Electricity Markets with Hydro

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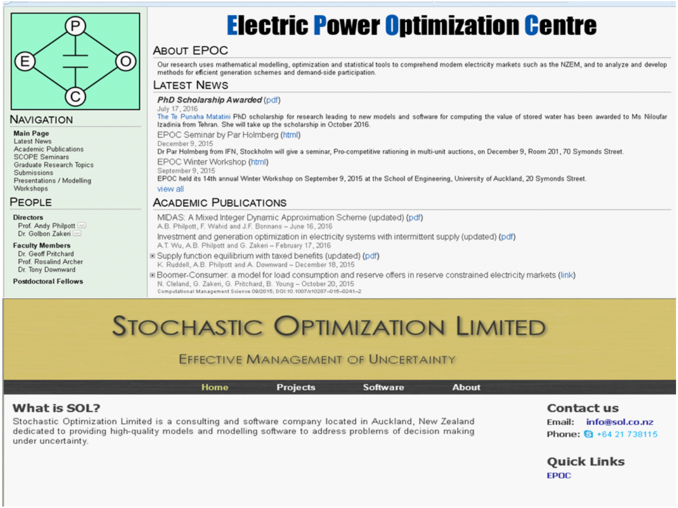
Talk at UFSC, Florianopolis, July 20, 2016.

Who am I?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Our research uses mathematical modelling, optimization and statistical tools to comprehend modern electricity markets such as the NZEM, and to analyze and develop methods for efficient generation schemes and demand-side participation.
LATEST NEWS
PhD Scholarship Awarded (pdf)
July 17, 2016
The Te Punaha Matatini PhD scholarship for research leading to new models and software for computing the value of stored water has been awarded to Ms Niloufar Izadinia from Tehran. She will take up the scholarship in October 2016.
EPOC Seminar by Par Holmberg (html)
December 9, 2015
Dr Par Holmberg from IFN, Stockholm will give a seminar, Pro-competitive rationing in multi-unit auctions, on December 9, Room 201, 70 Symonds Street.
EPOC Winter Workshop (html)
September 9, 2015
EPOC held its 14th annual Winter Workshop on September 9, 2015 at the School of Engineering, University of Auckland, 20 Symonds Street.
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ACADEMIC PUBLICATIONS
MIDAS: A Mixed Integer Dynamic Approximation Scheme (updated) (pdf)
A.B. Philpott, F. Wahid and J.F. Bonnans – June 16, 2016
Investment and generation optimization in electricity systems with intermittent supply (updated) (pdf)
A.T. Wu, A.B. Philpott and G. Zakeri – February 17, 2016
Supply function equilibrium with taxed benefits (updated) (pdf)
K. Ruddell, A.B. Philpott and A. Downward – December 18, 2015
Boomer-Consumer: a model for load consumption and reserve offers in reserve constrained electricity markets (link)
N. Cleland, G. Zakeri, G. Pritchard, B. Young – October 20, 2015
Computational Management Science 09/2015; DOI:10.1007/s10287-015-0241-2
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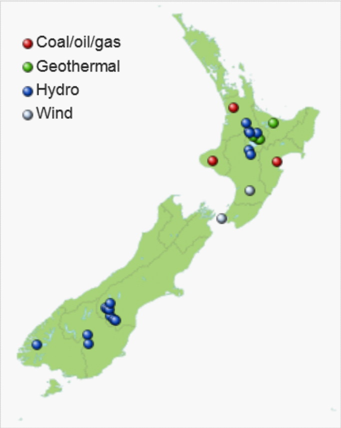
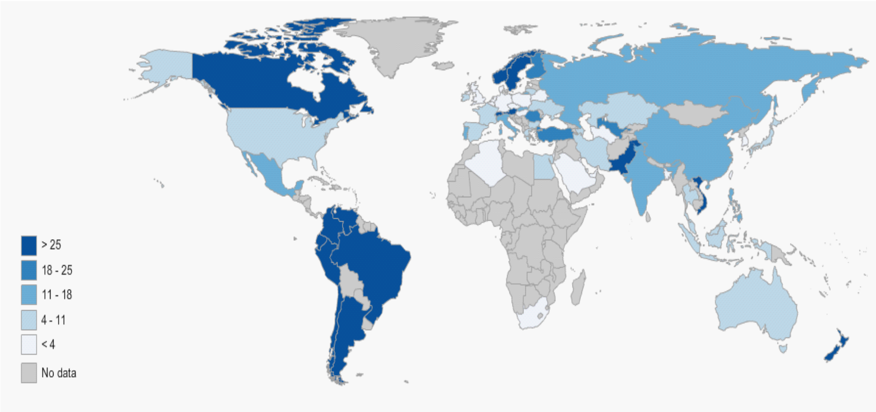
New Zealand cares about hydroelectricity



