(Multistage) risk-averse electricity capacity expansion

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Application: Planning for a net-zero carbon economy

Recommendation 1

Emissions budget levels

We recommend the Government set and meet the emissions budgets as outlined in the table below. These emissions budgets are expressed using GWP_{100} values from the IPCC's *Fifth Assessment Report (AR5)* for consistency with international obligations relating to Inventory reporting.

	2019	Emissions budget 1 (2022 – 2025)	Emissions budget 2 (2026 – 2030)	Emissions budget 3 (2031 – 2035)
All gases, net (AR5)		290 $MtCO_2e$	312 $MtCO_2e$	253 $MtCO_2e$
Annual average	78.0 $MtCO_2e$	72.4 $MtCO_2e$/yr	62.4 $MtCO_2e$/yr	50.6 $MtCO_2e$/yr

New Zealand CO_2 emission budgets (NZCCC May 31, 2021).

Electricity investment in renewable energy

1. Many countries want to grow renewable electricity capacity.
2. NZ: Climate Change Commission (CCC) sets carbon budgets to reach a net zero status by 2050.
3. This will translate to emission prices for electricity generators.
4. Principal-agent model: government policy determines emission price and generators invest in (mainly renewable) technology (see e.g. Quiroga, Sauma, and Pozo, 2019).
5. Research question: what happens when there is uncertainty and investors are risk averse?

Principal agent model in perfect, complete markets
[Ralph &Smeers 2015, Ehrenman et al 2011, P.,Ferris & Wets, 2016]

Theorem

(Risked equilibrium) If markets are competitive, convex and complete, and agents optimize using similar coherent risk measures, then partial equilibrium of the electricity market investment game is the same as the solution to a risk averse stochastic optimization problem (social planning problem).

How to deal with an incomplete market for risk.

Summary

Summary

Two-stage social planning problem
[Ferris & P., 2021]

- Social planner s minimizes a coherent risk measure ρ_s.
- Example: convex combination of expectation $\mathbb{E}$ and worst case $\mathbb{W}$ of loss distribution Z_s:

$$\rho_s(Z) = (1-\sigma)\mathbb{E}[Z_s] + \sigma\mathbb{W}[Z_s]$$

- When distribution finite, express as optimal value function.

$$\begin{aligned} \rho_s(Z) = \min \quad & \sigma\theta_s + (1-\sigma)\textstyle\sum_\omega \mathbb{P}(\omega)Z_s(\omega) \\ s.t. \quad & \theta_s \geq Z_s(\omega) \end{aligned}$$

Social planning problem example
[Kok, P., Zakeri, 2018]

$$
\begin{aligned}
SP: \quad \min \quad & \textstyle\sum_a \kappa_a x_a + \rho_s\left(\sum_{t\in\mathcal{T}} Z_s(\omega,t)\right) \\
\text{s.t.} \quad Z_s(\omega,t) \quad = \quad & \textstyle\sum_a (C_a + e_a\tau) y_a(\omega,t) \\
& + \textstyle\sum_b v_b q_b(\omega,t) - r_b(d_b(\omega,t) - q_b(\omega,t)) \\
z_a \quad \le \quad & u_a + x_a, \\
y_a(\omega,t) \quad \le \quad & \mu_a(\omega,t) z_a, \\
q_b(\omega,t) \quad \le \quad & d_b(\omega,t), \\
\textstyle\sum_b d_b(\omega,t) \quad \le \quad & \textstyle\sum_a y_a(\omega,t) + \sum_b q_b(\omega,t), \\
x, z, y, q \quad \ge \quad & 0.
\end{aligned}
$$

Summary

Generator agent (a)

Generators minimize capital cost plus risk-adjusted losses

$$
\begin{aligned}
\min \quad & \kappa_a x_a + \rho_a\left(\textstyle\sum_{t\in\mathcal{T}} Z_a(\omega,t)\right), \\
\text{s.t.} \quad Z_a(\omega,t) &= (C_a + \tau e_a - \pi(\omega,t))\, y_a(\omega,t) \\
z_a &\leq u_a + x_a, \qquad [\nu_a] \\
y_a(\omega,t) &\leq \mu_a(\omega,t) z_a, \qquad [\sigma_a(\omega,t)] \\
x_a, z, y &\geq 0.
\end{aligned}
$$

