Modelling 100 percent renewable electricity

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Determine generators’ output to reliably meet the load

- $\sum \text{Gen MW} \geq \sum \text{Load MW}$, at all times.
- Power flows cannot exceed lines’ transfer capacity.
Single market, single good: equilibrium

Walras: \( 0 \leq s(\pi) - d(\pi) \perp \pi \geq 0 \)

Market design and rules to foster competitive behavior/efficiency

- Spatial extension: Locational Marginal Prices (LMP) at nodes (buses) in the network
- Supply arises often from a generator offer curve (lumpy)
- Technologies and physics affect production and distribution (e.g. capacities, fluid flows)
The setup: agents $a = (\text{solar, wind, diesel, consumer})$
A (competitive) equilibrium

\[ u_a \text{ solves } AO(a, \pi) : \min_{u_a \in U_a, \pi} C_{a, \pi}(u_a) \]

and

\[ 0 \leq \sum_{a \in A} g_a(u_a) \perp \pi \geq 0 \]

- Actions \( u_a \) (dispatch, curtail, generate, shed), with costs \( C_{a, \pi} \)
- One optimization per agent, coupled with solution of complementarity (equilibrium) constraint: \( g_a \) converts actions into energy
- Overall, a (Generalized) Nash Equilibrium problem (or a MOPEC), solvable as a large scale complementarity problem (replacing the optimizations by their KKT conditions) using the PATH solver
- Model to understand behaviour of (rational) agents assuming price taking (\( \pi \)) behavior
- What is the gold standard?

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100 percent renewables

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System Optimization

SO: \[ \min_u \sum_{a \in \mathcal{A}} C_a(u_a) \]
\[ \text{s.t. } \sum_{a \in \mathcal{A}} g_a(u_a) \geq 0 \]
\[ u_a \in \mathcal{U}_a \]

- Lagrangian theory shows MOPEC is equivalent to SO under behavioral assumptions (perfectly competitive) and some standard technical assumptions.
- Could use as a counter-factual to determine if agents are in practice acting perfectly competitively.
- So what are the issues?
There’s more: dynamics and uncertainties

- Lousy solution - no transfer of energy across time: need dynamics
- Storage allows energy to be moved across stages (batteries, pump, compressed air, etc)
- Uncertainties (wind flow, cloud cover, rainfall, demand) $\omega_a(n)$
- Scenario tree is data
- Nodes $n \in \mathcal{N}$, $n_+$ successors
- State and shared variables (storage, prices)
- Power distribution not modeled (single consumer location)

$T$ stages (e.g. $t \in 0, 1, 2, 3, 4, 5, 6$)
Add storage (smoother) to uncertain supply
Modelling 100% renewable electricity

- Electricity generation worldwide emits greenhouse gases so to reduce greenhouse gases one can reduce nonrenewable electricity generation.
- Why not reduce nonrenewable electricity generation to zero?
- Aspiration: a 100% renewable electricity system for NZ.
- Implications: what does 100% renewable mean?
- Shutdown all thermal plants? Won’t this be expensive?
- Keep some thermal plants, but use sparingly (in a low-hydrology year)?
- Control GHG emissions from electricity generation to below an accepted threshold?
- Is this a constraint on average, or almost always, or with high probability?
How big, and how to operate?

Electric Power Optimization Centre (EPOC) modelling systems in this talk:

- **DOASA**: [Dynamic Outer Approximation Sampling Algorithm] hydro-thermal optimization model of NZ electricity system (C++/Gurobi)
- **vSPD**: Electricity Authority version of SPD [Scheduling, Pricing and Dispatch] (GAMS/Cplex)
- **HydrovSPD**: vSPD with hydro river chains modelled over 48 periods (GAMS/Cplex)
- **GEMstone**: GEM [Generation Expansion Model] with stochastic optimization (GAMS/Conopt)
- **CRAGE**: Competitive Risk-Averse Generation Expansion (GAMS/PATH)
What are models good for?

- **GEMstone** reveals the implications of the aspiration: 100% renewable
- **GEMstone** determines a system investment plan to achieve the aspiration or get close to it;
- **DOASA/HydrovSPD** tests the robustness of the investment in dry winters;
- **CRAGE** determines how to get close to the system optimum using incentives.