Location of major power stations (100 MW or over) in New Zealand.

Who else cares about hydro?



2012 world hydro electricity generation as a percentage of national total
(Source: BP Statistical Review of World Energy, 2013)

The New Zealand wholesale electricity market

- -1987: New Zealand Electricity Department (NZED).
- 1987: Electricity Corporation of New Zealand (ECNZ).
- 1993: Electricity Market Company (later called M-Co) established for the design of a wholesale electricity market.
- 1994: ISO Transpower separated from ECNZ and established as a stand-alone state-owned enterprise.
- 1996: An interim wholesale market is put in place allowing ECNZ and Contact to begin competing.
- April 1996: Contact Energy commenced operations.
- October 1996: The reformed wholesale electricity market (NZEM) begins trading.
- 1998: Electricity Reform Act 1998:

  Contact Energy privatized

  ECNZ becomes three competing state-owned enterprises.

  Energy companies split their retail and lines businesses.

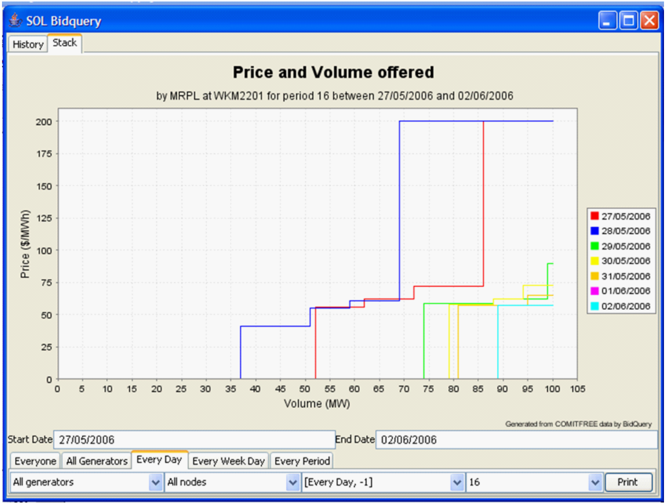
The New Zealand wholesale electricity market

- 2000: Ministerial Inquiry into electricity industry
- November 2000: Electricity Governance Establishment Project.
- 2003: Rules developed by EGEP fail to gain sufficient support in industry referendum.
- 2004: Electricity Commission takes over control of NZEM.
- 2008: Energy crisis and Wolak report.
- 2009: Ministerial Review leads to reforms with 29 measures.
- 2010: Electricity Authority takes over from Electricity Commission.

How does NZ wholesale electricity spot market work?

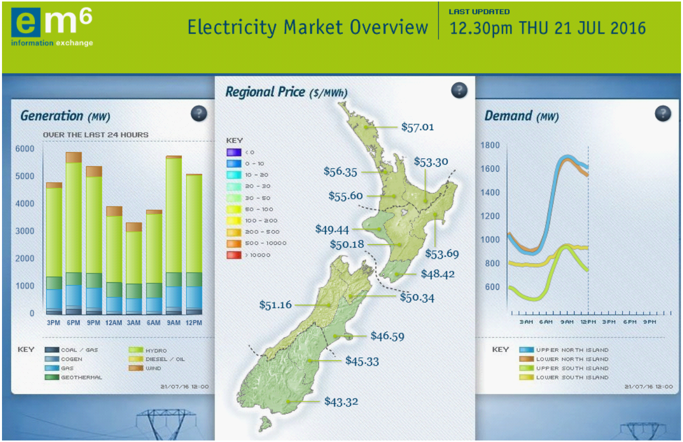
- Every trading period (30 minutes), generators submit to the ISO piecewise constant supply functions with at most 5 steps.
- The ISO solves a single period economic dispatch model to compute dispatch and prices (dual variables) for 285 nodes. The ISO also computes a sequence of provisional dispatches and prices for future trading periods using indicative offers and forecast demand, and makes the provisional prices and dispatches public.
- The generators plan the next set of offers to make based on observed dispatch, price, and the observed provisional outcomes.
- In theory, perfectly competitive generators will offer supply functions that approximate their marginal cost of production.