Risk measure is combination of expectation and worst case

$$Z_a(\omega, t) = (C_a + \tau e_a - \pi(\omega, t)) y_a(\omega, t)$$

$$\begin{aligned}
\min \quad & \kappa_a x_a + \alpha \theta_a + (1-\alpha) \textstyle\sum_\omega \mathbb{P}(\omega) \sum_{t \in \mathcal{T}} Z_a(\omega, t)) \\
s.t. \quad & \theta_a \geq \textstyle\sum_{t \in \mathcal{T}} Z_a(\omega, t), \qquad [\alpha \lambda_a(\omega)] \\
& z_a \leq u_a + x_a, \qquad [\nu_a] \\
& y_a(\omega, t) \leq \mu_a(\omega, t) z_a, \qquad [\sigma_a(\omega, t)] \\
& x, z, y \geq 0.
\end{aligned}$$

KKT(a): Optimality conditions for generator a

$$
\begin{array}{rcll}
1 = & \sum \lambda_a(\omega) & \perp & \theta_a, \\
0 \leq & \theta_a - Z_a(\omega) & \perp & \lambda_a(\omega) \geq 0 \\
0 \leq & u_a + x_a - z_a & \perp & \nu_a \geq 0 \\
0 \leq & \mu_a(\omega,t) z_a - y_a(\omega,t) & \perp & \sigma_a(\omega,t) \geq 0 \\
0 \leq & \kappa_a - \nu_a & \perp & x_a \geq 0 \\
0 \leq & \nu_a - \sum_\omega \sum_{t\in\mathcal{T}} \mu_a(\omega,t)\sigma_a(\omega,t) & \perp & z_a \geq 0 \\
0 \leq & \alpha\lambda_a(\omega)(C_a + \tau e_a - \pi(\omega,t)) + \sigma_a(\omega,t) & & \\
 & +(1-\alpha)\mathbb{P}(\omega)(C_a + \varepsilon\eta_a - \pi(\omega,t)) & \perp & y_a(\omega,t) \geq 0
\end{array}
$$

Buyer agent (b)

Electricity buyer (retailer) b minimizes risk-adjusted net cost of customer supply.

$$
\begin{aligned}
\min \quad & \rho_b\left(\textstyle\sum_{t\in\mathcal{T}} Z_b(\omega, t)\right), \\
\text{s.t.} \quad Z_b(\omega, t) &= (r_b + v_b - \pi(\omega, t)) \cdot q_b(\omega, t) \\
&\quad + (\pi(\omega, t) - r_b) \cdot d_b(\omega, t), \\
q_b(\omega, t) &\geq 0.
\end{aligned}
$$

Risk measure is combination of expectation and worst case

$$Z_b(\omega, t) = (r_b + v_b - \pi(\omega, t)) \cdot q_b(\omega, t) + (\pi(\omega, t) - r_b) \cdot d_b(\omega, t)$$

$$\begin{aligned} \min \quad & \beta\theta_b + (1-\beta) \textstyle\sum_{\omega} \mathbb{P}(\omega) \sum_{t \in \mathcal{T}} Z_b(\omega, t) \\ s.t. \quad & \theta_b \geq \textstyle\sum_{t \in \mathcal{T}} Z_b(\omega, t), \qquad [b\lambda_b(\omega)] \\ & q_b(\omega, t) \leq d(\omega, t), \qquad [\psi_b(\omega, t)] \\ & q_b(\omega, t) \geq 0. \end{aligned}$$

KKT(b): Optimality conditions for buyer b

$$Z_b(\omega, t) = (r_b + v_b - \pi(\omega, t)) \cdot q_b(\omega, t) + (\pi(\omega, t) - r_b) \cdot d_b(\omega, t)$$

$$\begin{array}{llll}
1 = & \sum \lambda_b(\omega) & \perp \ \theta_b, & \\
0 \leq & \theta_b - \sum_{t \in \mathcal{T}} Z_b(\omega, t) & \perp \ \lambda_b(\omega) & \geq 0 \\
0 \leq & \beta \lambda_b(\omega)(r_b + v_b - \pi(\omega, t)) + \psi_b(\omega, t) + (1-\beta)\mathbb{P}(\omega)(r_b + v_b - \pi(\omega, t)) & \perp \ q_b(\omega, t) & \geq 0 \\
0 \leq & d_b(\omega, t) - q_b(\omega, t) & \perp \ \psi_b(\omega, t) & \geq 0
\end{array}$$

