A Squirrel’s Dilemma: The Value of Distributed Storage in the Transition to a Low Carbon Electric Grid

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International Association for Energy Economics
New York, June 18\textsuperscript{th} 2014
Outline

Motivation

Background

Formulation

Setup

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Motivation, Renewables

Wind Blows Strongest Between 9:00 pm & 5:00 am, When Demand Is Weakest

Source: NREL, WWIS, FERC T4

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Motivation, Renewables

Wind Blows Strongest Between 9:00 pm & 5:00 am, When Demand Is Weakest

Source: NREL, CAISO

Each Day is a different color.

Wind profile pattern in April 2007

Source NREL, CAISO
Motivation, Renewables

Wind Blows Strongest Between 9:00 pm & 5:00 am, When Demand Is Weakest

Source: NREL, FERC

Each Day is a different color.

Wind profile pattern in April 2007

Source: NREL, CAISO

[Lamadrid et al. (2014)]
General Research Question
Formulate a Social Planner Problem of Electricity Network with Three fundamental Characteristics

1. **Flexible** includes distributed resources, new technologies, new agents

2. **Secure** (Robust?) optimality under different conditions

3. **Economical** compensation for costs imposed and benefits
This Presentation

1. Policy: General Effects of Increasing Wind Penetration
2. Internalizing the Externality: Sensitivity to Paying Economic Ramping Costs
3. Complementary Roles: Optimal use of Storage Technologies
4. Economic Tradeoffs
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Day-Ahead Electricity Market without Random Generators

Problem Setup
Wind capacity task force: [Keane et al. (2011)], Reserve requirements for RES [Halamay et al. (2011)]

OPF

- [Carpentier et al. (1996)]
- [Chen et al. (2005)], Co-Optimization
- [Condren et al. (2006)], Ex-post evaluation
- [Outhred (1998)], self-commitment
- [Lesieutre et al. (2005)] Load Pockets

Electricity Markets

- [Kamat and Oren (2004)]: two settlement markets and contract formation
- [Joskow and Tirole (2007)]: Model for demand management with heterogeneous consumers
- [Sioshansi and Denholm (2010)], Ancillary S.
- [Eto (2002)] Congestion
- [USCongress (2005)], Reliability Organization
- [NERC (2011)], Standards for Operation

Proposed Model

- Co-optimizing energy and reserves → solve optimal amounts [Chen et al. (2005)]
- Use of Network
- Economic management of demand
- Modeling of renewables uncertainty
- Engineering and Economical modeling of Energy Storage Systems (ESS)
Two Types of Uncertainty

Motivation Background Formulation Setup Results Conclusions
Two Types of Uncertainty

MW Injections

High Probability Path
Load Following Ramp Up Capacity
Load Following Ramp Down Capacity
PDF States
PDF Contingencies
Expected Dispatch

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Formulation

**Probability Weighted Sum of**
- Cost of Energy
- Cost of Deviations
- Consumer Surplus
- Contingency Reserve
- Load Following Reserve
- Wear-and-Tear
- Transversality For Storage

Subject to
- Network Constraints
- Demand and Generator's
  - physical limits
  - ramping limits
  - settlement contracts
- Energy Storage Systems (ESS) constraints

**Objective Function**

\[
\min_{G_{itsk}, R_{itsk}, LNS_{jtsk}} \sum_{t \in T} \sum_{s \in \mathcal{S}} \sum_{k \in \mathcal{K}} \pi_{tsk} \left\{ \sum_{i \in \mathcal{I}} \left[ C_i(G_{itsk}) + \right. \right.
\]

\[
+ \text{Inc}_{its}^+(G_{itsk} - G_{itsc})^+ + \text{Dec}_{its}^-(G_{itsc} - G_{itsk})^+ \left. \right. \left. \right. \left. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \righthand_side_variables
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Input Information

1. Network, based on [Allen et al.(2008)], heavily modified
2. Mapping wind sites, PCA on historical data [NREL(2010)]
3. Load profile, data from New York and New England [NYISO(2011)]
4. Transition matrix, k-means++ clustering to specify the scenarios for the day[Guojun Gan(2007)]
North East Test network

