informs TUTORIALS

Applying Production and Inventory Management Theory to Sustainable Energy Systems

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INFORMS 2011 Sessions on Energy

- Search in these Clusters:
  - Energy, Natural Resources and the Environment
  - Manufacturing & Service Operations Management
  - Optimization
  - Simulation
  - Computing
  - Analytics
  - Service Science
  - Location Analysis
  - Junior Faculty Interest Group
  - Tutorials
- Plenary & Keynote:
  - The Electric Industry's Coming Transformation, by James E. Rogers, Duke Energy
  - Reprise of 2011 Edelman Award-Winning Presentation, by Midwest Independent Transmission System Operator

Goal of Today's Session

- Familiarize you with the operational challenges in energy systems, focused on the new challenges brought by intermittent generation resources
- Discuss the opportunities of applying production and inventory management theory to address these challenges
- Convince you that you can (and want to) include energy sustainability in your new research directions!

Outline

Electricity industry background and operational challenges

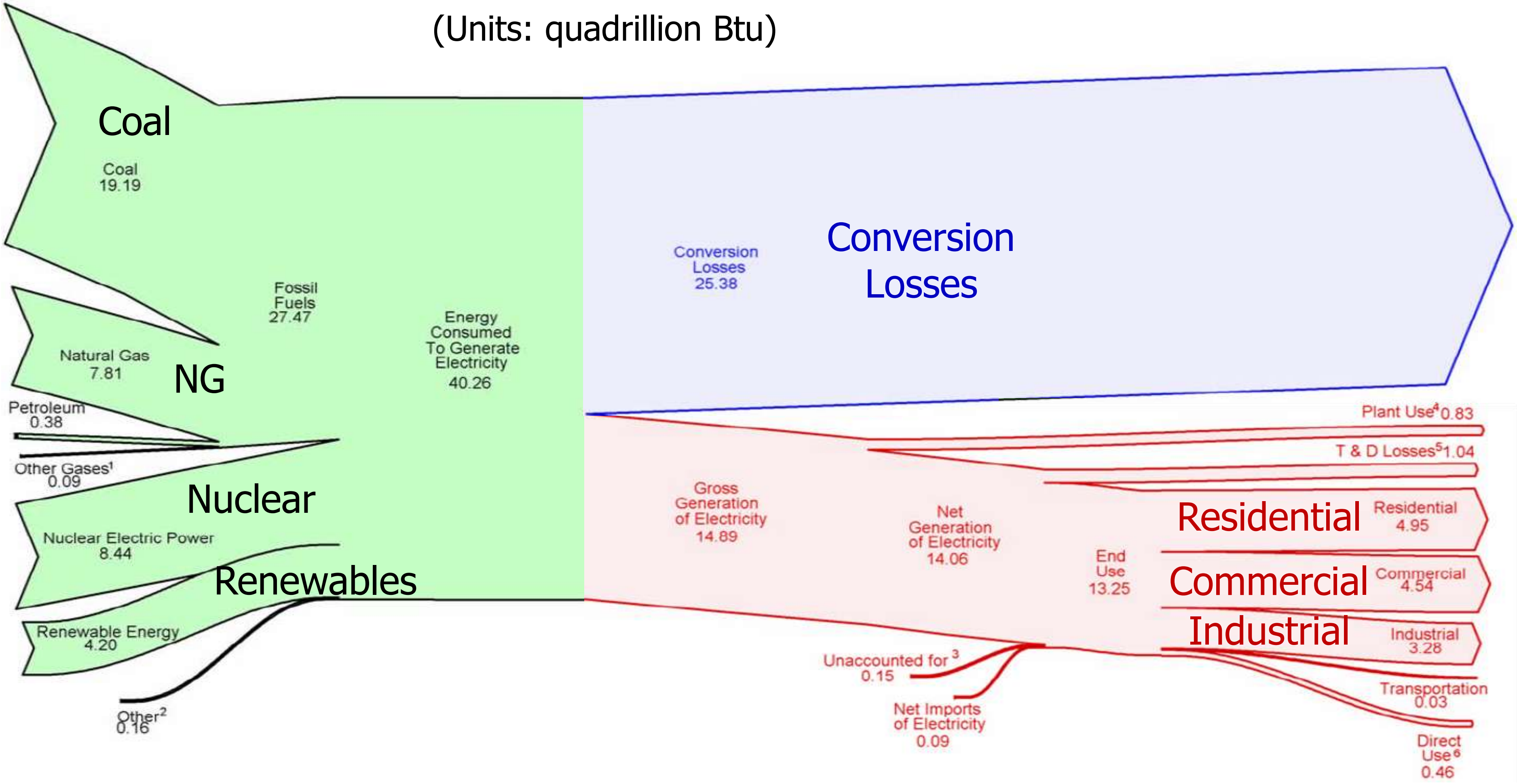
Opportunities of applying OM theory to address these challenges

Examples

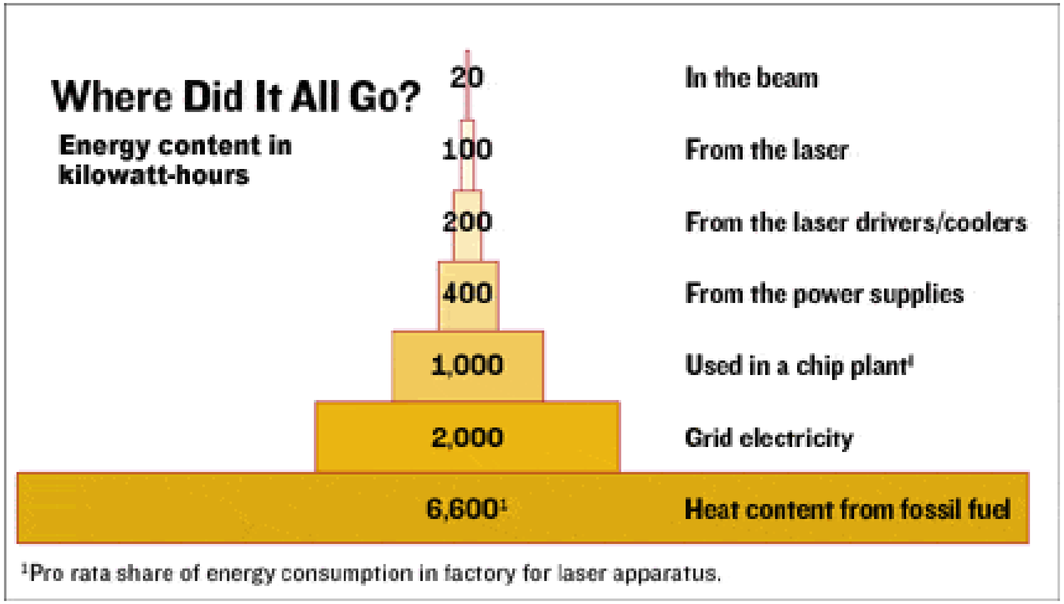
U.S. Electricity Flow 2010

Source: EIA Annual Energy Review 2010, p. 233

(Units: quadrillion Btu)



Energy Pyramid for a Laser Beam

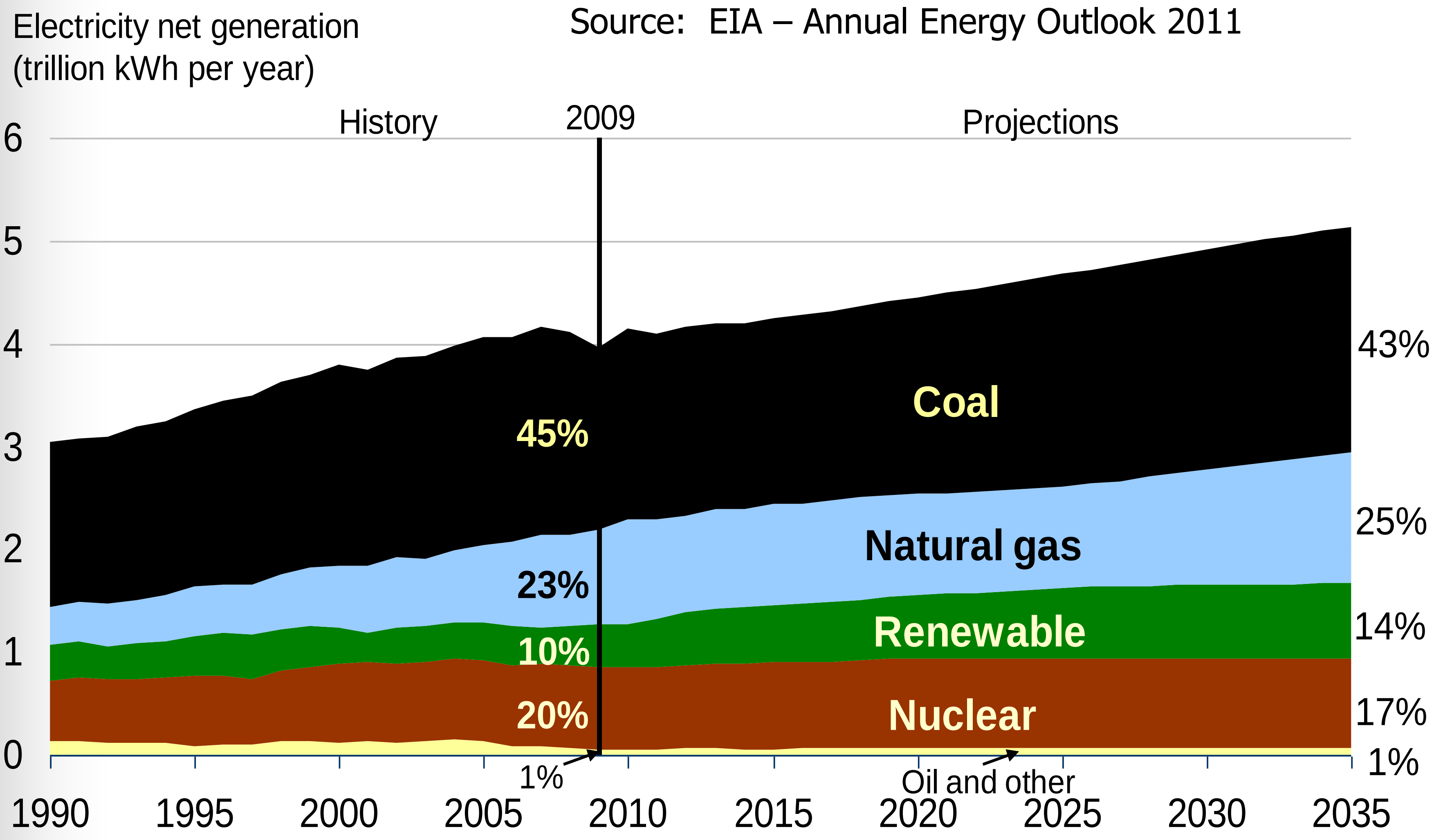


- Source: Huber. 2004. The Virtue of Waste. Forbes. http://www.forbes.com/forbes/2004/1213/116.html
- "The second law of thermodynamics dictates that if the input energy is of a sufficiently low grade (a coal flame, for example), two units of it must be funneled into a machine at one end to emerge as one unit of high-grade energy at the other. That means one unit of input becomes entirely useless heat."

Heat Rate and Thermal Efficiency

- 1 KWh = 3,412.14 Btu
- Heat Rate: The amount of heat (measured in Btu) required to produce one 1 KWh of electricity.
- Thermal Efficiency = 3412.14 / Heat Rate
- Examples:
  - Coal-fired power plant: >10,000 Btu/KWh, <34 %
  - Nuclear: >10,000 Btu/KWh, <34 %
  - Natural gas-fired power plant: 8,000 ~ 9,000 Btu/KWh about 40% efficiency
  - Combined cycle gas-fired plant: 7,000 Btu/KWh, ~50%
  - Cogeneration (combined heat and power, CHP) > 90%

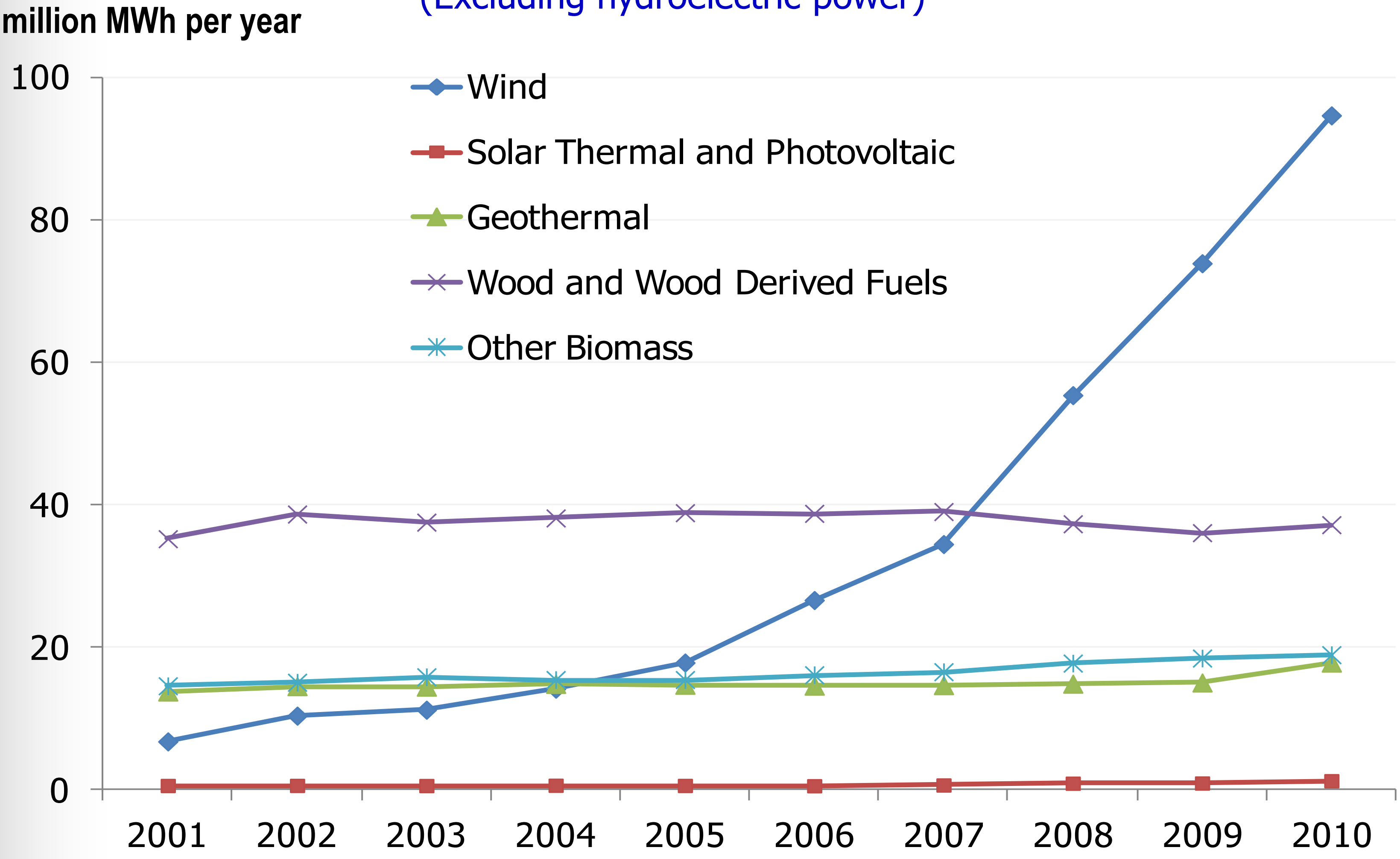
Power Generation in the U.S.



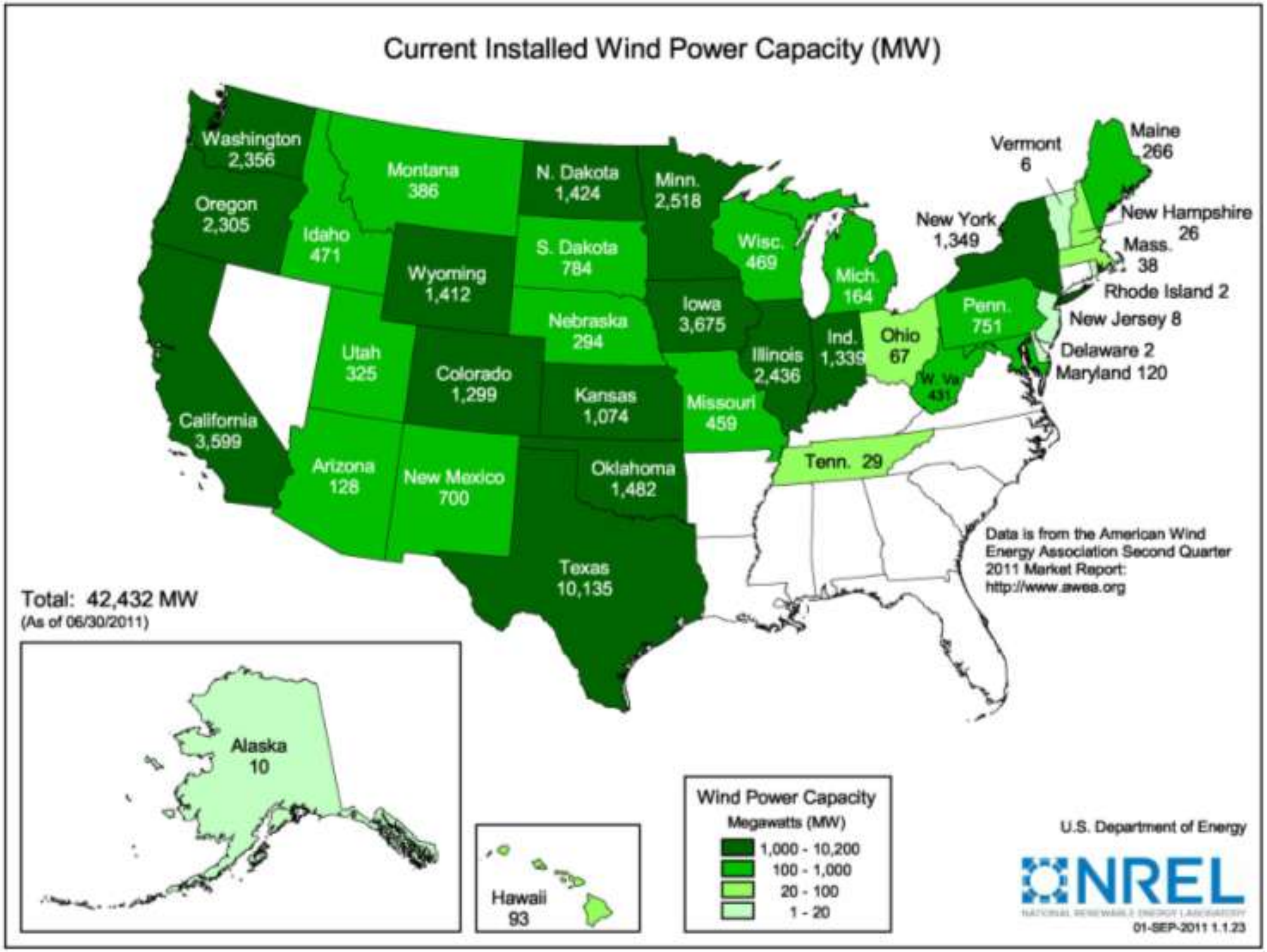
Source: EIA – Annual Energy Outlook 2011

U.S. Renewable Energy Generation

Source: EIA – Electric Power Annual, Released November 2011
(Excluding hydroelectric power)



Installed Wind Capacity 2011



Current Installed Wind Power Capacity (MW)

Total: 42,432 MW
(As of 06/30/2011)

Data is from the American Wind Energy Association Second Quarter 2011 Market Report: http://www.awea.org