MC: Market-clearing conditions

$$0 \leq \sum_a y_a(\omega, t) + \sum_b q_b(\omega, t) - \sum_b d_b(\omega, t) \quad \perp \quad \pi(\omega, t) \geq 0.$$

Principal solves optimization problem

$$
\begin{aligned}
P: \quad \min \quad & \textstyle\sum_a \kappa_a x_a + \sigma\theta_s \\
+(1-\sigma) \quad & \textstyle\sum_\omega \mathbb{P}(\omega)(\sum_a Z_a(\omega, t) + \sum_b Z_b(\omega, t)) \\
s.t. \quad & \theta_s \geq \textstyle\sum_{t\in\mathcal{T}} \sum_a Z_a(\omega) + \sum_{t\in\mathcal{T}} \sum_b Z_b(\omega) \\
& KKT(a), \qquad a \in \mathcal{A}, \\
& KKT(b), \qquad b \in \mathcal{B}, \\
& MC.
\end{aligned}
$$

Summary

Reformulate KKT conditions using binary variables

[Fortuny-Amat & McCarl, 1981]

Replace

$$0 \leq F(x,y) \perp x \geq 0$$

with

$$\begin{aligned} 0 &\leq x \leq Mz \\ 0 &\leq F(x,y) \leq M(1-z) \\ z &\in \{0,1\} \end{aligned}$$

Principal-agent problem is MIQP

- Because of bilinear terms from choosing worst-case probability distribution using multpliers, we get a mixed integer quadratic program.
- Solve MIQP using Gurobi.
- Advantage: Global optimality of MIQP enables search for multiple equilibria (Gerard et al 2018).
- Disadvantage: Big M constraints do not scale well.

Summary

Case study

Example

	Wind	Coal	Gas
Initial capacity (GW)	0	0	0
Capital costs ($/MW/h)	23.75	75.00	22.50
SRMC ($/MWh)	0.01	42.00	70.00
CO2Emission (t/MWh)	0.00	0.99	0.40

Example

Load (GW)	NI	SI	Total	Hours/day
peak	4.1	2.2	6.3	6
offpeak	2.4	1.7	4.1	12
shoulder	3.1	2	5.1	6

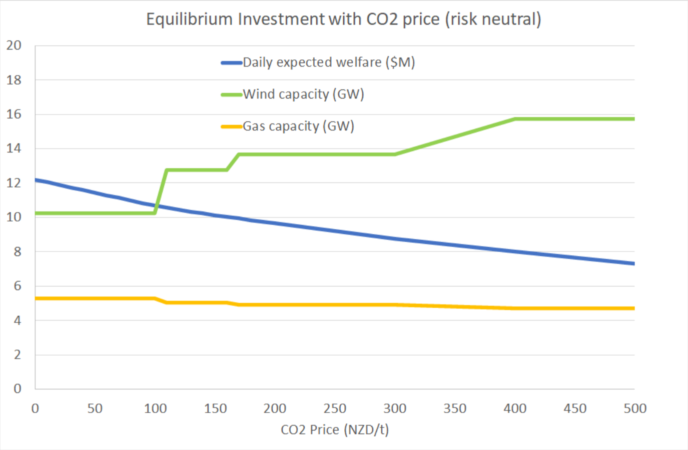
Wind load factors have three scenarios

Example

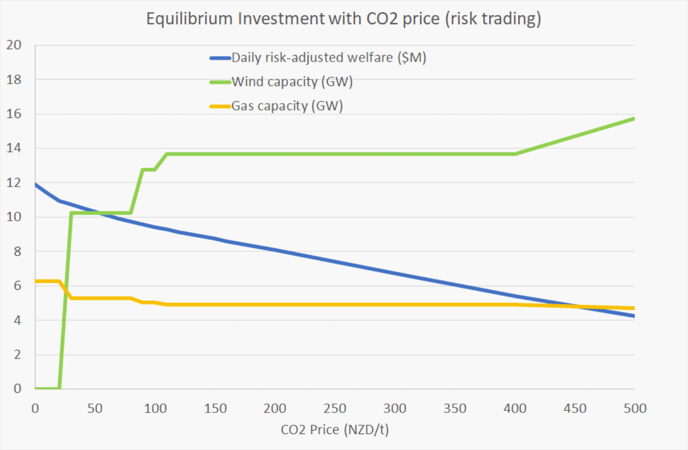
Wind load factor	Low	Medium	High
peak	0.1	0.3	0.4
offpeak	0.3	0.4	0.4
shoulder	0.2	0.3	0.4

