Planning a 100 percent renewable electricity system

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Open for Business

- This talk is about formulating models to advise government policy.
- What is the role of mathematics in this process?
- What is the role of planning and plans?
- How do we think about uncertainty?
- How should we represent business decisions in our plan?

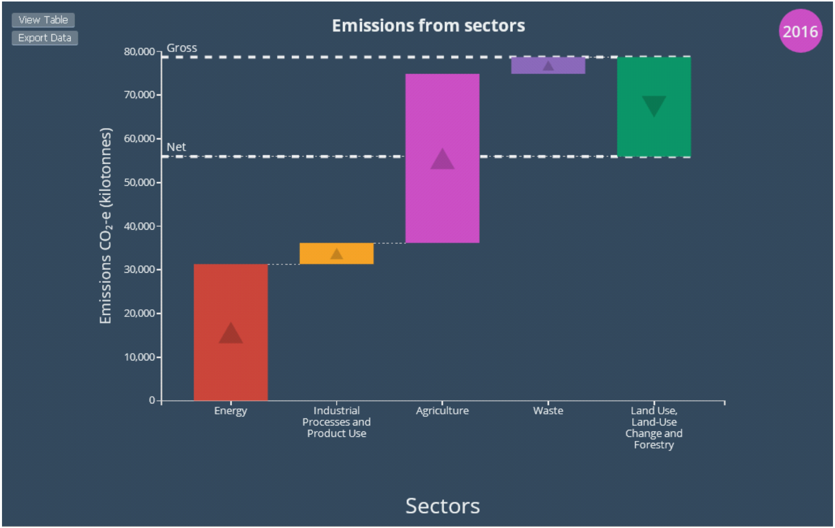
New Zealand: How to implement Jacinda's deal

3. Request the Climate Commission to plan the transition to 100% renewable electricity by 2035 (which includes geothermal) in a normal hydrological year.
    a. Solar panels on schools will be investigated as part of this goal.
4. Stimulate up to $1 billion of new investment in low carbon industries by 2020, kick-started by a Government-backed Green Investment Fund of $100 million.

Confidence and Supply Agreement between the New Zealand Labour Party and the Green Party of Aotearoa New Zealand 3

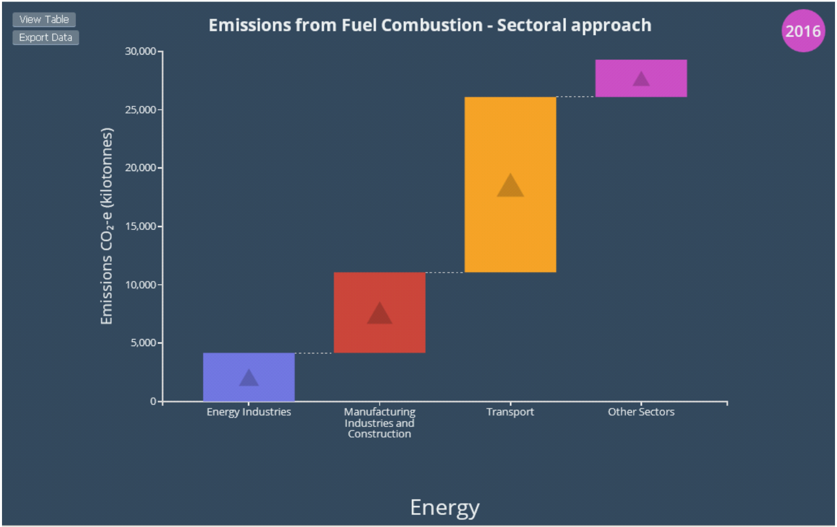
Confidence and Supply Agreement between Labour Party and Green Party, October 2017.
(https://www.greens.org.nz/sites/default/files)

