Modelling 100 percent renewable electricity

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What is EPOC?

- Electric Power Optimization Centre (EPOC) founded in 2002 at UoA.
- Electricity modelling "Winter" workshops held every year since 2002. See www.epoc.org.nz/workshops.html
- EPOC modelling systems in this talk:
  - DOASA: hydro-thermal optimization model of NZ electricity system (C++/Gurobi)
  - vSPD: Electricity Authority version of SPD (GAMS/Cplex)
  - HydrovSPD: vSPD with hydro river chains modelled over 48 periods (GAMS/Cplex)
  - GEMstone: GEM with stochastic optimization (GAMS/Conopt)
  - CRAGE: Competitive Risk-Averse Generation Expansion (GAMS/PATH)

Motivation for this talk

- 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.
- What are 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.

Implications: what does 100% renewable mean?

- Shutdown all thermal plant? Won't this be expensive?
- Keep some thermal plant, 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?
- Planning for future years involves uncertainty, so we need stochastic models.
    - we need to know if capacity plans affect security of supply?

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?

Summary

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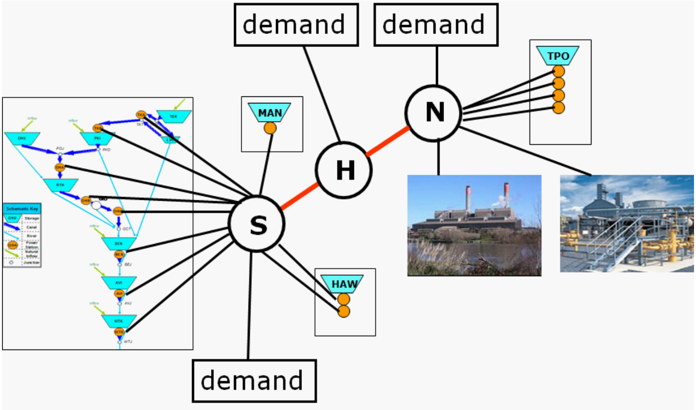
1. Introduction
2. GEMstone
3. DOASA/HydrovSPD
4. CRAGE
5. Conclusions

GEMstone for a single node

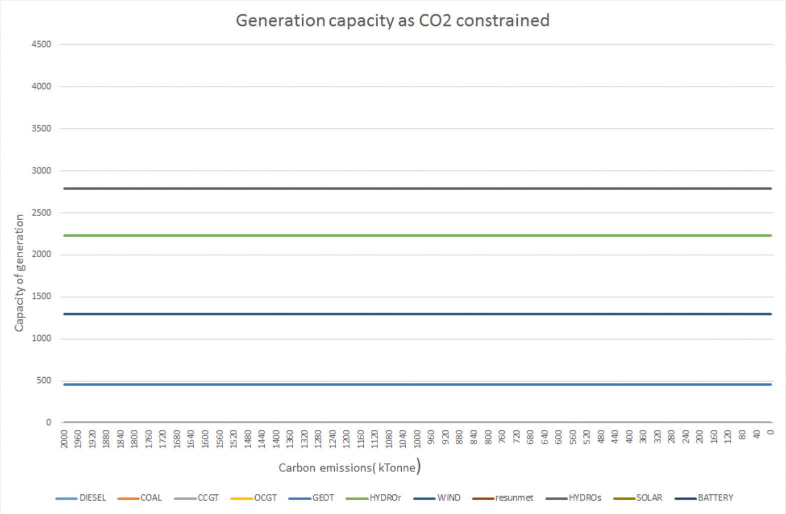
Plant k has current capacity U_k, expansion x_k at capital cost K_k per MW, maintenance cost L_k per MW, and SRMC C_k. Minimize fixed and expected variable costs.

