The relative weighting of the base case can be a little bit off if $u=0$ because of this simplification.

Looking out to other formulations

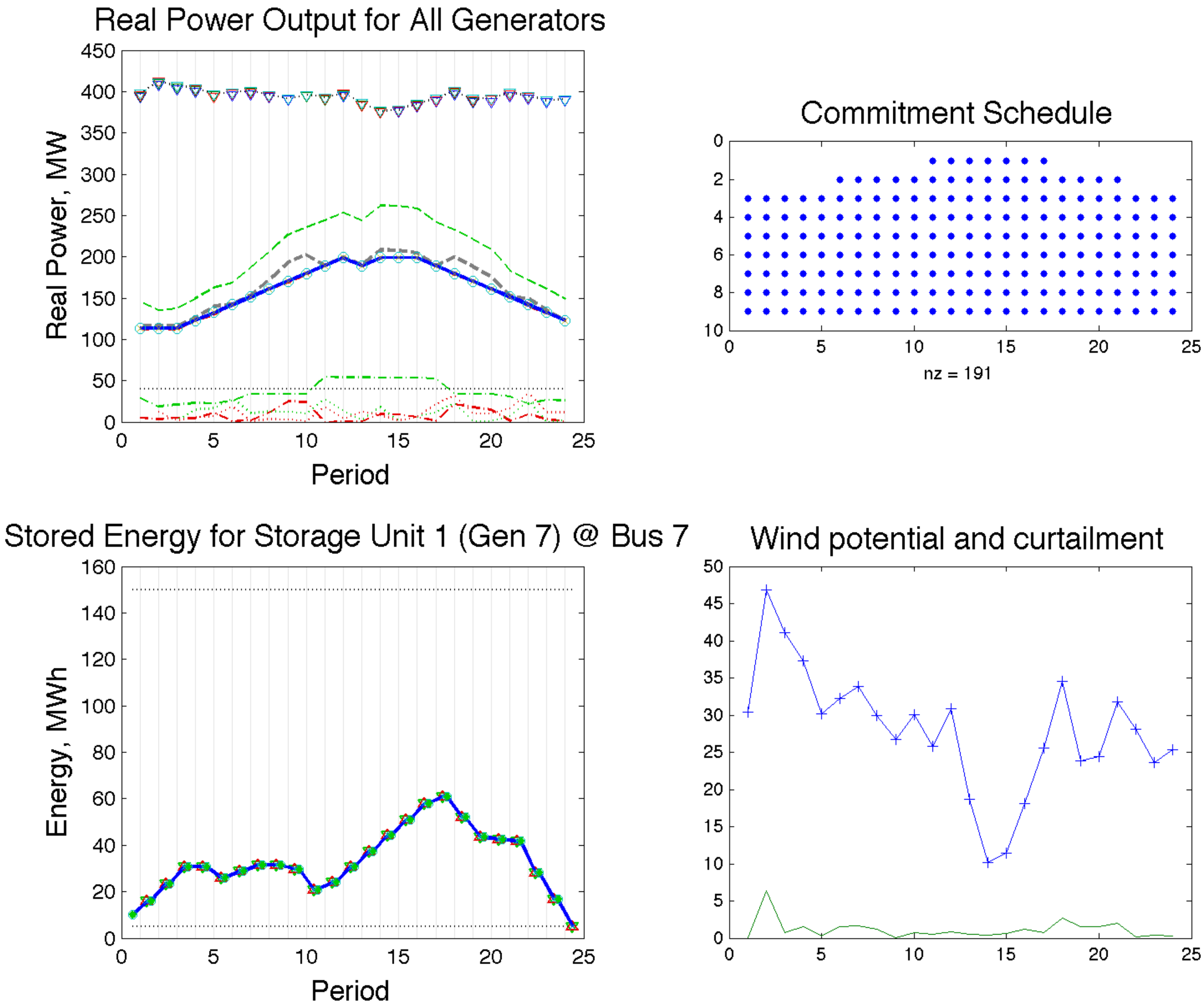
- There are tighter UC MIP formulations, but the better ones are aimed at network-less power balance and fixed reserve formulations.
- The binary variables enter the simple power balance constraints: injections split in fixed u-weighted Pmin plus a variable (Pg-Pmin) with zero lower bound.
- In a formulation with an explicit DC network flow (such as the single-QP version of the multi-period SuperOPF), the binary variables would enter into a staggering amount of network constraints, complicating the cuts.
- Not included yet: prescribed startup curves.