What do supply functions look like?

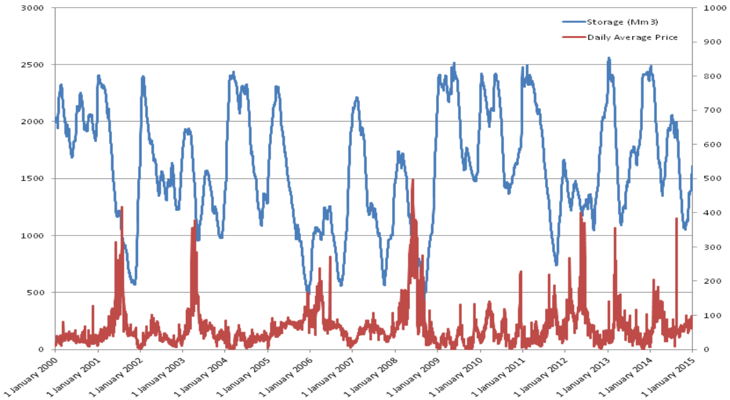


Energy offers from hydro generator at 8am on consecutive days in 2006.

New Zealand electricity prices July 21, 2016



New Zealand electricity prices and reservoir levels



New Zealand electricity prices and reservoir levels over last 15 years.

What is this talk about?

- Market design for hydro-dominated electricity systems.
- Compare Colombia and New Zealand
- Different approaches to security of energy supply.
- Contrast:

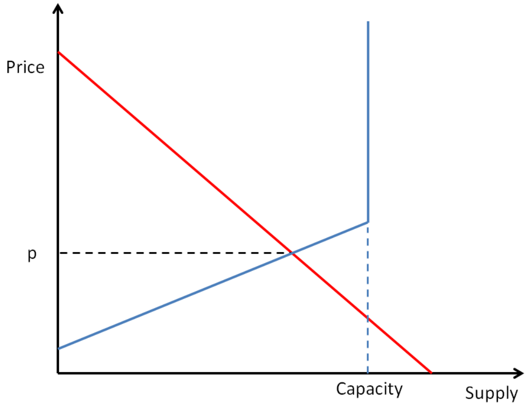
  Colombia: auction of firm energy obligations mirrors capacity market;

  New Zealand: mirrors energy-only market.
- Pros and cons of these.
- I give a personal view, that is not necessarily shared by others in NZ.

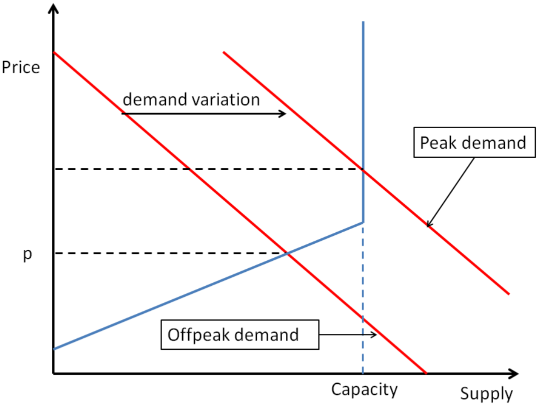
Summary

Summary

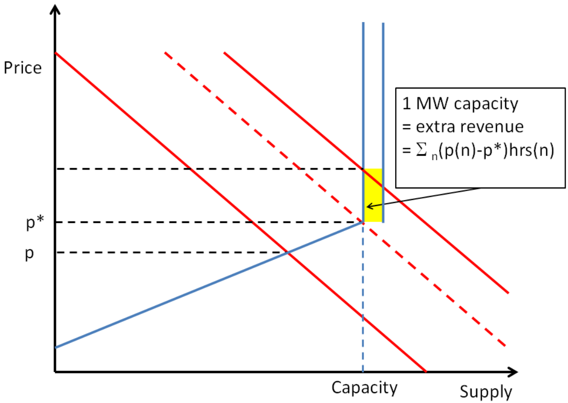
Economics of competitive equilibrium
(von der Fehr & Harbord, 1995)