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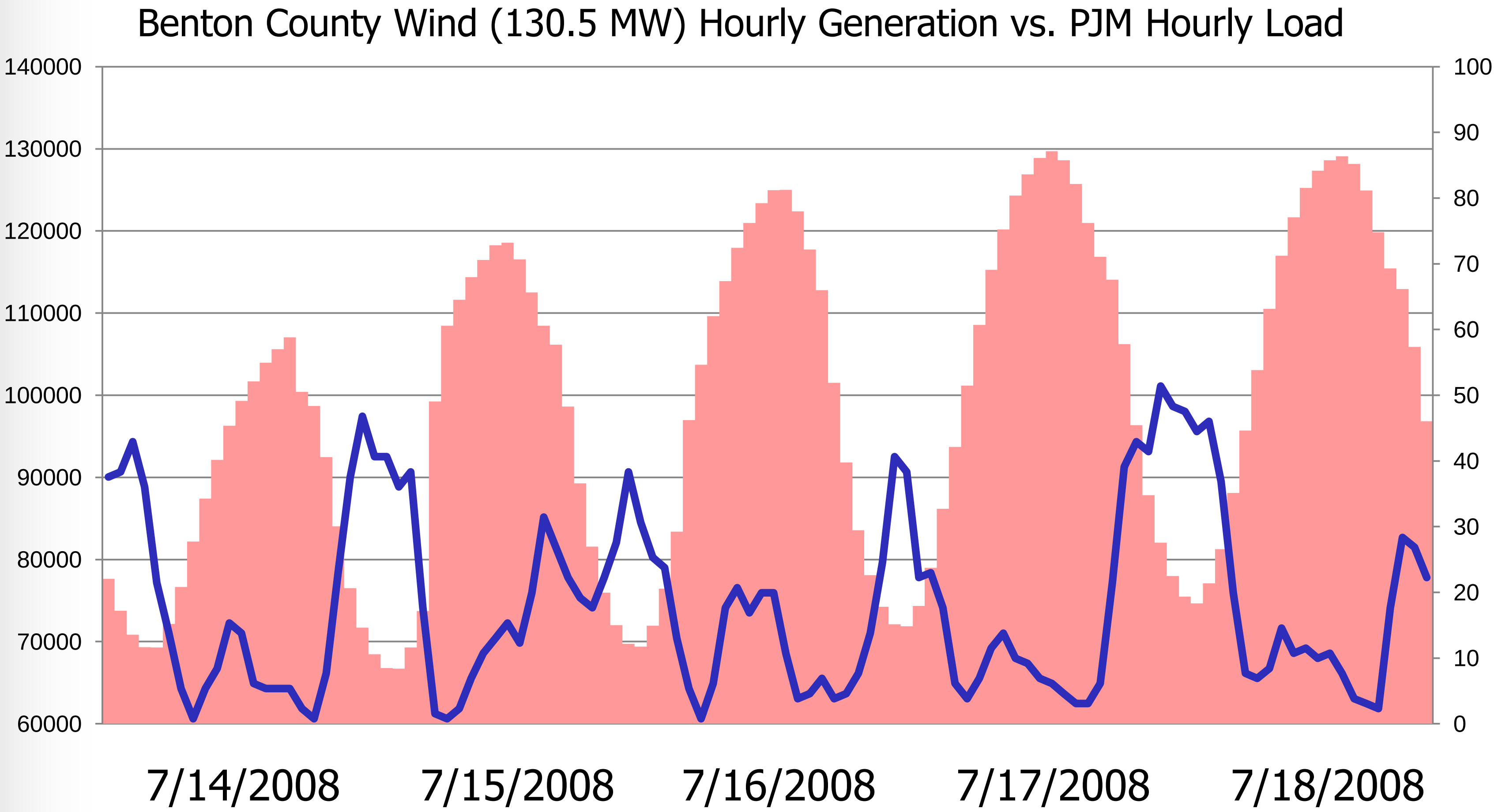
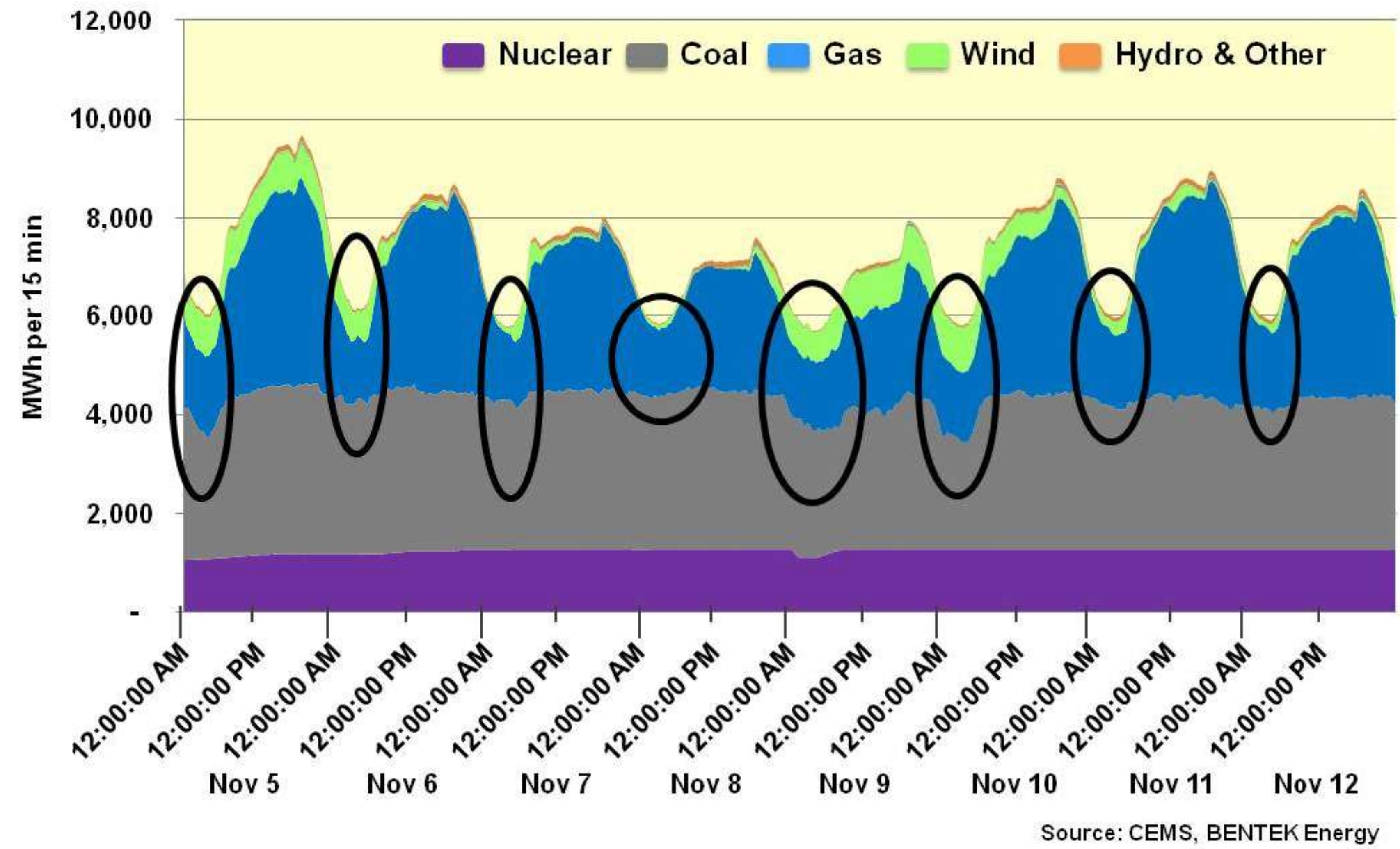
Wind Power Characteristics



Source: Linowes. 2010. Wind Energy: An Assessment.
Mid-America Regulatory Conference: www.marc-conference.org/2010/

Coal and Gas Plants Are Cycled as Wind Generation Increases: Texas

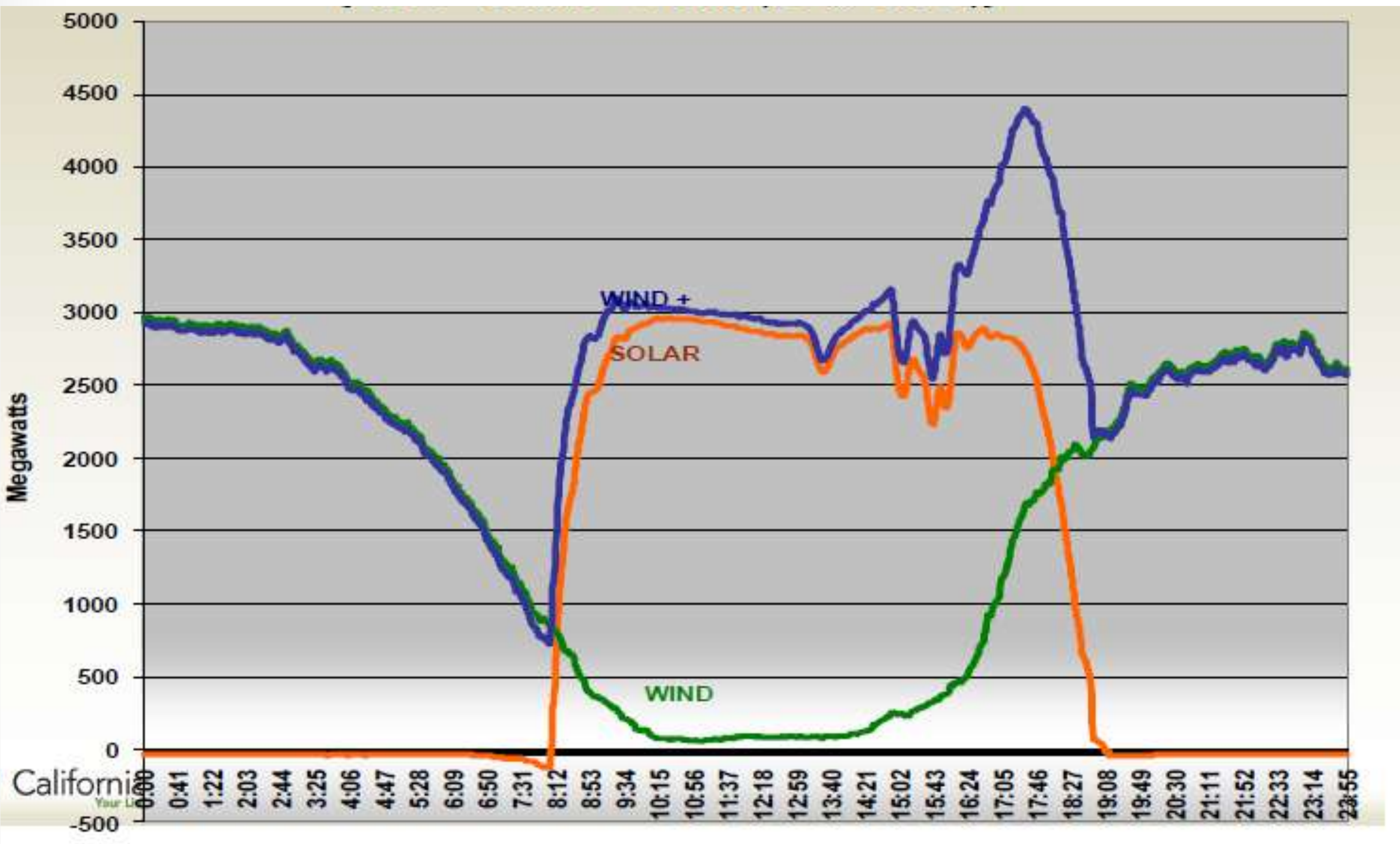


Source: CEMS, BENTEK Energy

Combined Solar and Wind

Wind and solar production in California under a 20% RPS

Source: ISO/RTO Council. 2010. Variable Energy Resources, System Operations and Wholesale Markets



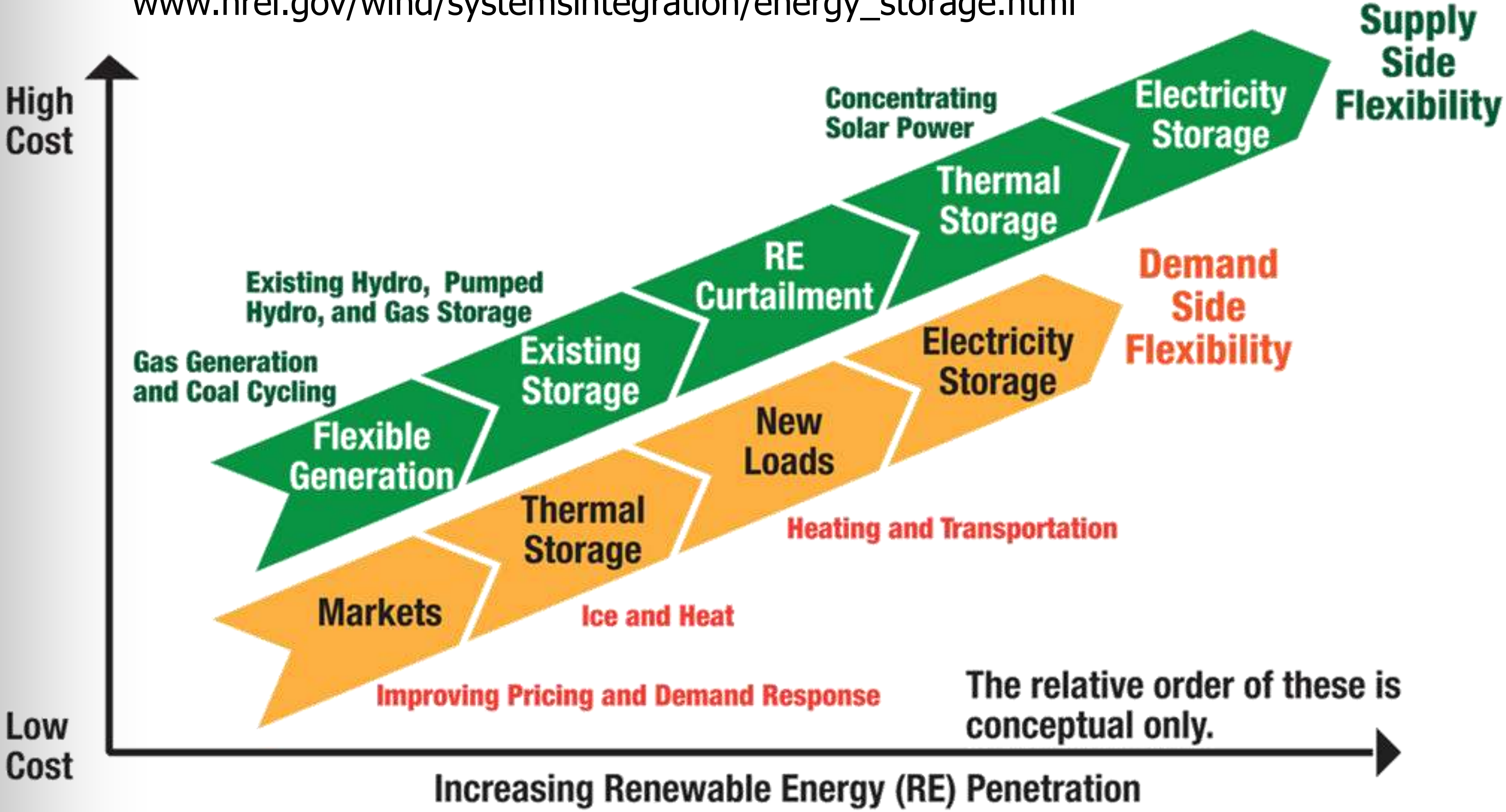
Operational Challenges in Integrating Intermittent Generation

- Less efficient unit commitment due to forecast errors in wind production
- Increased (net) load following requirements
- Increased regulation requirements
- Increased contingency reserve requirements
- Increased frequency and magnitude of minimum generation events

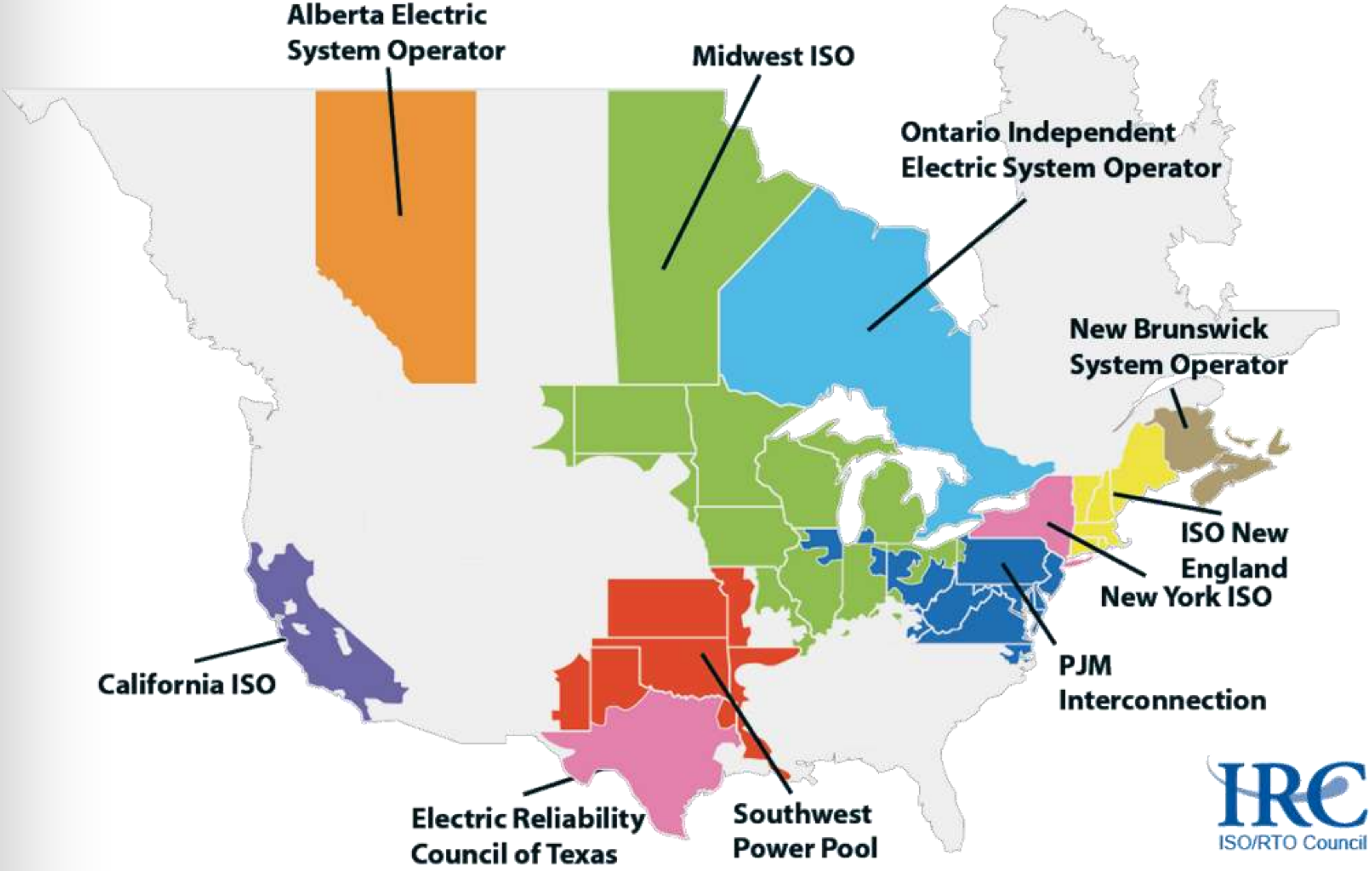
Flexibility Supply Curve

National Renewable Energy Lab (NREL)

www.nrel.gov/wind/systemsintegration/energy_storage.html

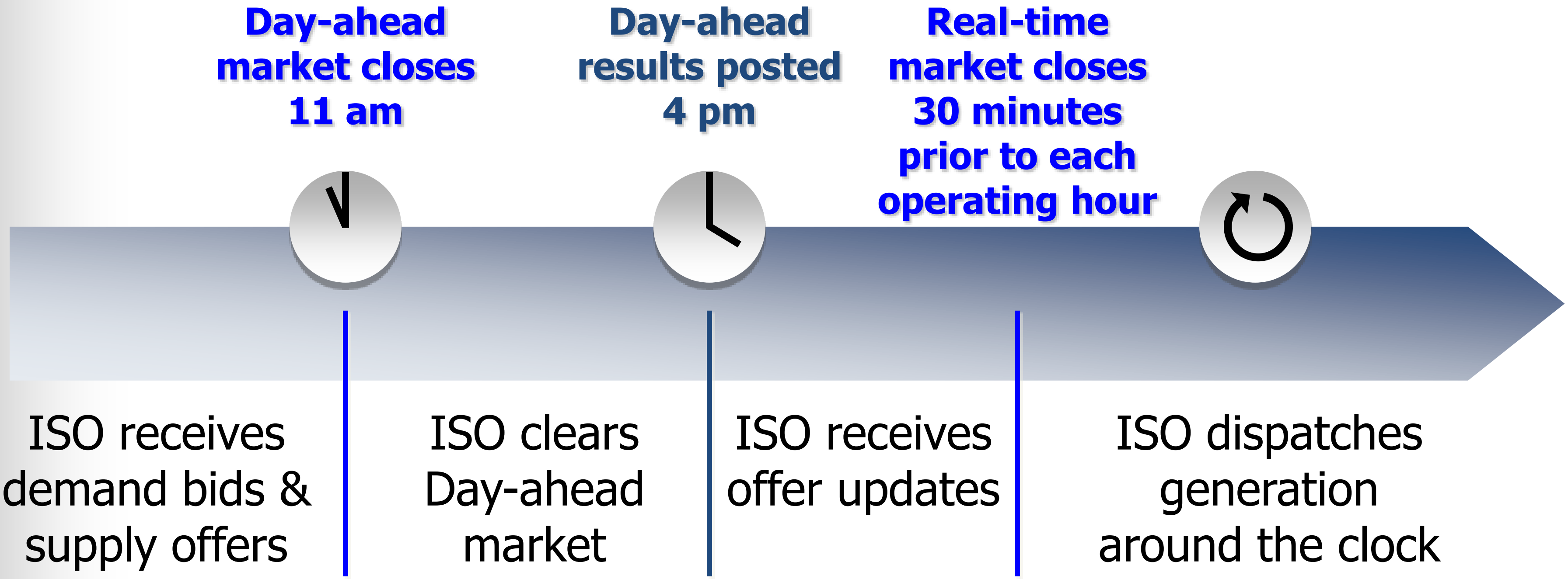


Electricity System Operators (ISOs/RTOs)



Market Timeline

Simplified for tutorial purpose.



Day-ahead market closes 11 am

Day-ahead results posted 4 pm

Real-time market closes 30 minutes prior to each operating hour

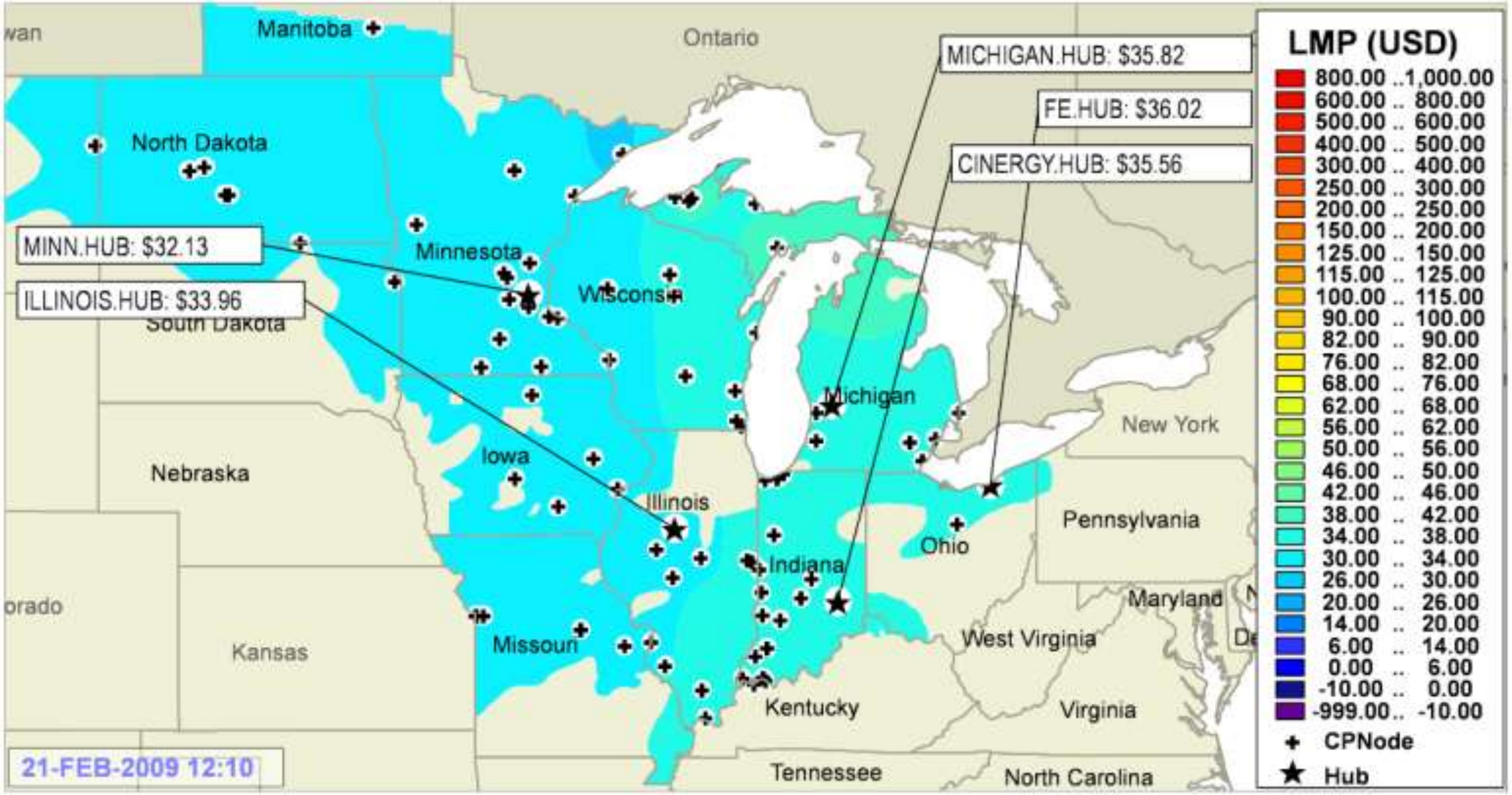
ISO receives demand bids & supply offers

ISO clears Day-ahead market

ISO receives offer updates

ISO dispatches generation around the clock

Locational Marginal Prices (LMP)



