Payment mechanisms and risk-aversion in electricity markets with uncertain supply

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Joint work with Golbon Zakeri
(thanks to Andy Philpott)

ISMP, Bordeaux, July 2018.

ORC, Massachusetts Institute of Technology
Work performed at Electric Power Optimization Centre, University of Auckland

A problem: The cost of being deterministic is increasing

- Historically, electricity markets comprised hydro+thermal generators
  - Dispatch participants deterministically.
- Wind, solar not known apriori.

Common solution: two markets; forward + real-time. (C.f. PJM)

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Some problems with this approach:

- If the forward market is deterministic, wind causes pricing inconsistencies between the markets (Zavala et al, 2017).
- If the forward market is deterministic, then generators may not achieve cost recovery, even in expectation.
- Efficiency cost in being deterministic.
  - Leaving money on the table.
  - Economic & political pressure to invest in wind & solar generation; the cost of being deterministic is increasing.

A solution: Use stochastic programming

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- First stage: minimize expected cost of generation plus deviating from a setpoint, provide setpoint to generators.
- Nature selects a realisation of wind generation.
- Second stage: minimize generation cost plus cost of deviating from setpoint, implement dispatch policy.

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2. Does implementing SDM cause one-sided wealth transfers?
    - Are they in favour of consumers or generators?
    - Under what conditions?

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1. How do we pay participants?
    - Do we retain revenue adequacy and cost recovery?
    - Do we need uplift payments?
2. Does implementing SDM cause one-sided wealth transfers?
    - Are they in favour of consumers or generators?
    - Under what conditions?
3. What happens if participants are risk-averse?
    - Do consumers or generators bear the resultant efficiency losses?
    - Under what conditions?

Reminder: How to price electricity without uncertainty

The market clearing problem:

$$\begin{aligned} \text{Min} \quad & c^\top X \\ \text{s.t.} \quad & \sum_{i \in T(n)} X_i + \tau_n(F) \geq D_n, & [\lambda_n], \\ & F \in \mathcal{F}, \\ & 0 \leq X \leq G. \end{aligned}$$

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Pricing relatively straightforward.

- Apply second welfare theorem.
  - Take Lagrangian by dualizing supply-demand balance.
  - Decouple Lagrangian by participant.
  - Yields revenue adequate, cost recovering uniform price.

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Pricing relatively straightforward.

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  - Take Lagrangian by dualizing supply-demand balance.
  - Decouple Lagrangian by participant.
  - Yields revenue adequate, cost recovering uniform price.
- Can we take the Lagrangian and decouple with uncertainty?

The stochastic dispatch mechanism (Zakeri et al, 2018)

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\text{Min} \quad & \mathbb{E}_\omega[c^T X(\omega) + r_u^T U(\omega) + r_v^T V(\omega)] \\
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& X(\omega) - U(\omega) + V(\omega) = x, && \forall \omega, \ [\mathbb{P}(\omega)\rho(\omega)] \\
& F(\omega) \in \mathcal{F}, && \forall \omega, \\
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- x is the forward setpoint, $X(\omega)$ is the dispatch in scenario ω.
- When taking the Lagrangian without uncertainty, we dualize supply-demand and retain remaining constraints.

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- x is the forward setpoint, $X(\omega)$ is the dispatch in scenario ω.
- When taking the Lagrangian without uncertainty, we dualize supply-demand and retain remaining constraints.
- Nonanticipativity is new. Should we dualize it?

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2. Dualizing both supply-demand & nonanticipativity yields pricing mechanism in λ, ρ.
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See (Cory-Wright, Philpott & Zakeri 2018) for more details.

Assumption for rest of talk: using first payment mechanism (simpler).

Three key questions:

How do we implement a stochastic dispatch mechanism?

1. How do we pay participants? ✓
   - Take Lagrangian of forward market clearing problem.
   - With RN generators, dualize supply-demand and obtain revenue adequacy+expected cost recovery.
   - With RN ISO, dualize supply-demand, nonanticipativity and obtain expected revenue adequacy+cost recovery.
2. Does implementing SDM cause one-sided wealth transfers?
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Does implementing SDM cause wealth transfers?