Economics of competitive equilibrium
(von der Fehr & Harbord, 1995)



Economics of competitive equilibrium
(von der Fehr & Harbord, 1995)

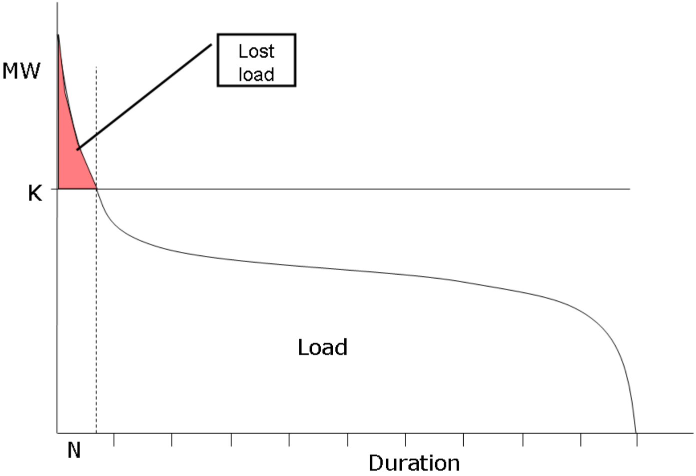


The theory according to Steven Stoft
(Power System Economics, 2002, p 15)

There are two demand-side flaws in electricity markets:

1. Lack of real-time metering and billing.
    - No customer response to high prices in real time.
2. Lack of real-time control of power flow to specific customers.
    - No market for reliability.

Excess inelastic demand leads to rationed supply



The installed capacity K is not sufficient to meet demand in N trading periods per year. There is "lost load".

The value of lost load (VOLL)

Consumers cannot respond to high prices in real time. If prices are very high then consumers buy when they would have chosen otherwise. It is welfare enhancing to disconnect them at the threshhold price

VOLL= "value of lost load"

VOLL price caps are optimal

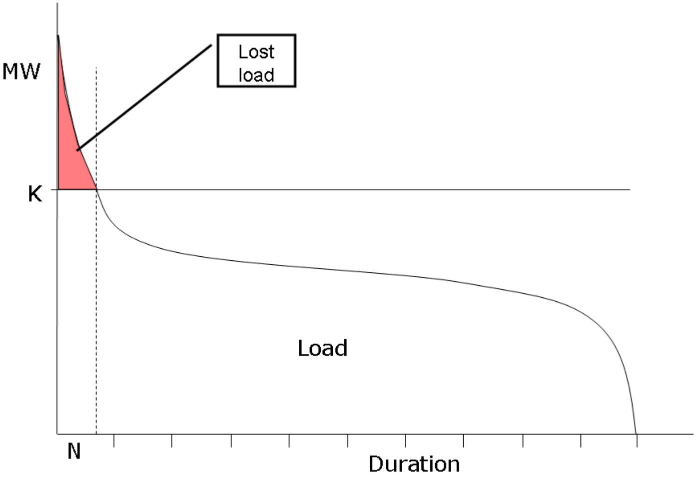
If it were possible to estimate VOLL accurately then setting a price cap P at VOLL would be a long-run equilibrium. Suppose demand exceeds plant capacity K for N hours per year. Let

$$\begin{aligned} f &= \text{the fuel cost (SRMC) at capacity (\$/MWh);} \\ C_K &= \text{the risk-adjusted annual amortized} \\ & \quad\ \text{capital cost of a peaking plant (\$/MW);} \end{aligned}$$

