The Value of Volatile Resources in Electricity Markets

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Increased deployment of renewable energy can lead to significant environmental benefits.
Introduction

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- However, the characteristics of renewable resources are very different from those of conventional resources
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It is imperative to understand their characteristics to fully harness the benefits of renewable resources
Introduction

DAM/RTM Dynamic model
Multi-settlement Electricity Market
Who Commands the Wind?
Numerical Results
Concluding Remarks

Renewable Portfolio Standards
www.dsireusa.org / February 2010

State renewable portfolio standard
State renewable portfolio goal
Solar water heating eligible
Minimum solar or customer-sited requirement
Extra credit for solar or customer-sited renewables
Includes non-renewable alternative resources

29 states + DC have an RPS
(6 states have goals)
Wind power is currently favored over all renewables
Wind power

- Wind power is currently favored over all renewables
- Its deployment presents major challenges in system operations due to its:
  - limited control capabilities
  - forecasting uncertainty
  - uncertainty and intermittency
Figure: Example of load and wind generation data
Different opinions...

“The Value of Wind - why more renewable energy means lower electricity bills,” Adam Bruce, Chairman, British Wind Energy Association

- “Wind is a free source of fuel. When the wind blows the UK’s electricity system has access to this free source and the power generated is automatically accepted onto the system”
- “Wind energy means lower bills; it’s as simple as that”
Different opinions...

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- "Wind energy means lower bills; it’s as simple as that”

“Wind power’s dirty secret? Its carbon footprint”

- "Wind power is touted as the cleanest and greenest renewable energy resource”
- “You’ve got a non-carbon-emitting source of energy that’s free,” said Doug Johnson of the Bonneville Power Administration
- “However, Todd Wynn of the Cascade Policy Institute says it’s not as clean as advocates claim. He says it’s simply because the wind is volatile and doesn’t blow all the time”
Scope

Goal of this work

Understand how volatility impacts the value of wind generation

Focus: Competitive market setting
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Beyond mean energy...
We evaluate impacts of wind resources by focussing on two parameters: penetration and volatility of wind generation.
**Scope**

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Understand how volatility impacts the value of wind generation
Focus: Competitive market setting

**Beyond mean energy...**
We evaluate impacts of wind resources by focussing on two parameters: *penetration* and *volatility* of wind generation.

**Vehicle**
Dynamic electricity market model,
- Multi-settlement structure
- Captures wind volatility
- Ramping constraints
The day-ahead market (DAM) is cleared one day prior to the actual production and delivery of energy.

**Economic world...**

Forward markets for electricity which improve market efficiency and serve as a hedging mechanism.
Day-ahead market motivations

The day-ahead market (DAM) is cleared one day prior to the actual production and delivery of energy.

Economic world...
Forward markets for electricity which improve market efficiency and serve as a hedging mechanism

...Physical world
Facilitate the scheduling of generating units
Real-time market (RTM)

At close of the DAM: The ISO generates a schedule of generators to supply specific levels of power for each hour over the next 24 hour period.

RTM = Balancing Market

As supply and demand are not perfectly predictable, the RTM plays the role of fine-tuning this resource allocation process.
Figure: March 4, 2010 CAISO forecast and real-time supply and demand
DAM/RTM

Notation

- Total demand at time $t$, $D_{\text{ttl}}(t) = d_{\text{da}}(t) + D(t)$,
- Total capacity at time $t$, $G_{\text{ttl}}(t) = g_{\text{da}}(t) + G(t)$
- Total reserve at time $t$,
  \[ R_{\text{ttl}}(t) = G_{\text{ttl}}(t) - D_{\text{ttl}}(t) = G(t) - D(t) + r_{\text{da}}(t) \]

DAM Reserve policy

\[ r_{\text{da}}(t) \equiv r_{0_{\text{da}}} \text{ is constant.} \]
RTM Model

RTM model of Cho & Meyn consists of the following components:

Volatility

Deviation in demand $D$ is modeled as a driftless Brownian motion with instantaneous variance $\sigma^2$.

Friction

Generation cannot increase instantaneously: There exists $\zeta \in (0, \infty)$ such that,

$$\frac{G(t') - G(t)}{t' - t} \leq \zeta, \quad \text{for all } t \geq 0, \text{ and } t' > t.$$
Write $dG(t) = \zeta dt - dI(t)$, with $I$ non-decreasing, to model the upper bound on the rate of increase in generation.
RTM Model

Write \( dG(t) = \zeta dt - dI(t) \), with \( I \) non-decreasing, to model the upper bound on the rate of increase in generation.

