Optimization in Energy and Environmental Systems

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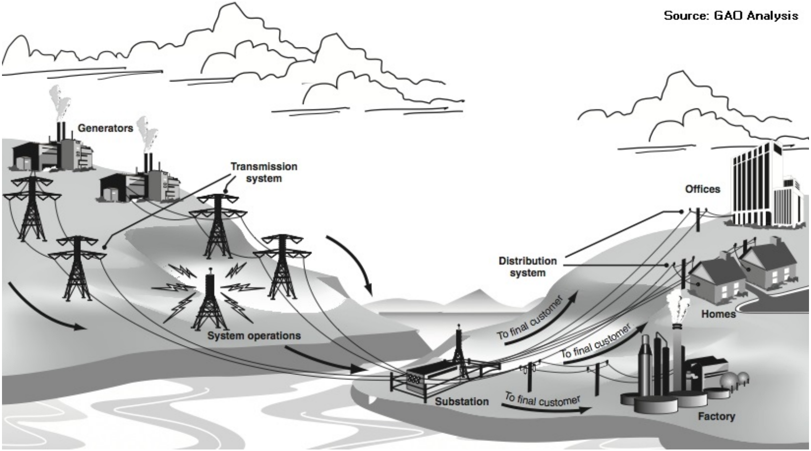
A Scary Energy Winter Is Coming. Don't Blame the Greens

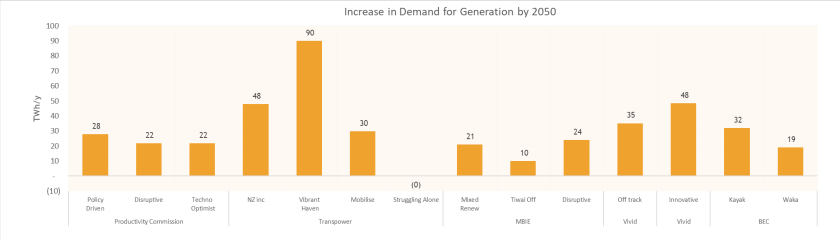
- Thomas Friedman (NY Times, Oct 5, 2021)
- "The good news is that every major economy has signed onto reducing its carbon footprint by phasing out dirtier fuels like coal to heat homes and to power industries. The bad news is that most nations are doing it in totally uncoordinated ways, from the top down, and before the market has produced sufficient clean renewables like wind, solar and hydro."
- "Achieving the scale of clean energy that we need requires not only wind, solar and hydro, but also a carbon tax in every major industrial economy, nuclear power and natural gas as a bridge."
- Can optimization help improve this situation?

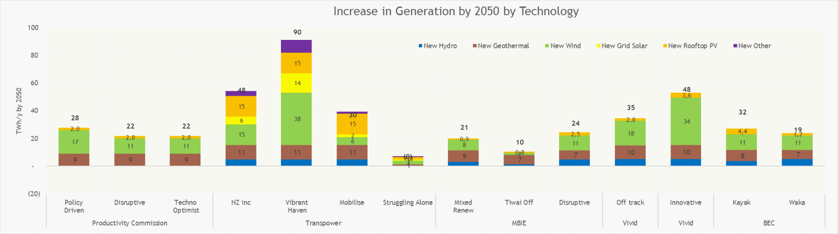
Engineering, Economics and Environment



- Determine generators' output to reliably/economically meet the load
- Power flows cannot exceed lines' transfer capacity
- Tradeoff: Impose environmental regulations/incentives

Data uncertainty: multiple futures (ω)