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

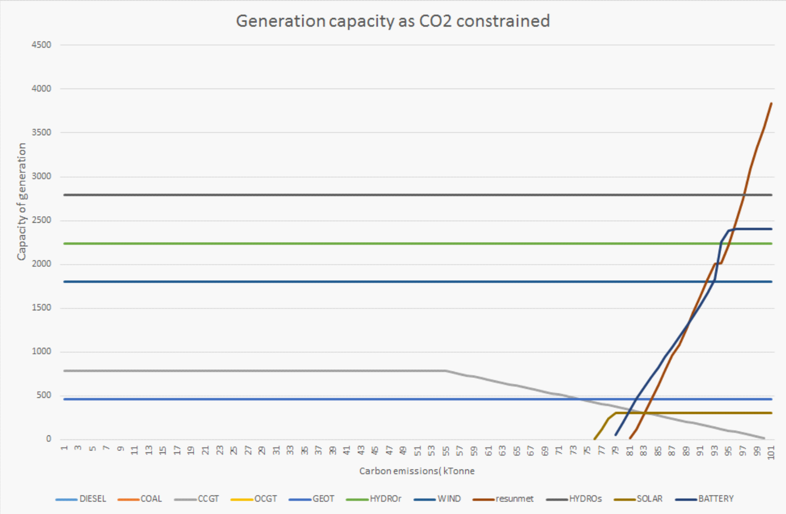
A three-node transmission network



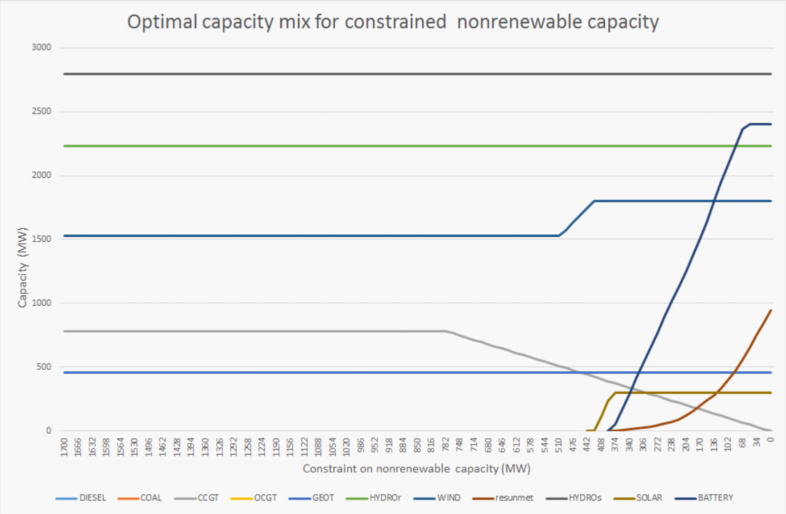
Deterministic result: 100% renewable in a wet year (2016)



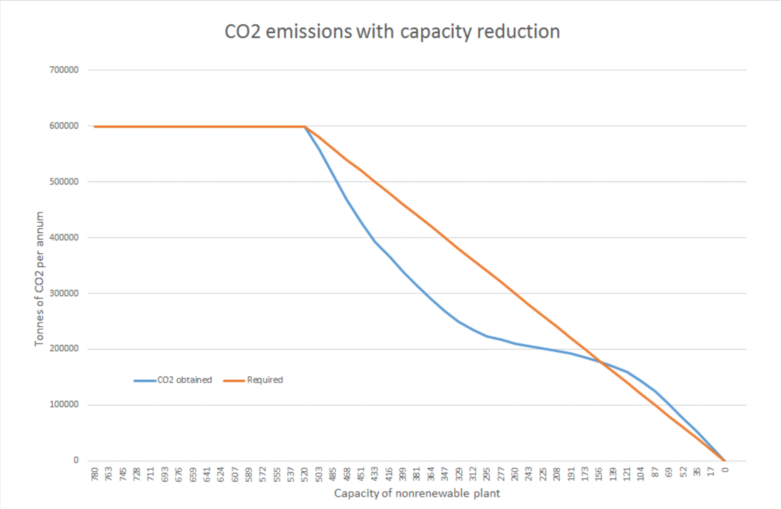
Deterministic result: 100% renewable in a dry year (2008)



