Modelling 100 percent renewable electricity

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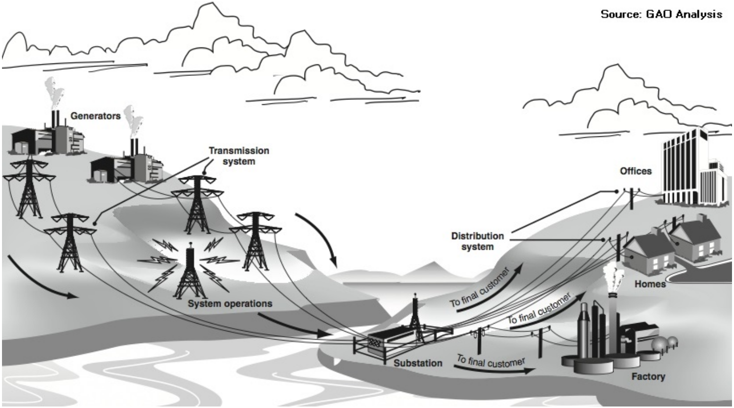
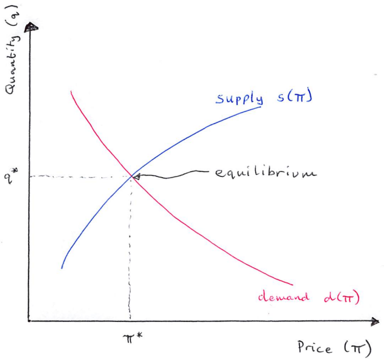
Power generation, transmission and distribution



- Determine generators' output to reliably meet the load
  - $\sum$ Gen MW $\geq \sum$ Load MW, at all times.
  - Power flows cannot exceed lines' transfer capacity.

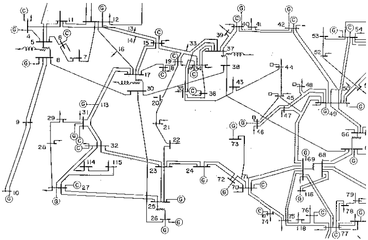
Single market, single good: equilibrium



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

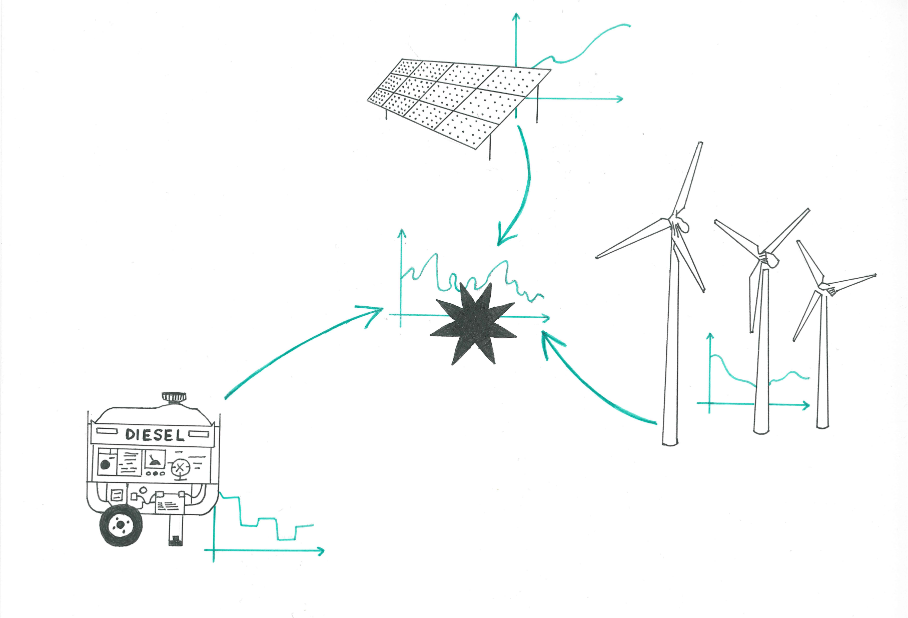
Market design and rules to foster competitive behavior/efficiency

- 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 =(solar, wind, diesel, consumer)



A (competitive) equilibrium

$$u_a \text{ solves AO}(a, \pi): \quad \min_{u_a \in \mathcal{U}_{a,\pi}} C_{a,\pi}(u_a)$$

and

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

- 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 (π) behavior
- What is the gold standard?