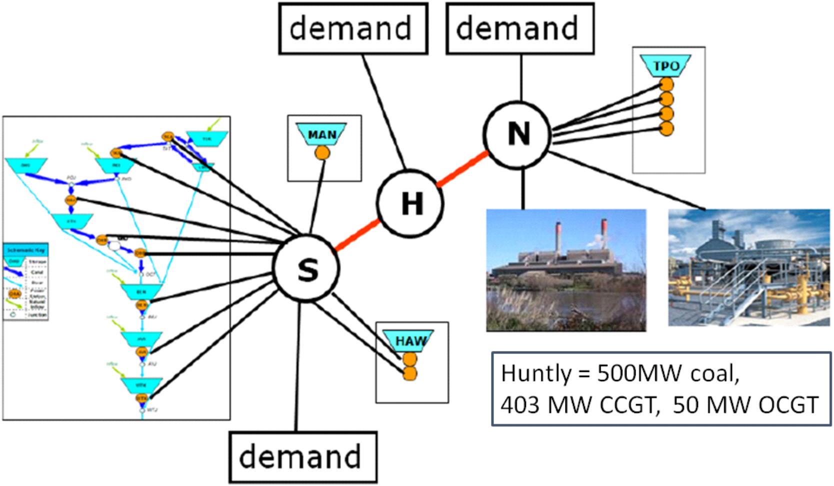




14 scenarios (ω) for electricity demand and generation mix in 2050.
There are 14 different optimal plans: which to select, if any?

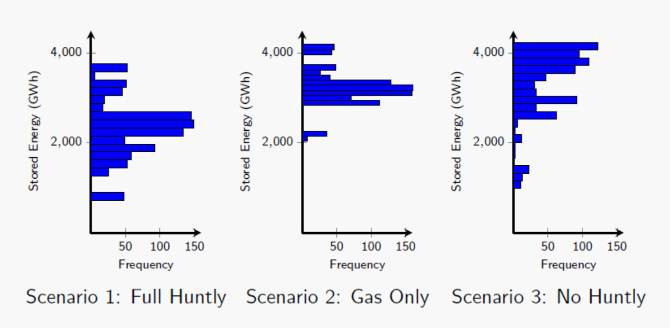
Jacinda - what does fully renewable in electricity mean?

- Permanently shutdown all thermal plants?
- Control GHG emissions from electricity generation?



Closing plants often increases average emissions (Fulton)

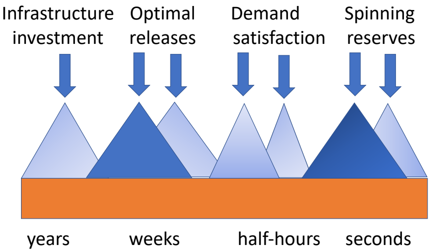
- Hydro can act as a giant battery
- Simulation runs: Reduce plant capacity, store more water "in case of dry winter":



- 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. Tradeoff: Burning fuel to achieve this increases emissions.

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)



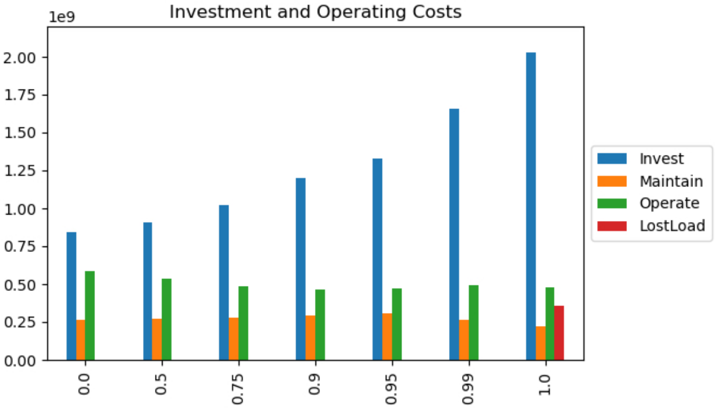
- Tradeoff: Uncertainty, cost and operability, regulations, security/robustness/resilience
- Needs modelling at finer time scales

Simplified two-stage stochastic optimization model

- Capacity decisions are z at cost $K(z)$
- 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:

$$
\begin{array}{llrcl}
\text{P:} & \min\limits_{z,y,q \in X} & K(z) & + & \mathbb{E}_\omega[C(y(\omega)) + Vq(\omega)] \\
 & \text{s.t.} & y(\omega) & \leq & z, \\
 & & y(\omega) & \geq & d(\omega) - q(\omega), \\
 & & z_{\mathcal{N}} & \leq & (1-\theta) z_{\mathcal{N}}(2017)
\end{array}
$$

Costs as we impose tighter emission restrictions



- Markets based on marginal (operating) prices
- Tradeoff: Building more (renewable) capacity costs more, but makes operations cheaper - how to recover the fixed cost investment
- Operational costs dominated (at 100% renewable) by load shedding

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.