We set retail price of electricity =\$200/MWh and VOLL=\$1000/MWh for all consumers

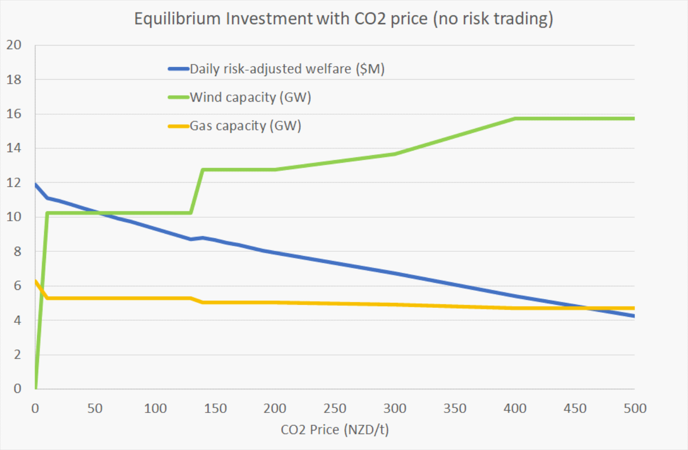
Risk neutral social plan (sigma=0)



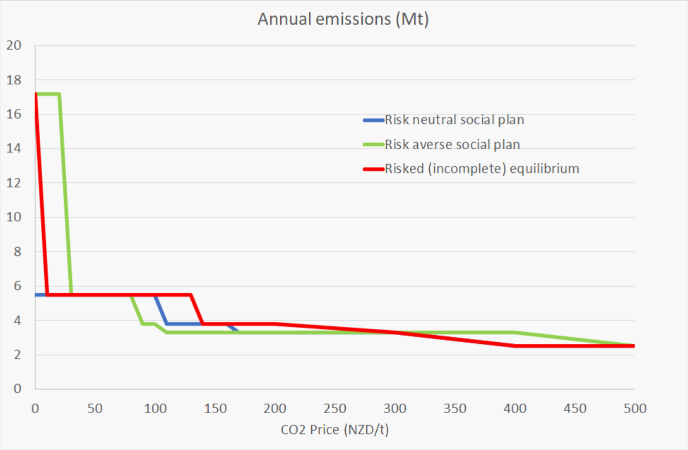
Risk averse social plan (alpha = beta = sigma = 0.5)



Risk averse equilibrium (sigma = 0.5)



Average CO2 emissions with CO2 price



In this example, CO_2 emissions decrease with carbon tax but risk trading can increase emissions.

Equilibrium solutions when $CO2$ tax = \$10/t

Solution for CO2 price = $10/t	Wind	Coal	Gas	MaxPrice	Purchaser	System
Capacity (GJ) (incomplete)	10.250	0.000	5.275	$614.05		
Capacity (GJ) (complete)	0.000	0.000	6.300	$212.70		
RA daily welfare (M) (incomplete)	$ -	$ -	$ -		$ 1.64	$ 11.13
RA daily welfare (M) (complete)	$ -	$ -	$ -		$ 11.42	$ 11.42

- Incomplete case: in low-wind peak load scenario, high prices pay for wind capacity. Lack of risk trading between generators and purchaser leads to low purchaser welfare.
- Complete case: Welfare is enhanced by risk trading between gas generator and purchaser but more gas generation increases emissions from 5.5Mt p.a. to 17.2 Mt p.a.

Conclusion

- Emission budgets stimulate renewable investment through carbon prices.
- Investment might be socially suboptimal if risk averse agents cannot trade risk.
- Competitive equilibrium in incomplete risk market might achieve CO_2 budget at a lower carbon price.
- Next talk: assume there is enough risk trading to deliver social optimum and plan accordingly.

Conclusion

THE END

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