No changes in generation/load out of NY-NE
Geographical Location
Wind Sites
Demand Modeling

3 regions in NE
- North (ME, NH, VT)
- South (CT, RI, MA)
- Boston

4 regions in NY
- NY1: Western NY
- NY2: Eastern NY
- NYC: Zone J
- Long Island: Zone K
Uncertainty of Load and Wind Speed

- 16 ARMAX models estimated for hourly temperature $= f(\text{Cycles})$
- 16 ARMAX models estimated for hourly $\log(\text{Wind Speed} + 1) = f(\text{Temperature, Cycles})$
- 7 ARMAX model estimated for hourly $\log(\text{Load}) = f(\text{CDD, HDD, Cycles})$
- Simulate Hourly profiles of wind speed and load for any specified day given a temperature forecast
- Load model estimates temperature-sensitive load(TSL) and non-TSL
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Simulation Cases

Wind Inputs

- Wind/conventional capacity: 24%
- Capacity factor of wind: 21%
- Potential wind generation could supply 7.5% of daily energy needs

Storage

- Same locations as wind
- Steady state conditions, cyclic constraints
- Two threshold prices, transversality conditions

Deferrable Demand

Demand divided each hour in

- conventional demand
- demand for space cooling
- demand for hot water
Results

3 main cases

- Base Wind: 16GW of wind capacity at 16 locations
- Wind+Collocated Storage: 34GWh
- Wind+Deferrable Demand: 34GWh

Wind and Ramping Increases

- Increases from 0 to 100% of max wind capacity (from 1 to 20)
- Increases from 1 to $1000 \times$ the initial ramping (w-t) costs [Lew et al.(2013)]
Increasing Wind Penetration

Total Objective Function

Savings in energy cost offset by the increases in other internalized costs (ancillary services, LNS)
Wear-and-tear Cost Levels

Total Welfare
No Storage available to mitigate impacts of wind
Total Wind Generation, Adding Storage

![Heatmap showing wind generation with ramp levels and wind penetration]

- **Ramp Levels**:
  - 0
  - 0.5
  - 1
  - 1.5
  - 2
  - 2.5
  - $10^5$

- **Wind Penetration**:
  - 2
  - 4
  - 6
  - 8
  - 10
  - 12
  - 14
  - 16
  - 18
  - 20

- Storage Effect:
  - 14% higher expected wind amounts dispatched (MW/day)

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Total Wind Generation, Adding Storage

Storage Effect
14% higher expected wind amounts dispatched (MW/day)
Expected Generation Cost
Expected Generation Cost

Fuel Cost Displacement
Expensive Energy sources, savings between 9 and 15% ($1000/day)

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Wholesale Cost

E[Total Wholesale Cost]

Wind Penetration

Ramp Levels

E[Total Wholesale Cost]

Wind Penetration

Ramp Levels

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Wholesale Cost, Same Scale

Network Effects
Lower wholesale cost thanks to reduced congestion
LNS $\times$ VOLL, same scale

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Total Wind Generation, Collocated vs Distributed

E[Wind Generation]

Wind Penetration

Ramp Levels

0
0.5
1
1.5
2
2.5
\times 10^5

Storage Effect

More cases with higher expected wind amounts dispatched (MW/day)

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Total Wind Generation, Collocated vs Distributed

Storage Effect
More cases with higher expected wind amounts dispatched (MW/day)
Expected Generation Cost, Collocated vs Distributed

E[Generation Cost]

Wind Penetration

Ramp Levels

Collocated storage lowers the expected fuel cost ($1000/day)
Expected Generation Cost, Collocated vs Distributed

Optimal Fleet Management
Collocated storage lowers the expected fuel cost ($1000/day)

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Social Welfare, Collocated vs Distributed

E[Obj F]
Wind Penetration
Ramp Levels
9
9.05
9.1
9.15
9.2
x 10
9
Outline

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Some Take Aways

1. High penetrations of renewable generation lower the wholesale price of energy **BUT** increase the internalized ramping and capacity costs for the conventional generators, “missing money”

2. Collocated storage **increases** the amounts of accommodated wind, lowers total system costs and increases overall total welfare (operationally)

3. Deferrable Demand (DD) **centrally controlled** by an ISO: effective and economically efficient way to reduce ramping costs and flatten the daily pattern of conventional generation.
Further Work

- Analyze Benefits in terms of Capital Costs for Different Ramping Levels (Past Work: Collocated Storage NOT Economical, Deferrable Demand MOST Beneficial) [Lamadrid et al.(2014)]
- Characterize Congestion Effects, difficult, network reduction dependent
- Effects on Emissions ($SO_2$, $NO_x$, $CO_2$), internalizing Ramping Costs [Callaway and Fowlie(2009)], [Kaffine et al.(2013)].