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

Environmental constraints

Some capacity z_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:

$$\mathbb{E}_\omega[\sum_{k \in \mathcal{E}} \beta_k y_k(\omega)] \leq (1 - \theta)\mathbb{E}_\omega[\sum_{k \in \mathcal{E}} \beta_k y_k(\omega, 2017)],$$

(reduce CO2 emissions compared with 2017)

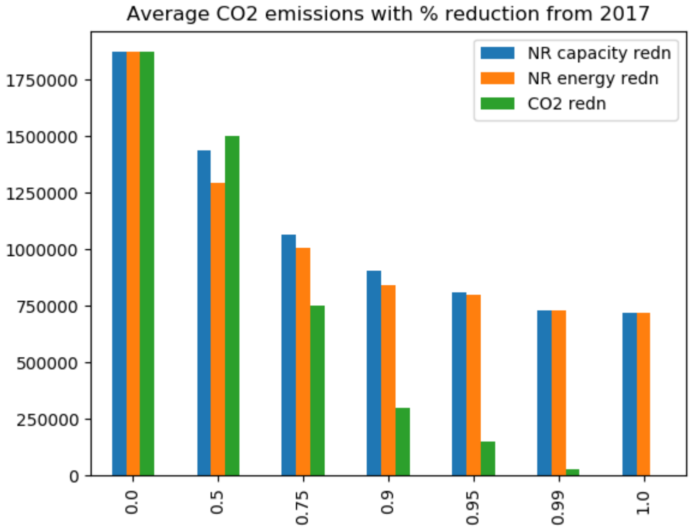
$$\sum_{k \in \mathcal{N}} z_k \leq (1 - \theta) \sum_{k \in \mathcal{N}} z_k(2017),$$

(reduce non-renewable capacity compared with 2017)

$$\mathbb{E}_\omega[\sum_{k \in \mathcal{N}} y_k(\omega)] \leq (1 - \theta)\mathbb{E}_\omega[\sum_{k \in \mathcal{N}} y_k(\omega, 2017)],$$

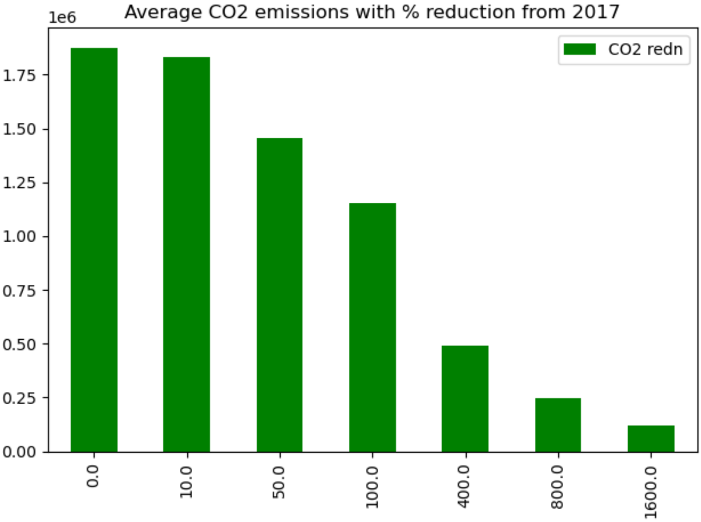
(reduce non-renewable generation compared with 2017)