New Zealand greenhouse gas emissions



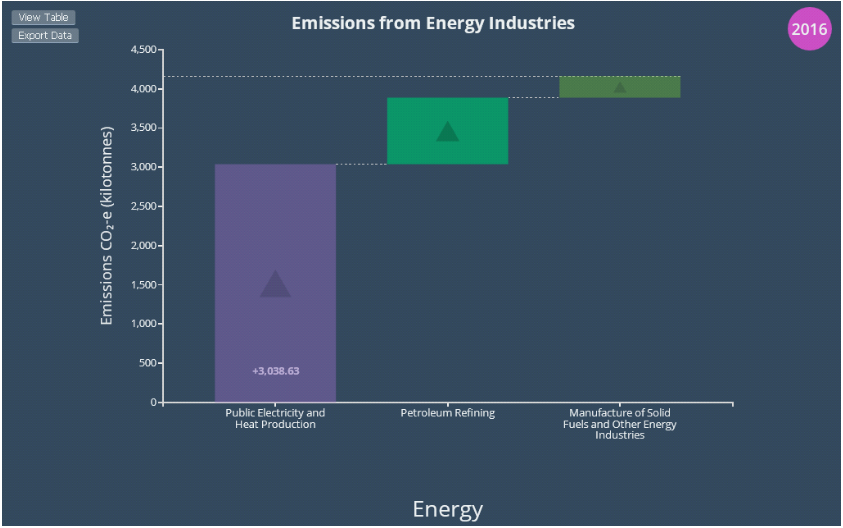
Total GHG emissions in 2016 were 80 M t CO2 equivalent.

New Zealand greenhouse gas emissions



Total CO2 emissions in 2016 were 30 M t.

New Zealand greenhouse gas emissions



Total CO2 emissions from electricity in 2016 were 3 M t.

New Zealand's electricity system in one slide

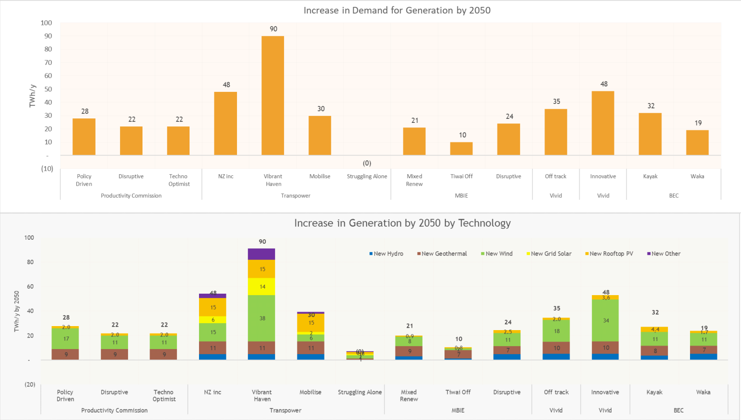
- 55% of New Zealand electricity comes from hydro generation.
- New Zealand cannot import or export electricity (aluminium excepted).
- Hydro reservoirs hold about 8 weeks of storage if plant run at full capacity.
- Electricity system currently has ample generation and transmission capacity, but...
- ...electricity system is susceptible to risk of seasonal low inflows ("dry winter").

A mathematical modelling approach to planning

- Build and solve a social plannning model that optimizes electricity capacity investment with constraints on CO2 emissions.
- Social planning solution should be stochastic: i.e. account for future uncertainty
- Social planning solution should be risk-averse: because the industry is.
- Approximate the outcomes of the social plan by a competitive equilibrium with risk-averse investors.
- Compensate for market failures from imperfect competition or incomplete markets.

Uncertainty is experienced at different time scales

- Demand growth, technology change, capital costs are long-term uncertainties (years).
- Seasonal inflows to hydroelectric reservoirs are medium-term uncertainties (weeks).
- Levels of wind and solar generation are short-term uncertainties (half hours).
- Very short term effects from random variation in renewables and plant failures (seconds).



14 scenarios for electricity demand and generation mix in 2050 under different assumptions.

Computing the right capacity mixture

- Needs modelling at finer time scales.
- Find the optimal mix of capacity so as to enable
  - optimal releases from hydroelectric reservoirs with uncertain inflows.
  - meet demand with random variations in wind and solar.
  - spinning reserve capacity to deal with random plant failures
- Building more capacity costs more, but makes operations cheaper - seek a least-cost sweet spot.

Simplified two-stage stochastic optimization model

- Capacity decision are x at cost $K(x)$
- Operating decisions are: generation y at cost $C(y)$, loadshedding q at cost Vq.
- Random demand is $d(\omega)$.
- Minimize capital cost plus expected operating cost:

$$
\begin{array}{llrcl}
\text{P:} & \min & K(x) & + & \mathbb{E}_\omega[C(y(\omega)) + Vq(\omega)] \\
& \text{s.t.} & y(\omega) & \leq & x, \\
& & y(\omega) + q(\omega) & \geq & d(\omega), \\
& & y(\omega), q(\omega) & \geq & 0.
\end{array}
$$

More realistic model

Plant k has current capacity U_k, expansion x_k at capital cost K_k per MW, maintenance cost L_k per MW, and operating cost C_k. Minimize fixed and expected variable costs. Here $t = 0, 1, 2, 3$, is a season and $w(t)$ is reservoir storage at end of season t.