Reserve process regarded as a controlled stochastic system,

\[
dR(t) = \zeta dt - dI(t) - dD(t)
\]

with control \( I \).
Market Analysis

Market analysis assumptions:

**Cost**

The production cost is a linear function of $G(t)$, of the form $cG(t)$ for some constant $c > 0$. 
Market Analysis

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**Cost**

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**Value of power**

Consumer obtains $v$ units of utility per unit of power consumed: Utility to the consumer $= v \min(D(t), G(t))$. 
Market Analysis

Disutility from power loss

The consumer suffers utility loss if demand is not met:
Disutility to the consumer = $c^{bo}|R(t)|$ whenever $R(t) < 0$. 
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Perfect competition
The price of power \(P(t)\) in the RTM is assumed to be exogenous (it does not depend on the decisions of the market agents).
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Perfect competition

The price of power \( P(t) \) in the RTM is assumed to be exogenous (it does not depend on the decisions of the market agents).

“price-taking assumption”
The objectives of the consumer and the supplier are specified by the respective welfare functions,

Welfare functions

\[ W_S(t) := P(t)G(t) - cG(t) \]
\[ W_D(t) := v \min(D(t), G(t)) - c^{bo} \max(0, -R(t)) - P(t)G(t) \]
Market Analysis

The consumer and supplier each optimize the discounted mean-welfare

Discounted mean-welfare expressions

For given initial values of generation and demand $g = G(0)$, $d = D(0)$, the respective discounted rewards are denoted

$$K_S(g, d) := \mathbb{E} \left[ \int e^{-\gamma t} W_S(t) \, dt \right],$$
$$K_D(g, d) := \mathbb{E} \left[ \int e^{-\gamma t} W_D(t) \, dt \right],$$

where $\gamma > 0$ is the discount rate.
Market Analysis

The social planner’s problem is defined as the maximization of the total discounted mean welfare,

Social planner’s objective

\[ K(g, d) = \mathbb{E}\left[ \int e^{-\gamma t} (\mathcal{W}_S(t) + \mathcal{W}_D(t)) \, dt \right] . \]
Market Analysis

The optimal reserve process is a reflected Brownian motion (RBM) on the half-line \((-\infty, \bar{r}^*]\), with

Reserve threshold

\[ \bar{r}^* = \frac{1}{\theta_+} \log \left( \frac{c^{bo} + \nu}{c} \right) . \]

where \(\theta_+\) is the positive solution to the quadratic equation

\[ \frac{1}{2} \sigma^2 \theta^2 - \zeta \theta - \gamma = 0 \]
Market Analysis

The *equilibrium price functional* is a piecewise constant function of the equilibrium reserve process,

\[ p^e(r^e) = (v + c^{bo}) \mathbb{I}\{r^e < 0\} \]

The sum \( c^{bo} + v \) is in fact the maximum price the consumer is willing to pay, often called the *choke-up price.*
A little bit of technical details...

On substituting the price into the respective welfare functions:

Expected welfare values

\[
E[\mathcal{W}_S^*(t)] = (v + c^{bo}) \left( E[D(t) \mathbb{I}\{R^e(t) \leq 0\}] + E[R^e(t) \mathbb{I}\{R^e(t) \leq 0\}] \right) - cE[R^e(t)]
\]

\[
E[\mathcal{W}_D^*(t)] = -(v + c^{bo}) E[D(t) \mathbb{I}\{R^e(t) \leq 0\}]
\]

where \( R = R^e \) is the equilibrium reserve process.
How does this look?

**Figure:** Model price dynamics
Familiar, right?

**Figure: Real-world price dynamics**
Coupling DAM/RTM

Multi-settlement market model: A coupling of the DAM and RTM.

Consumers’ welfare in the multi-settlement market

\[ W_D^{\text{ttl}}(t) := v \min(D^{\text{ttl}}(t), G^{\text{ttl}}(t)) - c^{\text{bo}} \max(0, -R(t)) \]

\[ - P^e(t)G(t) - p^{\text{da}}(t)g^{\text{da}}(t) \]
DAM/RTM Consumer’s welfare

Principle of optimality $\implies$ Formulae for total discounted mean welfare,

Consumers’ mean welfare in the multi-settlement market

$$K_{D}^{\text{ttl}} = K_{D}^{*}(r) + \gamma^{-1}(r - G(0))(\bar{p}^{e}(r) - \bar{p}^{\text{da}})$$

$$+ \int_{0}^{\infty} (v - p(t))d^{\text{da}}(t)e^{-\gamma t}dt.$$ 

in which $K_{D}^{*}(r)$ corresponds to the RTM welfare.
Coupling DAM/RTM

Total supplier welfare: Through similar and simpler arguments,

Suppliers' welfare in the multi-settlement market

\[ \mathcal{W}_{\text{ttl}}^S(t) = \mathcal{W}_S(t) + (p^{\text{da}}(t) - c^{\text{da}}) g^{\text{da}}(t) \]  (1)
DAM/RTM Supplier’s Welfare