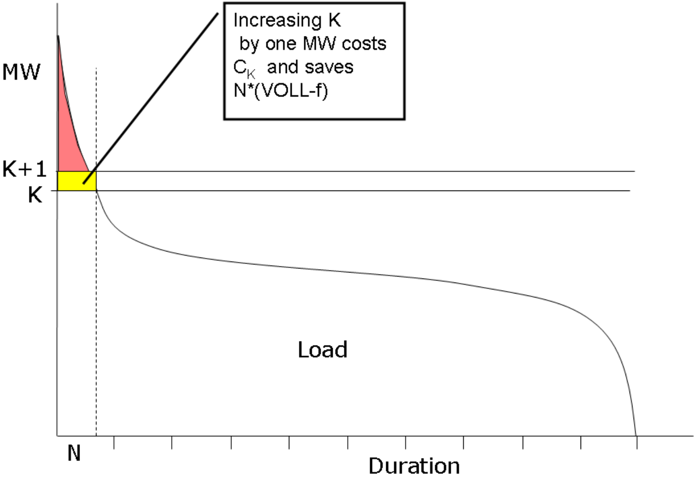
Then we get a fundamental equilibrium condition:

$$N * (P - f) = C_K$$

VOLL price caps are optimal



VOLL price caps are optimal



Choosing a cap value P determines system reliability

If the regulator sets a price cap P that is not equal to VOLL then in the absence of other policy settings, it is making a long-run reliability decision. The value P determines number of outage periods

$$N = \frac{C_K}{P - f}$$

1. If P is high then N (number of shortages) in equilibrium will be small. Price peaks will be infrequent but enormous. High P incentivizes market power.
2. If P is low then alleviates market power but N (number of shortages) in equilibrium needs to be large for market entry. Large N is bad if consumers wish to have more reliability. With small N there is missing money. Either increase P or make capacity payment to bring N down.
3. Both approaches affected by lumpiness in supply.

Possible solutions to the missing money problem

$$N = \frac{C_K}{P - f}$$

1. Have no cap at all and rely on other forces (e.g. market entry or demand response) to limit market power.
2. Choose a high cap P (or no cap) and use monitoring to control market power.
3. Choose a low cap P and buy capacity in a separate market (*capacity market*).
4. Choose a high cap P and require a reserve margin at dispatch, so prices hit P whenever the margin is invaded.

What do the experts say?

Bill Hogan: Advocates energy only markets with a reserve margin.
Peter Cramton: Lack of demand response at margin and low prices require a capacity market.
David Harbord: Capacity market design needs care. Market power exercise in descending clock auctions.
Thomas-Olivier Leautier: Growing demand elasticity improves performance of energy-only markets. In two-stage Cournot equilibrium models, energy-only markets get closer to optimal investments than capacity markets.

Summary

Markets with stored hydro are different

- Thermal plant are built to meet peak capacity requirements.
- Water for hydro generation is free, so stored water has no value if there is no risk of shortage.
- Could apply equilibrium arguments for hydro generation capacity assuming SRMC=0.
- In practice there is always some risk of water shortage.

(This results in a marginal water value that represents the future opportunity cost of releasing the water now for generation.)

- Thermal plant need to be paid to be available to alleviate these shortages.

Cramton and Stoft firm energy market

- Colombia suffers from shortages in El Nino events.
- ISO seeks to procure firm energy obligations that guarantee enough energy to get through such a year without shortage.
- Shortages signalled when spot price hits scarcity price P.

What is a firm energy obligation?

- Each generator is certified for

  its nameplate capacity (maximum output rate), and
  its firm energy
  (average energy output rate in worst inflow year).
- Example for a thermal plant would be 1000MW, 900MW
- Example for a hydro plant would be 100MW, 30MW.
- ISO procures enough firm energy to cover demand duration curve in driest year.
- Firm energy called on only when price exceeds P.

What is a firm energy obligation?