$$
\begin{aligned}
\text{P:} \quad \min \psi &= \textstyle\sum_k (K_k x_k + L_k z_k) + \sum_t \mathbb{E}_\omega [Z(t,\omega)] \\
\text{s.t.} \quad Z(t,\omega) &= \textstyle\sum_b T(b) \left(\sum_k C_k y_k(t,\omega,b) + Vq(t,\omega,b) \right), \\
x_k &\leq u_k, \\
z_k &\leq x_k + U_k, \\
y_k(t,\omega,b) &\leq \mu_k(t,\omega,b) z_k, \\
\textstyle\sum_b T(b) y_k(t,\omega,b) &\leq \nu_k(t,\omega) \textstyle\sum_b T(b) z_k \ + w(t-1) - w(t), \\
q(t,\omega,b) &\leq d(t,\omega,b), \\
d(t,\omega,b) &\leq \textstyle\sum_k y_k(t,\omega,b) + q(t,\omega,b), \\
w(t) &\leq W, \\
y, q, w &\geq 0.
\end{aligned}
$$

Operating costs are random

Plant k has current capacity U_k, expansion x_k at capital cost K_k per MW, maintenance cost L_k per MW, and operating cost C_k. Transfer energy $w(t)$ from season t to season $t+1$. Minimize fixed and expected variable costs. Here $T(b)$ is the number of hours in load block b of annual load duration curve.

$$
\begin{array}{rrcl}
\text{P:} & \min \psi & = & \sum_k (K_k x_k + L_k z_k) + \sum_t \mathbb{E}_\omega [Z(t,\omega)] \\
\text{s.t.} & Z(t,\omega) & = & \sum_b T(b) \left(\sum_k C_k y_k(t,\omega,b) + Vq(t,\omega,b)\right), \\
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$$

Shedding load incurs VOLL penalties

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. Transfer energy $w(t)$ from season t to season $t+1$. Minimize fixed and expected variable costs.

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\text{P:} & \min \psi & = & \sum_k (K_k x_k + L_k z_k) + \sum_t \mathbb{E}_\omega [Z(t,\omega)] \\
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\end{array}
$$

Capacity of wind and run-of-river is random in a season

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.

$$
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w(t) &\leq W, \\
y, q, w &\geq 0.
\end{aligned}
$$

Energy input from reservoir inflows is random in a season

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.

$$
\begin{array}{rrcl}
\text{P:} & \min \psi & = & \sum_k (K_k x_k + L_k z_k) + \sum_t \mathbb{E}_\omega [Z(t,\omega)] \\
\text{s.t.} & Z(t,\omega) & = & \sum_b T(b) \left(\sum_k C_k y_k(t,\omega,b) + Vq(t,\omega,b)\right), \\
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\end{array}
$$

Accounting for CO2 emissions

Some capacity x_k, $k \in \mathcal{N}$, is "non renewable".
Some generation $y_k(\omega)$, $k \in \mathcal{E}$ emits $\beta_k y_k(\omega)$ tonnes of CO2.
For a choice of $\theta \in [0,1]$ constraint is either:

$$\mathbb{E}_\omega \left[\sum_{k\in\mathcal{E}} \beta_k y_k(\omega)\right] \leq \theta \mathbb{E}_\omega \left[\sum_{k\in\mathcal{E}} \beta_k y_k(\omega, 2017)\right],$$

(reduce CO2 emissions compared with 2017)

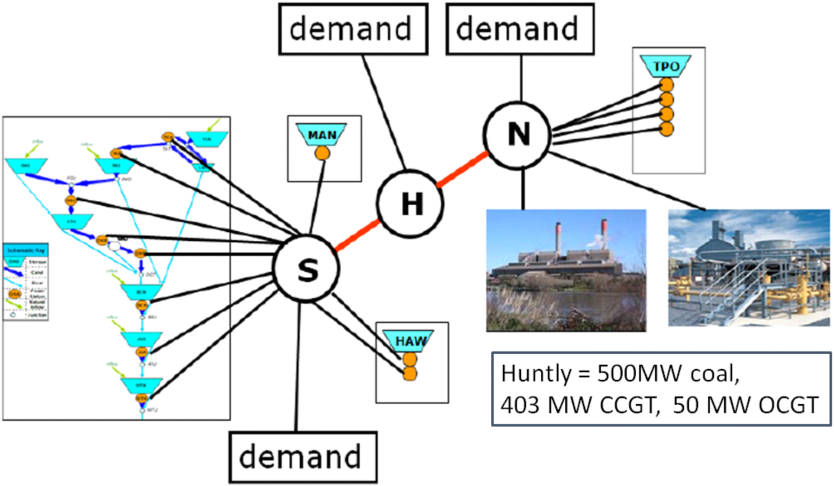
$$\mathbb{E}_\omega \left[\sum_{k\in\mathcal{N}} y_k(\omega)\right] \leq \theta \mathbb{E}_\omega \left[\sum_{k\in\mathcal{N}} y_k(\omega, 2017)\right],$$