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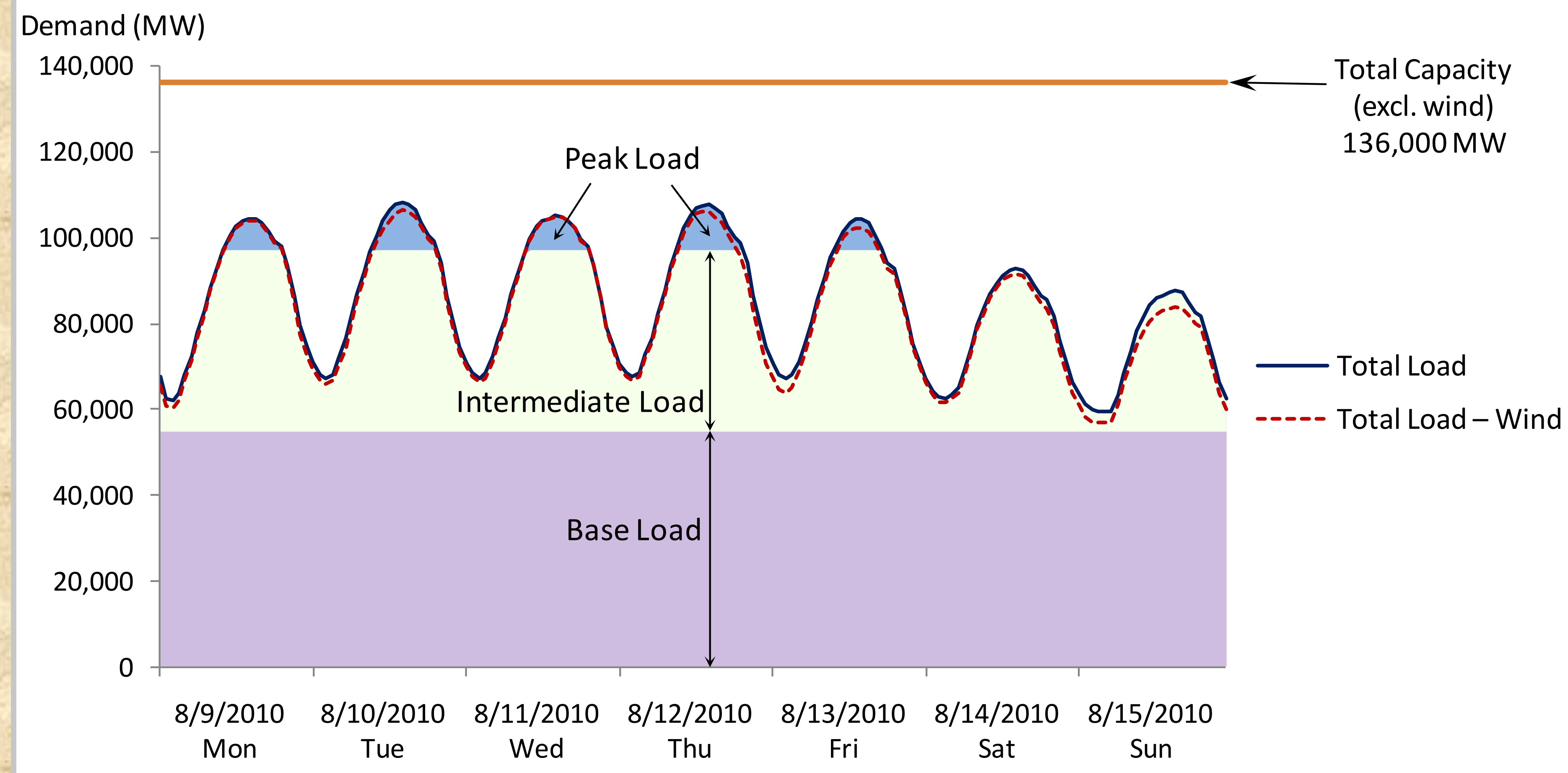
Balancing Supply (Generation) and Demand (Load)



Operational Challenges in Electricity Systems

- Balancing supply and demand in real time with limited storage
  - Made more difficult by intermittency
- Increased requirements on:
  - (Net) load following
  - Regulation
  - Operating reserve
- Optimal use of various levers to balance the system:
  - Flexible generation
  - Energy storage
  - Renewable energy curtailment
  - Demand response
- Transmission constraints
- Distributed generation and storage

Outline

Electricity industry background and operational challenges

Opportunities of applying OM theory to address these challenges

Examples

Similarities and Differences between Electricity Industry & Other Industries

	Electricity Industry	Other Manufacturing and Service Industries
Goal	Matching supply with demand	
Demand Characteristics	Predictable variations • Intra-day, intra-week, intra-year seasonality Unpredictable variations	
	Single commodity	Single or multiple products
Supply Characteristics	Multi-mode production	
	• Baseload generation (push) • Intermediate-load generation • Peaking generation (pull)	• Efficient production (push) • Responsive production (pull)
	Supply variabilities	
	• Plant outage • Intermittent generation	• Machine breakdown • Random yield
Inventory	Store electricity in other forms: Energy conversion loss	Store goods in warehouses: Holding cost

Similarities and Differences between Electricity Industry & Other Industries

	Electricity Industry	**Other Manufacturing and Service Industries**
Scheduled production	Commit production quantity before uncertainties realize	
Unscheduled production	Contingency reserves	Alterative suppliers
Production capacity	Capacity expansion and contraction	
	• Costly startup and shutdown of generation units	• Costly expansion and closedown of factories
Transportation	Transmission network: • Zero lead time • Capacity is a very long-term decision • Has to obey electrical laws	Supply network: • Often significant lead time • Capacity is less difficult to adjust • No electrical laws
Dynamic pricing	Emerging practice	Common practice

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Electricity industry background and operational challenges

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Examples

Examples

- Firm level:
  - Newsvendor problem
  - Warehouse problem

- System level:
  - Capacity management problem
  - Network flow problem

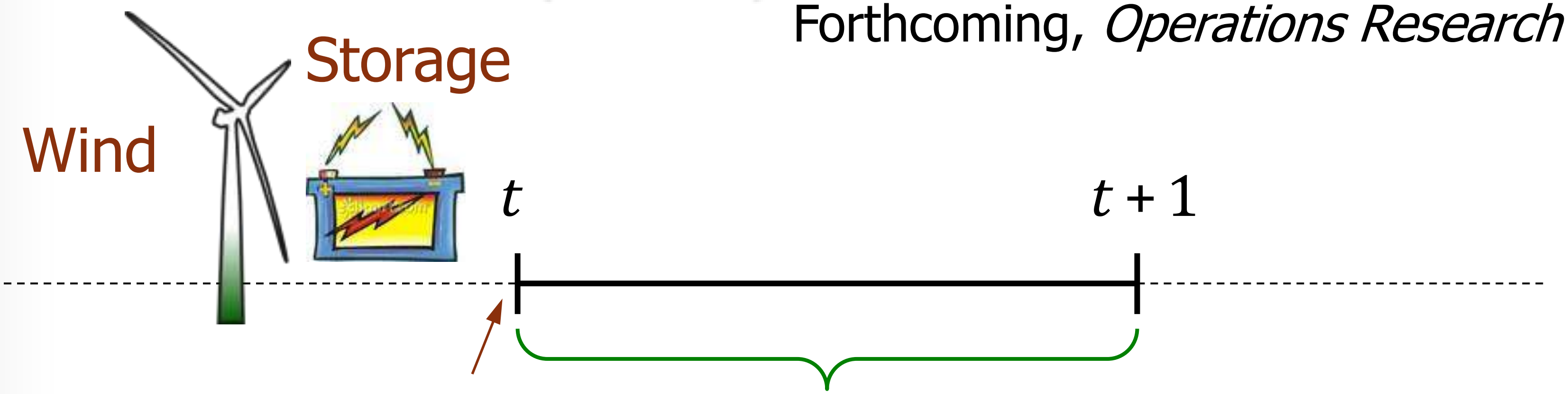
Examples

- Firm level:
  - *Newsvendor problem*
  - Warehouse problem

- System level:
  - Capacity management problem
  - Network flow problem

Kim and Powell (2011)

Optimal energy commitments with storage and intermittent supply. Forthcoming, *Operations Research*



Wind

Storage

t

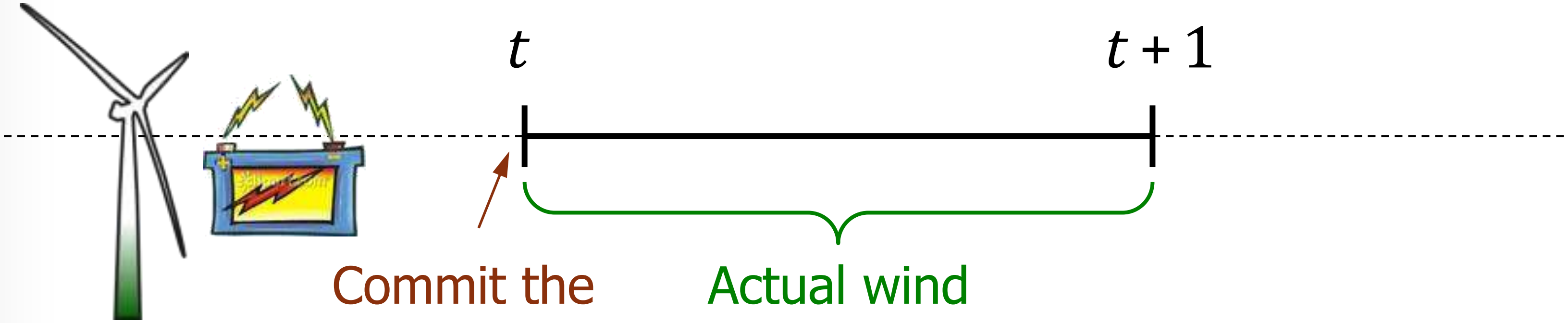
$t+1$

Commit the amount to sell during $[t, t+1)$

Actual wind generation realizes

- Actual wind generation $>$ Commitment: Store excess energy (subject to the conversion loss and the storage capacity)
- Actual wind generation $<$ Commitment: Use the stored energy (subject to the conversion loss and the stored amount)
- Actual wind generation + Storage $<$ Commitment: Pay a penalty

Newsvendor Tradeoff



Commit the amount to sell during $[t, t+1)$

Actual wind generation realizes

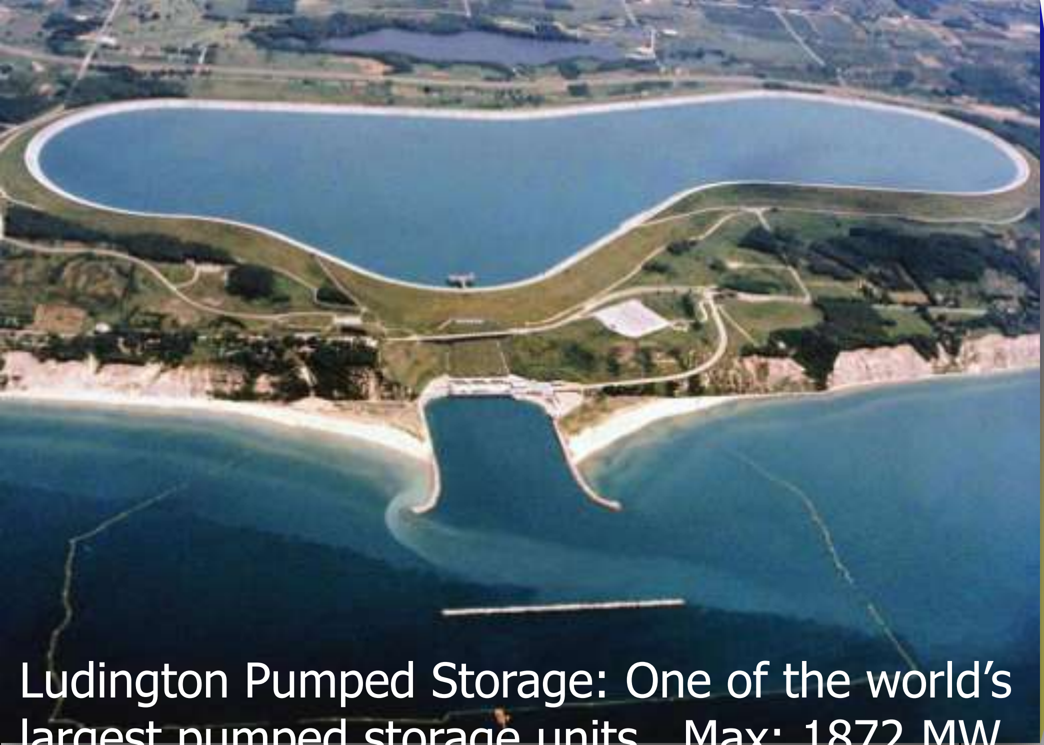
- Cost of over-commitment: Penalty on not meeting the committed quantity
- Cost of under-commitment: Storing energy leads to conversion loss; energy exceeding the storage capacity is lost
- Derive a close-form solution that resembles the newsvendor quantity under a set of assumptions:
    - Electricity price is mean-reverting;
    - Wind generation has a uniform distribution;
    - Assume away complicated storage physics.

Examples

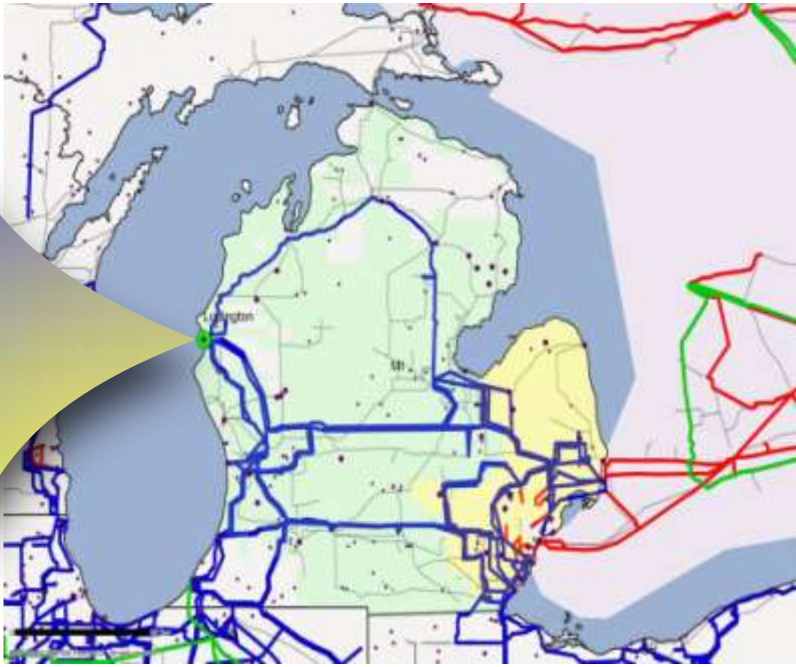
- Firm level:
  - Newsvendor problem
  - *Warehouse problem*
- System level:
  - Capacity management problem
  - Network flow problem

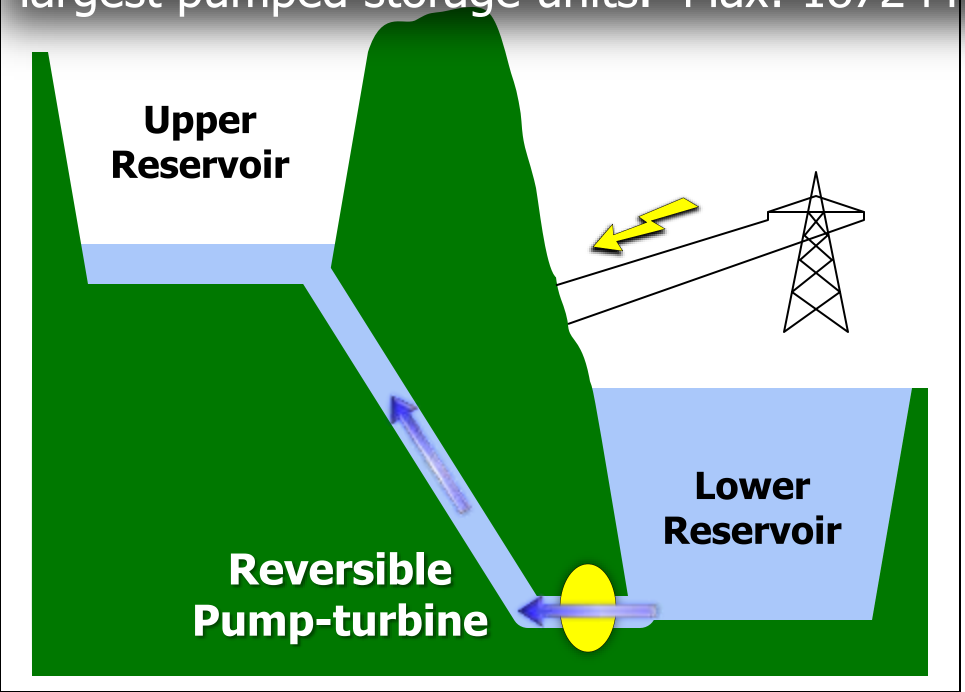
Warehouse Problem

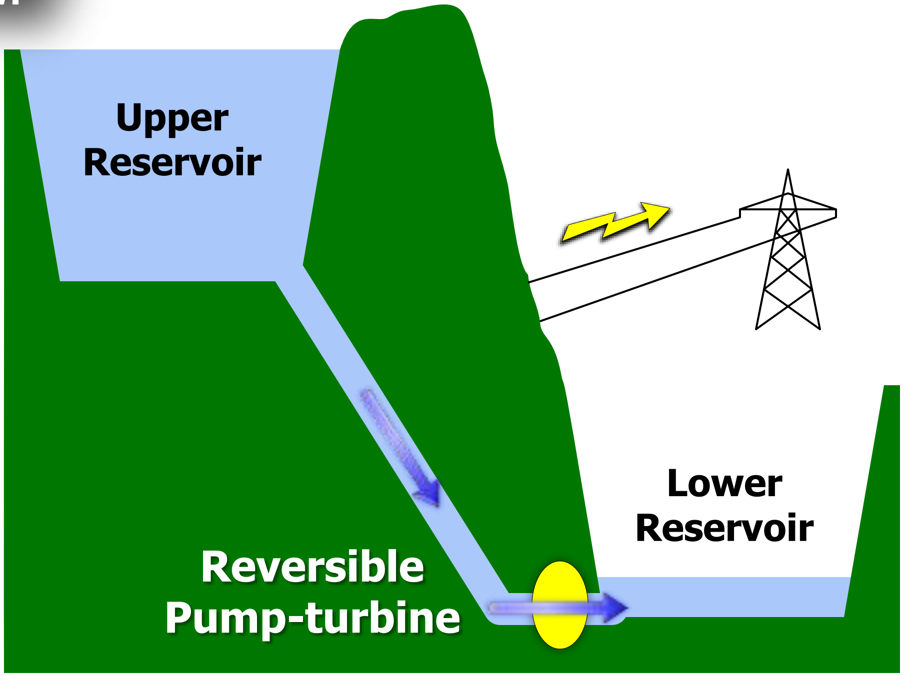
- Given a warehouse with fixed capacity and an initial inventory, under seasonal price and cost variations, what is the optimal pattern of purchasing (or production), storage and sales?
- Recent development:
  Secomandi (2010), Lai, Margot, Secomandi (2010),
  Wu, Wang, Qin (2011)
- Challenges in energy storage operations and valuation:
  - Multi-factor price process
  - The feasible range of storage input and output depends on storage level
  - Threshold level above which pumping cannot restart (hydroelectric pumped storage)



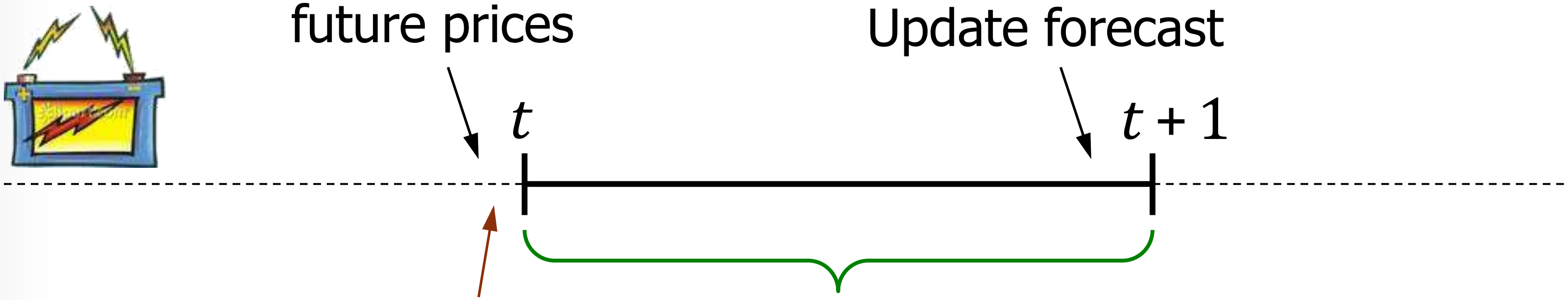
Ludington Pumped Storage: One of the world’s largest pumped storage units. Max: 1872 MW.