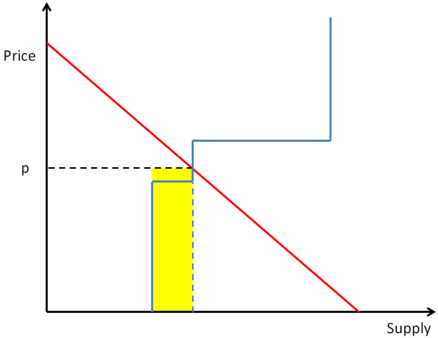
- If a generator sells QMWh of firm energy in the auction, then this obliges it to supplying the load pro rata up to Q when the price exceeds P.
- Hydro generators have to supply it according to a load-following schedule.
- Base-load generators have to supply it according to a flat schedule.
- Generators are paid \$$P$ per MWh for firm energy supplied
- If spot price $p > P$ and generator supplies q it receives extra payment

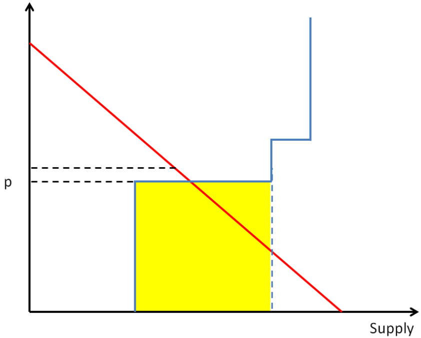
$$p(q-Q)_+ - (p-P)(Q-q)_+$$

The auction for firm energy

- ISO runs a descending clock auction to procure firm energy obligations.
- ISO pays an option price for each MWh of obligation procured.
- Similar to auctions in capacity markets (New England, UK).
- These have some desirable properties when lots of bidders and goods are divisible, but susceptible to market power exercise when bidders are pivotal.
- Solution: randomize demand and/or hold a secondary uniform-price sealed-bid auction.

Pivotal strategy

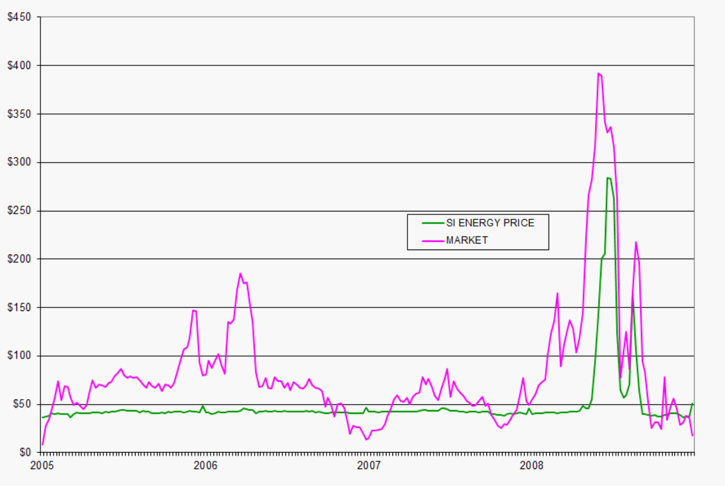




New Zealand uses light-handed regulation

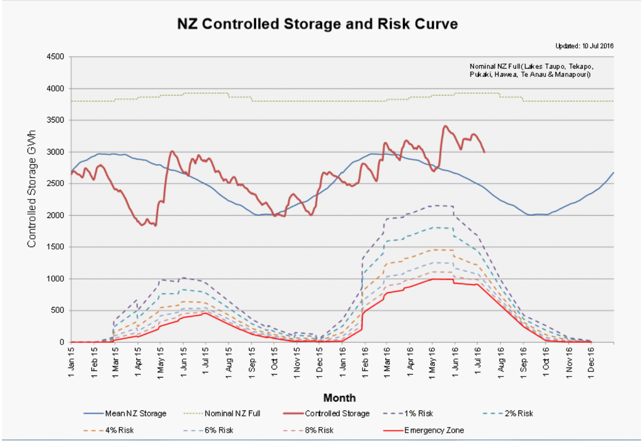
- Spot market gives prices that reflect agent's views of marginal cost (for thermal fuel or opportunity cost of water).
- Water for each hydro agent is valued by the agent using expectations of future prices, and their own inflow model.
- If competition is imperfect then this is highly circular. High future payoff expectations of imperfect competition give high current marginal water values, so current system marginal cost can be argued to be high.
- Future price expectations under uncertainty drive prices higher than risk-neutral perfectly competitive levels.
- But large generators are vertically integrated which reduces market-power incentive.

South Island prices



South Island weekly average prices in market (pink) and counterfactual (green)

Shortage risk: ISO publishes hydro risk curves



Source: www.systemoperator.co.nz/sites/default/files/bulk-upload/documents/HydroRiskCurveNZ.pdf. Savings campaign called when 10% risk curve is reached.