Could impose constraints almost surely instead of in expectation or with risk measure (small impact) or use chance constraints

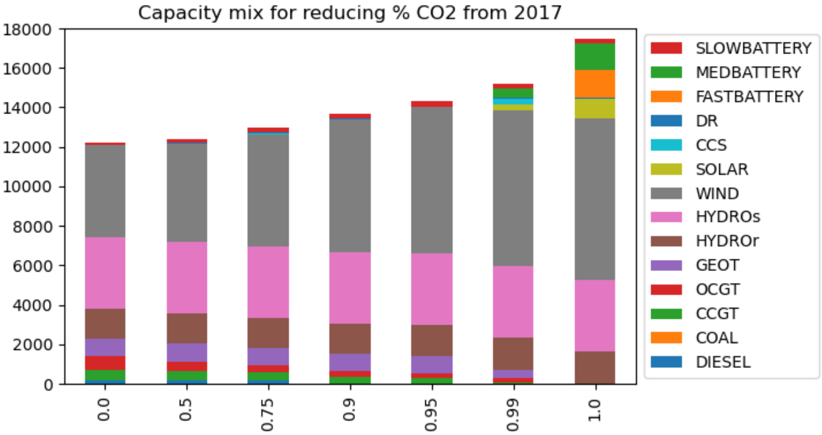


Since (renewable) geothermal and CCS emit some CO2 100% renewable yields modest reductions in CO2 emissions.

Average emissions for increasing carbon price ($ / tonne)



Technology choices as θ increases (% CO2 redn)



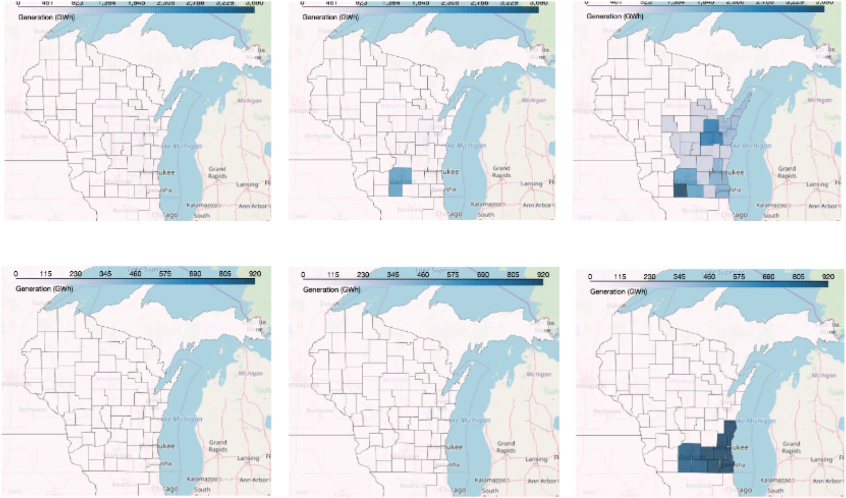
- Rich portfolio of renewable technologies used
- More capacity needed as more uncertain generation

Large pumped storage investment: Lake Onslow

Technology	Without			With		
	SI	HAY	NI	SI	HAY	NI
ONSLOW	0.0	0.0	0.0	1000.0	0.0	0.0
SLOWBATT	500.0	500.0	500.0	0.0	500.0	500.0
WIND	0.0	2049.9	5000.0	0.0	1407.4	5000.0