System Optimization

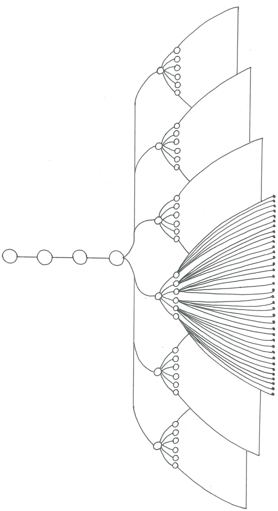
$$\text{SO:} \min_{u} \sum_{a \in \mathcal{A}} C_a(u_a)$$
$$\text{s.t.} \sum_{a \in \mathcal{A}} g_a(u_a) \geq 0$$
$$u_a \in \mathcal{U}_a$$

- 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?

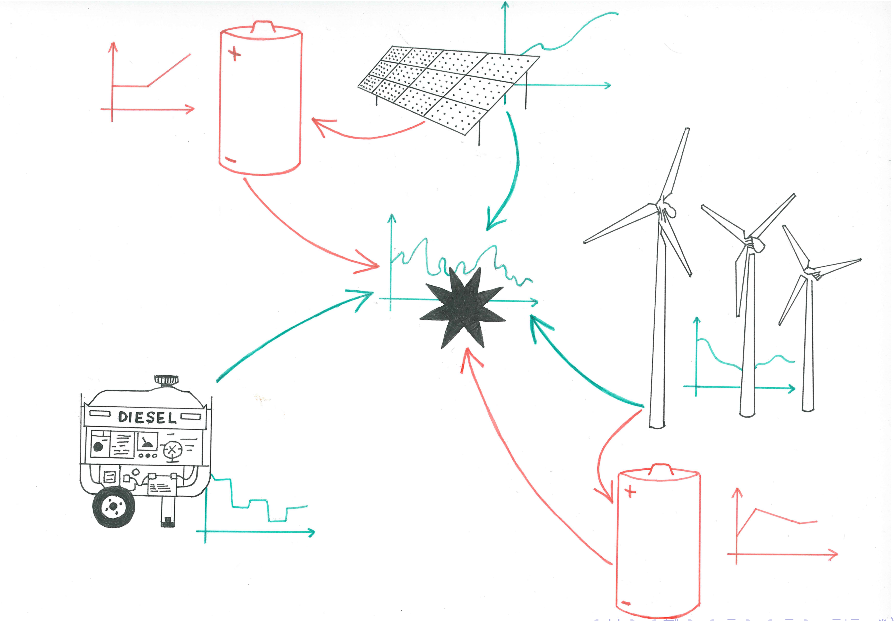
There's more: dynamics and uncertainties

- 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?

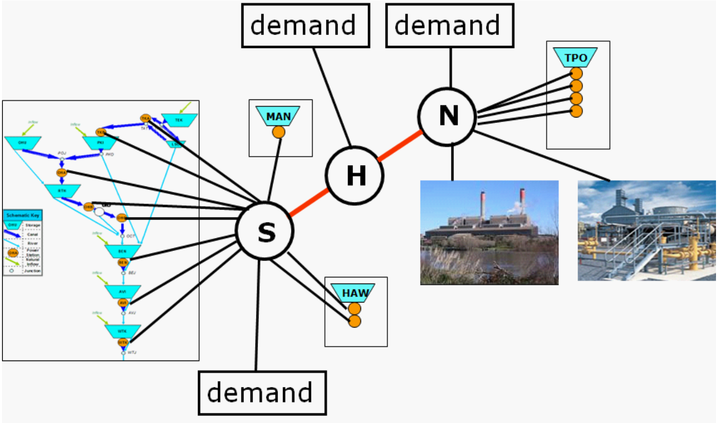
- GEMstone reveals the implications of the aspiration: 100% renewable
- GEMstone determines a system investment plan to achieve the aspiration or get close to it;
- DOASA/HydrovSPD tests the robustness of the investment in dry winters;
- CRAGE determines how to get close to the system optimum using incentives.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