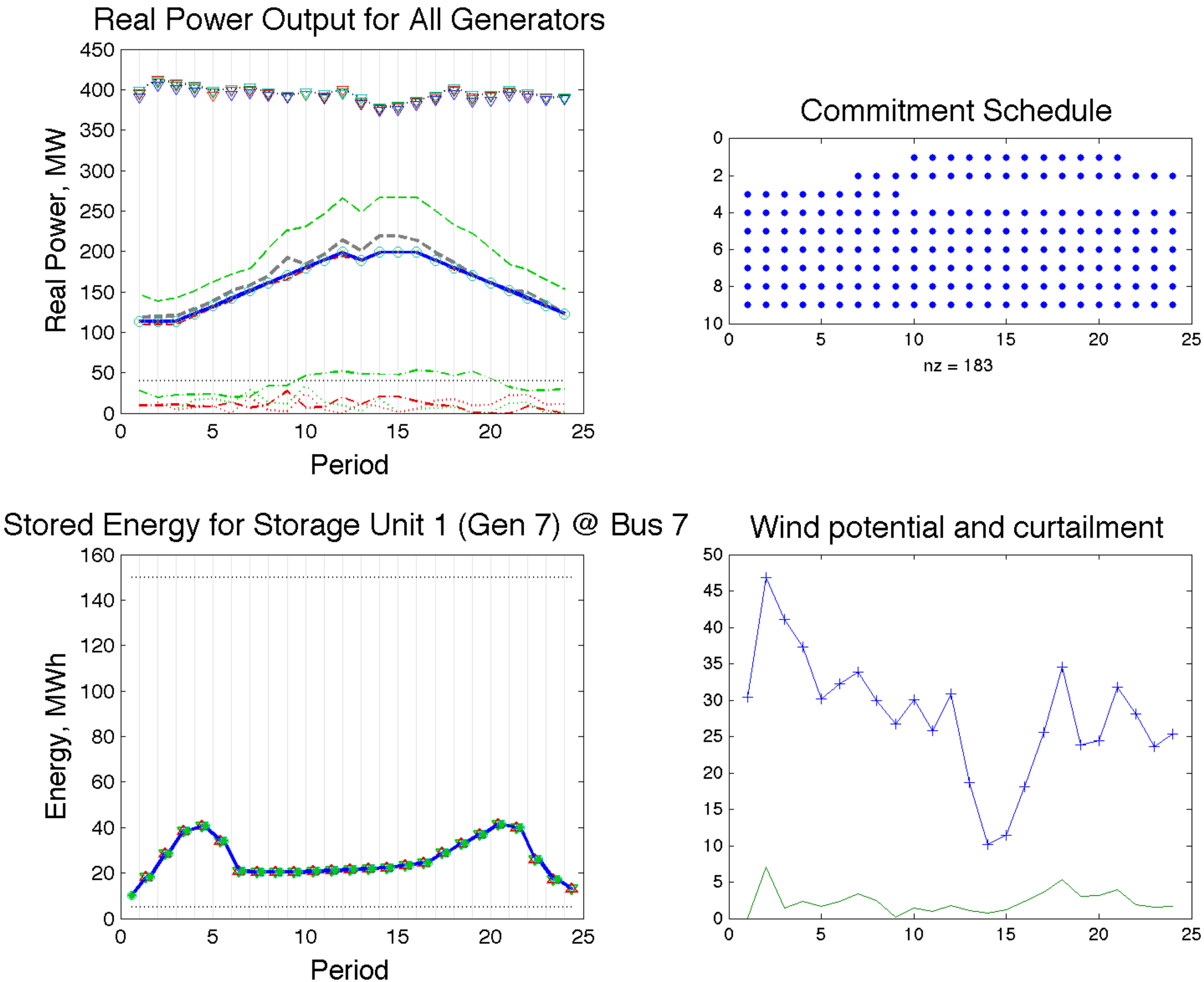
Status

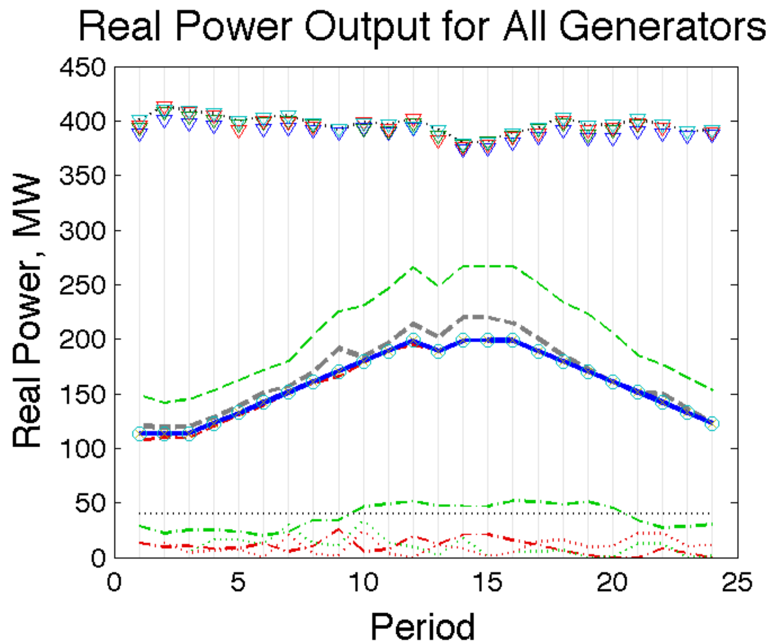
- Testing currently under way with 30 bus and 118 bus systems.
- A systematic exploration of parameter fine-tuning for CPLEX, Gurobi, is underway, and is necessary.
- Preliminary results in concordance with expectations given experience with continuous multi-period SuperOPF.
- Still not tested (but coded): Decomposition-based AC version. Each central problem much simpler than the corresponding MPSOPF with DC network.