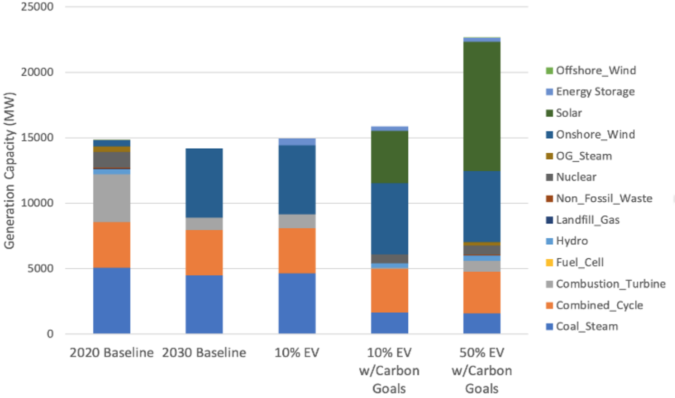
- Worried about the effects of dry winters and excess wind capacity
- Pumped storage costs amortized over long period
- Economical if emissions constraint is strict enough (i.e. no more than 5% of 2017 levels)
- Remove large battery in SI, reduce wind capacity at HAY

Wisconsin: wind and solar penetration

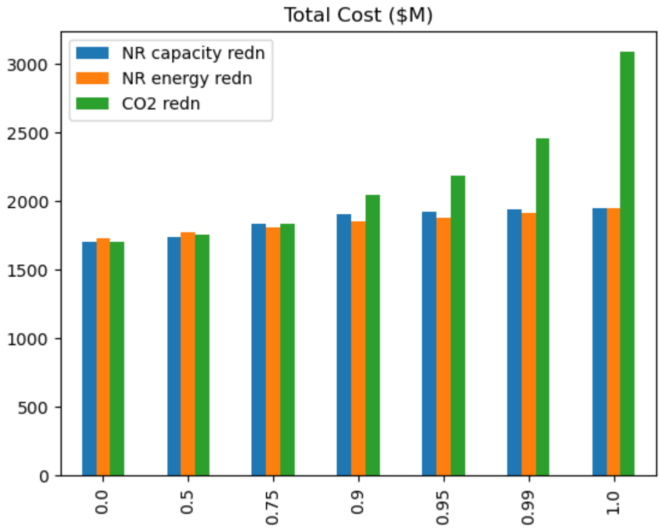


WEREWOLF model outputs: Renewable increases (wind and solar) for 0%, 40%, 80% carbon reduction policy scenarios in Wisconsin

Impact of Electric Vehicles on Generator Investments

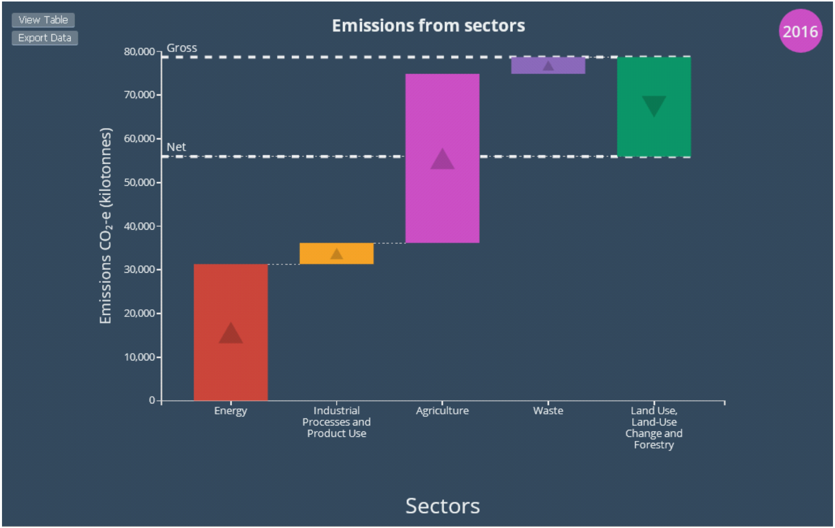


- Carbon Goals: 60% reduction on in-state carbon emissions
- Nuclear (low-carbon) used
- Coal steam generators shut down, supplanted by renewables
- Additional 180,000 MWh demand for EVs
- Storage investment needed
- Additional demand or carbon goals give more dramatic effects