Chen, J., Mount, T. D., Thorp, J. S., Thomas, R. J., 2005. Location-based scheduling and pricing for energy and reserves:


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URL http://ideas.repec.org/a/aen/journl/2010v31-03-a01.html

Thank you
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Questions?

Thanks to
The Lehigh Faculty Innovation Grant, The US Department of Energy through the Consortium for Electric Reliability Technology Solutions (CERTS), the Power Systems Engineering Research Center (PSERC), an NSF I/UCRC.
Co-Optimization

Graphically

1. power flow scenario, high probability case
2. power flow scenario, low probability case
3. root variable set, deviations, limits (e.g. contracts, incs/decs, reserves)
4. transition constraint

In a nutshell

→ Minimize the Expected Cost of Dispatch over Different States of the System
### Definition of Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{T}$</td>
<td>Set of time periods considered, $n_t$ elements indexed by $t$.</td>
</tr>
<tr>
<td>$\mathcal{S}^t$</td>
<td>Set of scenarios in the system in period $t$, $n_s$ elements indexed by $s$.</td>
</tr>
<tr>
<td>$\mathcal{K}$</td>
<td>Set of contingencies in the system, $n_c$ elements indexed by $k$.</td>
</tr>
<tr>
<td>$\mathcal{I}$</td>
<td>Set of generators in the system, $n_g$ elements indexed by $i$.</td>
</tr>
<tr>
<td>$\mathcal{J}$</td>
<td>Set of loads in the system, $n_l$ elements indexed by $j$.</td>
</tr>
<tr>
<td>$\pi_{tsk}$</td>
<td>Probability of contingency $k$ occurring, in scenario $s$, period $t$.</td>
</tr>
<tr>
<td>$\rho_t$</td>
<td>Probability of reaching period $t$.</td>
</tr>
<tr>
<td>$G_{itsk}$</td>
<td>Quantity of apparent power generated (MVA).</td>
</tr>
<tr>
<td>$G_{itc}$</td>
<td>Optimal contracted apparent power generated (MVA).</td>
</tr>
<tr>
<td>$C_G(\cdot)$</td>
<td>Cost of generating ($\cdot$) MVA of apparent power.</td>
</tr>
<tr>
<td>$\text{Inc}_{its}^+(\cdot)$</td>
<td>Cost of increasing generation from contracted amount.</td>
</tr>
<tr>
<td>$\text{Dec}_{it}^-(\cdot)$</td>
<td>Cost of decreasing generation from contracted amount.</td>
</tr>
<tr>
<td>$\text{VOLL}_j$</td>
<td>Value of Lost Load, ($$.</td>
</tr>
<tr>
<td>$\text{LNS}<em>j(\cdot)</em>{tsk}$</td>
<td>Load Not Served (MWh).</td>
</tr>
<tr>
<td>$R^+_i &lt; \text{Ramp}_i$</td>
<td>$\left(\max(G_{itsk}) - G_{itc}\right)^+$, up reserves quantity (MW) in period $t$.</td>
</tr>
<tr>
<td>$C^+_R(\cdot)$</td>
<td>Cost of providing ($\cdot$) MW of upward reserves.</td>
</tr>
<tr>
<td>$R^-_i &lt; \text{Ramp}_i$</td>
<td>$\left(G_{itc} - \min(G_{itsk})\right)^+$, down reserves quantity (MW).</td>
</tr>
<tr>
<td>$C^-_R(\cdot)$</td>
<td>Cost of providing ($\cdot$) MW of downward reserves.</td>
</tr>
<tr>
<td>$L^+_i &lt; \text{Ramp}_i$</td>
<td>$\left(\max(G_{i,t+1,s}) - \min(G_{its})\right)^+$, load follow up (MW) $t$ to $t+1$.</td>
</tr>
<tr>
<td>$C^+_L(\cdot)$</td>
<td>Cost of providing ($\cdot$) MW of load follow up.</td>
</tr>
<tr>
<td>$L^-_i &lt; \text{Ramp}_i$</td>
<td>$\left(\max(G_{its}) - \min(G_{i,t+1,s})\right)^+$, load follow down (MW).</td>
</tr>
<tr>
<td>$C^-_L(\cdot)$</td>
<td>Cost of providing ($\cdot$) MW of load follow down.</td>
</tr>
<tr>
<td>$\text{Rp}_{it}^+(\cdot)$</td>
<td>Cost of increasing generation from previous time period.</td>
</tr>
<tr>
<td>$\text{Rp}_{it}^-(\cdot)$</td>
<td>Cost of decreasing generation from previous time period.</td>
</tr>
<tr>
<td>$f_s(p_{sc}, p_{sd})$</td>
<td>Value of the leftover stored energy in terminal states.</td>
</tr>
</tbody>
</table>
## Characteristics of the generation fleet, 36-Bus system