GEMstone for a single node

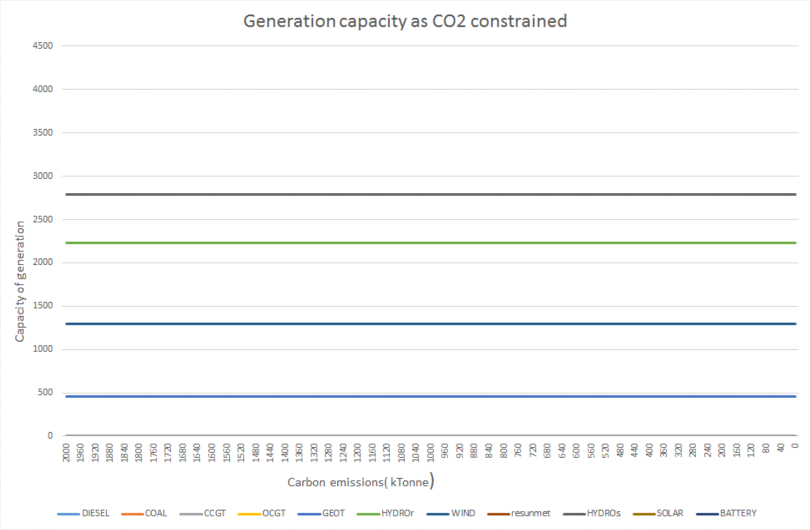
Plant k has current capacity U_k, expansion x_k at capital cost K_k per MW, maintenance cost L_k per MW, and SRMC C_k. Minimize fixed and expected variable costs.

$$
\begin{array}{lrcll}
\text{P:} & \min \psi & = & \sum_{k\in\mathcal{K}} (K_k x_k + L_k z_k) + \mathbb{E}_\omega[Z(\omega)] & \\
\text{s.t.} & Z(\omega) & = & \sum_{b\in\mathcal{B}} T(b) \left(\sum_k C_k y_k(\omega,b) + Vq(\omega,b)\right) & \\
& x_k & \leq & u_k, & k \in \mathcal{K} \\
& z_k & \leq & x_k + U_k, & k \in \mathcal{K} \\
& y_k(\omega,b) & \leq & \mu_k(\omega,b) z_k, & b\in\mathcal{B}, \omega\in\Omega, k\in\mathcal{K}, \\
& \sum_{b\in\mathcal{B}} T(b) y_k(\omega,b) & \leq & \nu_k(\omega) \sum_{b\in\mathcal{B}} T(b) z_k, & b\in\mathcal{B}, \omega\in\Omega, \\
& q(\omega,b) & \leq & d(\omega,b), & b\in\mathcal{B}, \omega\in\Omega, \\
& d(b) & \leq & \sum_{k\in\mathcal{K}} y_k(\omega,b) + q(\omega,b), & b\in\mathcal{B}, \omega\in\Omega.
\end{array}
$$