Energy Storage Problem



Unbiased
forecasts for
future prices

Update forecast

t

$t+1$

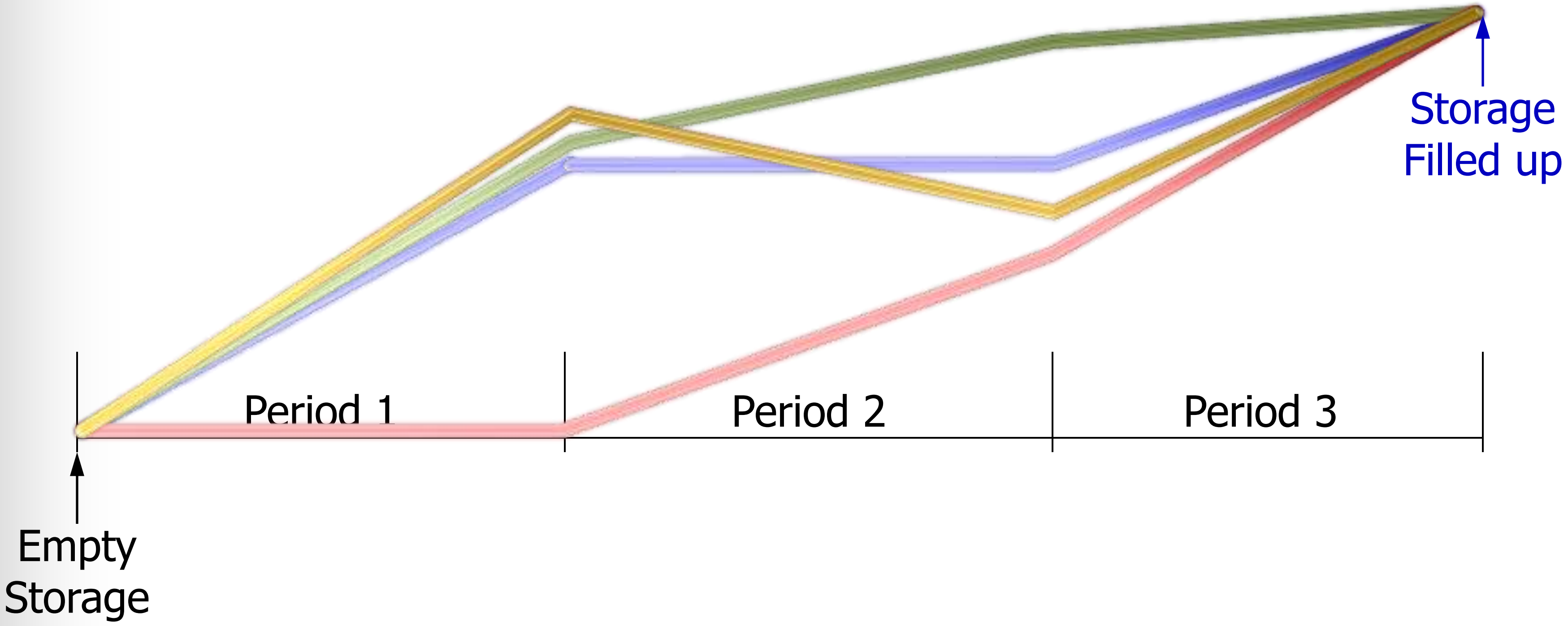
Decide the amount
to store or release
during $[t, t+1)$

Store/release

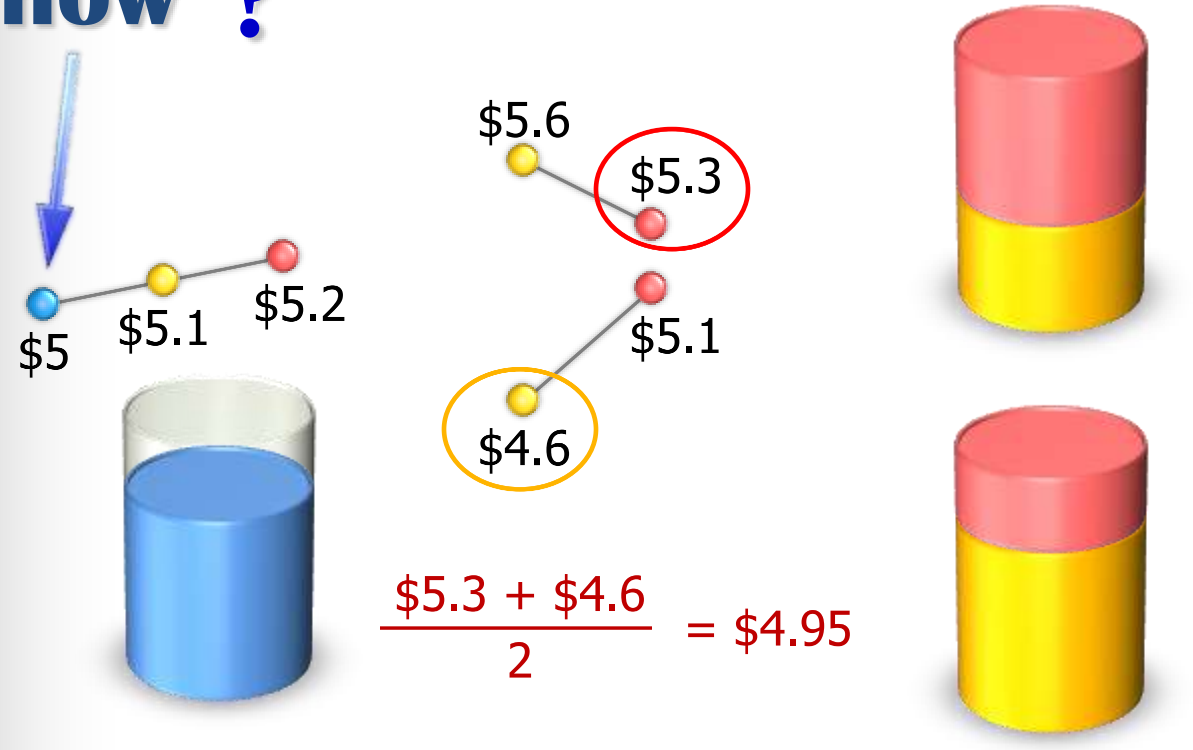
- Intrinsic policy (certainty equivalent control): Using the unbiased forecast as a deterministic input and solve a static optimization problem to generate a schedule for storing and releasing.
- Rolling Intrinsic policy: Re-optimize every period.

Off-Peak Season Problem

- Given an empty storage with storing and releasing capacities, what is the optimal strategy to fill up the storage?
- To derive insights, consider three periods:



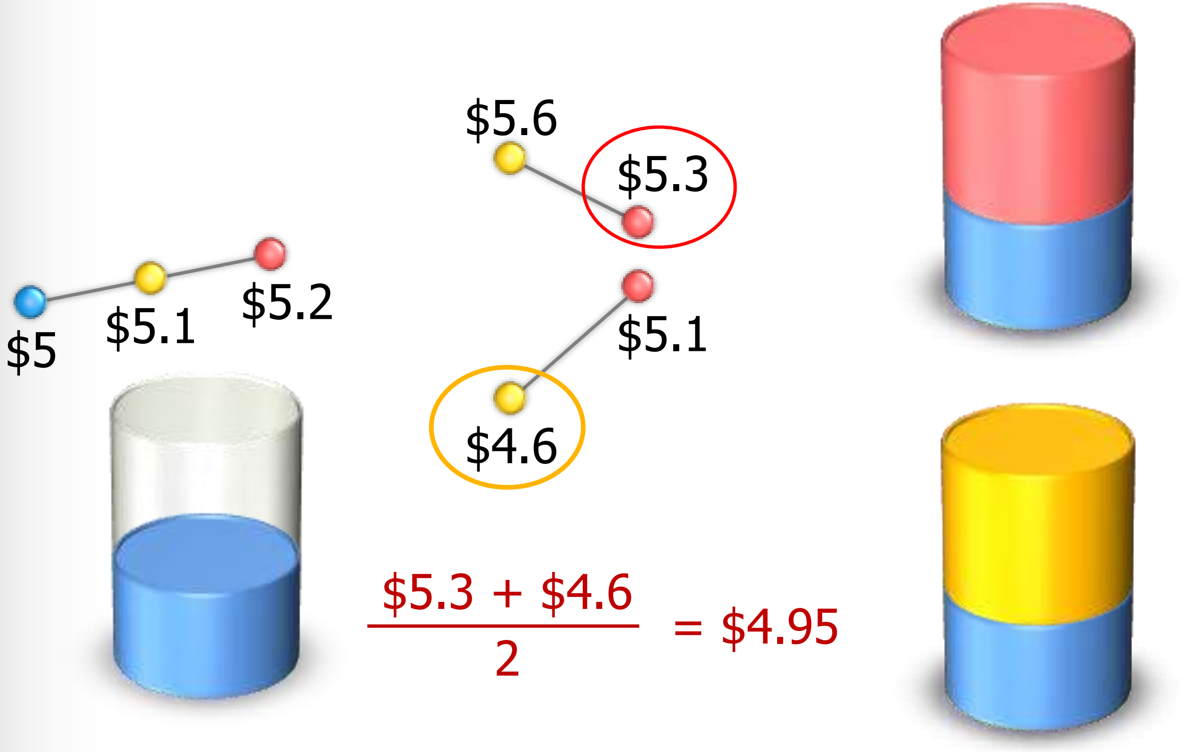
Should we buy as much as possible now ?



$$\frac{\$5.3 + \$4.6}{2} = \$4.95$$

- Minimum of two martingales is a super-martingale.
- Value of waiting

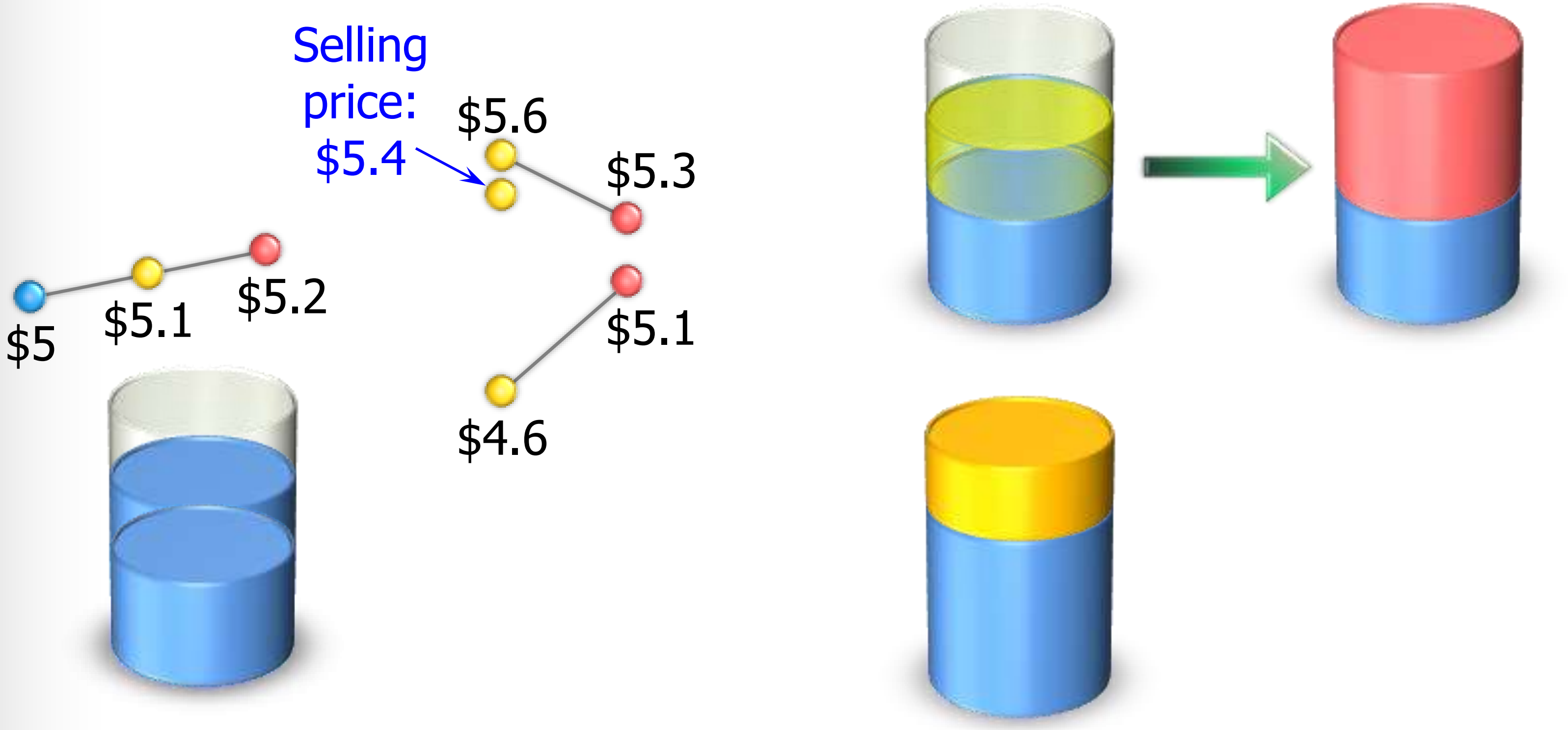
Should we do nothing but wait?



$$\frac{\$5.3 + \$4.6}{2} = \$4.95$$

- Minimum of two martingales is a super-martingale.
- Value of waiting

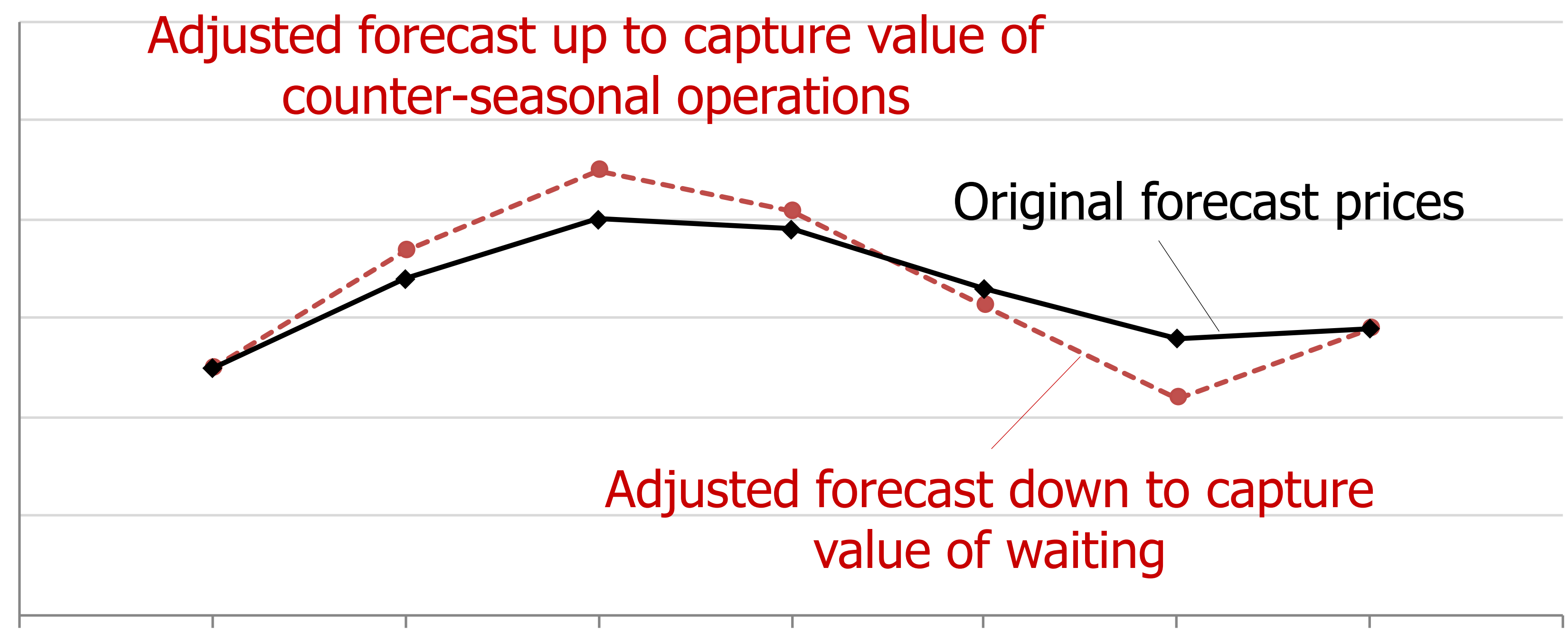
Is there a value of not delaying ?



- Value of counter-seasonal operations

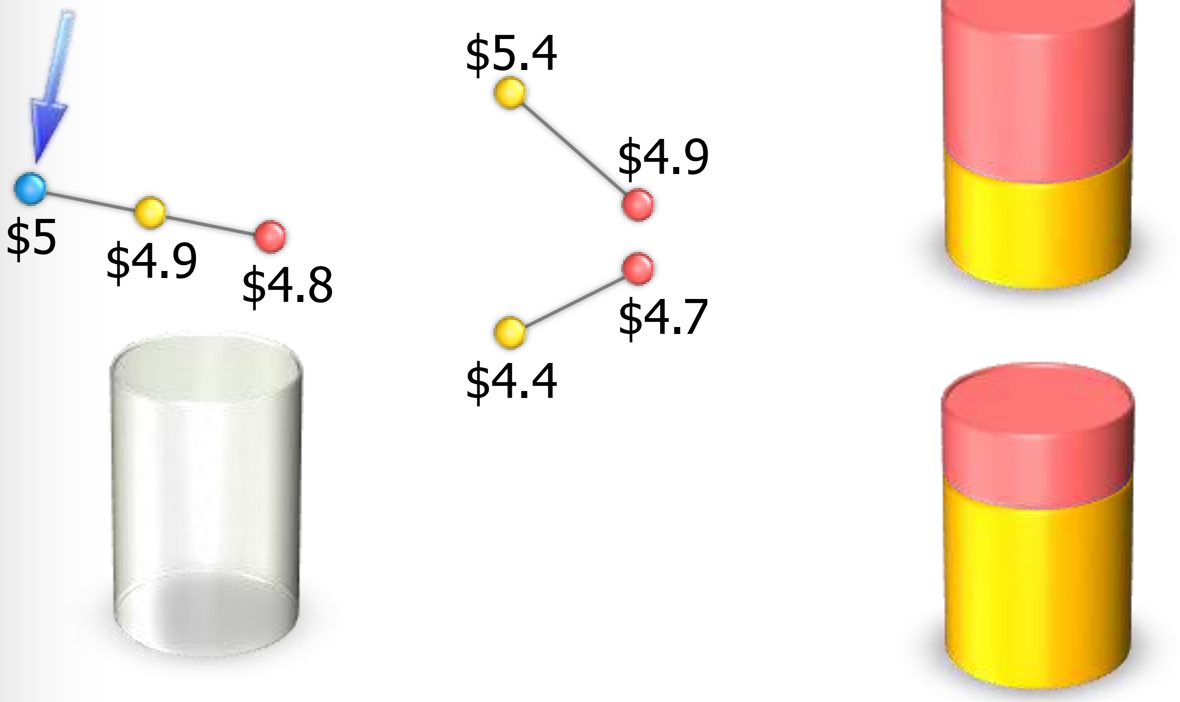
Forecast Adjusted Intrinsic Policy

- Step 1: Adjust forecast to reflect the option values
- Step 2: Solve deterministic optimization problem using adjusted forecast.

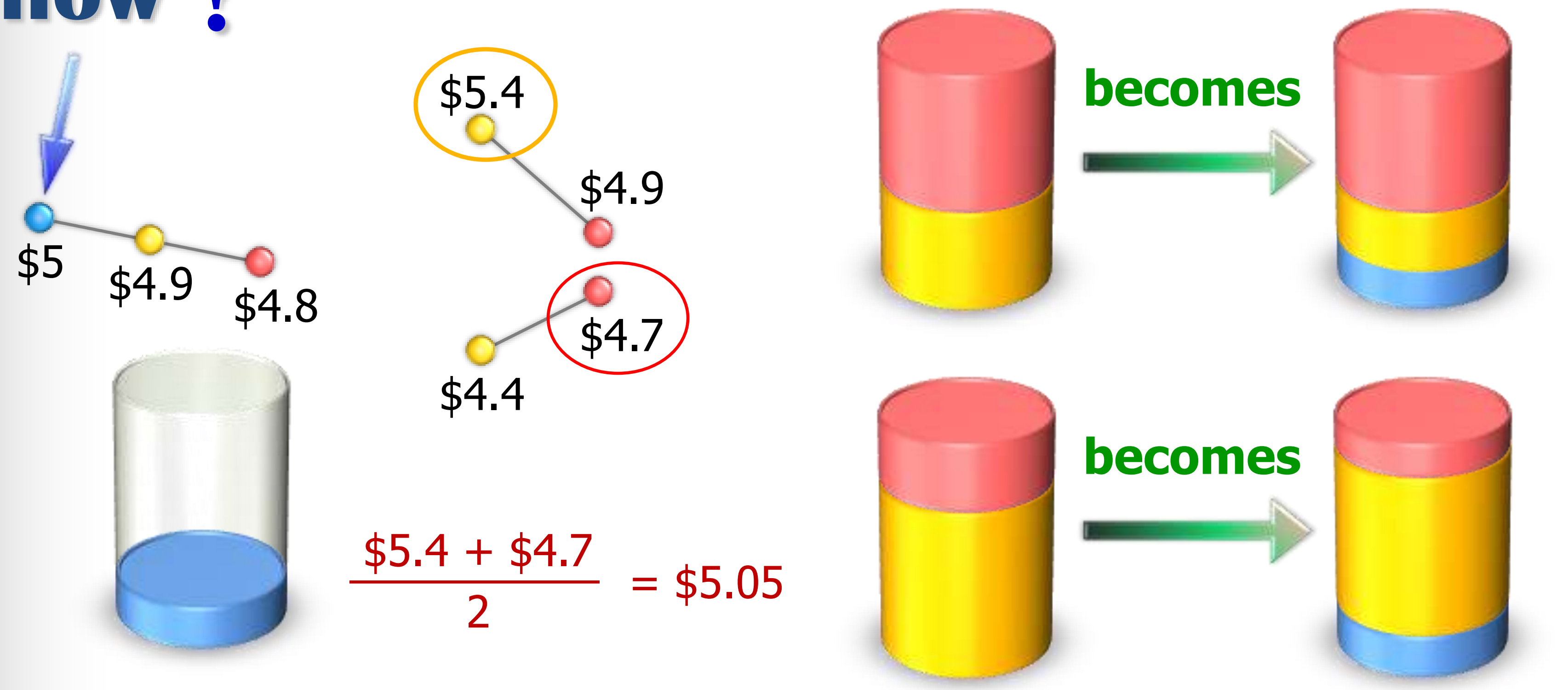


- Wu, Wang, Qin (2011) show that this policy is effective in recovering loss from the Rolling Intrinsic policy (natural gas storage setting).

Should we buy nothing now ?