### Summary of Generation Capacity and Load, NPCC system

<table>
<thead>
<tr>
<th>RTO</th>
<th>coal (GW)</th>
<th>ng (GW)</th>
<th>oil (GW)</th>
<th>hydro (GW)</th>
<th>nuclear (GW)</th>
<th>wind (GW)</th>
<th>refuse (GW)</th>
<th>Total Cap. (GW)</th>
<th>Load (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>isone</td>
<td>1,840</td>
<td>9,219</td>
<td>4,327</td>
<td>1,878</td>
<td>5,698</td>
<td>0</td>
<td>0</td>
<td>22.9</td>
<td>23.8</td>
</tr>
<tr>
<td>marit.</td>
<td>2,424</td>
<td>1,072</td>
<td>22</td>
<td>641</td>
<td>641</td>
<td>0</td>
<td>0</td>
<td>4.8</td>
<td>3.5</td>
</tr>
<tr>
<td>nyiso</td>
<td>4,557</td>
<td>18,185</td>
<td>5,265</td>
<td>7,345</td>
<td>4,714</td>
<td>30</td>
<td>55</td>
<td>40.1</td>
<td>38.2</td>
</tr>
<tr>
<td>ont.</td>
<td>5,287</td>
<td>3,594</td>
<td>0</td>
<td>779</td>
<td>12,249</td>
<td>0</td>
<td>0</td>
<td>21.9</td>
<td>21.1</td>
</tr>
<tr>
<td>pjm</td>
<td>14,453</td>
<td>14,611</td>
<td>8,915</td>
<td>2,604</td>
<td>12,500</td>
<td>0</td>
<td>0</td>
<td>53.1</td>
<td>51.6</td>
</tr>
<tr>
<td>quebec</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>28,562</td>
<td>46,681</td>
<td>18,530</td>
<td>14,048</td>
<td>35,802</td>
<td>30</td>
<td>55</td>
<td>143.7</td>
<td>138.4</td>
</tr>
<tr>
<td>Total NYNE</td>
<td>6,397</td>
<td>27,404</td>
<td>9,592</td>
<td>9,223</td>
<td>10,412</td>
<td>30</td>
<td>55</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>Rp.C.</td>
<td>30</td>
<td>10</td>
<td>10</td>
<td>60</td>
<td>60</td>
<td>0</td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Reserves Cost

LF Ramp–Up Reserve Cost
LF Ramp–Down Reserve Cost

Wind Penetration

Ramp Levels

300
400
500
600
700
800
900

2 4 6 8 10 12 14 16 18 20
LNS $\times$ VOLL, Adding Storage

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Wholesale Cost, Collocated vs Distributed

Congestion Component

But Wholesale Cost (including SO revenue and Wind Revenue) is lower with deferrable demand
Reserves Cost, Collocated vs Distributed
LNS × VOLL, Collocated vs Distributed

E\[Load Not Served\] * VOLL

E\[Load Not Served\] * VOLL