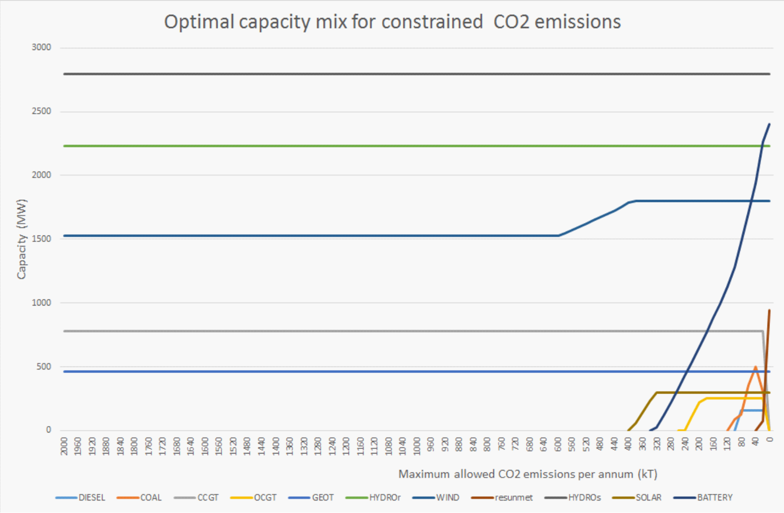
GEMstone result: eliminate nonrenewable capacity?



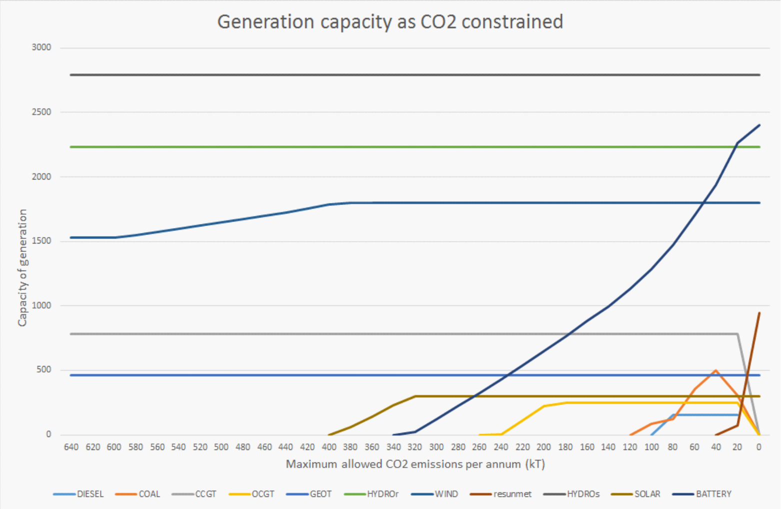
Emissions if eliminate nonrenewable capacity



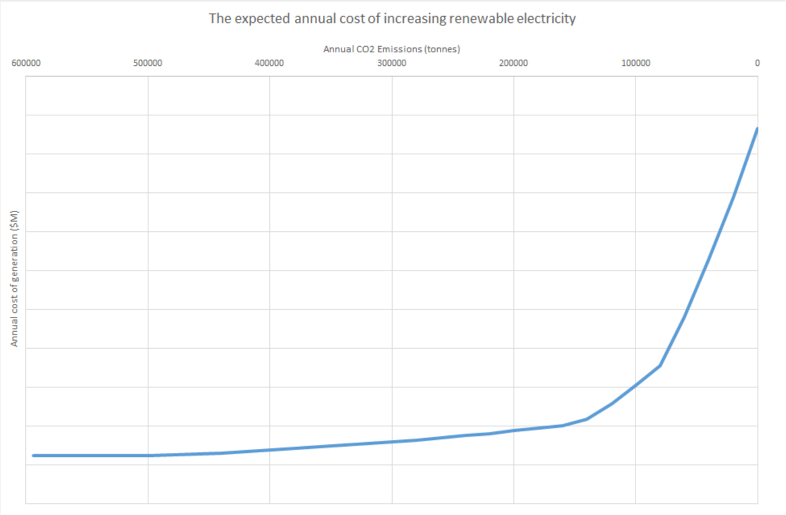
GEMstone result: eliminate average emissions