- Value of Stochastic Solution a.s. non-negative in long-run.
    - And $\$63,000$-$\$410,000$ in NZEM.
    - See (Cory-Wright & Zakeri 2018) for more on this.
    - How are these savings allocated between generators and consumers?
    - Under what conditions?

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- Overall: implementing SDM equivalent to one-sided wealth transfer.
  - Generators earn 10 times VSS, at expense of consumers.
- Mechanism for this behaviour arises from SDM's Lagrangian.
  - Nonanticipativity multiplier $+$ nodal price $+ \ldots =$ constant.
  - Nonanticipativity multiplier is monotone operator w.r.t pre-commitment.

Why don't we constrain pre-commitment to expected demand?

- Imposing additional constraints causes efficiency losses.
  - (Zakeri et al. 2018) has an example where imposing a first-stage constraint causes a 2% efficiency loss.
  - Unclear whether paying this "price of fairness" is worthwhile.
- With a first-stage constraint, we can do no better than expected revenue adequacy and expected cost recovery.
  - Assuming we are social-welfare maximizing.
  - If we attack KKT conditions directly, can obtain both, with system efficiency losses (c.f. Kazempour et al. 2018)

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3. What happens if participants are risk-averse?
    - Risk aversion causes efficiency losses.
    - Does it also cause a wealth transfer? Under what conditions?

Case I: Risk-aversion without risk-trading

The setup (C.f. Ralph+Smeers 2015):

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- Endow all generation agents with coherent risk measures.
- Second welfare theorem no longer applies.
  - Total system welfare lower than RN competitive equilibrium.
- Dispatch participants by solving a complimentarity problem.
- Want to perform sensitivity analysis.
  - To determine if SDM is robust to risk-averse generators.

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- Dispatch participants by solving a complimentarity problem.
- Want to perform sensitivity analysis.
  - To determine if SDM is robust to risk-averse generators.
  - Need to establish an existence result.

Case I: Risk-aversion without risk-trading

Theorem

Let the sample space be finite, and assume nodal prices capped by VOLL. Then, the risk-averse competitive equilibrium admits a solution.

- Proof: introduce market-clearing agent, apply Rosen's theorem.

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Theorem

Let the sample space be finite, and assume nodal prices capped by VOLL. Then, the risk-averse competitive equilibrium admits a solution.

- Proof: introduce market-clearing agent, apply Rosen's theorem.
- Solution may not be unique.
  - C.f. Henri Gerard's talk yesterday.

Risk-aversion: What happens to pre-commitment?

Theorem

Let generator i's real-time dispatch be $X_i(\omega)$ in each scenario ω. Endow generator i with risk measure ρ, which has Kusuoka representation:

$$\rho(Z) = -\mathbb{E}[Z] + \kappa \sup_{\mu \in D} \int_{\beta=0}^{\beta=1} \frac{1}{\beta} r_\beta[Z] \mu d\beta.$$

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Then, generator i's pre-commitment decision is:

$$x_i^* = F^{-1}_{X_i(\omega)}\Big(\frac{r_{u,i}}{(r_{u,i} + r_{v,i})(1 + \kappa(1 - \bar{\beta}))}\Big),$$

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Interpretation: Risk-aversion emphasises low payoffs in high wind periods, decreasing pre-commitment.

So what? Why should we care?

Theorem

Let generator be net-pivotal & risk-averse, collect risk-aversion in term $\alpha_i := \frac{1}{1+\kappa_i(1-\bar{\beta}_i)}$, where $\bar{\beta}_i := \int_0^1 \mu^{RN} \beta_i d\beta_i$, $\kappa_i \in [0, \frac{1}{\bar{\beta}_i}]$. Then, generator's expected risk-neutral profit is $(1-\alpha_i) r_{u,i} x_i^*$.