Planning for future years involves uncertainty, so we need stochastic models:

- we need to know if capacity plans affect security of supply?
- Security of supply refers to the electricity industry providing appropriate electricity system capabilities (such as generation and transmission capacity) and storable fuel supplies (such as water, gas and coal) to maintain normal supply to consumers.
Plant $k$ has current capacity $U_k$, expansion $x_k$ at capital cost $K_k$ per MW, maintenance cost $L_k$ per MW, and SRMC $C_k$. Minimize fixed and expected variable costs.

\begin{align*}
\text{P:} \quad & \min \psi = \sum_{k \in \mathcal{K}} (K_k x_k + L_k z_k) + \mathbb{E}_\omega [Z(\omega)] \\
\text{s.t.} \quad & Z(\omega) = \sum_{b \in \mathcal{B}} T(b) \left( \sum_{k \in \mathcal{K}} C_k y_k(\omega, b) + V q(\omega, b) \right) \\
& x_k \leq u_k, \quad k \in \mathcal{K} \\
& z_k \leq x_k + U_k, \quad k \in \mathcal{K} \\
& y_k(\omega, b) \leq \mu_k(\omega, b) z_k, \quad b \in \mathcal{B}, \omega \in \Omega, k \in \mathcal{K}, \\
& \sum_{b \in \mathcal{B}} T(b) y_k(\omega, b) \leq v_k(\omega) \sum_{b \in \mathcal{B}} T(b) z_k, \quad b \in \mathcal{B}, \omega \in \Omega, \\
& q(\omega, b) \leq d(\omega, b), \quad b \in \mathcal{B}, \omega \in \Omega, \\
& d(b) \leq \sum_{k \in \mathcal{K}} y_k(\omega, b) + q(\omega, b), \quad b \in \mathcal{B}, \omega \in \Omega.
\end{align*}
A three-node transmission network
Deterministic result: 100% renewable in a wet year (2016)
Deterministic result: 100% renewable in a dry year (2008)
GEMstone result: eliminate nonrenewable capacity?
Emissions if eliminate nonrenewable capacity

CO2 emissions with capacity reduction

- Blue line: CO2 obtained
- Orange line: Required

Capacity of nonrenewable plant

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GEMstone result: eliminate average emissions
GEMstone result: eliminate average emissions (detail)

Generation capacity as CO2 constrained
The expected cost of reducing average electricity emissions

The expected annual cost of increasing renewable electricity

Annual CO2 Emissions (tonnes)

Annual cost of generation (S$M)
GEMstone result: eliminate average emissions
GEMstone result: eliminate emissions almost surely
How do we get companies to follow the system plan?

**Second Welfare Theorem**: a system plan that minimizes the expected cost of meeting future demand yields energy prices in each state of the world. Each investment action in the plan is optimal for its investor when evaluated using these energy prices. It is a *Walrasian (partial) equilibrium*.

Then, why do electricity companies always do something different from the GEMstone system plan?
As a citizen, Dave Jones worries that climate change may imperil his two children, and theirs in turn. What exercises him, as California’s insurance commissioner, is the way in which a transition to a low-carbon economy might affect the financial health of his other charges—the state’s 1,300-odd insurers. On May 8th Mr Jones unveiled an examination of how well the investment portfolios of the 672 insurers with $100m or more in annual premiums align with the Paris Agreement’s goals.

“Investment plans in renewable energy and electric vehicles lag behind the International Energy Agency’s projections of what is needed.” Firms are not being risk-averse enough but insurers and banks will want to start seeing some risk aversion to climate adaptation soon.