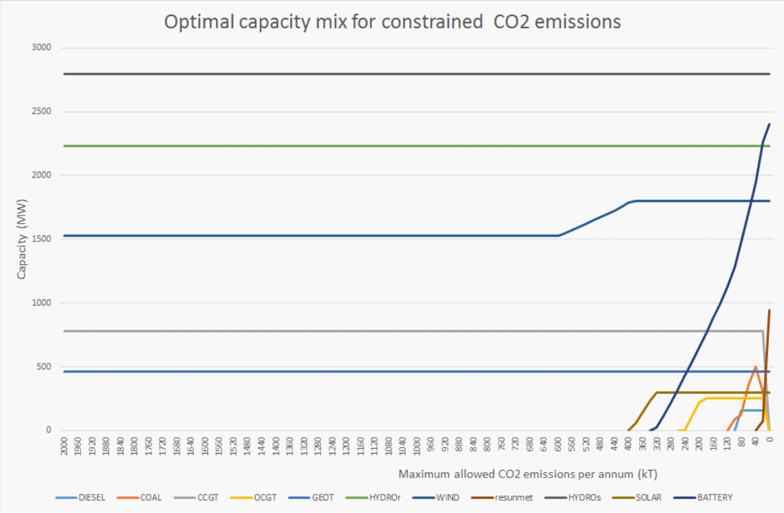
GEMstone result: eliminate average emissions (detail)



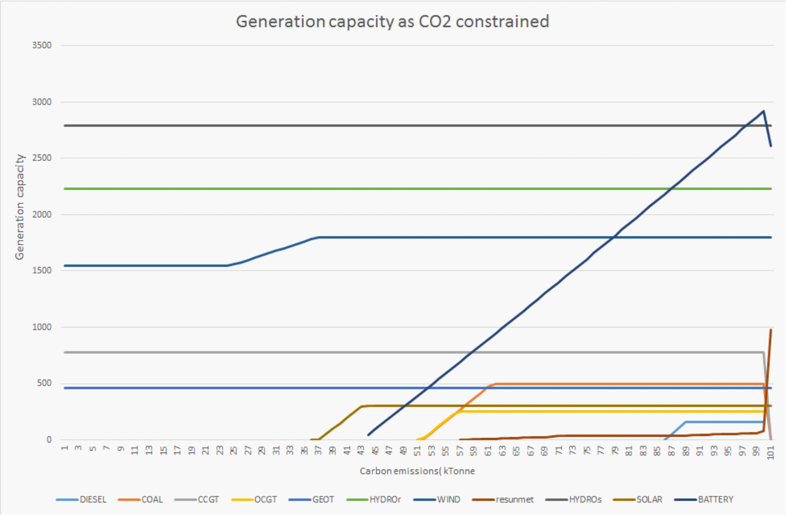
The expected cost of reducing average electricity emissions