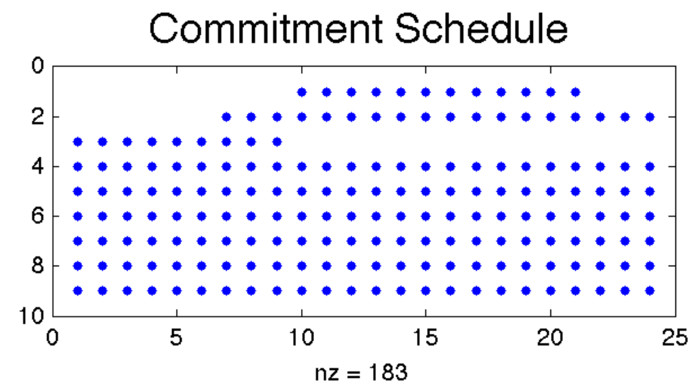
Example: 30 bus

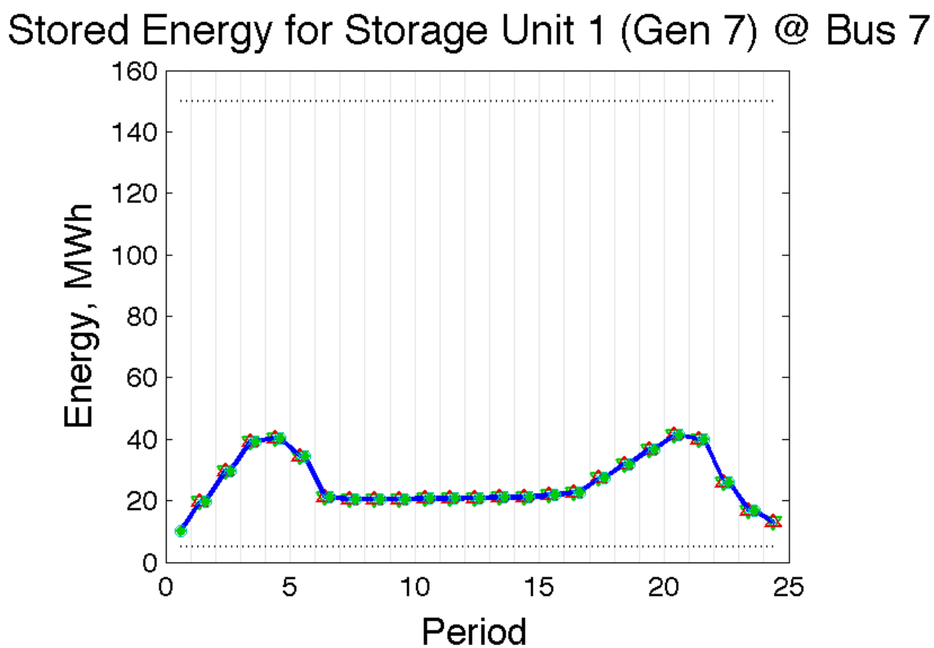
- Gens 1 & 2: large coal
- Gens 3 & 4: peakers
- Gens 5 & 6: medium coal
- Gen 7: storage (small)
- Gens 8 & 9: large wind
- Wind uncertainty increased from zero to actual forecast uncertainty; four wind scenarios (NREL)
- Contingencies: generator outages

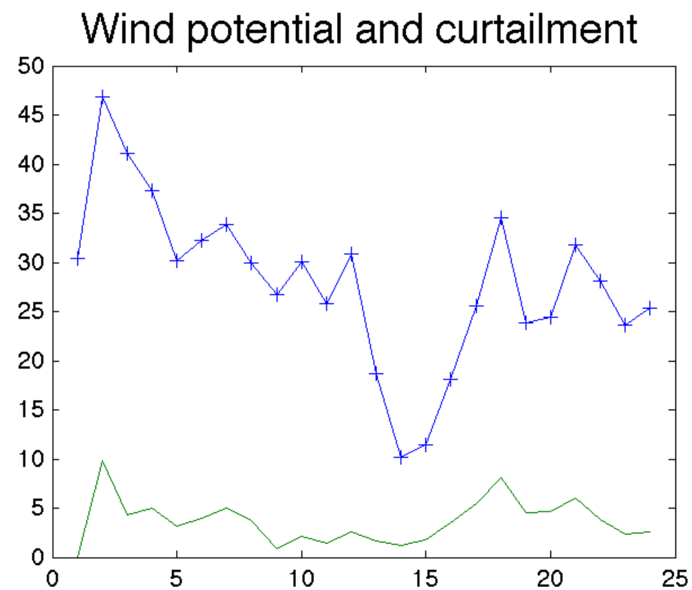

Real Power Output for All Generators
Real Power, MW
Period
Commitment Schedule
nz = 191
Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
Wind potential and curtailment

