Applying Production and Inventory Management Theory to Sustainable Energy Systems

Owen Wu
Ross School of Business
University of Michigan
11/14/2011
(Revised and published online 11/29)
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)

“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.

Electricity net generation (trillion kWh per year)

Source: EIA – Annual Energy Outlook 2011

History

2009

Projections


Electricity net generation

Natural gas

Renewable

Nuclear

Coal

45%

23%

10%

20%

1% 1% 1%

17%

14%

25%

43%
U.S. Renewable Energy Generation

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

milllion MWh per year

- Wind
- Solar Thermal and Photovoltaic
- Geothermal
- Wood and Wood Derived Fuels
- Other Biomass

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

Current Installed Wind Power Capacity (MW)


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

Benton County Wind (130.5 MW) Hourly Generation vs. PJM Hourly Load


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

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

Owen Q. Wu. 2011. Applying Production and Inventory Management Theory to Sustainable Energy Systems
Electricity System Operators (ISOs/RTOs)

- Alberta Electric System Operator
- Midwest ISO
- Ontario Independent Electric System Operator
- New Brunswick System Operator
- ISO New England
- New York ISO
- PJM Interconnection
- California ISO
- Electric Reliability Council of Texas
- Southwest Power Pool

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

- **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

Simplified for tutorial purpose.
Locational Marginal Prices (LMP)
Balancing Supply (Generation) and Demand (Load)

![Graph showing supply and demand over a period of days. The graph includes a line representing total capacity, excluding wind, which peaks at 136,000 MW. The graph also shows base load, intermediate load, and peak load over the days, with specific demand values for each day.]
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

<table>
<thead>
<tr>
<th>Electricity Industry</th>
<th>Other Manufacturing and Service Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>Matching supply with demand</td>
</tr>
<tr>
<td><strong>Demand Characteristics</strong></td>
<td>Predictable variations</td>
</tr>
<tr>
<td></td>
<td>• Intra-day, intra-week, intra-year seasonality</td>
</tr>
<tr>
<td></td>
<td>Unpredictable variations</td>
</tr>
<tr>
<td></td>
<td>Single commodity</td>
</tr>
<tr>
<td></td>
<td><strong>Supply Characteristics</strong></td>
</tr>
<tr>
<td></td>
<td>• Baseload generation (push)</td>
</tr>
<tr>
<td></td>
<td>• Intermediate-load generation</td>
</tr>
<tr>
<td></td>
<td>• Peaking generation (pull)</td>
</tr>
<tr>
<td></td>
<td>Multi-mode production</td>
</tr>
<tr>
<td></td>
<td>Supply variabilities</td>
</tr>
<tr>
<td></td>
<td>• Plant outage</td>
</tr>
<tr>
<td></td>
<td>• Intermittent generation</td>
</tr>
<tr>
<td></td>
<td>• Efficient production (push)</td>
</tr>
<tr>
<td></td>
<td>• Responsive production (pull)</td>
</tr>
<tr>
<td></td>
<td>• Machine breakdown</td>
</tr>
<tr>
<td></td>
<td>• Random yield</td>
</tr>
<tr>
<td><strong>Inventory</strong></td>
<td>Store electricity in other forms:</td>
</tr>
<tr>
<td></td>
<td>Energy conversion loss</td>
</tr>
<tr>
<td></td>
<td>Store goods in warehouses:</td>
</tr>
<tr>
<td></td>
<td>Holding cost</td>
</tr>
</tbody>
</table>
# Similarities and Differences between Electricity Industry & Other Industries

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

Electricity industry background and operational challenges

Opportunities of applying OM theory to address these challenges

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

- **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

- 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?


- 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

- 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?

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

\[
\frac{5.3 + 4.6}{2} = 4.95
\]
Should we do nothing but wait?

- 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?

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

\[ \frac{5.4 + 4.7}{2} = 5.05 \]
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*

![Graph showing capacity and production management phases](image)

- **Expansion phase**
- **Constant phase**
- **Downsizing phase**

Owen Q. Wu. 2011. Applying Production and Inventory Management Theory to Sustainable Energy Systems
Balancing Supply (Generation) and Demand (Load)

Demand (MW)

- Base Load
- Intermediate Load
- Peak Load
- Total Load
- Total Load – Wind

Total Capacity (excl. wind) 136,000 MW
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.