Principle of optimality $\implies$ Formulae for total discounted mean welfare,

Supplier’s mean welfare in the multi-settlement market

$$K_{S}^{\text{ttl}} = K_{S}^{*}(r) + \gamma^{-1}(r - G(0))(\bar{p}^{\text{da}} - c^{\text{da}})$$

$$+ \int_{0}^{\infty} (p(t) - c^{\text{da}}) d^{\text{da}}(t) e^{-\gamma t} \, dt.$$ 

in which $K_{S}^{*}(r)$ corresponds to the RTM welfare.
Integrating Wind...

Figure: Who Commands the Wind?
Extending the dynamic model

Goal

Extend the DA/RT market model to differentiate power generated by wind and by conventional generation units.
Extending the dynamic model

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Assumption

All the wind power available is injected into the system
Extending the dynamic model

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**Assumption**

All the wind power available is injected into the system.

**Key issue**

Conventional generators serve residual demand.
Extending the dynamic model

Goal

Extend the DA/RT market model to differentiate power generated by wind and by conventional generation units.

Assumption

All the wind power available is injected into the system.

Key issue

Conventional generators serve residual demand. Volatility of the residual demand will result in higher reserves in the dynamic market equilibrium.
Emerging issues

Not only mean energy

The details depend on both volatility of wind and its proportion of the overall generation

What about now?

If the penetration of wind resources is low, then the increase in load volatility will be negligible, and hence there will be negligible impact on the market outcomes
Emerging issues

Not only mean energy
The details depend on both volatility of wind and its proportion of the overall generation

What about now?
If the penetration of wind resources is low, then the increase in load volatility will be negligible, and hence there will be negligible impact on the market outcomes

What about in 2020?
Potential negative market outcomes are possible with a combination of high wind generation penetration and high volatility of wind
Approach

To quantify the impact of volatility we obtain expressions for the total welfare in two market models, differentiated by who commands the wind generating units.
Who Commands the Wind?

**Approach**

To quantify the impact of volatility we obtain expressions for the total welfare in two market models, differentiated by who **commands** the wind generating units.

**Main finding**

Volatility can have **tremendous** impact on the market outcomes.
Who Commands the Wind?

**Approach**
To quantify the impact of volatility we obtain expressions for the total welfare in two market models, differentiated by who commands the wind generating units.

**Main finding**
Volatility can have tremendous impact on the market outcomes.

**Asymmetric and surprising result**
The supplier can achieve significant gains, even when the consumer commands the wind.
Consumers command the wind

Wind generating units are commanded by the demand side:

Consumers’ and suppliers’ welfare expressions

\[ W_{D,W}^{ttl}(t) = v \min(D^{ttl}(t), G^{ttl}(t) + G^{ttl}_W(t)) \]
\[ - c^{bo} \max(0, -R(t)) \]
\[ - P(t)G(t) - p(t)g^{da}(t) \]

\[ W_{S,W}^{ttl}(t) = (P(t) - c^{rt})G(t) + (p(t) - c^{da})g^{da}(t) \]
Consumers command the wind

Welfare expressions: DAM/RTM decomposition

\[ W_{D,W}^{\text{ttl}}(t) = W_{D,W}^{rt}(t) + \{ v d_{da}(t) - p(t) (d_{da}(t) - g_{W}^{da}(t)) \} + \{ (P(t) - p(t)) r_{0}^{da} + v G_{W}(t) \} \]

\[ W_{S,W}^{\text{ttl}}(t) = W_{S,W}^{rt}(t) + (p(t) - c_{da}) g_{da}(t) \]

\( W_{D,W}^{rt}(t), W_{S,W}^{rt}(t) \): Welfare obtained in the RTM with residual demand \( D_{\text{net}}(t) \).
Suppliers command the wind

The other alternative is to consider wind as part of the supply side,

Consumers’ welfare

\[
W_{D,W}^{ttl}(t) = v \min(D_{ttl}(t), G_{W}^{ttl}(t) + G_{W}^{ttl}(t)) \\
- c^{bo} \max(0, -R(t)) \\
- P(t)(G(t) + G_{W}(t)) - p(t)(g_{da}^{ntl}(t) + g_{W}^{da}(t)) \\
= W_{D,W}^{rt}(t) \\
+ \{(v - p(t))d_{W}^{da} + (P(t) - p(t))r_{W}^{da}\} \\
+ (v - P(t))G_{W}(t)
\]
Suppliers command the wind