(reduce non-renewable generation compared with 2017)

$$\sum_{k\in\mathcal{N}} x_k \leq \theta \sum_{k\in\mathcal{N}} x_k(2017),$$

(reduce non-renewable capacity compared with 2017)

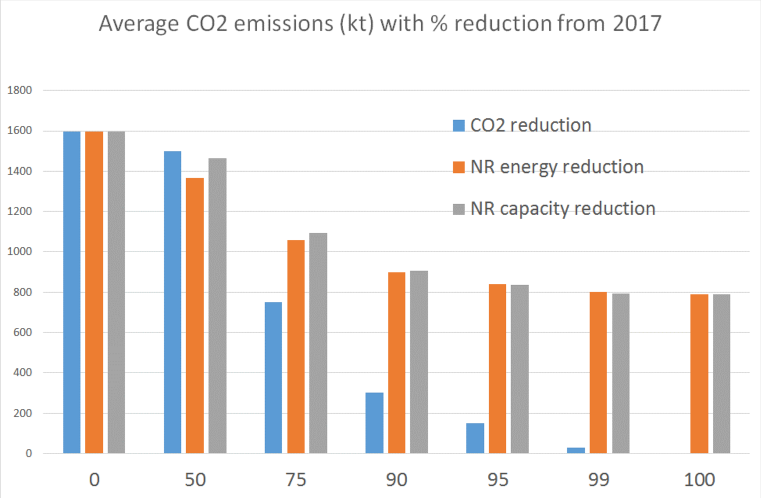
More about New Zealand



Non renewable capacity reduction can increase emissions

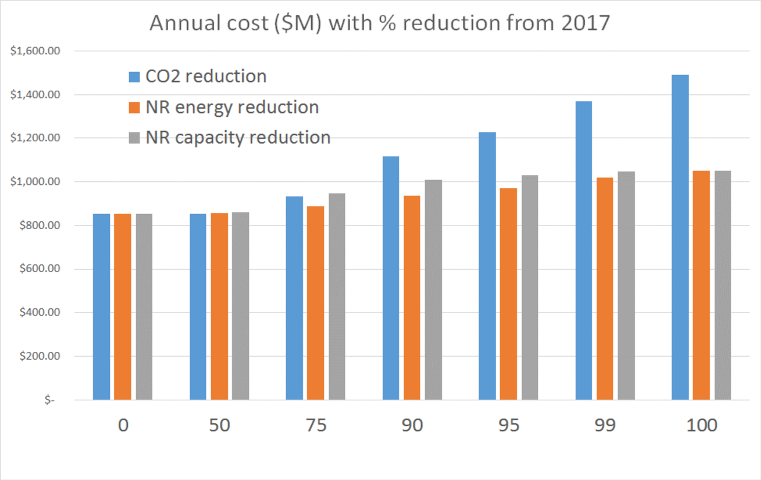
- Many instances of the model where a reduction of non-renewable plant capacity ceteris paribus increases average emissions.
- Hydro-reservoir inflows are susceptibe to dry winter risk.
- With high nonrenewable plant capacity, dry winters can be dealt with just before they have an effect, so reservoir levels in summer need not be full.
- With low nonrenewable plant capacity, can't wait till last minute and reservoir levels in summer need to be close to full just in case. Burning fuel to achieve this increases emissions.