- Production cost $c(q)$
  - $\frac{c(q)}{q}$ 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
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

- Peaking capacity
- Intermediate capacity
- Part-load penalty
- Cycling cost
- Min-gen penalty
- Peaking premium

Demand on flexible resources
Dispatchable capacity of Intermediate-load units
## Similarities and Differences between Electricity Industry & Angelus and Porteus

<table>
<thead>
<tr>
<th></th>
<th>Electricity Industry</th>
<th>Angelus and Porteus (2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demand</strong></td>
<td>Demand stochastically rises and falls</td>
<td>Repeat every 24 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Once</td>
</tr>
<tr>
<td><strong>Supply</strong></td>
<td>Dispatchable capacity can be adjusted at a cost</td>
<td>Fully controllable production</td>
</tr>
<tr>
<td></td>
<td>Intermittent generation (wind)</td>
<td>Fully controllable production</td>
</tr>
<tr>
<td></td>
<td>Curtailment possible</td>
<td>No curtailment</td>
</tr>
<tr>
<td><strong>Cost structure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peaking cost</td>
<td>Shortage cost</td>
</tr>
<tr>
<td></td>
<td>Part-load penalty</td>
<td>Capacity overhead cost</td>
</tr>
<tr>
<td></td>
<td>Start-up cost</td>
<td>Costly expansion</td>
</tr>
<tr>
<td></td>
<td>Shutdown does not yield return</td>
<td>Contraction yields a return</td>
</tr>
<tr>
<td></td>
<td>Minimum generation penalty</td>
<td>No minimum generation penalty</td>
</tr>
<tr>
<td><strong>Inventory</strong></td>
<td>Store electricity in other forms: Energy conversion loss</td>
<td>Store goods in warehouses: Holding cost</td>
</tr>
<tr>
<td><strong>Capacity adjustment</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Key Model Features: Wu and Kapuscinski (2011)

- Part-load penalty and min-gen penalty:
  ⇒ High capacity and low demand is undesirable

- Peaking premium:
  ⇒ Low capacity and high demand is undesirable

- 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 $\Delta^u_t$ starts up in period t, then $\gamma^u \Delta^u_t$ will become dispatchable in period t+1.

- The remaining $(1 - \gamma^u) \Delta^u_t$ is pending. In every following period, fraction $\gamma^u$ of the pending capacity will become dispatchable.

- Ramping-down process is similar: $\Delta^d_t$, $\gamma^d$
Capacity Adjustment Model

- Dispatchable capacity
- Pending-up capacity $R_t^u$ or pending-down capacity $R_t^d$
- Newly added pending-up $\Delta_t^u$ or pending-down capacity $\Delta_t^d$

\[ \gamma^u = 0.8 \quad \gamma^d = 0.9 \]
The Model without Storage

- **States:**
  - $D_t$: vector of factors driving the demand $D_t$ (net the baseload) (e.g. weather factors, time of day, time of year)
  - $W_t$: vector of factors driving the wind power $W_t$ (e.g., weather regimes, turbulences, time of day)
  - $K_{t-1} = \left( K_{t-1}^u, R_{t-1}^u, R_{t-1}^d \right)$ dispatchable and pending capacities of intermediate-load units

<table>
<thead>
<tr>
<th>Actions</th>
<th>Priority Dispatch</th>
<th>Economic Curtailment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity $K_t$</td>
<td>$K_t \in \left[ K_t^\text{min}, K_t^\text{max} \right]$</td>
<td>$K_t^\text{max} = K_t^o + \gamma^u (K^I - K_{t-1} - R_{t-1}^u)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K_t^\text{min} = K_t^o - \gamma^d (K_{t-1} - R_{t-1}^d)$</td>
</tr>
<tr>
<td>Production $Q_t$</td>
<td>$Q_t = (D_t - W_t)^+$</td>
<td>$Q_t \in \left[ (D_t - W_t)^+, D_t \right]$</td>
</tr>
<tr>
<td>Curtailment $w_t$</td>
<td>$w_t = Q_t + W_t - D_t$</td>
<td>$w_t \in \left[ (W_t - D_t)^+, W_t \right]$</td>
</tr>
</tbody>
</table>
Model for Economic Curtailment without Storage

\[
V_t(D_t, W_t, K_{t-1}) = \min_{K_t, Q_t} \left\{ C(Q_t \land K_t, K_t) \right. \\
+ (Q_t - K_t)^+ c^P \\
+ (\alpha K_t - Q_t)^+ p \\
+ \left( \frac{K_t - K_t^o}{\gamma^u} \right)^+ c^s \\
+ \left. \rho E_t \left[ V_{t+1}(D_{t+1}, W_{t+1}, K_t) \right] \right\}
\]

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

\[
R_t^u = (1 - \gamma_u) R_{t-1}^u + \frac{1-\gamma_u}{\gamma_u} (K_t - K_t^o)^+ \\
R_t^d = (1 - \gamma_d) R_{t-1}^d + \frac{1-\gamma_d}{\gamma_d} (K_t^o - K_t)^+
\]

Intermediate-load units production cost
Peaking cost
Min-gen penalty
Cycling cost

\[
C(Q, K) = n c \left( \frac{Q}{n} \right) \\
n = \frac{K}{\kappa}
\]
Load Decomposition