Should we buy nothing now ?



$$\frac{\$5.4 + \$4.7}{2} = \$5.05$$

- Maximum of two martingales is a sub-martingale.
- Value of avoiding adverse price
- Similar forecast adjustment method exists

Summary of Energy Storage Problem

- Storage technologies are advancing:
    - Compressed air energy storage, batteries, flywheels, hydrogen storage, capacitors …
- Valuation of energy storage is crucial for the viability of future energy storage projects.
- Optimal use (store and release) of the storage are crucial for maximizing the value of storage.
- Distributed small storage vs. central large storage

Examples

- Firm level:
  - Newsvendor problem
  - Warehouse problem

- System level:
  - *Capacity management problem*
    - Angelus and Porteus (2002)
    - Wu and Kapuscinski (2011)
  - Network flow problem

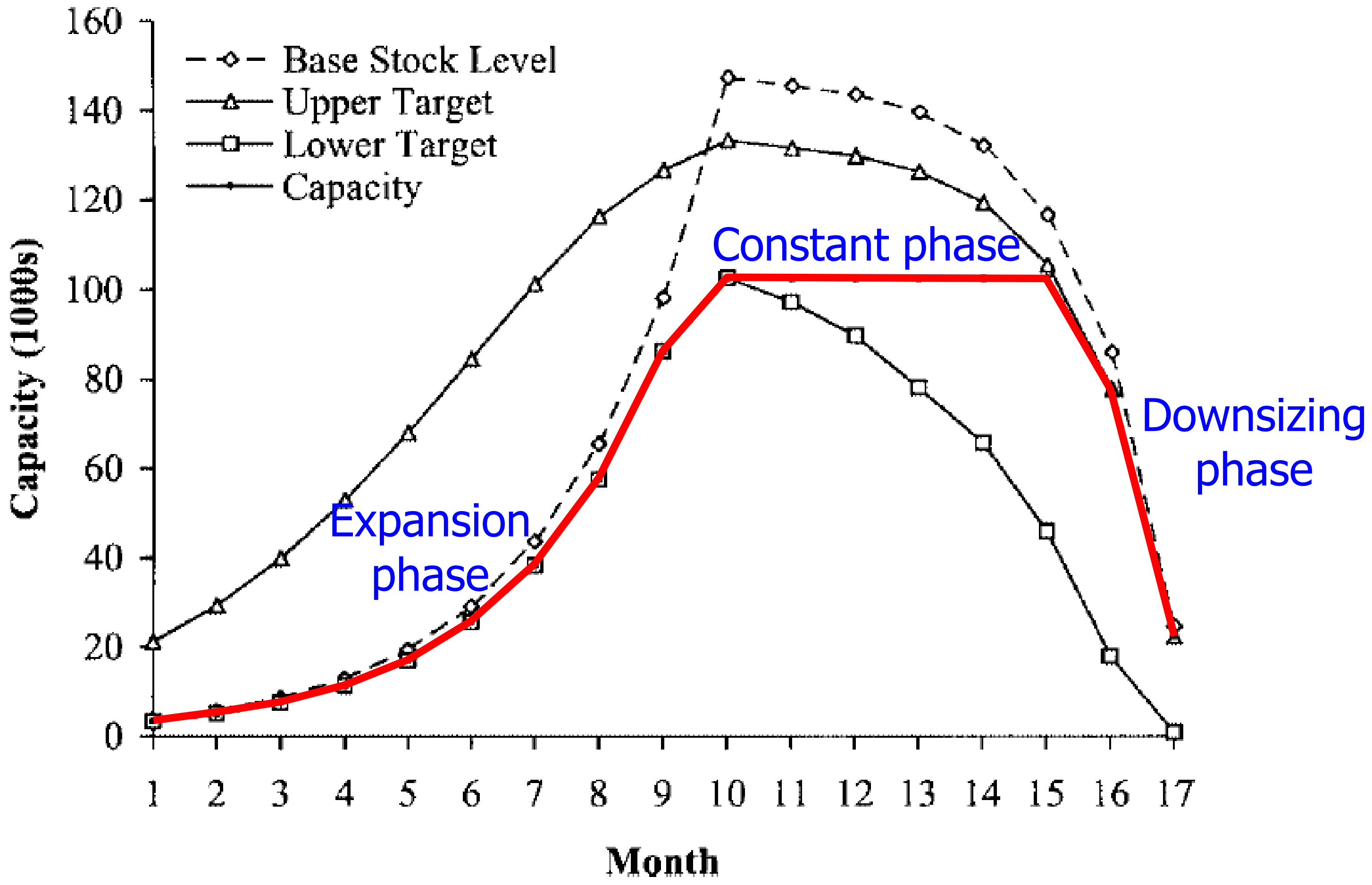
Angelus and Porteus (2002)

Simultaneous capacity and production management of short-life-cycle, produce-to-stock goods under stochastic demand, *Management Science*

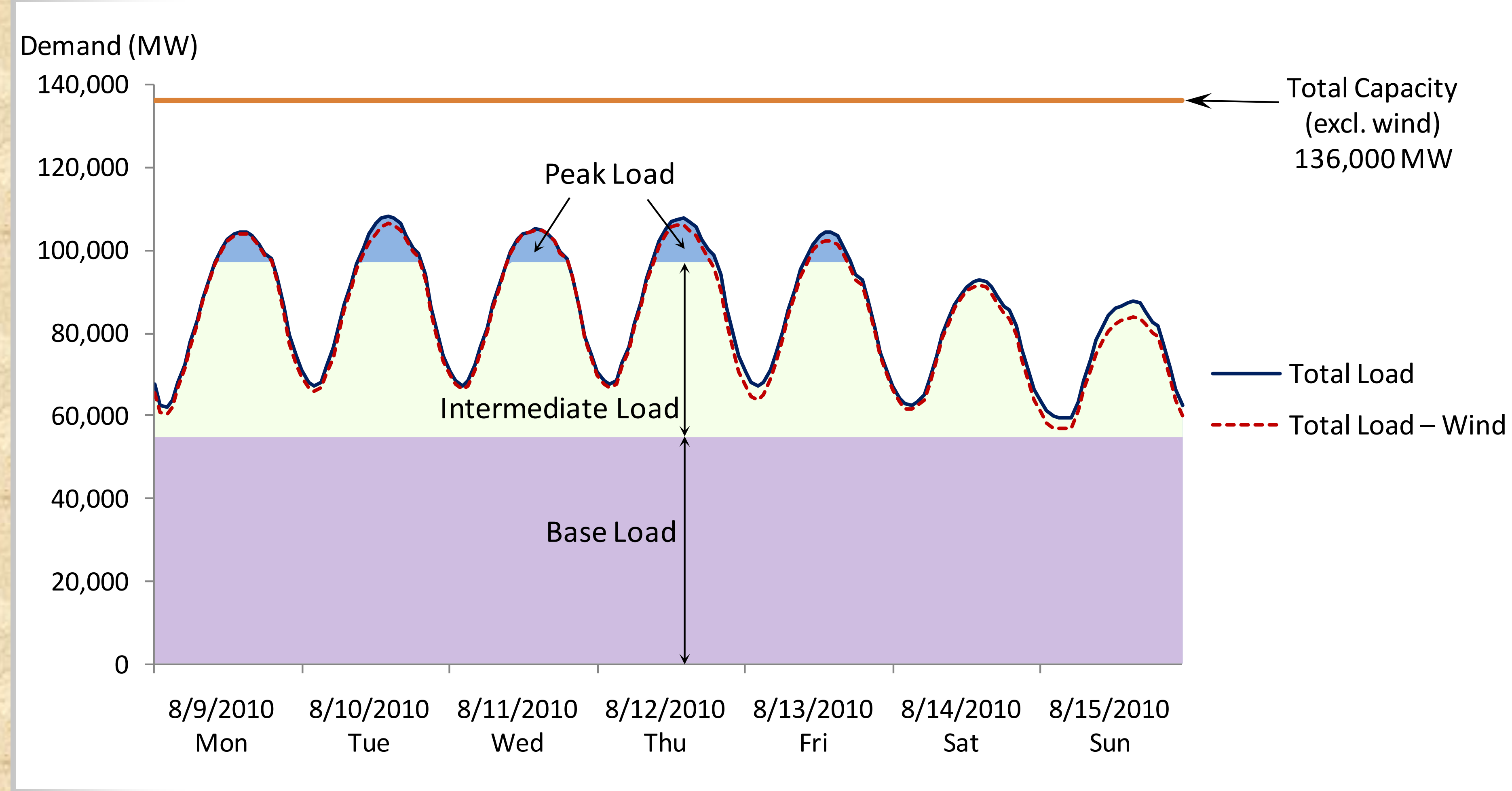
- Joint decision of capacity and production under uncertain demand
- Sequence of events and costs in each period:
  - Decide new capacity level, which becomes available immediately. (Adding capacity incurs a cost; selling capacity yields a return; capacity incurs an overhead cost.)
  - Produce to stock.
  - Demand realizes. (Selling price is fixed.)
  - Unmet demand are lost with a shortage penalty; unsold units are disposed (model 1) or carried over to the next period (model 2).

Angelus and Porteus (2002)

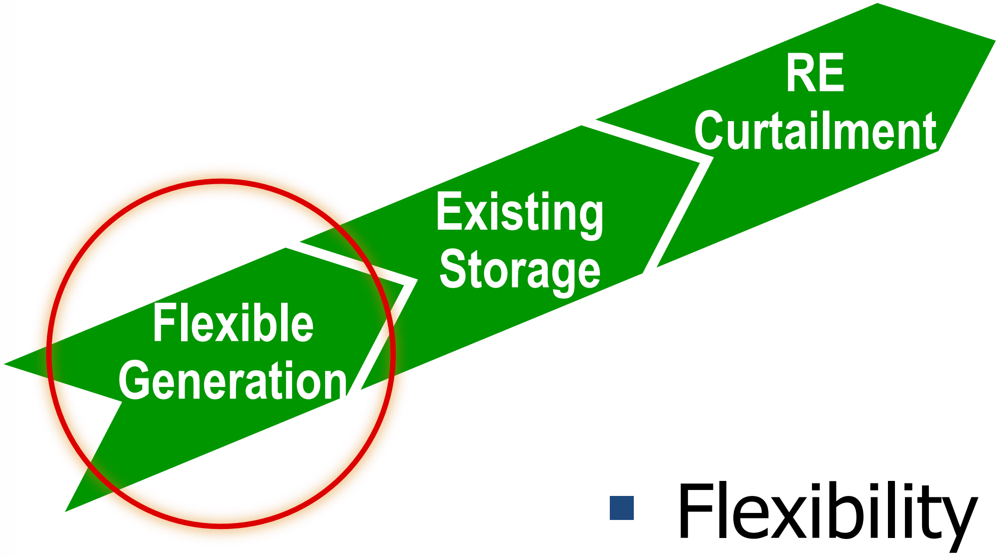
Simultaneous capacity and production management of short-life-cycle, produce-to-stock goods under stochastic demand, *Management Science*



Balancing Supply (Generation) and Demand (Load)



System Balancing Cost



- Flexibility is costly:
  - Cycling cost
  - Part-load penalty
  - Min-gen penalty
  - Peaking premium

Cost of Flexibility: Cycling Cost

- What is it?
  - The cost of fuel that must be consumed to warm up the unit and bring it to normal working conditions
  - Wear and tear cost
- How much is it?
  - Startup of a 1000-MW natural gas combined cycle unit requires about 10,000 Mbtu. At gas price \$5 / Mbtu, it costs \$50,000 per startup, or \$50 per MW of capacity per startup.
  - Startup of a 520-MW coal unit requires about 41,000 Mbtu. At coal price \$3 / Mbtu, it costs \$235 per MW of capacity per startup.
  - Wear and tear cost is comparable to startup fuel cost.

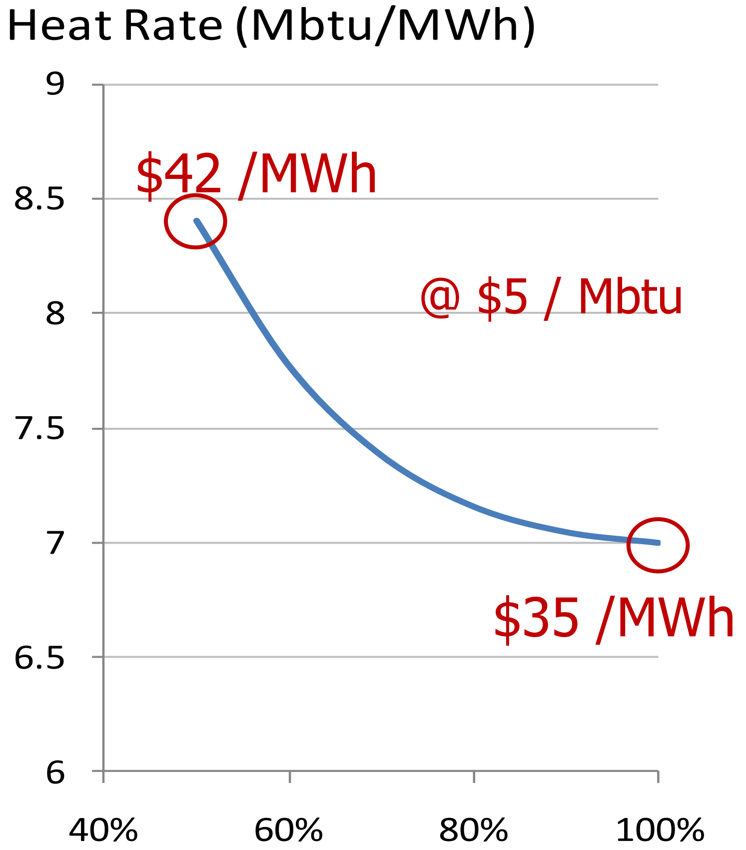
Cost of Flexibility: Part-Load Penalty

- What is it?
  - Units with part load can be ramped up quickly to meet the demand, but operating the units at part load is less efficient.
- How much is it?
  - For a typical CCGT, the cost increases by 20% per MWh when operating at the half load.

Ref: Boyce (2010): Handbook for Cogeneration and Combined Cycle Power Plants

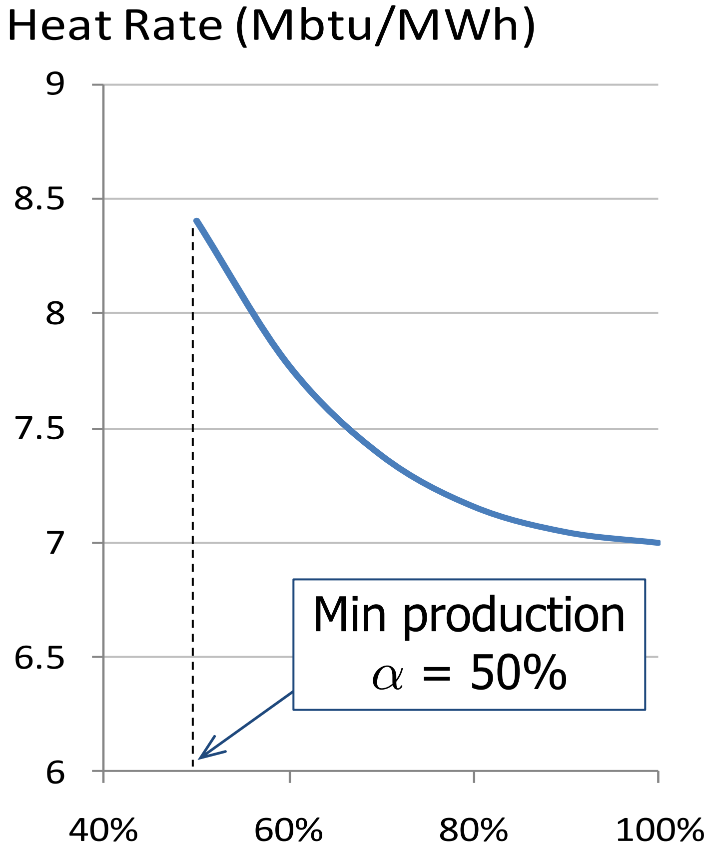
- Production cost $c(q)$

$c(q)/q$ decreases in q



Cost of Flexibility: Min-Gen Penalty

- What is it?
  - Part load cannot drop below a minimum generation (min-gen) level, otherwise extra cost is incurred to keep the unit from damage.
- How much is it?
  - In practice, emergency procedures are activated when min-gen events occur.
  - \$1000 / MWh for NGCC unit
    \$2000 / MWh for coal unit


Heat Rate (Mbtu/MWh)

Min production
α = 50%

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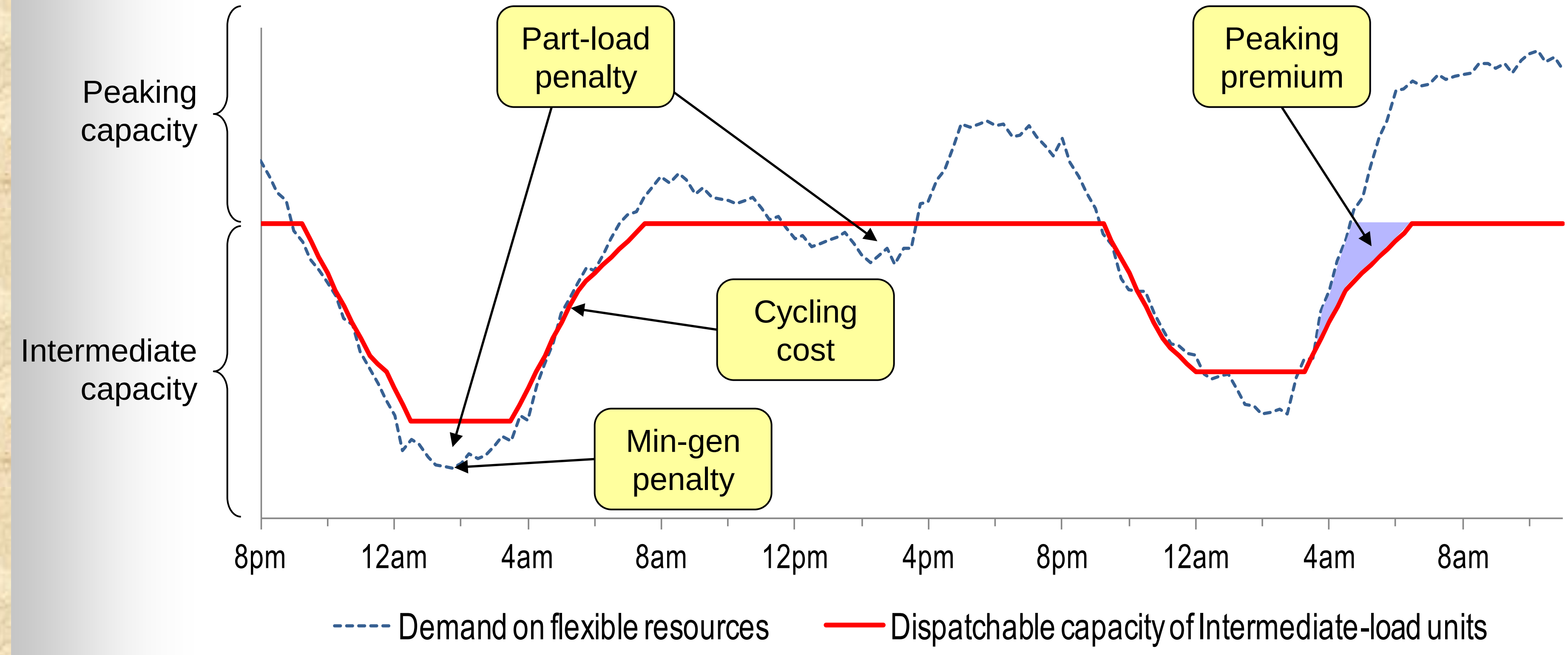
Cost of Flexibility: Peaking Premium

- What is it?
  - The extra cost of using peaking units to serve demand that could not be served by intermediate-load units due to ramp limit. Peaking units are typically single-cycle gas-fired or oil-fired turbines.
- How much is it?
  - At gas price \$5/Mbtu, peaking unit production cost is about \$50 / MWh, \$15 / MWh (\$20 / MWh) more than the cost of NGCC (coal) unit at full load.

Cost of Flexibility



Similarities and Differences between Electricity Industry & Angelus and Porteus

	Electricity Industry	Angelus and Porteus (2002)
Demand	Demand stochastically rises and falls	
	Repeat every 24 hours	Once
Supply	Dispatchable capacity can be adjusted at a cost	
	Intermittent generation (wind)	Fully controllable production
	Curtailment possible	No curtailment
Cost structure	Peaking cost	Shortage cost
	Part-load penalty	Capacity overhead cost
	Start-up cost	Costly expansion
	Shutdown does not yield return	Contraction yields a return
	Minimum generation penalty	No minimum generation
Inventory	Store electricity in other forms: Energy conversion loss	Store goods in warehouses: Holding cost
Capacity adjustment	Takes time	Immediate

Key Model Features: Wu and Kapuscinski (2011)

- Part-load penalty and min-gen penalty:

  $\Rightarrow$ High capacity and low demand is undesirable
- Peaking premium:

  $\Rightarrow$ Low capacity and high demand is undesirable

$\Downarrow$

- Need to match capacity with demand, but …
  - Capacity adjustment is costly: cycling cost
  - Capacity adjustment takes time
  - Intermittent generation increases balancing costs
- Curtailment may help reducing the balancing costs.

Capacity Adjustment Model

- If capacity of size Δ_t^u starts up in period t, then $\gamma^u \Delta_t^u$ will become dispatchable in period t+1.
- The remaining $(1-\gamma^u)\Delta_t^u$ is pending. In every following period, fraction γ^u of the pending capacity will become dispatchable.
- Ramping-down process is similar: $\Delta_t^d, \ \gamma^d$

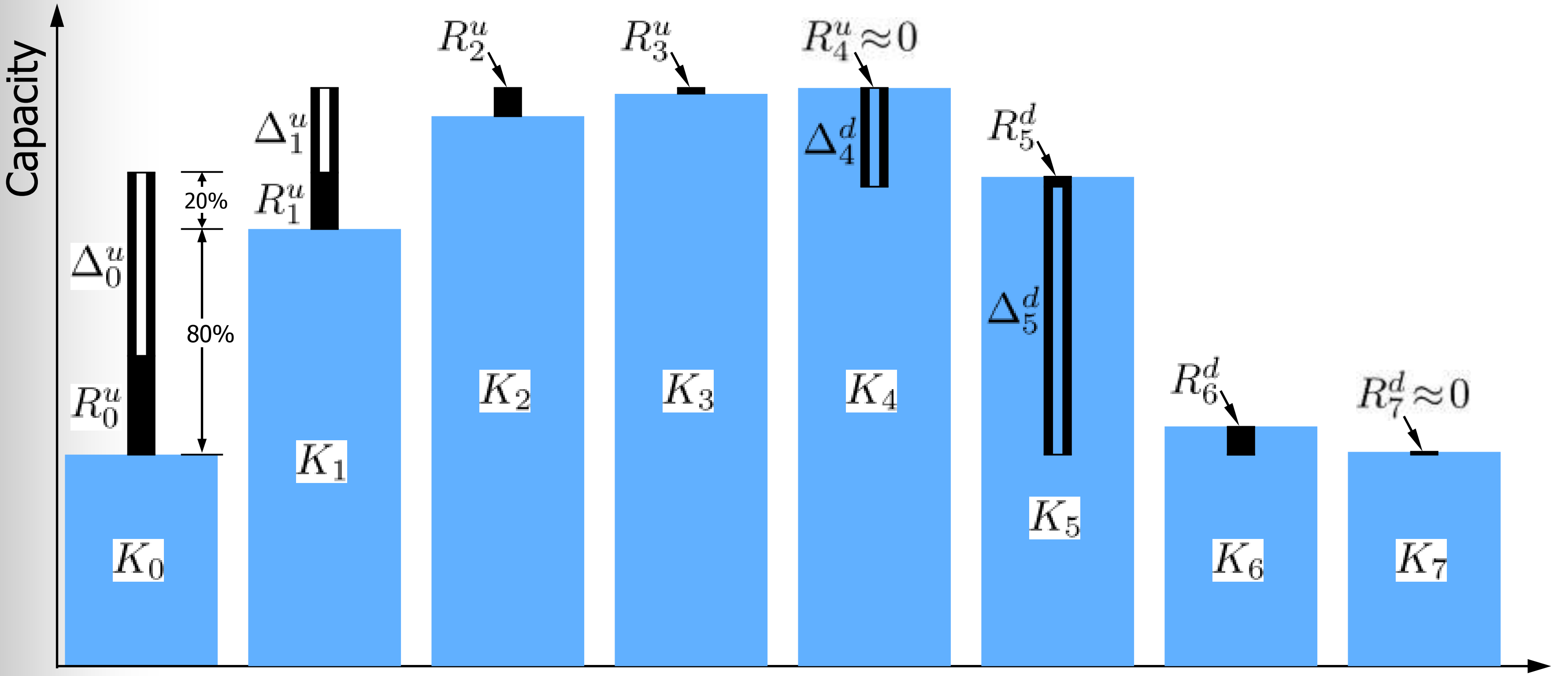
Capacity Adjustment Model

🟦 Dispatchable capacity

■ Pending-up capacity R_t^u or pending-down capacity R_t^d

▭ Newly added pending-up Δ_t^u or pending-down capacity Δ_t^d

$\gamma^u = 0.8 \qquad \gamma^d = 0.9$



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The Model without Storage

- States:
  - $\mathbf{D}_t$: vector of factors driving the demand D_t (net the baseload) (e.g. weather factors, time of day, time of year)
  - $\mathbf{W}_t$: vector of factors driving the wind power W_t (e.g., weather regimes, turbulences, time of day)
  - $\mathbf{K}_{t-1} = (K_{t-1}, R^u_{t-1}, R^d_{t-1})$ dispatchable and pending capacities of intermediate-load units

Actions	Priority Dispatch	Economic Curtailment
Capacity K_t	$K_t \in [K_t^{\min}, K_t^{\max}]$	$K_t^{\max} = K_t^o + \gamma^u(K^I - K_{t-1} - R^u_{t-1})$ $K_t^{\min} = K_t^o - \gamma^d(K_{t-1} - R^d_{t-1})$
Production Q_t	$Q_t = (D_t - W_t)^+$	$Q_t \in [(D_t - W_t)^+, D_t]$
Curtailment w_t	$w_t = Q_t + W_t - D_t$	
	$w_t = (W_t - D_t)^+$	$w_t \in [(W_t - D_t)^+,\ W_t]$