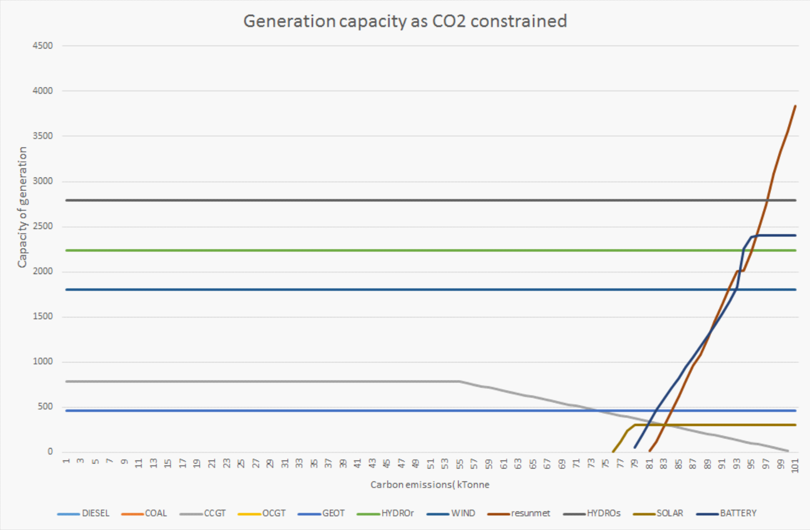
A three-node transmission network



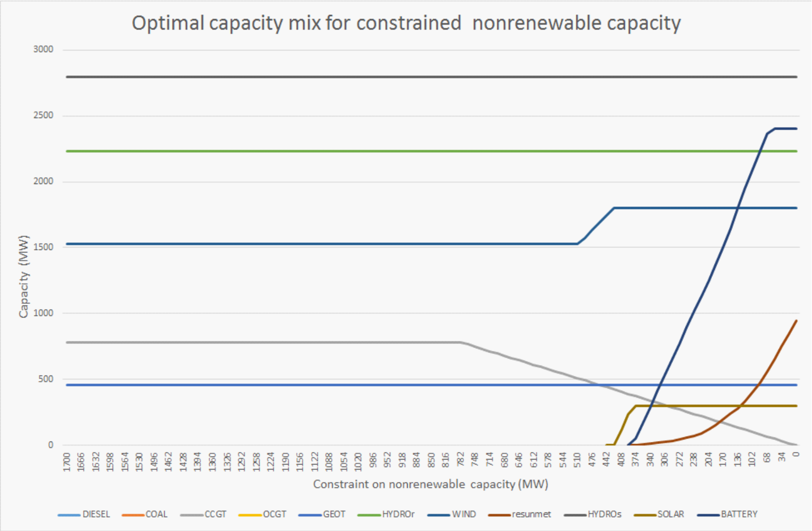
Deterministic result: 100% renewable in a wet year (2016)



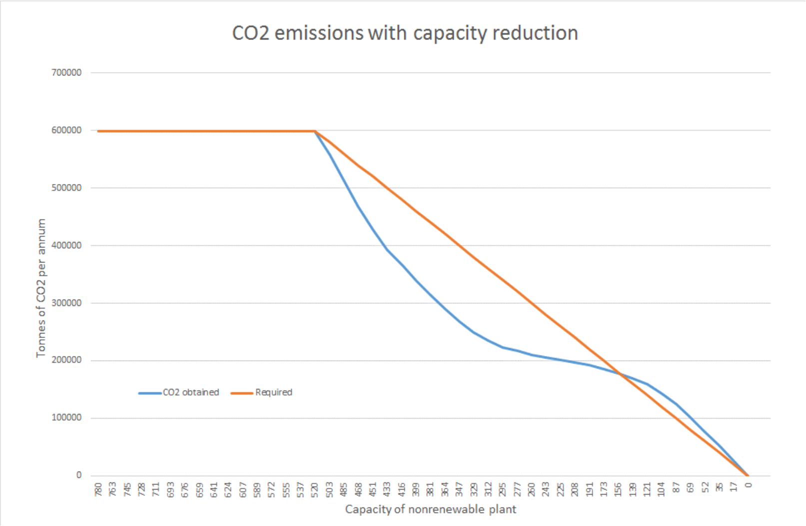
Deterministic result: 100% renewable in a dry year (2008)