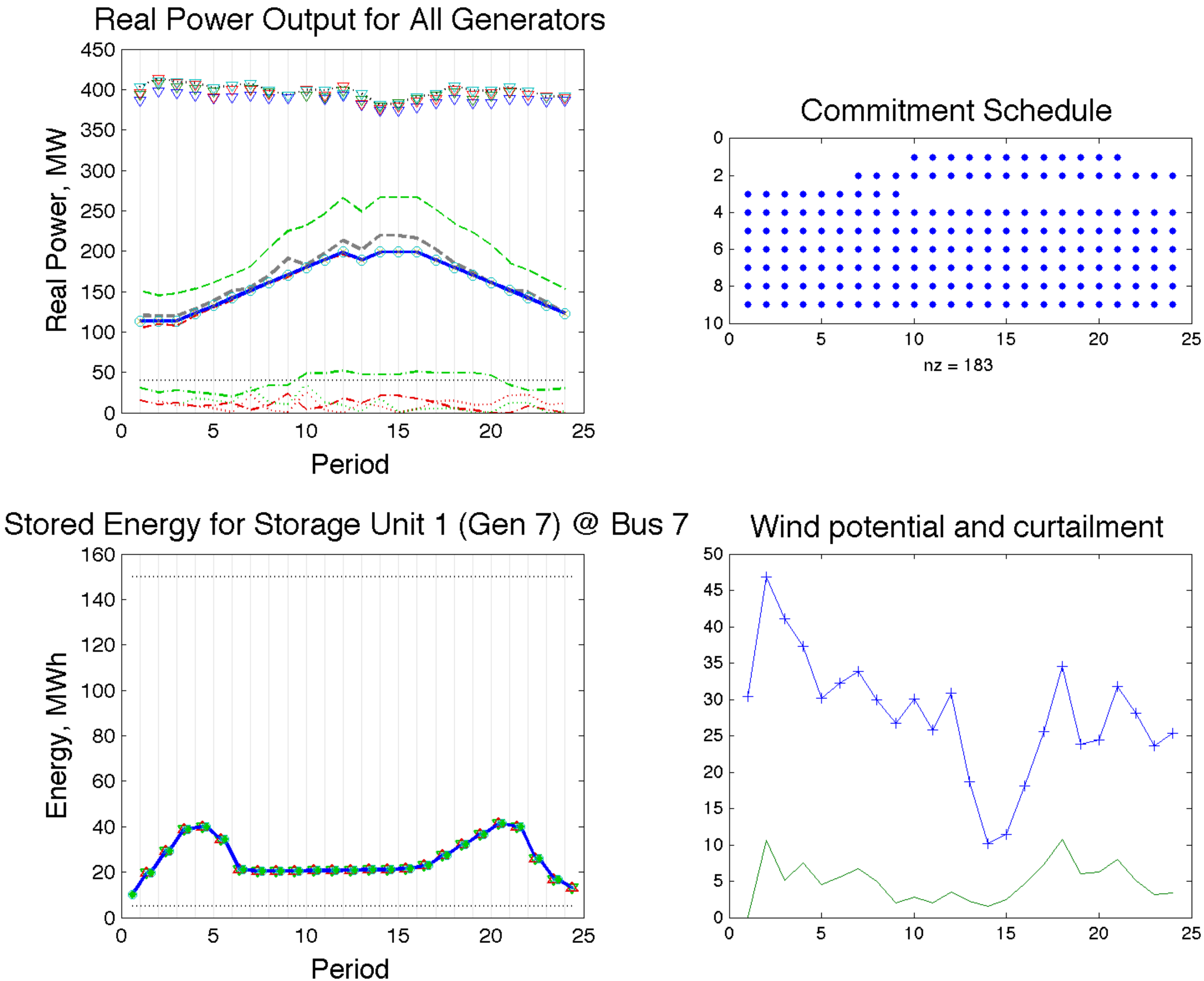

Real Power Output for All Generators
Real Power, MW
Period
Commitment Schedule
nz = 183
Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
Wind potential and curtailment