Shortage risk

- ISO calls a savings campaign when 10% risk invaded. Retailers compensate all customers at $10.50 per week.
- No intervention in the market since 2008, even though dry years. Low demand (Christchurch, GFC) and big geothermal and wind investments have suppressed prices.
- So no recent tests of security of supply policy.
- Recent explosion in numbers of small retail companies in the market, exploiting surplus energy capacity. Welcome retail competition but exposed to dry-year risk in coming years.
- So watch this space....

Summary

Perfect competition and social planning

- Under some restrictive assumptions...
- perfectly competitive partial equilibrium optimizes a social planning problem...

  ...so in principle we can find a market equilibrium by solving a suitable optimization model.
- Assumptions: price-taking, completeness, convexity

Perfect competition and workable competition

- Perfectly competitive partial equilibrium* optimizes a social planning problem...

  ...so in principle we can find an equilibrium by solving a suitable optimization model.

- Perfect competition in electricity markets does not exist, so regulators aim for workable competition. Nevertheless, perfectly competitive models are very useful

  as benchmarks;
  as indicators of market inefficiencies.

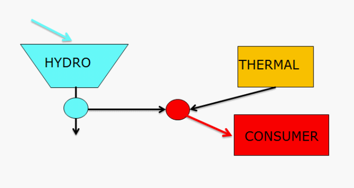
*A partial equilibrium is one which is based on only a restricted range of data, a standard example is price of a single product, the prices of all other products being held fixed during the analysis.

Equilibrium and optimization: single period

$$\text{DSP: min} \quad \sum_{j\in\mathcal{T}} f_j(v_j) - \sum_{c\in\mathcal{C}} c_c(d_c)$$

$$\text{s.t.} \quad \sum_{i\in\mathcal{H}} g_i(u_i) + \sum_{j\in\mathcal{T}} v_j \geq \sum_{c\in\mathcal{C}} d_c, \qquad [p]$$

$$u \in \mathcal{U}, \quad v \in \mathcal{V}.$$



u *hydro* water flow rate
v *thermal* generation
d_c *demand*

Social plan = risk neutral perfectly competitive equilibrium

To minimize Lagrangian for DSP with Lagrange multiplier p we solve each agent problem separately.

$$\begin{aligned} \mathrm{HP}(i)\text{:max} \quad & pg_i(u_i) \\ \text{s.t.} \quad & u_i \in \mathcal{U}_i. \end{aligned}$$

$$\begin{aligned} \mathrm{TP}(j)\text{: max} \quad & pv_j - f_j(v_j) \\ \text{s.t.} \quad & v_j \in \mathcal{V}_j. \end{aligned}$$

$$\mathrm{CP}(c)\text{: max} \quad c_c(d_c) - pd_c.$$

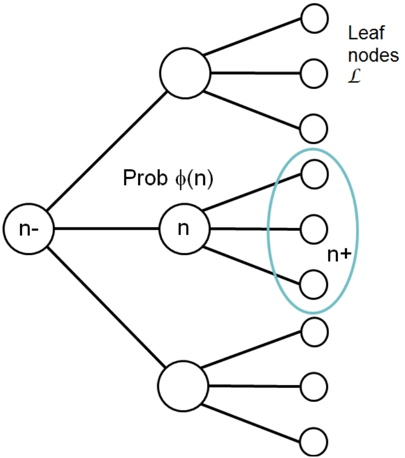
Social plan = perfectly competitive equilibrium

This defines a perfectly competitive equilibrium defined by the individual optimality conditions and market clearing condition.

$$
\begin{aligned}
\text{CE:} \quad & u_i \in \arg\max \mathrm{HP}(i), \\
& v_j \in \arg\max \mathrm{TP}(j), \\
& d_c \in \arg\max \mathrm{CP}(c), \\
& 0 \leq \textstyle\sum_{i\in\mathcal{H}} g_i(u_i) + \sum_{j\in\mathcal{T}} v_j - \sum_{c\in\mathcal{C}} d_c \perp p \geq 0.
\end{aligned}
$$

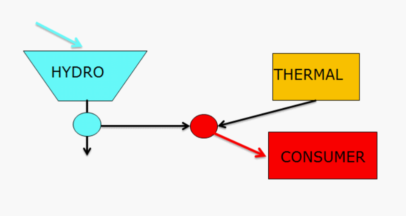
Solutions to CE can be computed in GAMS/EMP as a MOPEC (Ferris, Dirkse, Jagla, Meeraus, 2013) but easier to solve DSP when they give the same answer.