Compare CO2 emissions from reduction strategies



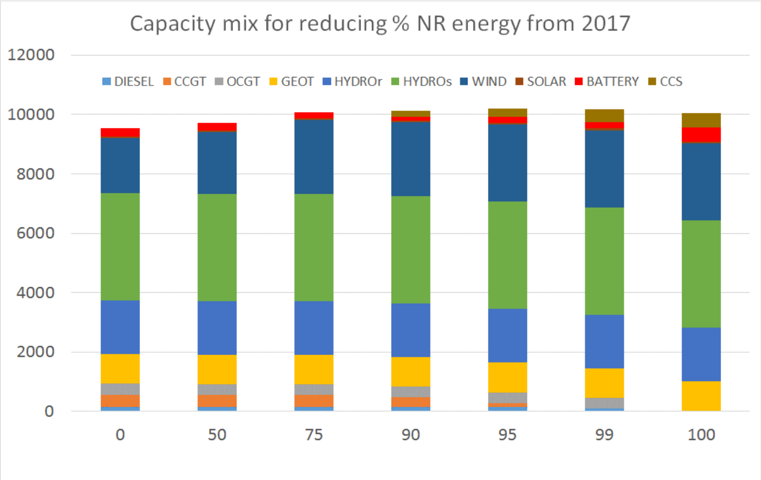
Since (renewable) geothermal and CCS emit some CO2 100% renewable yields modest reductions in CO2 emissions.

Compare cost of reduction strategies as θ increases



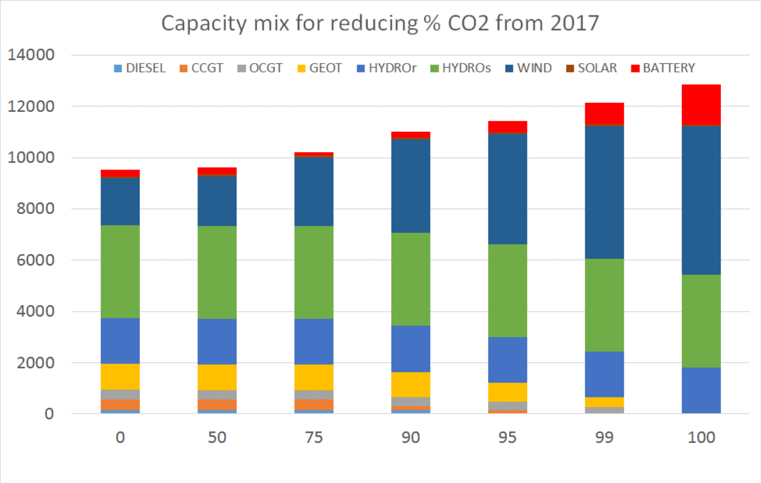
Cost of actually reaching zero CO2 emissions (without geothermal or CCS) increases as we approach the limit.

Technology choices as θ increases (NR energy)



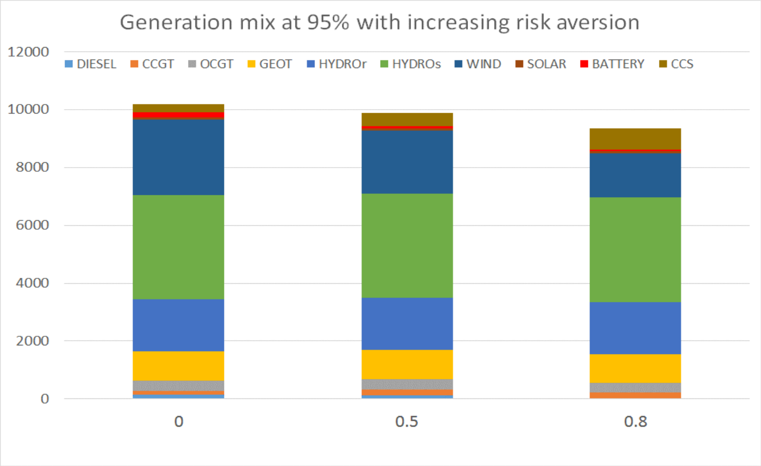
Wind and batteries increase modestly as well as CCS (renewable) as 100% approaches.

Technology choices as θ increases (CO2 emissions)



Investments in wind and batteries increase with reductions in geothermal.

Risk-averse solutions for 95% NR energy reduction



Risk aversion modelled using $(1-\lambda)E[Z] + \lambda \text{AVaR}_{0.90}(Z)$, for $\lambda = 0$, $\lambda = 0.5$, $\lambda = 0.8$.

Conclusions

- 100% renewable electricity system has several interpretations with different implications.
- Policy should choose the objective function not the action: e.g. reducing thermal capacity ceteris paribus can increase average emissions.
- Uncertainty in the model makes a difference.
- Electricity system has uncertainties at many time scales. Can include these in a single model with some approximations.
- If geothermal and CCS are renewable then 100% renewable is feasible, but emission reduction is modest.
- 100% emission reduction in NZ electricity is needlessly expensive given proportion of electricity emissions.
- Next steps: A multistage model, and its competitive equilibrium counterpart.