Model for Economic Curtailment without Storage

$$V_t(\mathbf{D}_t, \mathbf{W}_t, \mathbf{K}_{t-1})$$

Intermediate-load units production cost

$$C(Q, K) = nc\left(\frac{Q}{n}\right)$$

$$n = K/\kappa$$

$$= \min_{K_t, Q_t} \Big\{ C(Q_t \wedge K_t, K_t)$$

Peaking cost

$$+ (Q_t - K_t)^+ c^P$$

Min-gen penalty

$$+ (\alpha K_t - Q_t)^+ p$$

Cycling cost

$$+ \frac{(K_t - K_t^o)^+}{\gamma^u} c^s$$

$$+ \rho \mathsf{E}_t \big[V_{t+1}(\mathbf{D}_{t+1}, \mathbf{W}_{t+1}, \mathbf{K}_t) \big] \Big\}$$

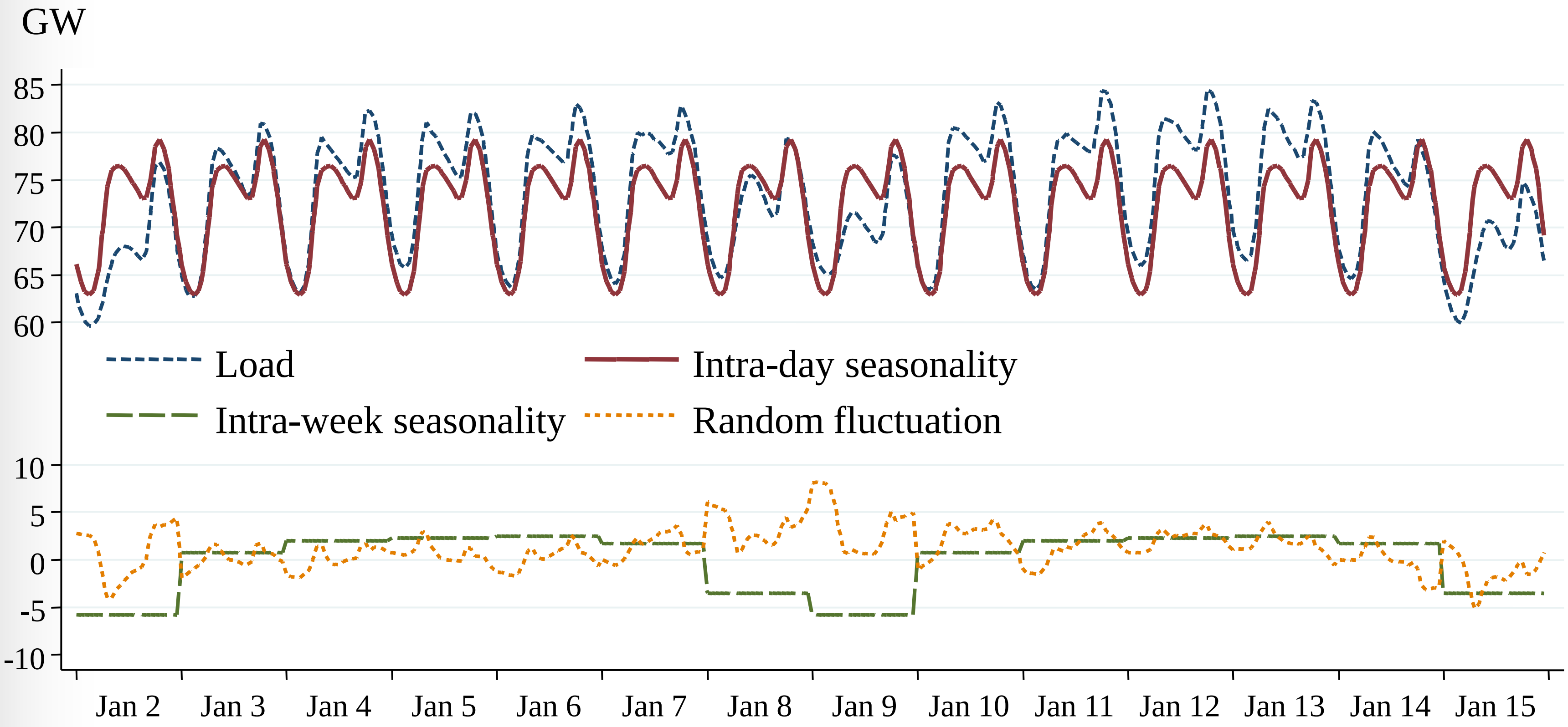
$$s.t. \; K_t \in [K_t^{\min},\; K_t^{\max}], \quad Q_t \in [(D_t - W_t)^+,\; D_t],$$

$$R_t^u = (1 - \gamma^u) R_{t-1}^u + \tfrac{1-\gamma^u}{\gamma^u} (K_t - K_t^o)^+$$

$$R_t^d = (1 - \gamma^d) R_{t-1}^d + \tfrac{1-\gamma^d}{\gamma^d} (K_t^o - K_t)^+$$

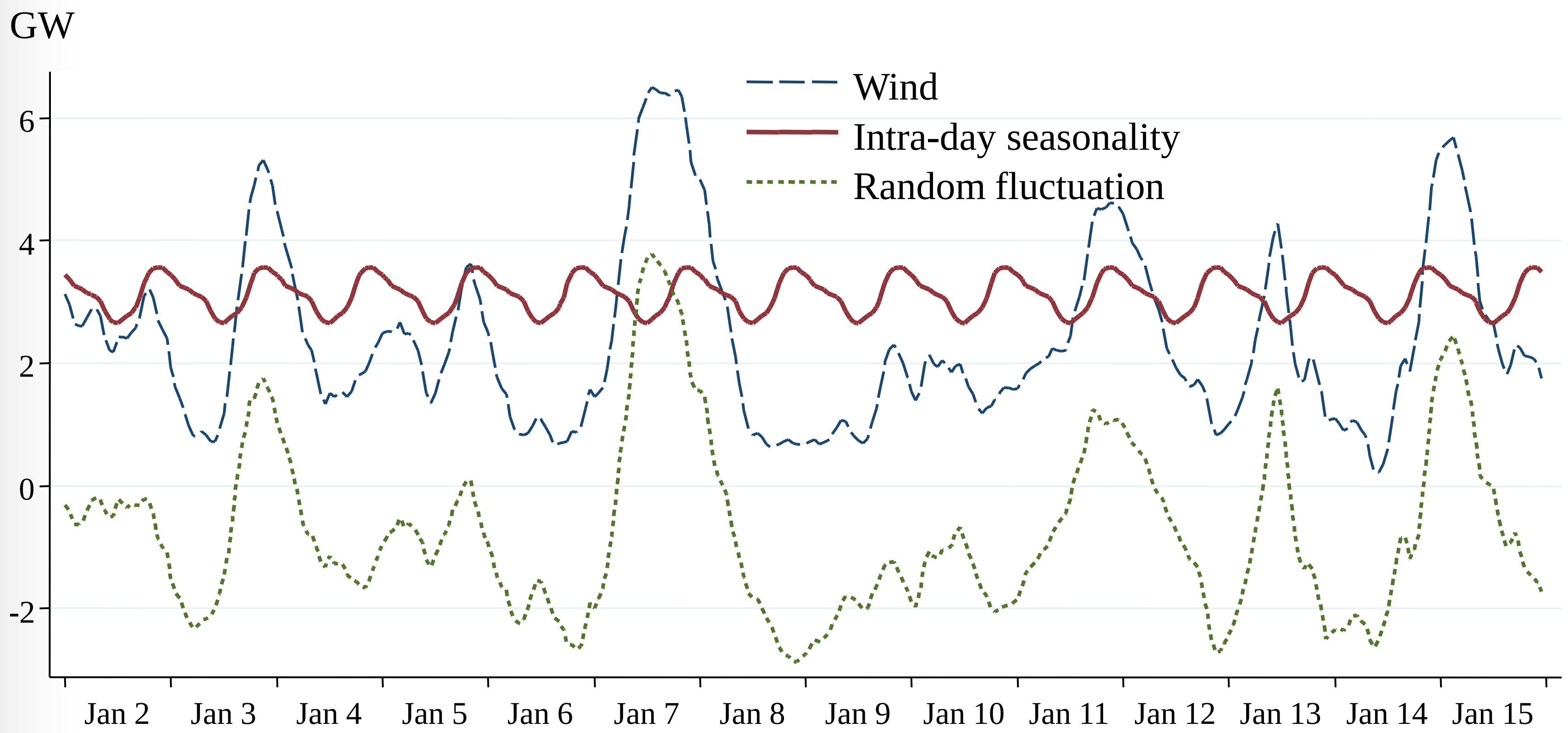
Load Decomposition

Load in Midwest ISO footprint (Data from www.midwestmarket.org)



Wind Decomposition

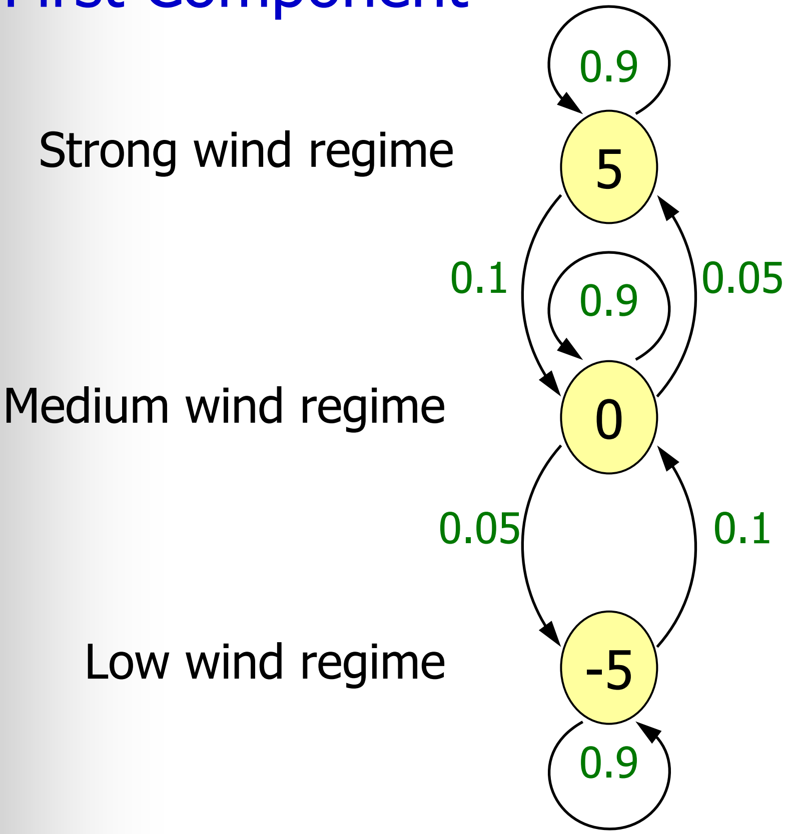
Wind in Midwest ISO footprint (Data from www.midwestmarket.org)



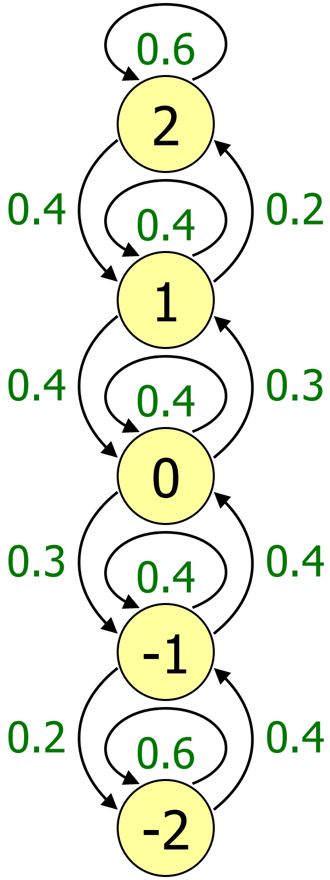
- Random fluctuation is modeled by a two-dimensional Markov model:
  - The first Markov process models random regime switching
  - The second Markov process models variations within regimes

Example of Two-Factor Wind Model

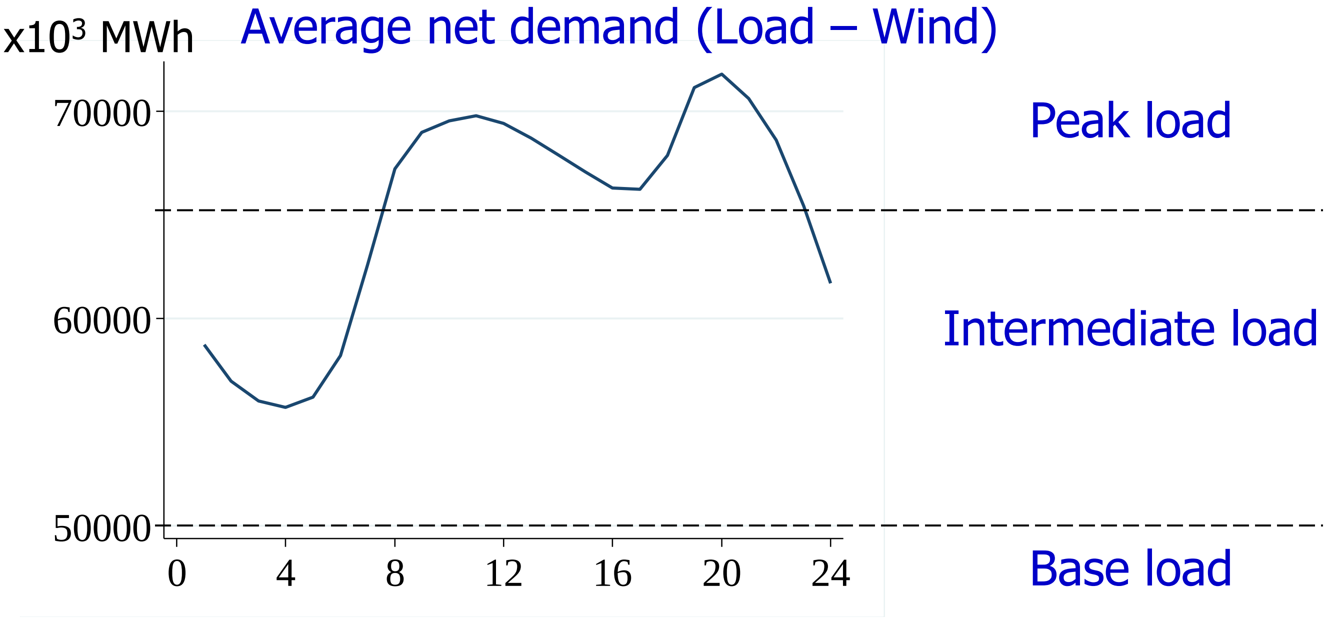
First Component



Second Component



Generation Fleet Size



- Base load generation: 50,000 MW
- Intermediate capacity: 15,000 MW
- Peaking capacity: Large enough

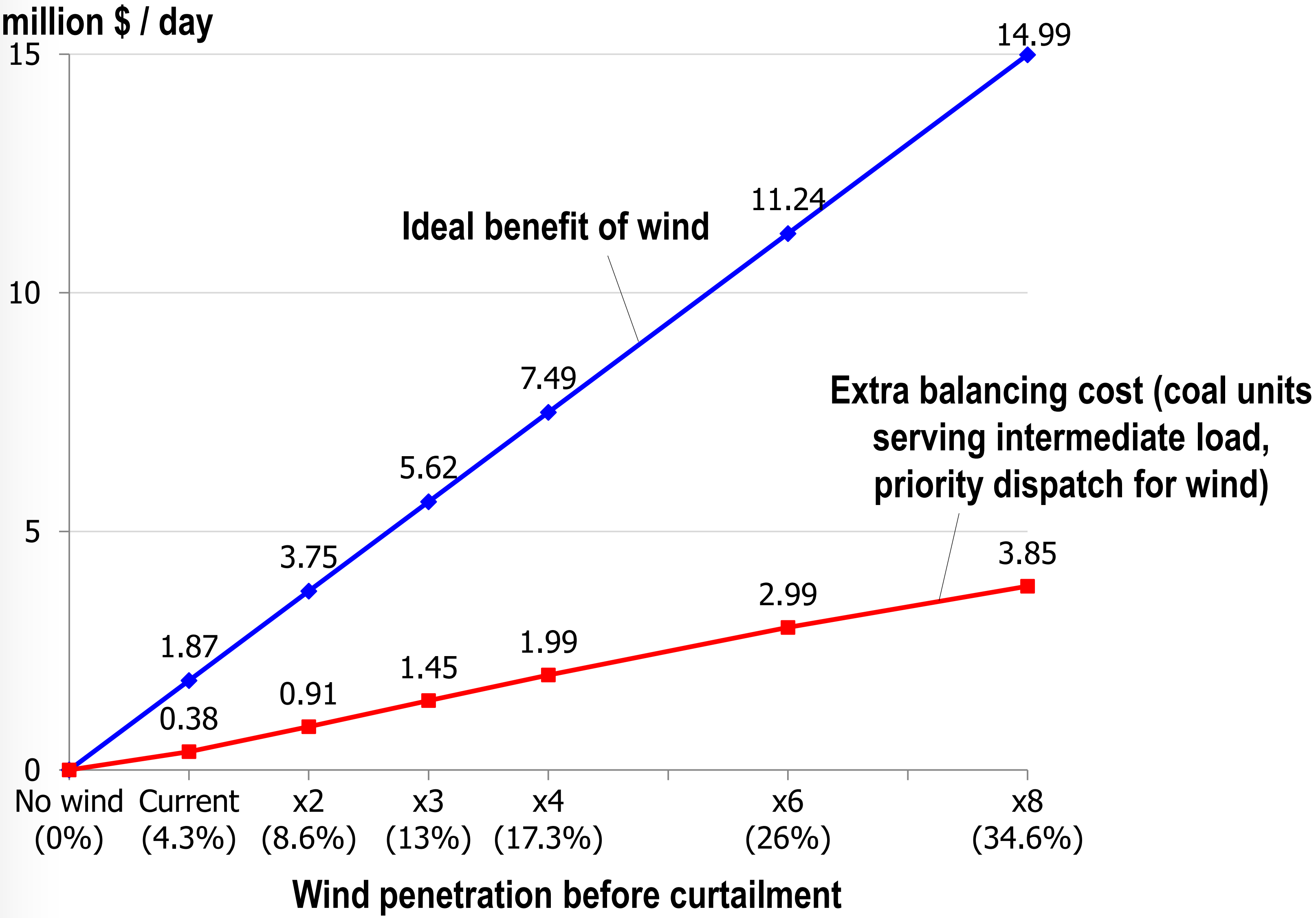
Problem Size

- 7 random load levels
- 15 random wind power levels
- 19 capacity levels for intermediate-load units implying 1,330 capacity states
- 25 storage levels
- Total number of states in each period:
  7 x 15 x 1,330 x 25= 3.5 million
- 96 periods per day (24 hr x 4 periods per hr)
- Total number of states: 335 million

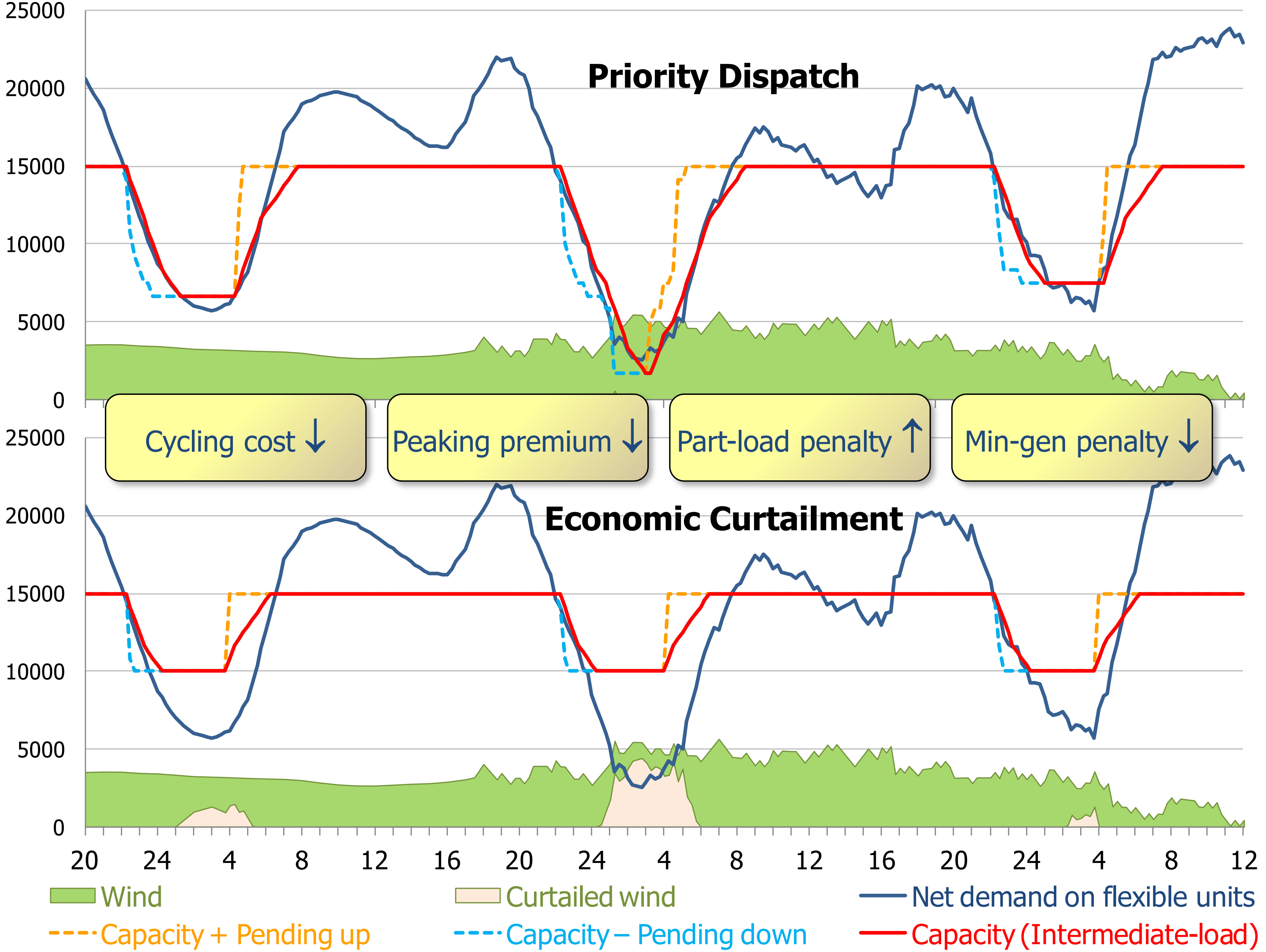
Value of Curtailment ?

- When storage is absent, what drives the value of renewable energy curtailment and is this value significant?