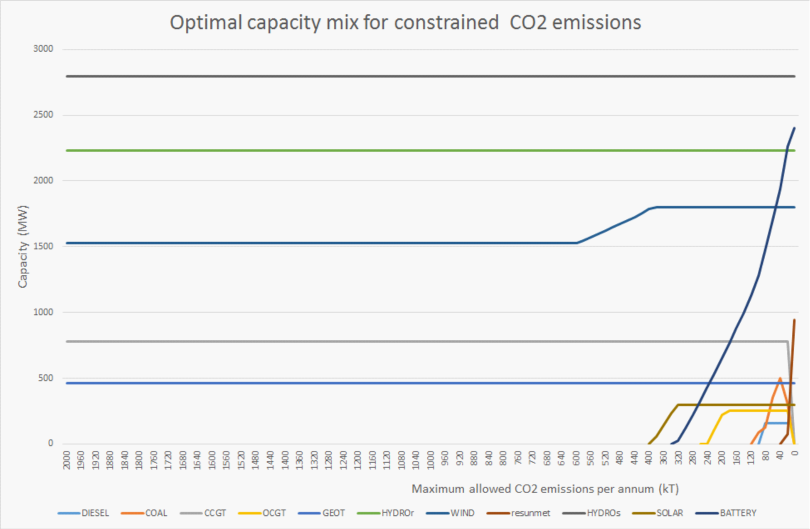
GEMstone result: eliminate nonrenewable capacity?



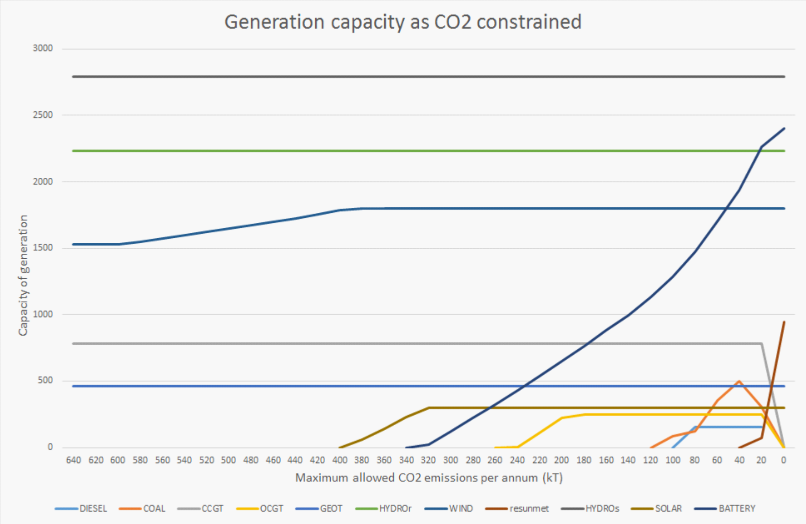
Emissions if eliminate nonrenewable capacity



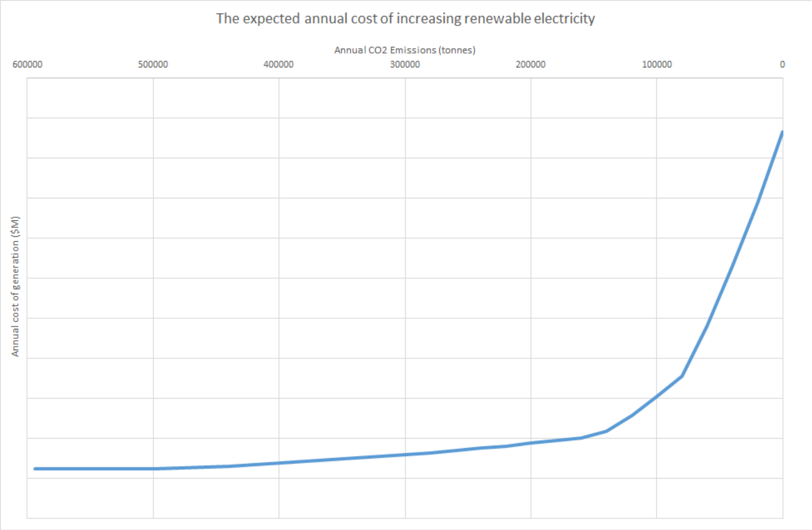
GEMstone result: eliminate average emissions