Suppliers' welfare

\[
W_{S,W}^{\text{ttl}}(t) = (P(t) - c^{\text{rt}})G(t) + P(t)G_{W}(t) + (p(t) - c^{\text{da}})g^{\text{da}}(t) + p(t)g^{\text{da}}_{W}(t)
\]

\[
= W_{S,W}^{\text{rt}}(t) + (p(t) - c^{\text{da}})g^{\text{da}}(t) + P(t)G_{W}(t) + p(t)g^{\text{da}}_{W}(t)
\]

The welfare gain \(p(t)g^{\text{da}}_{W}(t)\) is now taken by the suppliers
Numerical Results: Setting the stage I

Parameters used in all of our experiments:

Parameters [$/MWh]

Cost of blackout and value of consumption:

\[ c^{bo} = 200,000 \quad v = 50 \]

Cost and prices of generation: \( c^{rt} = 30 \), and

\[ c^{da} = 0.75 \times c^{rt}, \quad p^{da} = 0.85 \times c^{rt} \]

Discount factor: \( \gamma = 1/12 \) (12 hour time horizon).
Numerical Results: Setting the stage II

Parameters (physical)

Ramp limit: $\zeta = 200$ MW/min

Mean demand: $\bar{D} = 50,000$ MW

Standard deviation: $\sigma = 500$ MW.
Penetration and volatility

Coefficient of variation to capture the relative volatility of wind:

\[ c_v = \frac{\sigma_w}{\mathbb{E}[G_{ttl}^W(t)]} \]

Percentage of wind penetration:

\[ k = 100 \times \frac{\mathbb{E}[G_{ttl}^W(t)]}{\bar{D}} \]
Numerical Results: Volatility Impacts

Figure: Optimal reserves depend on penetration and coefficient of variation.
Numerical Results: Volatility Impacts

Figure: Social planner’s welfare.
Numerical Results: Consumers command the wind

Figure: Consumer and supplier welfare when consumer owns wind for different coefficient of variation $c_v$ and $c^{da} < p^{da} < c^{rt}$. 
Facing wind volatility

The results of this paper invite many questions:

C1

The impact of demand management and storage on the market
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C1
The impact of demand management and storage on the market

C2
The impact of supply management and storage on the market.
E.g., modern wind turbines allow pitch angle control.
Facing wind volatility

C3

Mechanisms to reduce consumers *and* suppliers exposure to supply-side volatility.
Facing wind volatility

**C3**

Mechanisms to reduce consumers *and* suppliers exposure to supply-side volatility.

**C4**

How to create policies to protect participants on both sides of the market, while creating incentives for R&D on renewable energy?
The main messages...

It is not so easy...

The main message of this paper is that consumer welfare may fall dramatically as more and more wind generation is dispatched.

A beautiful world...

This is true even under the most ideal circumstances:
The main messages...

It is not so easy...

The main message of this paper is that consumer welfare may fall dramatically as more and more wind generation is dispatched.

A beautiful world...

This is true even under the most ideal circumstances:
- consumers own all wind generation resources and
- price manipulation is excluded
The main messages...

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A beautiful world...

This is true even under the most ideal circumstances:

- consumers own all wind generation resources and
- price manipulation is excluded

No “ENRON games” – no “market power”
Concluding remarks

- **Volatility** and **mean** energy are key parameters for new energy sources. Our results show that resource volatility can have **tremendous** impacts on the market outcomes.
- Currently adopted wind integration schemes can be **harmful** for consumers with larger wind penetration.
- Suppliers can achieve **significant** gains *even when the consumer commands the wind*.
Concluding remarks

- Who faces the *uncertainty* and *risk* associated to volatile resources is a big challenge from an economic viewpoint.
- Under certain conditions consumers are better off *not dispatching wind*. 
Concluding remarks

- Who faces the uncertainty and risk associated to volatile resources is a big challenge from an economic viewpoint.
- Under certain conditions consumers are better off not dispatching wind.
- Storage and demand management emerge as solutions for a smooth integration of wind power.
Concluding remarks

- Market analysis requires **dynamic** rather than snapshot models
- Greater wind penetration will require **redesigns** of both power system operations and electricity markets
Figure: Celebrating with Dutch Babies after finishing part of this work