GEMstone result: eliminate average emissions

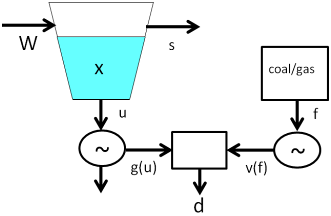


GEMstone result: eliminate emissions almost surely



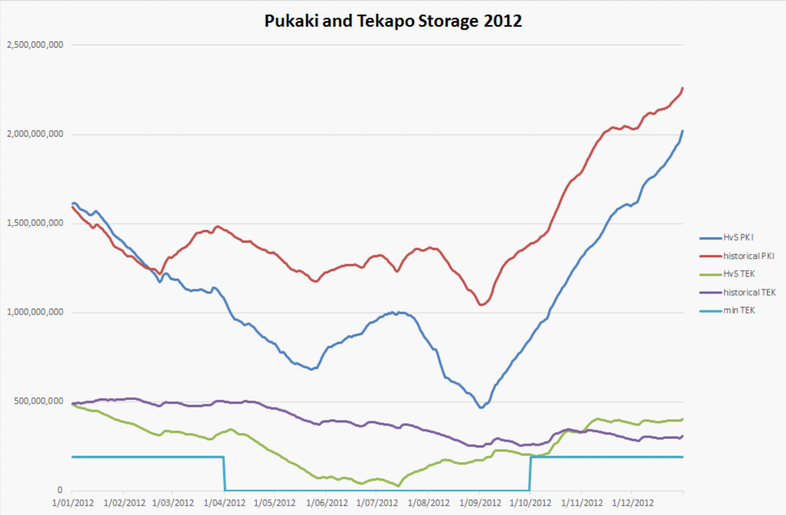
Summary

DOASA/HydrovSPD

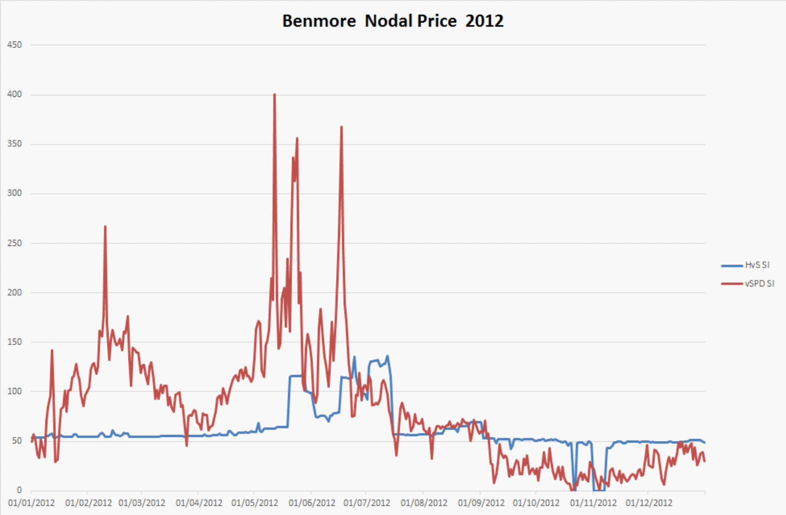


- Use water or thermal plant generation?
- DOASA computes an expected marginal water value for stored water under perfect competition.
- Requires solution of massive scale stochastic optimization using SDDP algorithm.
- Water is not released if its expected marginal value exceeds SRMC of thermal plant.
- Policy simulated in HydrovSPD.

Outcomes from DOASA/HydrovSPD



Outcomes from DOASA/HydrovSPD



Summary

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

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

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

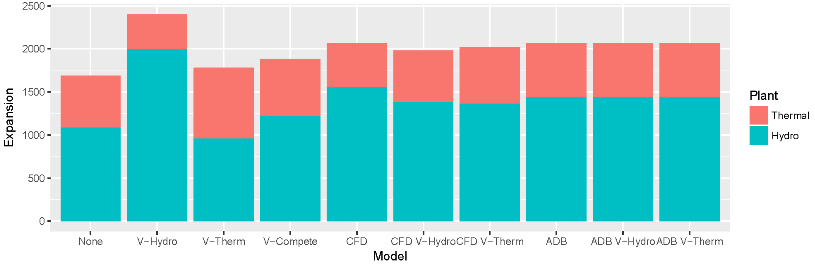
Risk trading can recover system optimum

- 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 adding contracts for trading risk can be identified from the difference between these solutions.

Outcomes



Different expansion plans arising from incomplete markets for risk. (Source Corey Kok PhD thesis).

Summary

Conclusions

- 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.
- DOASA made available as EMI-DOASA on the EA EMI site.
- All the EPOC models are currently calibrated to the New Zealand electricity system and ready to apply.

The End

THE END

References

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All references and this talk can be downloaded from www.epoc.org.nz