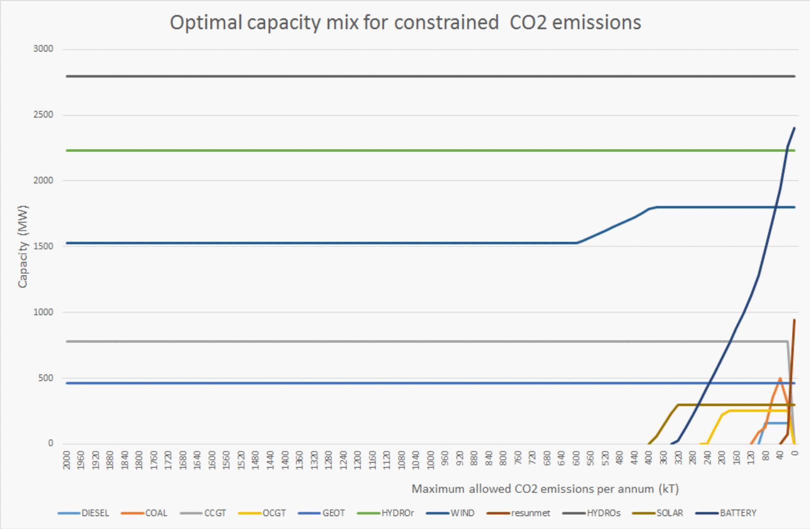
GEMstone result: eliminate average emissions (detail)



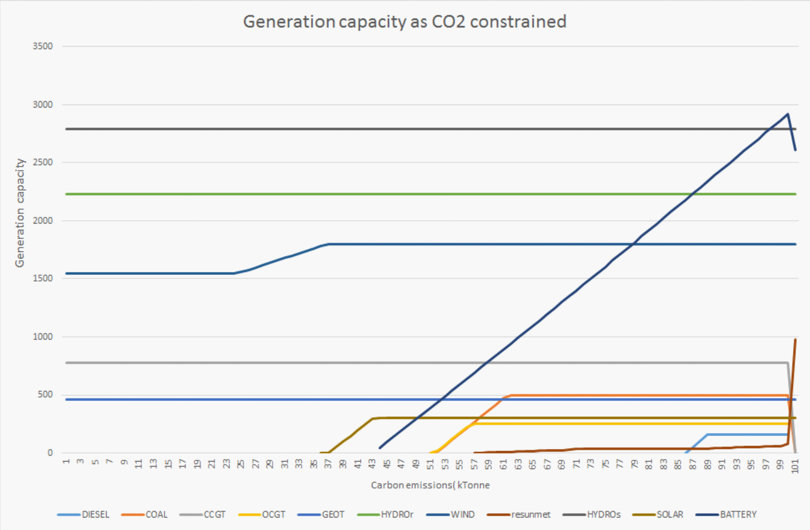
The expected cost of reducing average electricity emissions



GEMstone result: eliminate average emissions



GEMstone result: eliminate emissions almost surely



Competitive markets and expansion

- 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?

Economist article published last month

The Economist

Carbonated?