Ideal Benefit vs. Extra Balancing Cost



Owen Q. Wu. 2011. Applying Production and Inventory Management Theory to Sustainable Energy Systems



Priority Dispatch

Cycling cost ↓

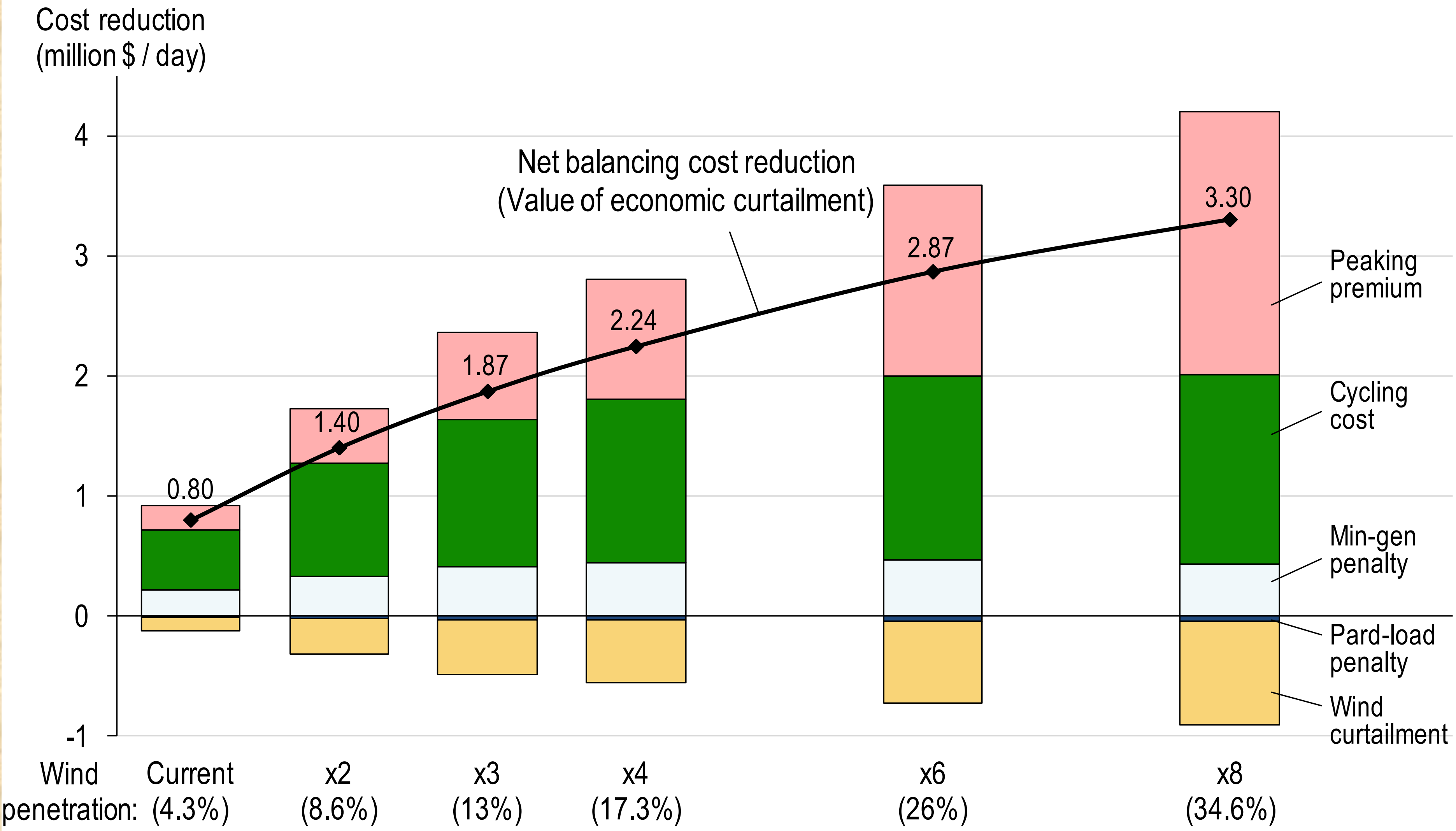
Peaking premium ↓

Part-load penalty ↑

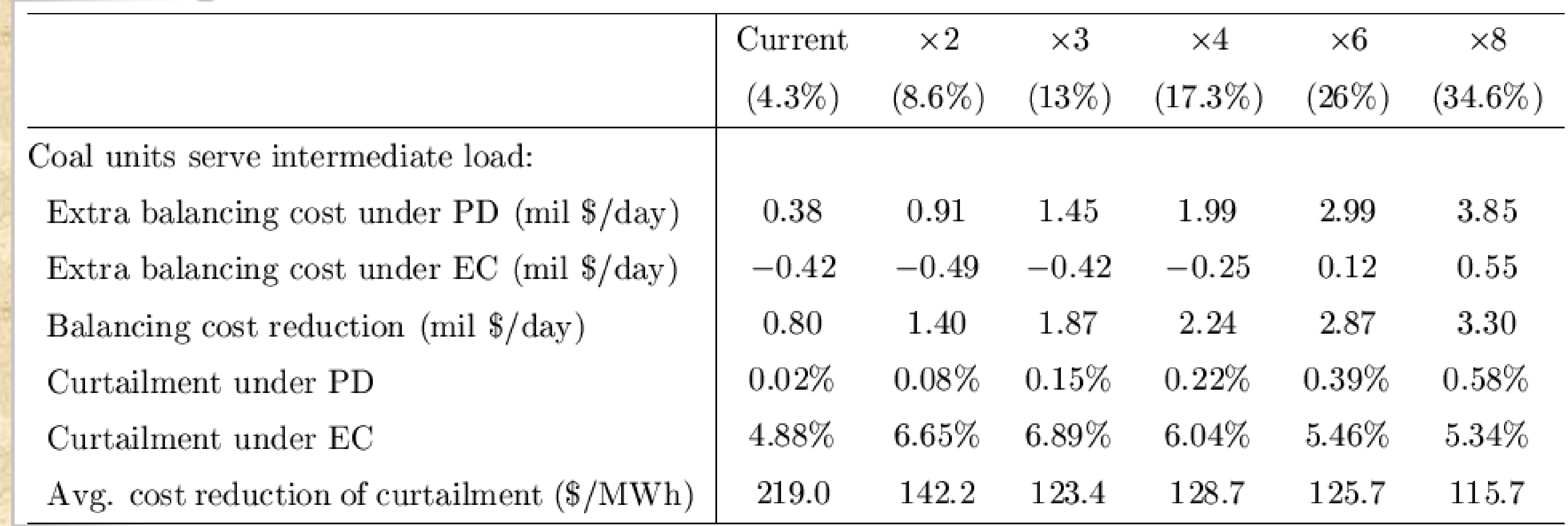
Min-gen penalty ↓

Economic Curtailment

Value of Economic Curtailment: Coal Units Serving Intermediate-Load



Impact of Economic Curtailment



	Current (4.3%)	×2 (8.6%)	×3 (13%)	×4 (17.3%)	×6 (26%)	×8 (34.6%)
Coal units serve intermediate load:						
Extra balancing cost under PD (mil $/day)	0.38	0.91	1.45	1.99	2.99	3.85
Extra balancing cost under EC (mil $/day)	−0.42	−0.49	−0.42	−0.25	0.12	0.55
Balancing cost reduction (mil $/day)	0.80	1.40	1.87	2.24	2.87	3.30
Curtailment under PD	0.02%	0.08%	0.15%	0.22%	0.39%	0.58%
Curtailment under EC	4.88%	6.65%	6.89%	6.04%	5.46%	5.34%
Avg. cost reduction of curtailment ($/MWh)	219.0	142.2	123.4	128.7	125.7	115.7

- With economic curtailment, the total system balancing cost may be lower than the balancing cost of the system without wind power.
- Optimally curtailing wind power is, on average, more valuable than using the wind power to offset the fossil generation.

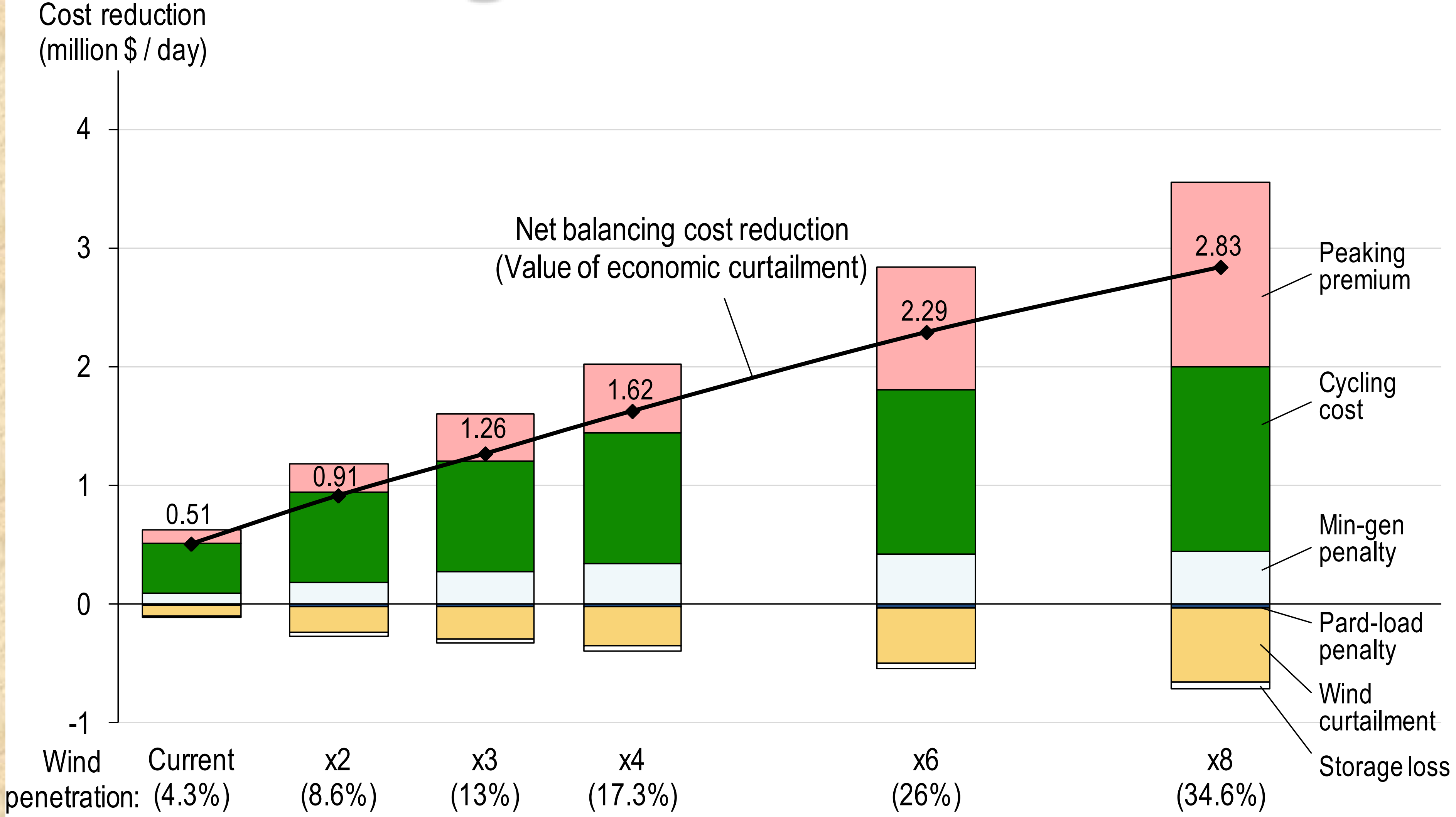
Value of Curtailment ?

- When storage is absent, what drives the value of renewable energy curtailment and is this value significant?
- When storage is present, would the storage operations significantly reduce the value of curtailment or even eliminate the need for curtailment?

Storage Model

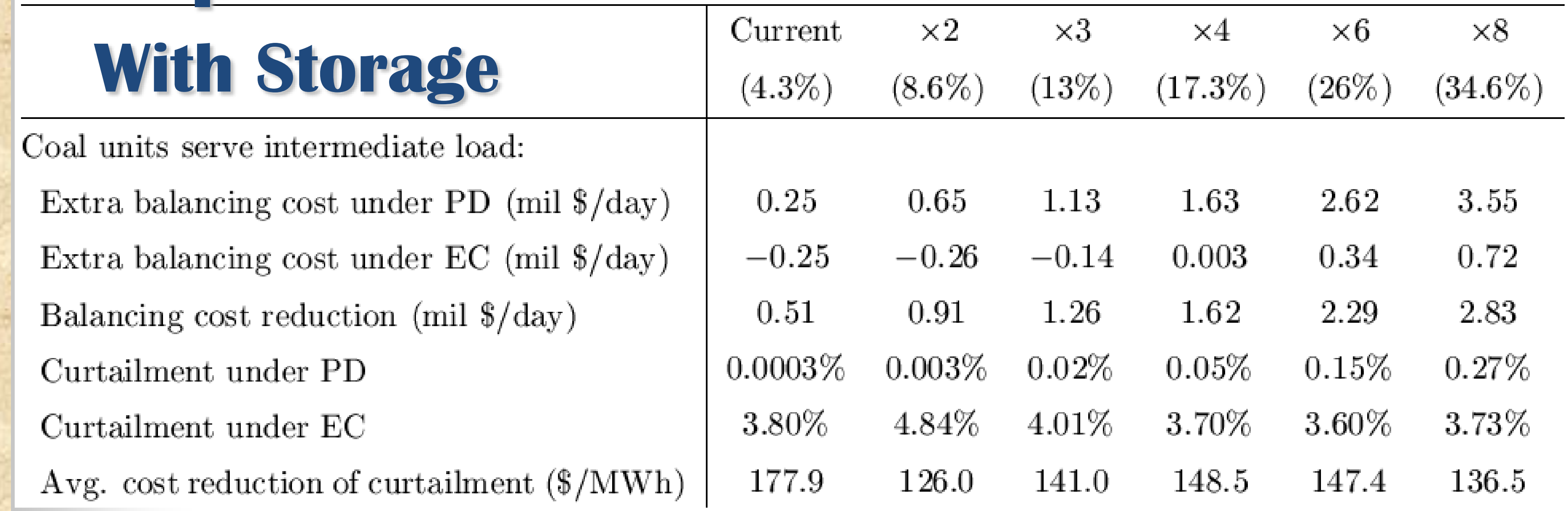
- Storage size: 12,000 MWh
- Pumping and generation speed: 2,000 MW
- Efficiency:
  - Pumping: 80%
  - Generation: 94%
  - Round-trip: 75.2%

Value of Economic Curtailment: With Storage



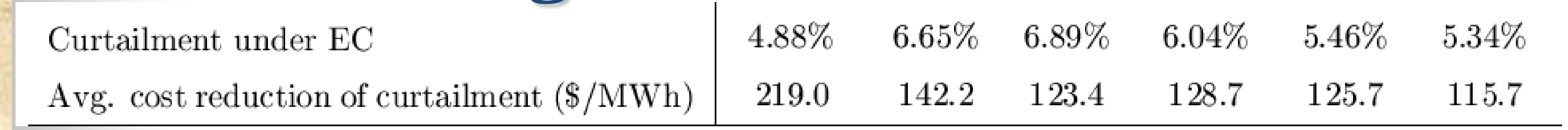
Impact of Economic Curtailment

With Storage



	Current (4.3%)	×2 (8.6%)	×3 (13%)	×4 (17.3%)	×6 (26%)	×8 (34.6%)
Coal units serve intermediate load:						
Extra balancing cost under PD (mil $/day)	0.25	0.65	1.13	1.63	2.62	3.55
Extra balancing cost under EC (mil $/day)	−0.25	−0.26	−0.14	0.003	0.34	0.72
Balancing cost reduction (mil $/day)	0.51	0.91	1.26	1.62	2.29	2.83
Curtailment under PD	0.0003%	0.003%	0.02%	0.05%	0.15%	0.27%
Curtailment under EC	3.80%	4.84%	4.01%	3.70%	3.60%	3.73%
Avg. cost reduction of curtailment ($/MWh)	177.9	126.0	141.0	148.5	147.4	136.5

Without Storage



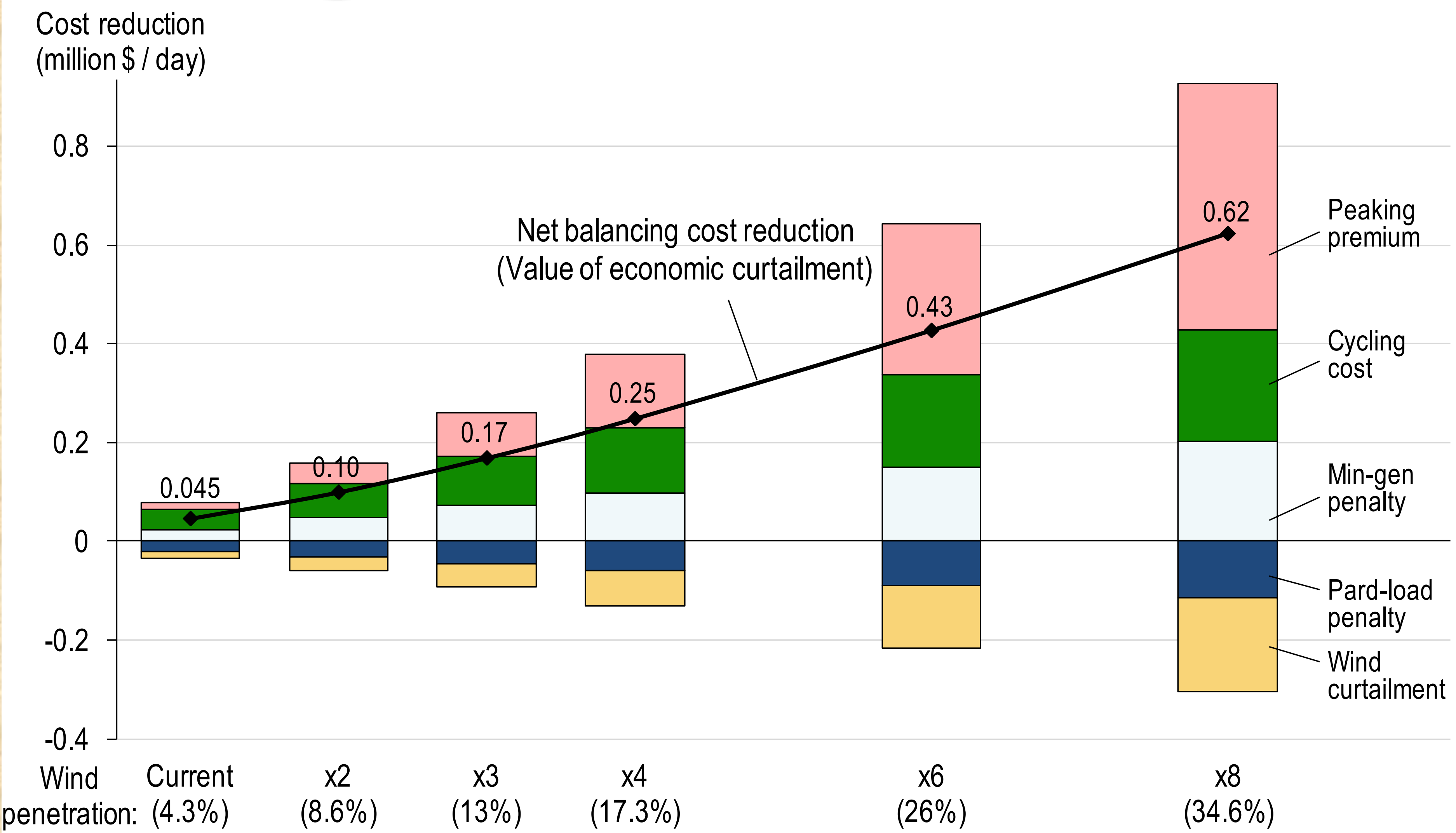
	Current (4.3%)	×2 (8.6%)	×3 (13%)	×4 (17.3%)	×6 (26%)	×8 (34.6%)
Curtailment under EC	4.88%	6.65%	6.89%	6.04%	5.46%	5.34%
Avg. cost reduction of curtailment ($/MWh)	219.0	142.2	123.4	128.7	125.7	115.7

- Dedicating the storage to reduce curtailment may not be the best use of the storage.
- Curtailing wind power may have a higher average contribution to the cost reduction when the storage is present than if storage is absent.

Value of Curtailment ?

- When storage is absent, what drives the value of renewable energy curtailment and is this value significant?
- When storage is present, would the storage operations significantly reduce the value of curtailment or even eliminate the need for curtailment?
- How much does the flexibility of the generation resources affect the value of curtailment?

Natural Gas Combined Cycle Units Serving Intermediate-load



Impact of Economic Curtailment

	Current (4.3%)	×2 (8.6%)	×3 (13%)	×4 (17.3%)	×6 (26%)	×8 (34.6%)
Coal units serve intermediate load:						
Extra balancing cost under PD (mil $/day)	0.38	0.91	1.45	1.99	2.99	3.85
Extra balancing cost under EC (mil $/day)	−0.42	−0.49	−0.42	−0.25	0.12	0.55
Balancing cost reduction (mil $/day)	0.80	1.40	1.87	2.24	2.87	3.30
Curtailment under PD	0.02%	0.08%	0.15%	0.22%	0.39%	0.58%
Curtailment under EC	4.88%	6.65%	6.89%	6.04%	5.46%	5.34%
Avg. cost reduction of curtailment ($/MWh)	219.0	142.2	123.4	128.7	125.7	115.7
NGCC units serve intermediate load:						
Extra balancing cost under PD (mil $/day)	0.087	0.23	0.41	0.63	1.11	1.66
Extra balancing cost under EC (mil $/day)	0.041	0.13	0.25	0.38	0.69	1.04
Balancing cost reduction (mil $/day)	0.045	0.10	0.17	0.25	0.43	0.62
Curtailment under PD	0.02%	0.08%	0.15%	0.22%	0.39%	0.58%
Curtailment under EC	0.47%	0.59%	0.74%	0.89%	1.20%	1.49%
Avg. cost reduction of curtailment ($/MWh)	134.5	128.5	126.0	122.7	117.5	114.3

