Systemic Risk and Renewable Energy

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Introduction

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- Increased reliance on intermittent resources implies higher operational risk.
- We explore the relationship between systemic risk in an electricty market with significant renewable generation capacity in a highly simplified model

Illustration: A Hydro-based Market

- A purely hydro-based market with $I > 0$ units of energy in storage and two stages.
- If x units are released in the first stage then

$$q = \max\{I - x + w, 0\}$$

units are available for consumption in the second stage where $w \geq 0$ is a random water inflow (with distribution F in $[0, \bar{w}]$).

Illustration: A Hydro-based Market

- Assume inelastic demand $d > 0$ in each stage and aggregate thermal capacity $k_T < d$ at marginal cost c_T.
- We assume $I + \bar{w} < d$, that is, thermal generation must be used in the second stage w.p. 1.
- Assuming an outage cost $v > c_T$ the total cost (over two stages) of releasing x in the first stage is

$$C(x) = c_T(d - x) + c_T \max\{d - q, k_T\} + R(x)$$

where

$$R(x) = v \max\{d - k_T - q, 0\}$$

is the outage cost.

Illustration: A Hydro-based Market

- Assuming $q > 0$, rationing takes place whenever

$$w < w(x) \triangleq d - k_T - I + x$$

- The expected value of total cost (over two stages) is:

$$\begin{aligned} E[C(x)] &= c_T(d-x) + c_T \int_{w(x)} (d - I + x - w)dF(w) \\ &\quad + v \int_0^{w(x)} (d - k_T - I + x - w)dF(w) \end{aligned}$$

Value at Risk

- The probability the rationing cost exceeds a threshold r is

$$\begin{aligned}
\Pr(R(x) > r) &= \Pr(v(d - k_T - q) > r) \\
&= \Pr(q < d - k_T - \tfrac{r}{v}) \\
&= \Pr(w < d - k_T - \tfrac{r}{v} + x - I) \\
&= F(d - k_T - \tfrac{r}{v} + x - I)
\end{aligned}$$

- $VaR_\alpha(x)$ is defined as

$$F(d - k_T - \frac{VaR_\alpha(x)}{v} + x - I) = 1 - \alpha$$

or equivalently,

$$VaR_\alpha(x) = v(d - k_T + x - I - F^{-1}(1 - \alpha))$$

CVaR and Optimal Dispatch

- The conditional value at risk

$$
\begin{aligned}
CVaR_\alpha(x) &= E[\,R(x)|\,R(x) > VaR_\alpha(x)] \\
&= \frac{1}{\alpha}\int_0^\alpha VaR_y(x)dy \\
&= v(d - k_T + x - I - \frac{1}{\alpha}\int_0^\alpha F^{-1}(1-y)dy)
\end{aligned}
$$

- A risk averse benevolent planner would solve

$$
\begin{aligned}
\min_{x\in[0,I]} \quad & E[C(x)] \\
\text{s.t} \quad & \\
& CVaR_\alpha(x) \leq \bar{R}
\end{aligned} \tag{1}
$$

CVaR and Optimal Dispatch

- Let $\mu^* \geq 0$ denote the Lagrange multiplier, (1) can be written as

$$\min_{x \in [0,I]} [E[C(x)] + \mu^*(CVaR_\alpha(x) - \bar{R})]$$

- First order condition is:

$$c_T = (v - c_T)F(d - k_T - I + x^*) + \mu^* v \tag{2}$$

Market Dispatch

- Assume the water in store is distributed accross N reservoirs each with level I_i ($\sum_i I_i = I$).
- In a market dispatch each reservoir determines independently how much to release $x_i \geq 0$ and individual inflow is $w_i \geq 0$.
- We assume $w_i = \rho_i w$ donde $\rho_i \in (0, 1)$ y $\sum_i \rho_i = 1$. The individual balance equation is $q_i = \max\{I_i - x_i + w_i, 0\}$.

Market Dispatch

- Let $q = \sum_i q_i$. The spot price in the second stage is:

$$\tilde{p}_2 = \begin{cases} 0 & q \geq d \\ c_T & q \in (d, d - k_T) \\ v & q < d - k_T \end{cases}$$

- The profits for firm i are given by

$$\Pi_i = p_1 x_i + \tilde{p}_2 q_i$$

Equilibrium

- The probability of outage is associated with the even

$$\sum_{i=1}^{N} q_i < d - k_T$$

when $q_i > 0$ this is equivalent to

$$\sum_{i=1}^{N} (l_i - x_i + w_i) = \sum_{i=1}^{N} (l_i - x_i) + w < d - k_T$$

- Thus outage occurs whenever $w < w(x)$.

Equilibrium

- Expected profit is

$$
\begin{aligned}
E[\Pi_i] &= p_1 x_i + E[\tilde{p}_2 q_i] \\
&= p_1 x_i + c_T \int_{w(x_i, x_{-i})} (I_i - x_i + \rho_i w) dF(w) \\
&\quad + v \int_0^{w(x_i, x_{-i})} (I_i - x_i + \rho_i w) dF(w)
\end{aligned}
$$

- Suppose each firm i aims to maximize expected profit.
- The first order condition is

$$p_1 = (v - c_T) F(d - k_T - \sum_{i \in I} (I_i - x_i^*)) \tag{3}$$

Equilibrium

- Comparing (2) and (3) we see that if $\mu^* = 0$ the market dispatch equals the optimal dispatch if $p_1 = c_T$
- If $\mu^* > 0$ the market delivers the optimal risk-constrained dispatch iff

$$p_1 = c_T - \mu^* v$$

- If $p_1 > c_T - \mu^* v$ then the market dispatch increases systemic risk (the firms release too much water in the first period)

Incentives

- Suppose an "uplift" of $\mu^* v$ is charged per unit in the first stage and in the second stage prices are $\tilde{p}_2' = \tilde{p}_2 + \mu^* v$
- The first order condition is

$$p_1 - \mu^* v = (v - c_T) F(d - k_T - \sum_{i \in I} (l_i - x_i^*))$$

Conclusions

- In a highly simplified model, we have shown how increased renewable capacity is likely to induce additional systemic risk in the operation of electricity markets.
- A simple "uplift" can provide the right incentives.
- However, in most electricity markets intermittency is heterogeneous. This implies differential effects on systemic risk.
- A topic for future research.