Markets may be underpricing climate-related risk

Investors and global warming

Business and finance | May 23rd 2018

- "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

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

$$
\begin{aligned}
P(a) : \min \Psi &= \sum_{k \in \mathcal{K}} (K_k x_k^a + L_k z_k^a) + \rho_a[Z^a(\omega)] \\
\text{s.t. } Z^a(\omega) &= \sum_{b \in \mathcal{B}} T(b) \Big(\sum_k C_k y_k^a(\omega, b) + V q^a(\omega, b) \\
&\quad - \pi(\omega, b) \left(\sum_{k \in \mathcal{K}} y_k^a(\omega, b) + q^a(\omega, b) - d(b) \right) \Big) \\
x_k^a &\le u_k^a, \quad k \in \mathcal{K} \\
z_k^a &\le x_k^a + U_k^a, \quad k \in \mathcal{K} \\
y_k^a(\omega, b) &\le \mu_k(\omega, b) z_k^a, \quad b \in \mathcal{B}, \omega \in \Omega, k \in \mathcal{K}, \\
\sum_{b \in \mathcal{B}} T(b) y_k^a(\omega, b) &\le \nu_k(\omega) \sum_{b \in \mathcal{B}} T(b) z_k^a, \quad b \in \mathcal{B}, \omega \in \Omega, \\
q^a(\omega, b) &\le d(\omega, b), \quad b \in \mathcal{B}, \omega \in \Omega,
\end{aligned}
$$

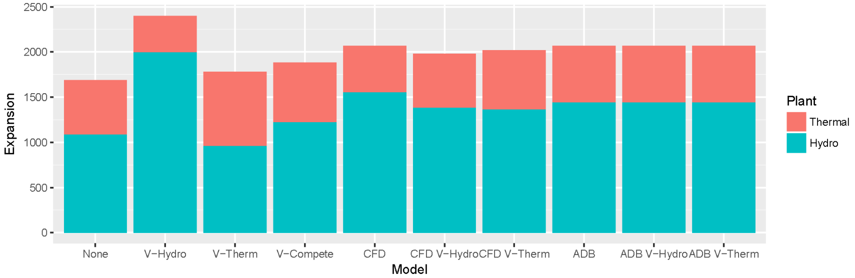
$$
0 \le \pi(\omega, b) \quad \perp \quad \sum_{k \in \mathcal{K}} y_k^a(\omega, b) + q^a(\omega, b) - d(b) \ge 0.
$$

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).

Conclusions/Questions/Comments

- What are EPOC models good for?
  - GEMstone reveals the implications of the aspiration;
  - 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.
- 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:

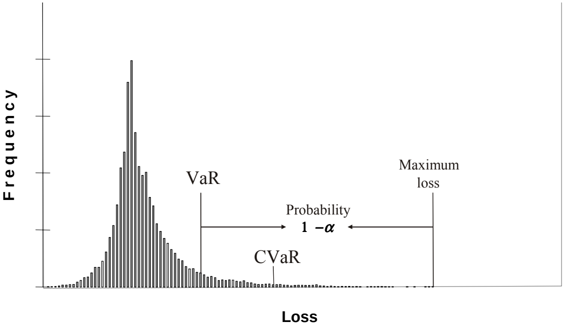
Battery:

Petrol generator:

Pump storage:

Risk modeling

- Modern approach to modeling risk aversion uses concept of risk measures
- $\overline{CVaR}_\alpha$: mean of upper tail beyond α-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 agents problem by:

$$
\begin{aligned}
\text{AO}(a,\pi,\mathcal{D}_a):\quad \min_{(\theta,u,x)\in\mathcal{F}} \quad & Z_a(0)+\theta_a(0) \\
\text{s.t.} \quad & x_a(n) = x_a(n_-) - u_a(n) + \omega_a(n) \\
& \theta_a(n) \geq \sum_{m\in n_+} p_a^k(m)(Z_a(m)+\theta_a(m)), \quad k\in K(n) \\
& Z_a(n) = C_a(u_a(n)) - \pi(n)g_a(u_a(n))
\end{aligned}
$$

- $p_a^k(m)$ are extreme points of the agents risk set at m
- No longer system optimization
- Must solve using complementarity solver