Expected profit is:

1. *Zero if generator is risk-neutral.*
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Question: With workable competition, can we tell if a net-pivotal generator is risk-averse or exercising market power?

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Question: With workable competition, can we tell if a net-pivotal generator is risk-averse or exercising market power?

One answer: Introduce risk trading.

Case II: Risk-aversion with risk-trading

The setup (C.f. Ralph+Smeers 2015):

- Endow all generation agents with coherent risk measures.
- Assume risk sets intersect.
- Allow participants to trade Arrow-Debreu securities on exchange.
- Second welfare theorem applies.
    - Solution exists, can solve via convex programming.
    - More welfare than no risk-trading, but less than RN equilibrium.

Risk-aversion II: What happens to pre-commitment?

Theorem

Let generator i's real-time dispatch be $X_i(\omega)$ in each scenario ω. Endow generator i with risk measure ρ, which has Kusuoka representation:

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Interpretation: Arrow-Debreu securities re-align incentives, emphasising high system costs in low wind periods & increasing pre-commitment.

So what? Why should we care? II:

- Being risk-averse decreases pre-commitment without a risk market.
- But increases pre-commitment with a risk market.
- More pre-commitment corresponds to lower prices.

So what? Why should we care? II:

- Being risk-averse decreases pre-commitment without a risk market.
- But increases pre-commitment with a risk market.
- More pre-commitment corresponds to lower prices.
- With risk-trading, can tell if net-pivotal generator is risk-averse or exercising market power.

An alternative to risk-trading

Alternatively, use cost-recovering payment mechanism derived earlier. In the presence of risk-averse generators, this:

- Removes incentive for a risk-averse net-pivotal generator to deviate.
- Corresponds to uniform price with feasible allocation of ADBs.
  - Higher social welfare than no risk-trading with uniform pricing.
  - But lower social welfare than fully liquid risk market.
  - Also corresponds to ISO assuming risk for free. Who pays for this?

Summary: How does stochastic dispatch work in practise?

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   - Both mitigated upon introducing financial instruments.

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Open question: How much of this translates to stoch. unit commitment?

For more on this, see:

- R. Cory-Wright, A. Philpott, and G. Zakeri. Payment mechanisms for electricity markets with uncertain supply. Operations Research Letters 46(1) 116-121, 2018.
- R. Cory-Wright and G. Zakeri. On efficiency savings, wealth transfers and risk-aversion in electricity markets with uncertain supply. Working paper, available at Optimization Online.
- Andy Philpott's plenary (Thursday 1:30-2:30 pm).

Selected References:

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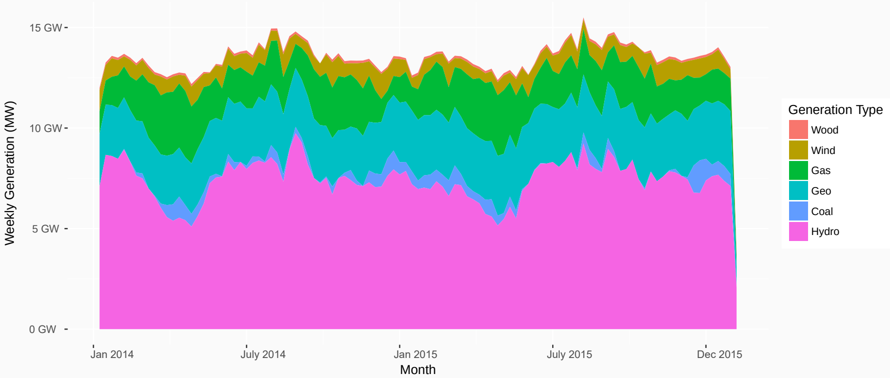
Thank You!

Questions?