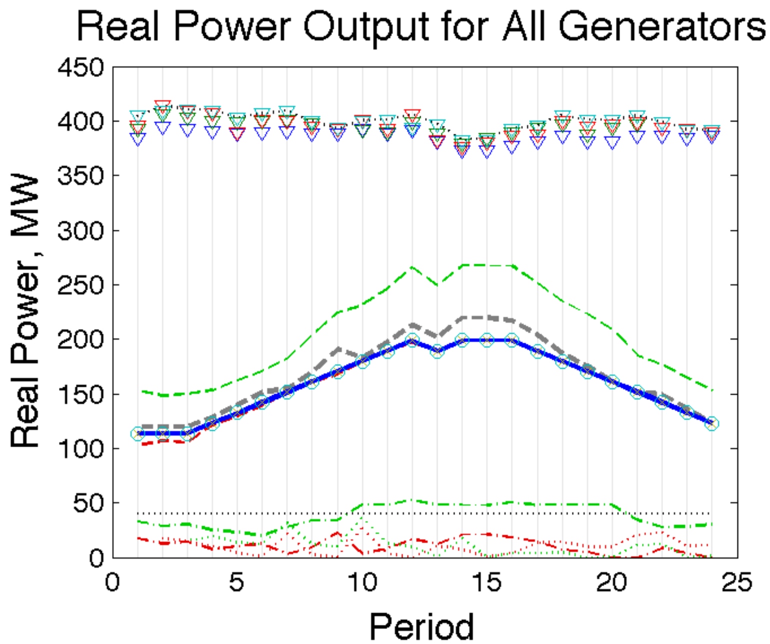

Real Power Output for All Generators
Real Power, MW
Period

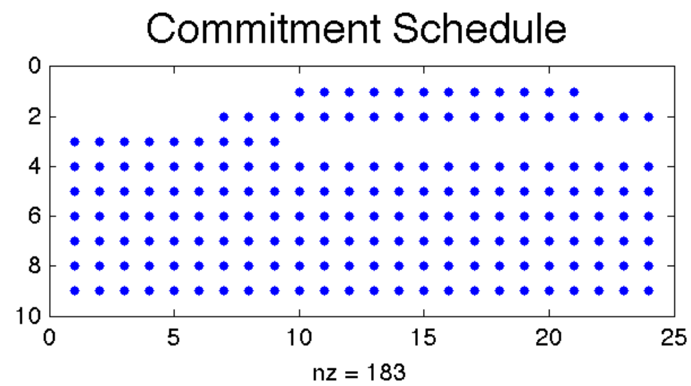

Commitment Schedule
nz = 183

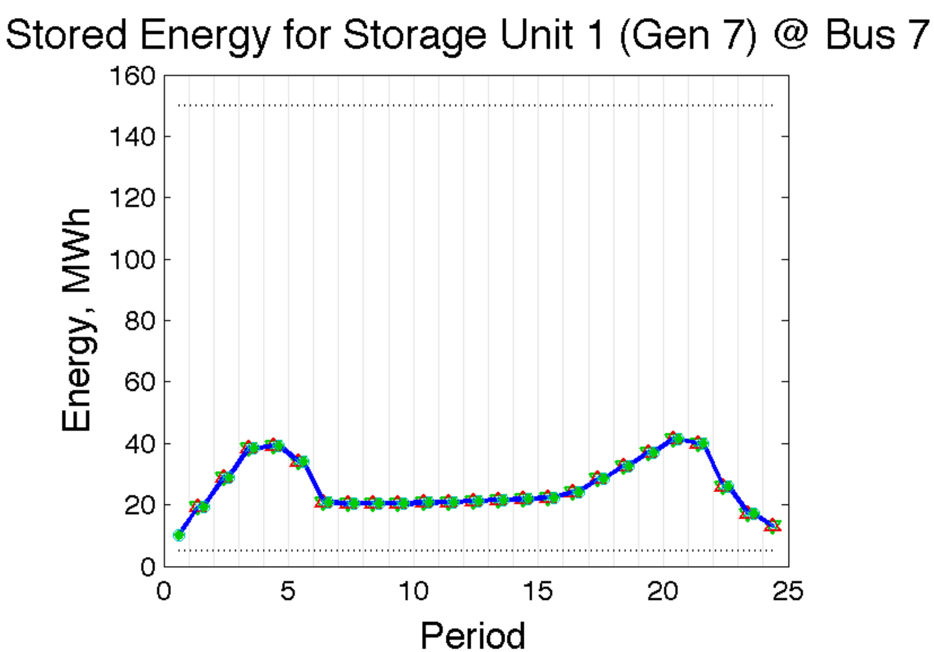

Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period