“Carbonated?” Markets may be underpricing climate-related risk

Investors and global warming
Risk and competition

- Why do electricity companies do something different from the GEMstone system plan?
- Companies expand capacity using debt and equity. Banks dislike risk, so expansion plans aim to reduce risk.
- **CRAGE** computes the risked partial equilibrium of competing companies.
- System expansion plans (**GEMstone**) can pool the risks of different cost streams, so risk-averse system optimization gives less risk. Risk-averse companies looking at only their profit streams will not do what the system deems optimal.
- **CRAGE** equilibrium \(\neq\) **GEMstone** optimum with social risk measure.
CRAGE

Simultaneous solution of

\[ P(a) : \min \Psi = \sum_{k \in \mathcal{K}} (K_k x^a_k + L_k z^a_k) + \rho_a[Z^a(\omega)] \]

s.t. \[ Z^a(\omega) = \sum_{b \in \mathcal{B}} T(b) \left( \sum_{k \in \mathcal{K}} C_k y^a_k(\omega, b) + Vq^a(\omega, b) - \pi(\omega, b) \left( \sum_{k \in \mathcal{K}} y^a_k(\omega, b) + q^a(\omega, b) - d(b) \right) \right) \]

\[ x^a_k \leq u^a_k, \quad k \in \mathcal{K} \]
\[ z^a_k \leq x^a_k + U^a_k, \quad k \in \mathcal{K} \]
\[ y^a_k(\omega, b) \leq \mu_k(\omega, b) z^a_k, \quad b \in \mathcal{B}, \omega \in \Omega, k \in \mathcal{K}, \]
\[ \sum_{b \in \mathcal{B}} T(b) y^a_k(\omega, b) \leq \nu_k(\omega) \sum_{b \in \mathcal{B}} T(b) z^a_k, \quad b \in \mathcal{B}, \omega \in \Omega, \]
\[ q^a(\omega, b) \leq d(\omega, b), \quad b \in \mathcal{B}, \omega \in \Omega, \]
\[ 0 \leq \pi(\omega, b) \perp \sum_{k \in \mathcal{K}} y^a_k(\omega, b) + q^a(\omega, b) - d(b) \geq 0. \]
Risk trading can recover system optimum

- **Contracts** for trading risk enable companies to enjoy pooled risk.
- Perfectly competitive markets can be **inefficient** if such contracts are missing.
- Example: Meridian-Genesis swaption contract enables more efficient operation of thermal and hydro plant by decreasing risk for both parties.
- Theorem (PFW, 2016; FP, 2018): If markets for risk (using **dynamic coherent risk measures**) are **complete** then a perfectly competitive (risk-averse) equilibrium corresponds to a risk-averse **social optimum** using a social risk measure.
- **CRAGE** equilibrium with contracts = **GEMstone** risk-averse optimum.
Modelling implications

- **CRAGE** model can predict competitive equilibrium investments in incomplete markets.
- **GEMstone** risk-averse optimum can provide a benchmark for complete market.
- The added value of incorporating **contracts** for trading risk can be identified from the difference between these solutions.

Different expansion plans arising from incomplete markets for risk.
(Source Corey Kok PhD thesis).
What are EPOC models good for?

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- **Combination of models (including transmission) provides effective decision tool at multiple scales**
- **Models based on NZ data, adaptable to other situations with modified inputs**
- **Many new settings available for deployment; need for more theoretic and algorithmic enhancements**
The Philpott bach problem

Solar panels:

Petrol generator:

Battery:

Pump storage:

100 percent renewables

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Risk modeling

- Modern approach to modeling risk aversion uses concept of risk measures
- CVaR\(_\alpha\): mean of upper tail beyond \(\alpha\)-quantile (e.g. \(\alpha = 0.95\))

- Dual representation in terms of risk sets: \(\mathcal{D}\)
  \[
  \rho(x) = \sup_{p \in \mathcal{D}} \mathbb{E}_p(x)
  \]

- Different agents have different risk profiles
- Recursive (nested) definition of expected cost-to-go
Risk averse equilibrium

Replace each agent's problem by:

\[
\text{AO}(a, \pi, D_a): \min_{(\theta, u, x) \in \mathcal{F}} \quad Z_a(0) + \theta_a(0)
\]

s.t. \( x_a(n) = x_a(n-) - u_a(n) + \omega_a(n) \)

\[
\theta_a(n) \geq \sum_{m \in n^+} p^k_a(m)(Z_a(m) + \theta_a(m)), \quad k \in K(n)
\]

\[
Z_a(n) = C_a(u_a(n)) - \pi(n)g_a(u_a(n))
\]

- \( p^k_a(m) \) are extreme points of the agents' risk set at \( m \)
- No longer system optimization
- Must solve using complementarity solver