Appendix A: Methodology

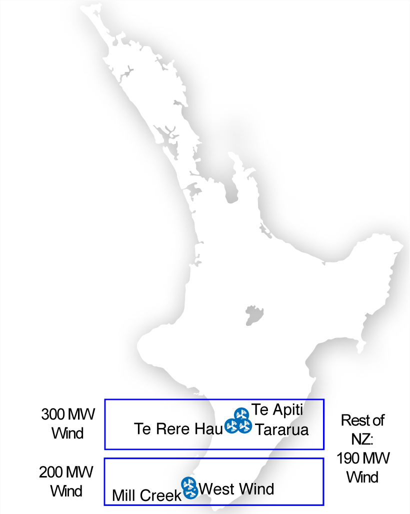
Composition of the NZEM in $2014 - 2015$: By week



Hydro dominated (55%) with geothermal (21%), gas (15%), wind (5.7%), coal (2.6%), and wood (0.8%).

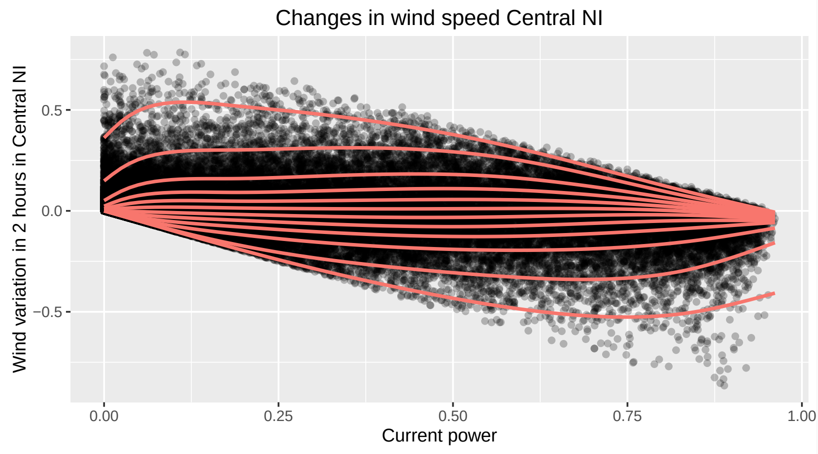
Scenario generation I: Wind farms modelled

CNI, Wellington: assume conditionally independent.



Scenario generation II

Ensemble forecasting via quantile regression



How to estimate the marginal deviation costs:

Costs of deviation are modelled by:

$$r_u = \frac{K}{\text{Generator Ramp Up Rate}},$$
$$r_v = \frac{K}{\text{Generator Ramp Down Rate}}.$$

Reserve prices indicate that $K \in [10, 100]$.

See (Khazaei et al. 2014, Zakeri et al. 2018) for details.

Appendix B: Sensitivity

Does implementing SDM cause wealth transfers?

Sensitivity analysis:

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- Fact #1: nonanticipativity multiplier ρ is maximal monotone operator w.r.t. pre-commitment decision x.

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$$\lambda_{j(i)} + \rho_i + \alpha_{l,i} - \alpha_{u,i} = c_i$$

for each generator i; α's are dual multipliers for $0 \leq X \leq G$.

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- Result #1: if implementing SDM increases pre-commitment decision x, real-time prices decrease, savings allocated to consumers.

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- Result #1: if implementing SDM increases pre-commitment decision x, real-time prices decrease, savings allocated to consumers.
- Result #2: if implementing SDM decreases pre-commitment decision x, real-time prices decrease, savings allocated to generators.

Appendix C: Risk-Aversion

So what? Why should we care? II:

Theorem

Let generator be net-pivotal & risk-averse, collect risk-aversion in term $\alpha_i := \frac{1}{1+\kappa_i(1-\bar{\beta}_i)}$, *where* $\bar{\beta}_i := \int_0^1 \mu^{RN} \beta_i d\beta_i$, $\kappa_i \in [0, \frac{1}{\bar{\beta}_i}]$. *Then, generator's expected risk-neutral profit is* $-(1-\alpha) r_{v,i} x_i^*$. *Expected profit is zero if generator is risk-neutral, and negative if generator is risk-averse.*

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N.b. Arrow-Debreu securities still ensure overall expected cost recovery.

Thank You!

Questions?