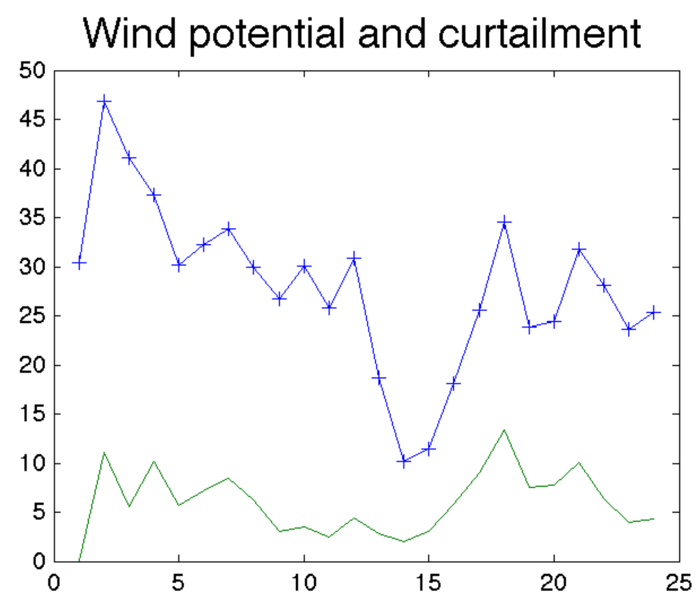

Wind potential and curtailment

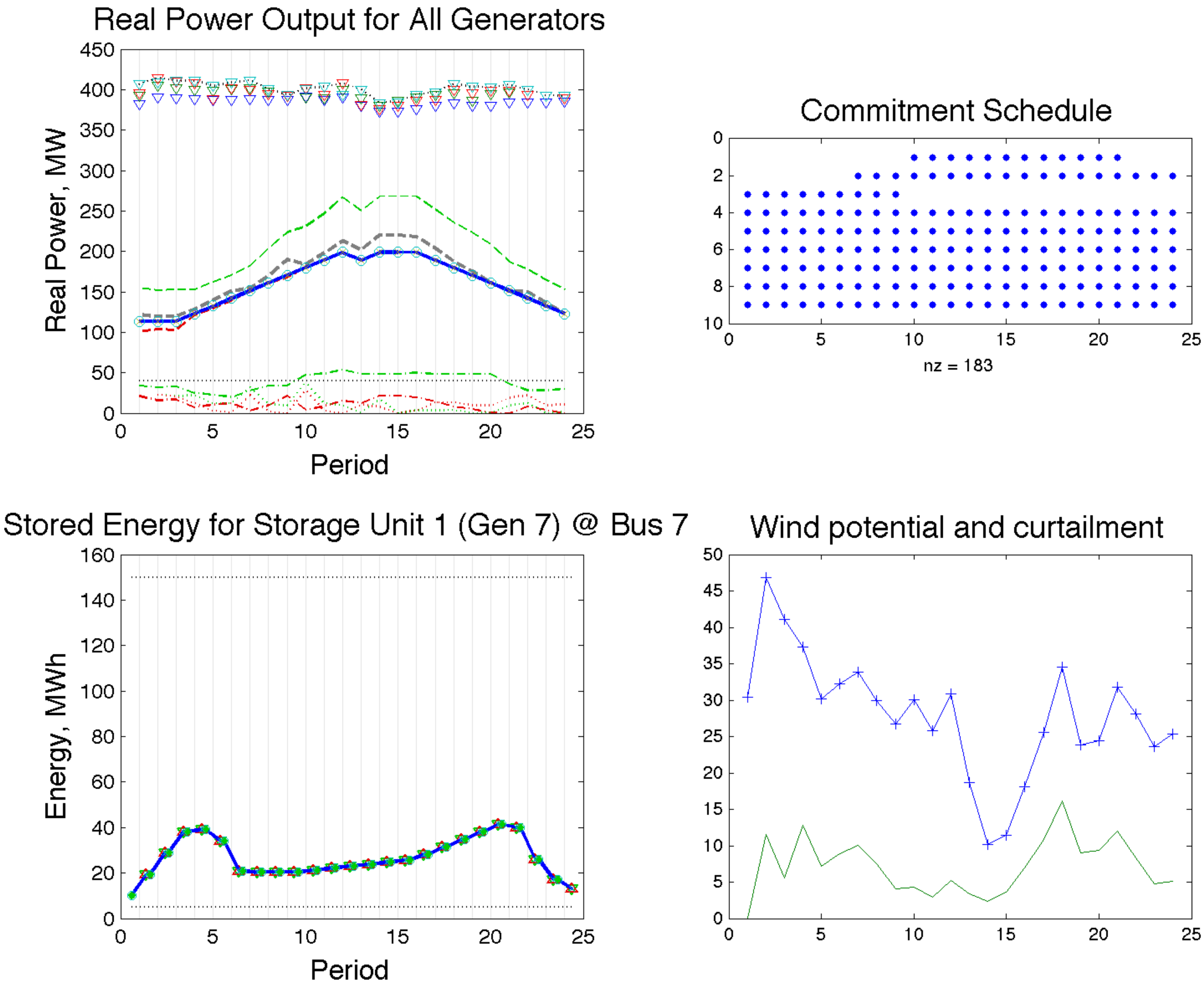

Real Power Output for All Generators
Real Power, MW
Period
Commitment Schedule
nz = 183
Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
Wind potential and curtailment