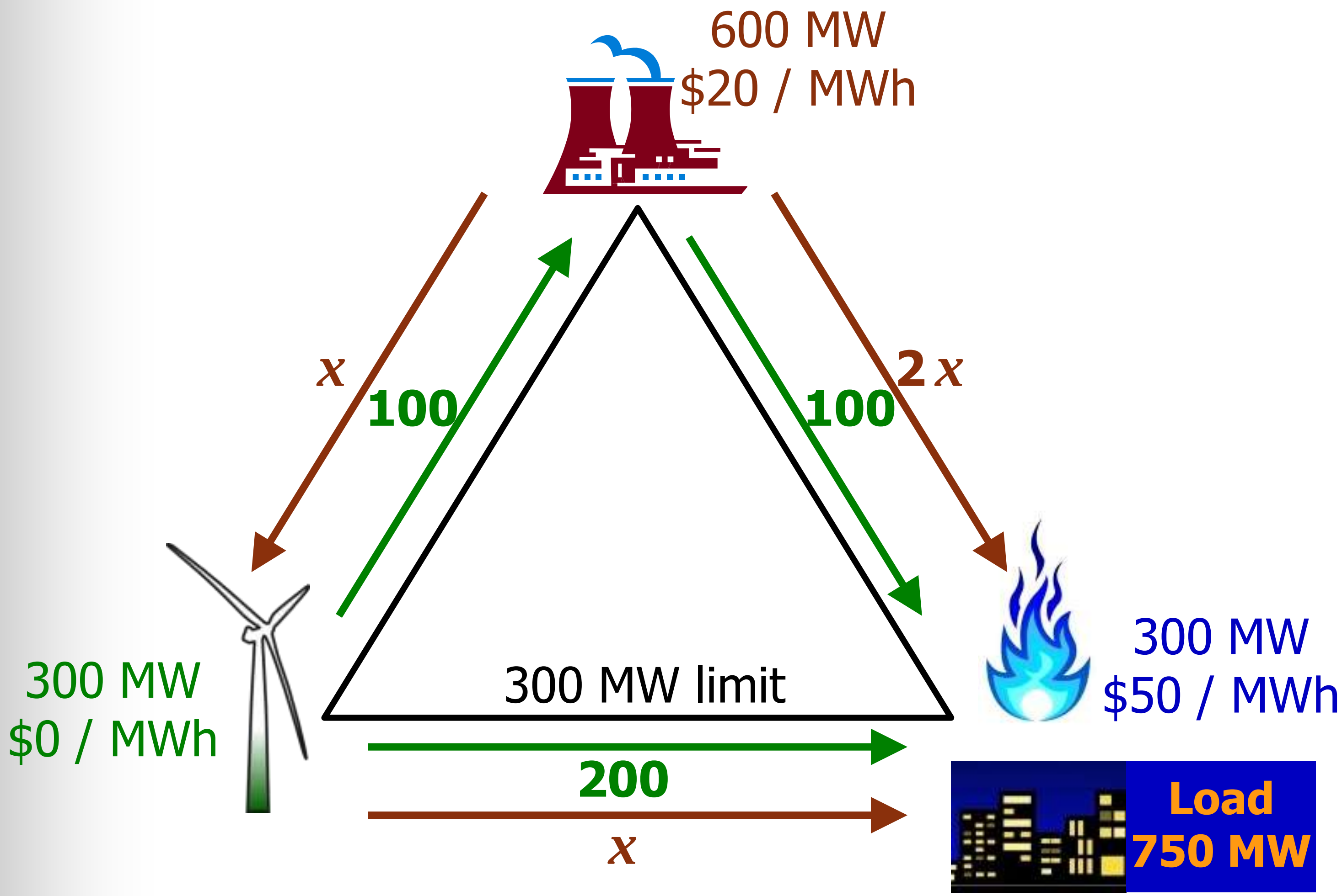
Examples

- Firm level:
  - Newsvendor problem
  - Warehouse problem

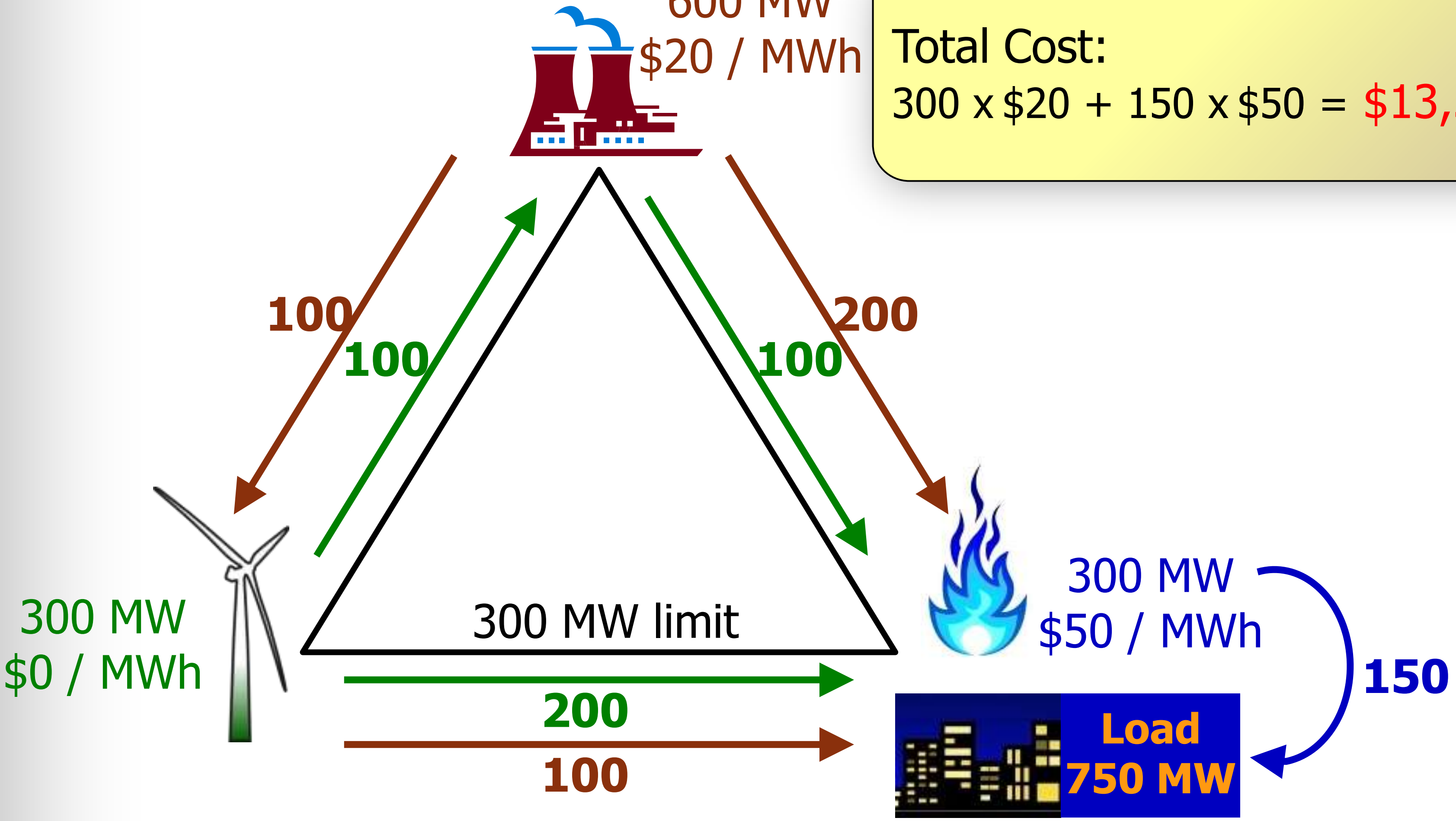
- System level:
  - Capacity management problem
  - *Network flow problem*

  Based on Ela (2009): Using economics to determine the efficient curtailment of wind energy, Technical Report, National Renewable Energy Laboratory

Three-Node Example



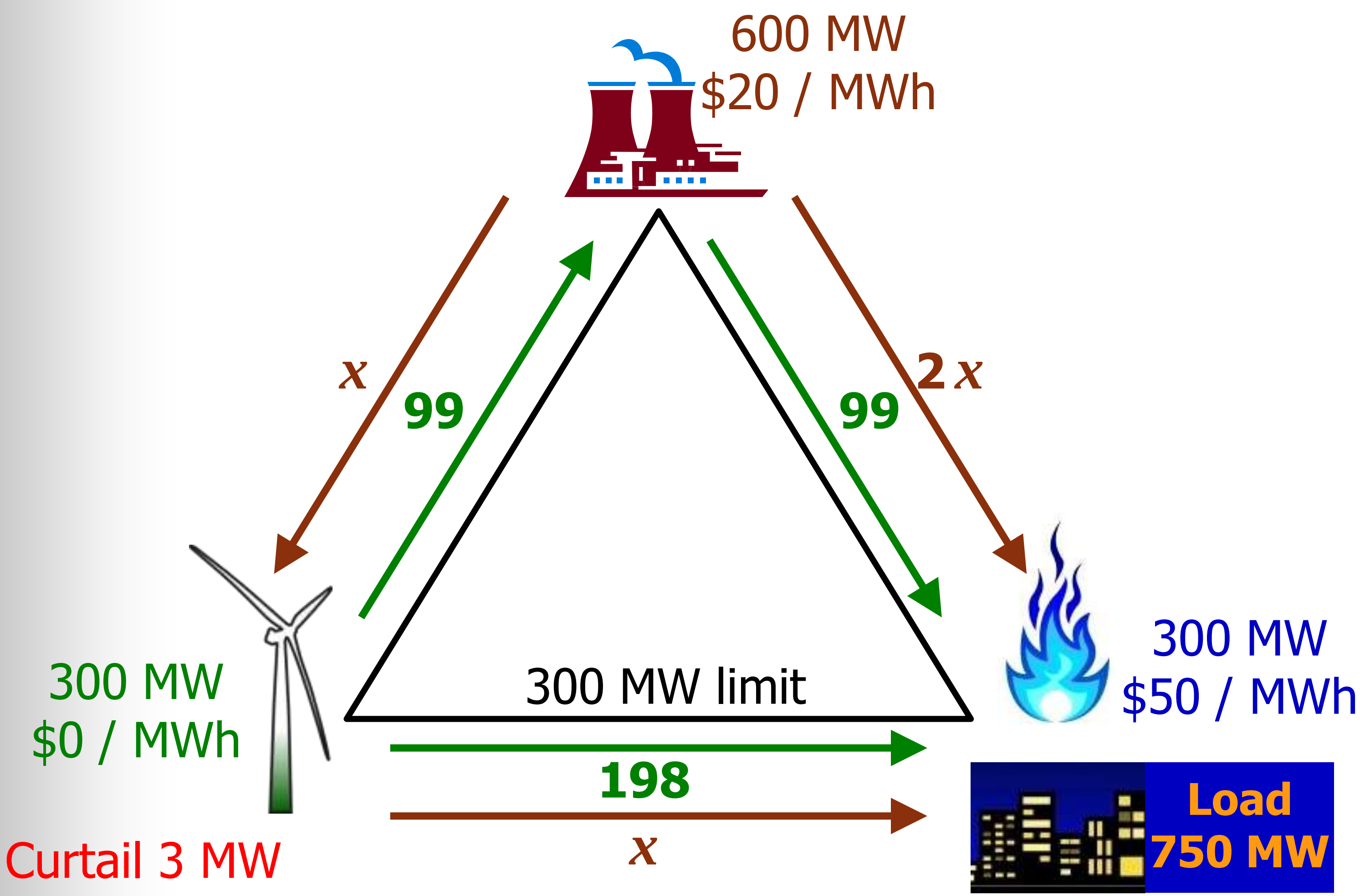
Three-Node Example



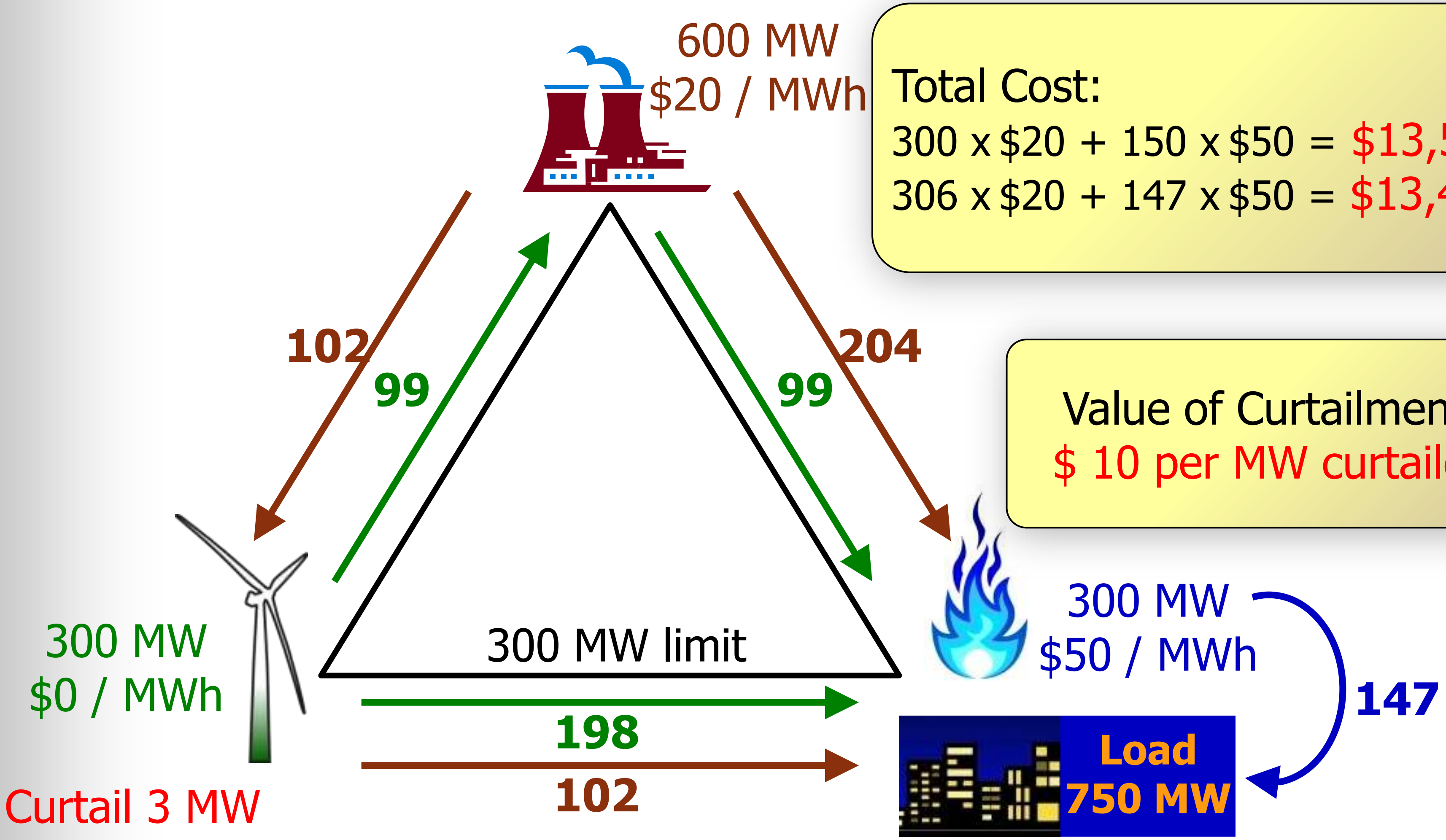
Total Cost:

300 x $20 + 150 x $50 = $13,500

Curtail Wind Generation



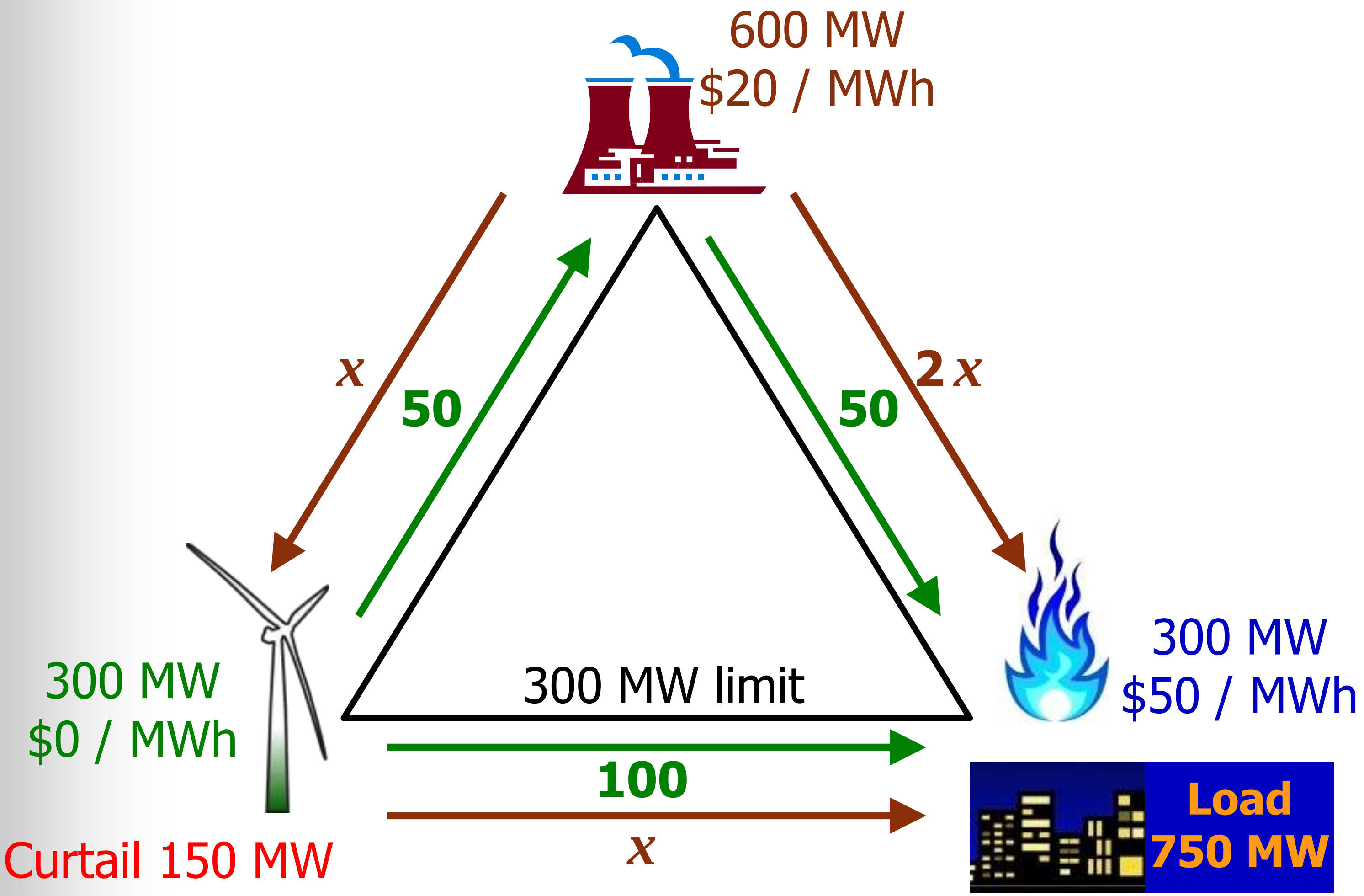
Curtail Wind Generation



Total Cost:
300 x $20 + 150 x $50 = $13,500
306 x $20 + 147 x $50 = $13,470

Value of Curtailment:
$ 10 per MW curtailed

Optimal Curtailment



600 MW
$20 / MWh

x

50

50

2 x

300 MW
$0 / MWh

300 MW limit

300 MW
$50 / MWh

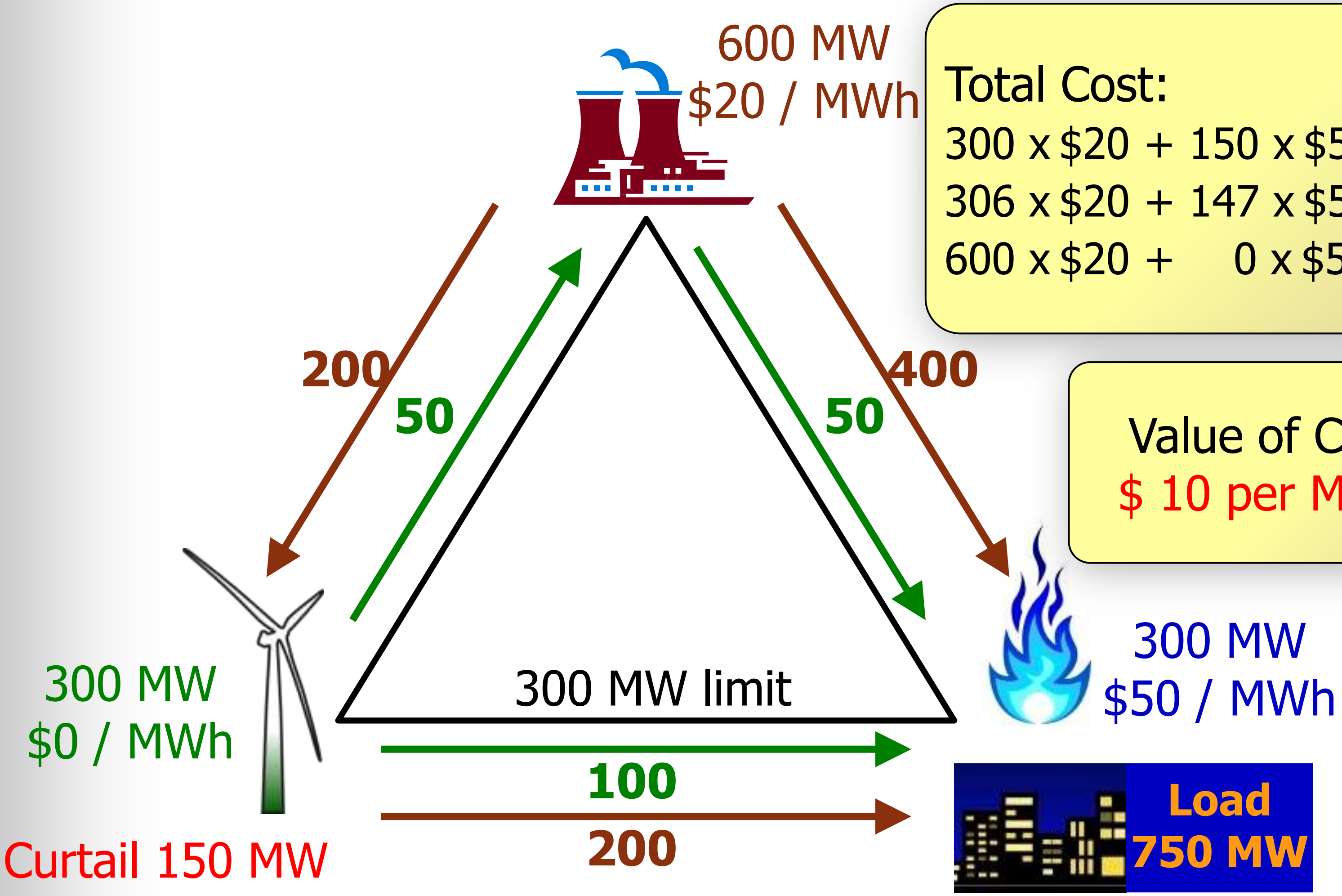
100

x

Load
750 MW

Curtail 150 MW

Optimal Curtailment



600 MW
$20 / MWh

200

50

400

50

300 MW limit

300 MW
$0 / MWh

Curtail 150 MW

100

200

300 MW
$50 / MWh

Load
750 MW

Total Cost:
300 x $20 + 150 x $50 = $13,500
306 x $20 + 147 x $50 = $13,470
600 x $20 + 0 x $50 = $12,000

Value of Curtailment:
$ 10 per MW curtailed

Summary of Three-Node Electrical Network Problem

- Electrical laws
- Transmission constraint
- Negative nodal price
- Value of economic curtailment

Selected References*

- Newsvendor:
  - Kim, J. H. and W. B. Powell. 2011. Optimal energy commitments with storage and intermittent supply. Forthcoming, *Operations Research.*
- Warehouse:
  - Secomandi, N. 2010. Optimal commodity trading with a capacitated storage asset. *Management Science.*
  - Lai, G., F. Margot, N. Secomandi 2010. An approximate dynamic programming approach to benchmark practice-based heuristics for natural gas storage valuation. *Operations Research.*
  - Wu, O. Q., D. D. Wang, Z. Qin. 2011. Seasonal Energy Storage Operations with Limited Flexibility.
- Capacity Management:
  - Angelus, A. and E. L. Porteus. 2002. Simultaneous capacity and production management of short-life-cycle, produce-to-stock goods under stochastic demand, *Management Science*.
  - Wu, O. Q. and R. Kapuscinski. 2011. Curtailing intermittent generation in electrical systems.
- Network flow:
  - Ela, E. 2009. Using economics to determine the efficient curtailment of wind energy. Technical Report, National Renewable Energy Laboratory.
- Dynamic pricing:
  - Adelman, D. and C. Uckun. 2011. Dynamic electricity pricing for smart homes.

* This reference list is for tutorial purpose and does not represent the comprehensive literature.

Energy Sustainability also Includes Conversion, Use, and Disposal Phases

- Principle of Life Cycle Assessment
- Moving towards energy sustainability requires:
  - Changes in the way energy is supplied
    - **Renewable** sources
    - Efficient means of **converting** energy
  - Changes in the way energy it is used
    - Efficient means of **utilizing** energy
  - Changes in the way of **disposing** energy equipments
    - Batteries and other storage devices

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Applying Production and Inventory Management Theory to Sustainable Energy Systems

Thank You!