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

GW

-10  0   5   10  15  20  25  30  35  40  45  50  55  60  65  70  75  80  85

Jan 2 Jan 3 Jan 4 Jan 5 Jan 6 Jan 7 Jan 8 Jan 9 Jan 10 Jan 11 Jan 12 Jan 13 Jan 14 Jan 15

-10  0   5   10  15  20  25  30  35  40  45  50  55  60  65  70  75  80  85

Load

Intra-day seasonality

Intra-week seasonality

Random fluctuation

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

Strong wind regime

Medium wind regime

Low wind regime

Second Component

© Owen Q. Wu
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: 
  \[ 7 \times 15 \times 1,330 \times 25 = 3.5 \text{ million} \]
- 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

Wind penetration before curtailment

Ideal benefit of wind

Extra balancing cost (coal units serving intermediate load, priority dispatch for wind)
Cycling cost ↓  Peaking premium ↓  Part-load penalty ↑  Min-gen penalty ↓

Priority Dispatch

Economic Curtailment

Wind  Curtailed wind  Net demand on flexible units  Capacity + Pending up  Capacity – Pending down  Capacity (Intermediate-load)
Value of Economic Curtailment: Coal Units Serving Intermediate-Load

Cost reduction (million $ / day)

Net balancing cost reduction (Value of economic curtailment)

Wind penetration: Current (4.3%) x2 (8.6%) x3 (13%) x4 (17.3%) x6 (26%) x8 (34.6%)

-1 0 1 2 3 4

Peaking premium
Cycling cost
Min-gen penalty
Pard-load penalty
Wind curtailment

Coal Units Serving Intermediate-Load

Value of Economic Curtailment:

- Current (4.3%)
- Wind penetration:
  - Current (4.3%)
  - x2 (8.6%)
  - x3 (13%)
  - x4 (17.3%)
  - x6 (26%)
  - x8 (34.6%)

- Cost reduction (million $ / day)
- Net balancing cost reduction (Value of economic curtailment)
Impact of Economic Curtailment

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

- 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%
## Impact of Economic Curtailment

### With Storage

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

### Without Storage

<table>
<thead>
<tr>
<th></th>
<th>Current (4.88%)</th>
<th>×2</th>
<th>×3 (6.89%)</th>
<th>×4 (6.04%)</th>
<th>×6 (5.46%)</th>
<th>×8 (5.34%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curtailment under EC</td>
<td>4.88%</td>
<td>6.65%</td>
<td>6.89%</td>
<td>6.04%</td>
<td>5.46%</td>
<td>5.34%</td>
</tr>
<tr>
<td>Avg. cost reduction of curtailment ($/MWh)</td>
<td>219.0</td>
<td>142.2</td>
<td>123.4</td>
<td>128.7</td>
<td>125.7</td>
<td>115.7</td>
</tr>
</tbody>
</table>

- 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

Cost reduction (million $ / day)

Net balancing cost reduction
(Value of economic curtailment)

Wind penetration:

<table>
<thead>
<tr>
<th>Current</th>
<th>x2</th>
<th>x3</th>
<th>x4</th>
<th>x6</th>
<th>x8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.3%)</td>
<td>(8.6%)</td>
<td>(13%)</td>
<td>(17.3%)</td>
<td>(26%)</td>
<td>(34.6%)</td>
</tr>
</tbody>
</table>

- Peaking premium
- Cycling cost
- Min-gen penalty
- Pard-load penalty
- Wind curtailment

© Owen Q. Wu
## Impact of Economic Curtailment

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

|                                |         |         |         |         |         |         |
| **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*

Three-Node Example

600 MW
$20 / MWh

100

2x

100

x

x

300 MW
$0 / MWh

600 MW
$20 / MWh

300 MW limit

300 MW
$50 / MWh

Load
750 MW

300 MW
$50 / MWh

300 MW
$0 / MWh

Total Cost:

\[300 \times \$20 + 150 \times \$50 = \$13,500\]
Curtail Wind Generation

600 MW
$20 / MWh

300 MW limit

300 MW
$0 / MWh

Curtail 3 MW

Load
750 MW

300 MW
$50 / MWh

198

x

99

2x

99
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

300 MW limit

300 MW $0 / MWh
Curtail 3 MW

600 MW $20 / MWh

102 99 204

198 102

147

Load 750 MW

300 MW $50 / MWh
Optimal Curtailment

- 600 MW, $20 / MWh
- 300 MW limit
- 100 MW

300 MW
$0 / MWh

Curtail 150 MW

600 MW
$20 / MWh

2x

50

Load
750 MW

300 MW
$50 / MWh

x

50

300 MW limit

© Owen Q. Wu
Optimal Curtailment

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:**

- **Warehouse:**

- **Capacity Management:**

- **Network flow:**

- **Dynamic pricing:**

* 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
Applying Production and Inventory Management Theory to Sustainable Energy Systems

Thank You!