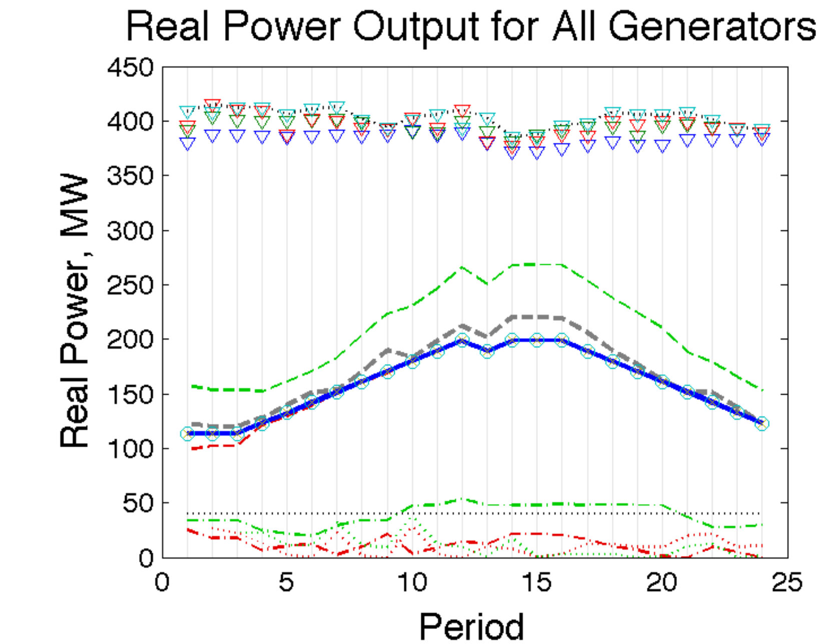

Real Power Output for All Generators
Real Power, MW
Period

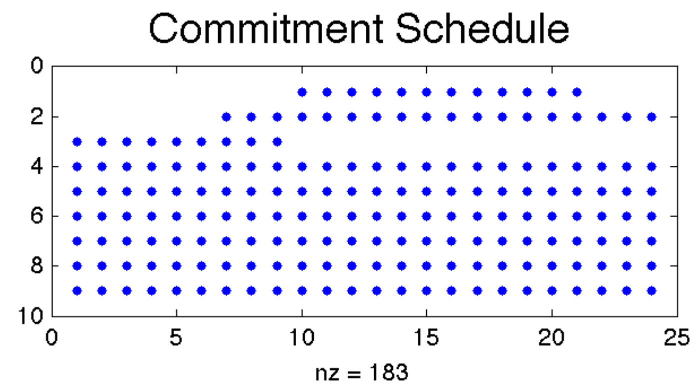

Commitment Schedule
nz = 183

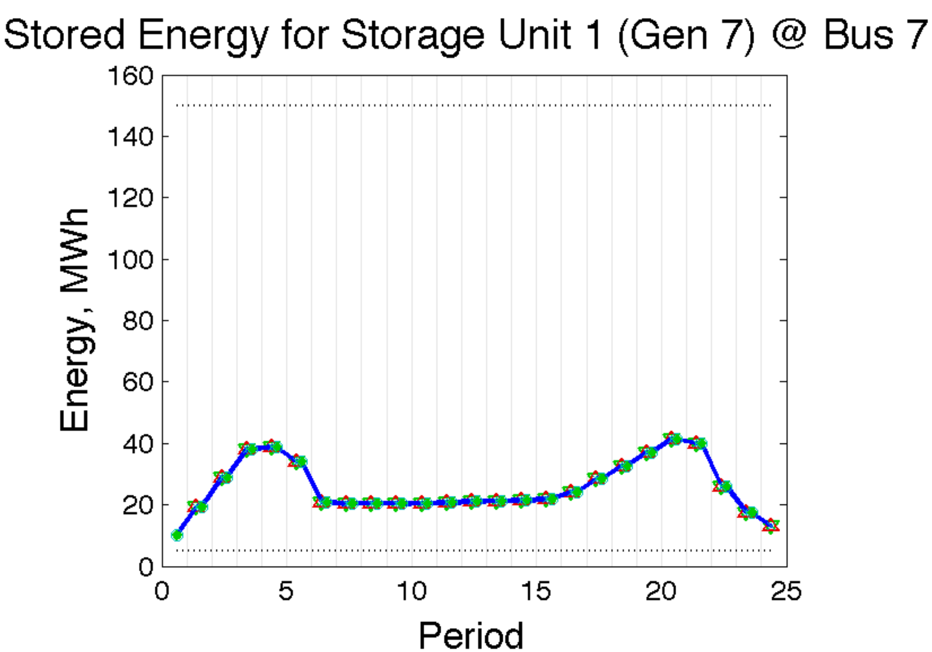

Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period

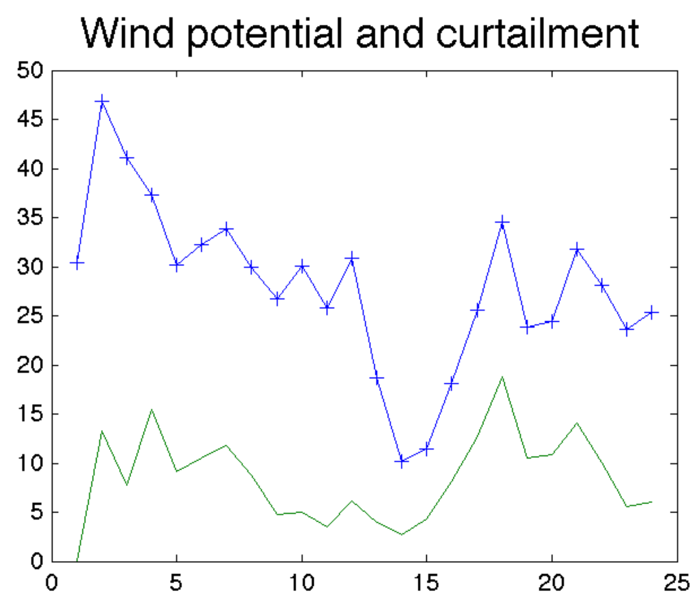

Wind potential and curtailment

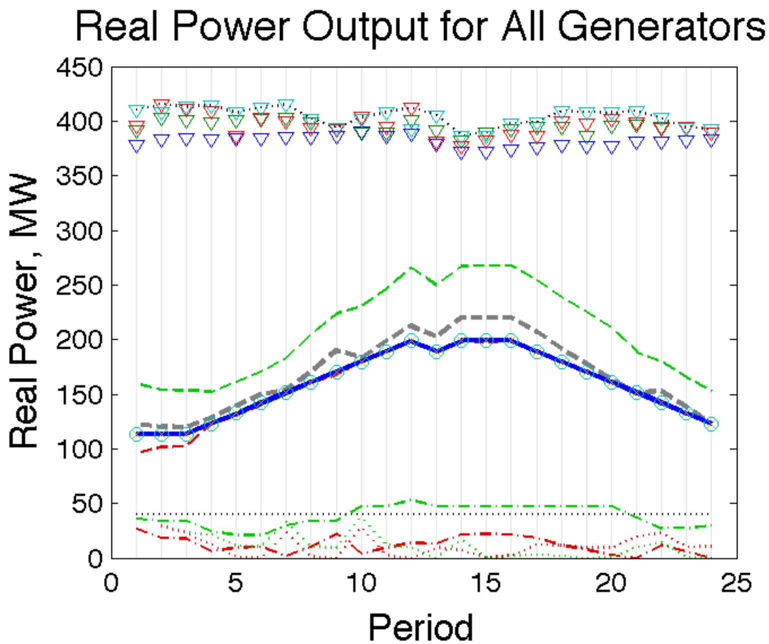

Real Power Output for All Generators
Real Power, MW
Period
0
50
100
150
200
250
300
350
400
450
0
5
10
15
20
25
Commitment Schedule
nz = 183
0
2
4
6
8
10
0
5
10
15
20
25
Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
0
20
40
60
80
100
120
140
160
0
5
10
15
20
25
Wind potential and curtailment
0
5
10
15
20
25
30
35
40
45
50
0
5
10
15
20
25


Real Power Output for All Generators
Real Power, MW
Period
0
50
100
150
200
250
300
350
400
450
5
10
15
20
25

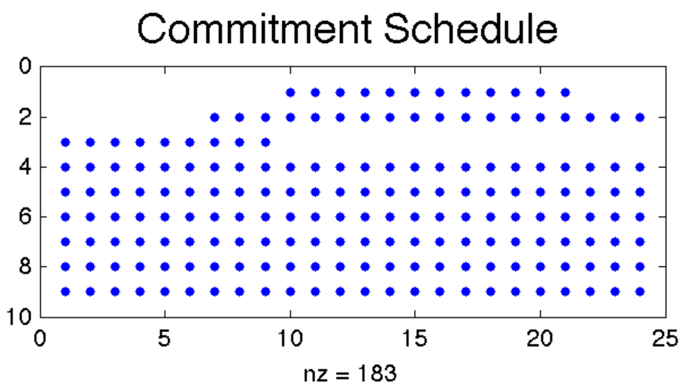

Commitment Schedule
nz = 183
0
2
4
6
8
10
5
15
20
25


Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
0
20
40
60
80
100
120
140
160
5
10
15
20
25