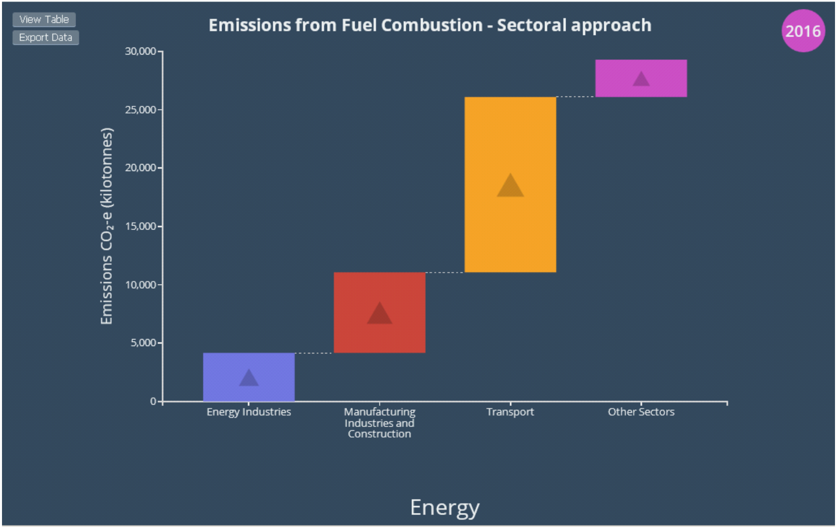
Cost of actually reaching zero CO_2 emissions (without geothermal or CCS) increases as we approach the limit.

New Zealand greenhouse gas emissions



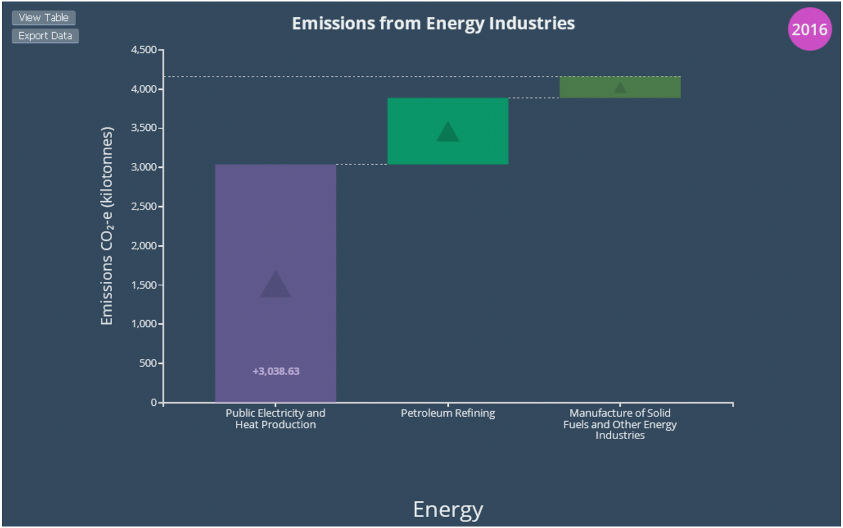
Total GHG emissions in 2016 were 80 M t CO2 equivalent.

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.

General equilibrium (with contracts/incentives)

Consumption d_k, energy y_j, flows f, prices π, σ

$$\text{Consumers} \quad \max_{d_k \in \mathcal{C}} \text{utility}(d_k) - T_C(\sigma, d, f, y) - \pi^T d_k$$

$$\text{Generators} \quad \max_{(y_j) \in \mathcal{G}} \text{profit}(y_j, \pi) - T_G(\sigma, d, f, y)$$

$$\text{Transport} \quad \min_{f \in \mathcal{F}} \text{cost}(f, \pi, \sigma)$$

Market clearing

$$0 \leq \pi \perp \sum_j y_j - \sum_k d_k - \mathcal{A} f \geq 0$$

$$0 \leq \sigma \perp E - \sum_j \mathcal{E}_j(y_j) \geq 0$$

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.
- 100% emission reduction in (NZ) electricity is needlessly expensive given proportion of electricity emissions.
- Next steps: A multistage model, and its competitive equilibrium counterpart.

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.