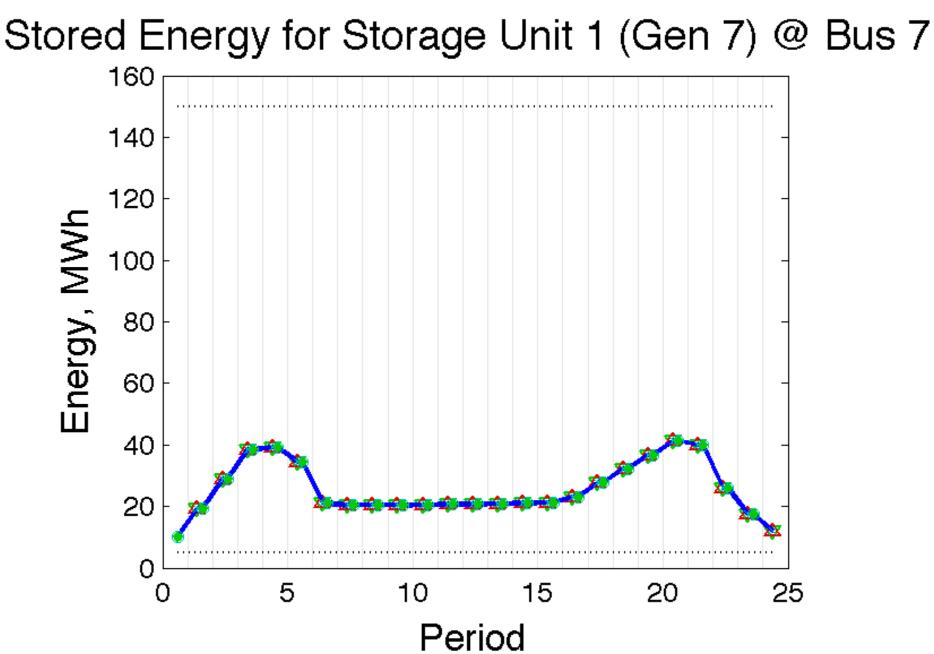

Wind potential and curtailment
0
5
10
15
20
25
30
35
40
45
50



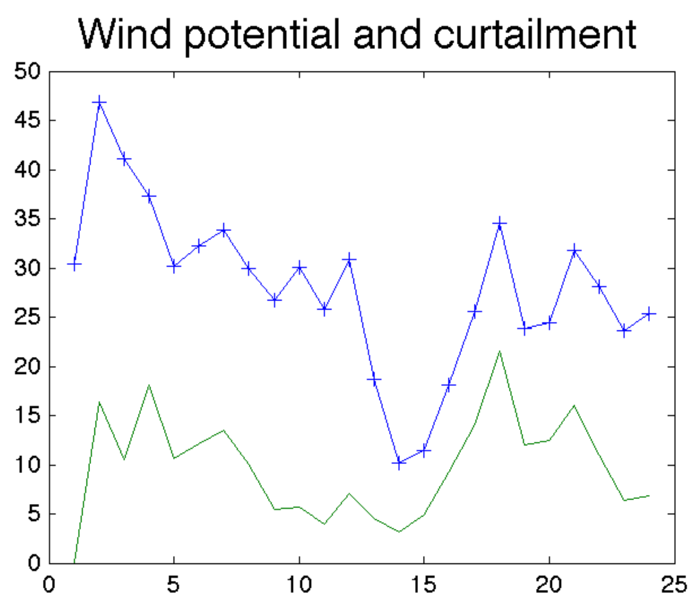
Real Power Output for All Generators
Real Power, MW
Period



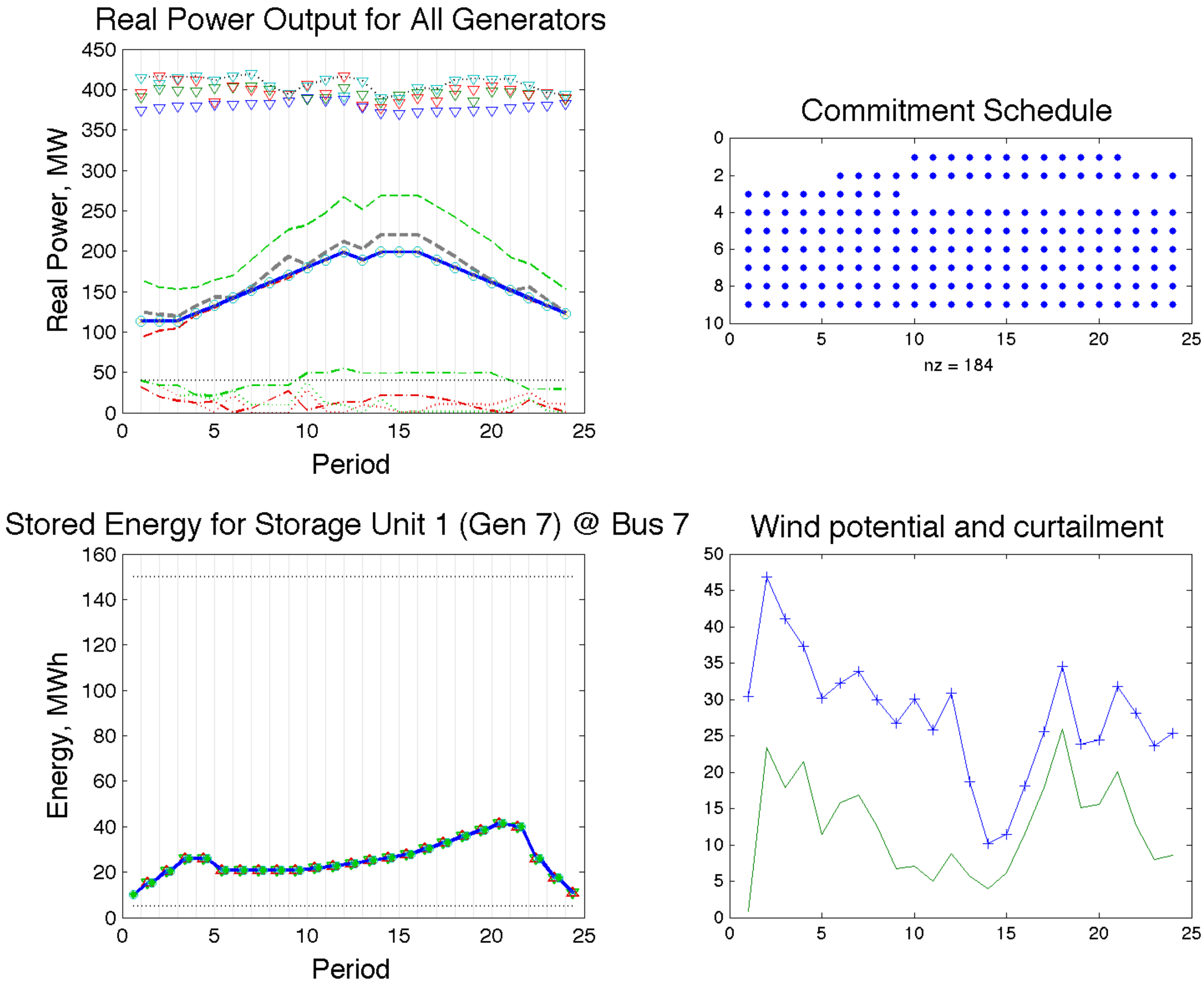
Commitment Schedule
nz = 183



Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period



Wind potential and curtailment



Real Power Output for All Generators
Real Power, MW
Period
0 50 100 150 200 250 300 350 400 450
0 5 10 15 20 25
Commitment Schedule
0 2 4 6 8 10
0 5 10 15 20 25
nz = 184
Stored Energy for Storage Unit 1 (Gen 7) @ Bus 7
Energy, MWh
Period
0 20 40 60 80 100 120 140 160
0 5 10 15 20 25
Wind potential and curtailment
0 5 10 15 20 25 30 35 40 45 50
0 5 10 15 20 25

Questions