Uncertain inflows: consider a scenario tree



Each node n spans a period (week) and corresponds to a realization $\omega(n)$ of reservoir inflows in that period.

Social plan minimizes total expected system disbenefit



$$\text{SSP: min} \quad \sum_{n\in\mathcal{N}} \phi(n) \left(\sum_{j\in\mathcal{T}} f_j(v_j(n)) - \sum_{c\in\mathcal{C}} c_c(d_c(n))\right) + \sum_{n\in\mathcal{L}} \phi(n) \sum_{i\in\mathcal{H}} Q_i(x_i(n))$$

$$\text{s.t.} \quad \sum_{i\in\mathcal{H}} g_i(u_i(n)) + \sum_{j\in\mathcal{T}} v_j(n) \geq \sum_{c\in\mathcal{C}} d_c(n), \qquad n \in \mathcal{N},$$

$$x_i(n) = x_i(n-) - u_i(n) - s_i(n) + \omega_i(n), \qquad i \in \mathcal{H}, n \in \mathcal{N},$$

$$u(n) \in \mathcal{U}, \quad v(n) \in \mathcal{V}, \quad x(n) \in \mathcal{X}, \quad s(n) \in \mathcal{S}.$$

Social plan = risk neutral perfectly competitive equilibrium

To minimize Lagrangian for social plan with Lagrange multipliers $\phi(n)p(n)$ we solve each agent problem separately.

$$\begin{array}{rll} \mathrm{HP}(i):\max & \sum_{n\in\mathcal{N}}\phi(n)p(n)g_i(u_i(n)) - \sum_{n\in\mathcal{L}}\phi(n)Q_i(x_i(n)) & \\ \text{s.t.} & x_i(n) = x_i(n-) - u_i(n) - s_i(n) + \omega_i(n), & n\in\mathcal{N}, \\ & u_i(n)\in\mathcal{U}_i, \quad x_i(n)\in\mathcal{X}_i, \quad s_i(n)\in\mathcal{S}_i. & \end{array}$$

$$\begin{array}{rl} \mathrm{TP}(j):\ \max & \sum_{n\in\mathcal{N}}\phi(n)(p(n)v_j(n) - f_j(v_j(n))) \\ \text{s.t.} & v_j(n)\in\mathcal{V}_j. \end{array}$$

$$\mathrm{CP}(c):\ \max \quad \sum_{n\in\mathcal{N}}\phi(n)\left(c_c(d_c(n)) - p(n)d_c(n)\right).$$

Social plan = perfectly competitive equilibrium

This defines a perfectly competitive equilibrium defined by the individual optimality conditions and market clearing condition.

$$\text{CE:} \quad u_i, x_i, s_i \in \arg\max \text{HP}(i),$$

$$v_j(n) \in \arg\max \text{TP}(j),$$

$$d_c(n) \in \arg\max \text{CP}(c),$$

$$0 \leq \sum_{i \in \mathcal{H}} g_i(u_i(n)) + \sum_{j \in \mathcal{T}} v_j(n) - \sum_{c \in \mathcal{C}} d_c(n) \perp p(n) \geq 0.$$

Potential incompleteness of the hydro model

Our model above was derived assuming a single hydro agent. It assumes

- all hydro generating stations are operated by a single agent;
- a single future value function $Q_i(x)$ for this agent/social planner.

With competing hydro agents, for separability we will require

- a future value function for the social planner that is the sum of individual hydro agent's values or a decision horizon long enough to discount the dependence at $n \in \mathcal{L}$ away;
- prices to enable efficient transfer of water between competing agents on a river chain (Lino et al, 2003).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Tauranga
Rotorua
Palmerston North
Wellington
Nelson
New Zealand
Christchurch
Queenstown
Dunedin
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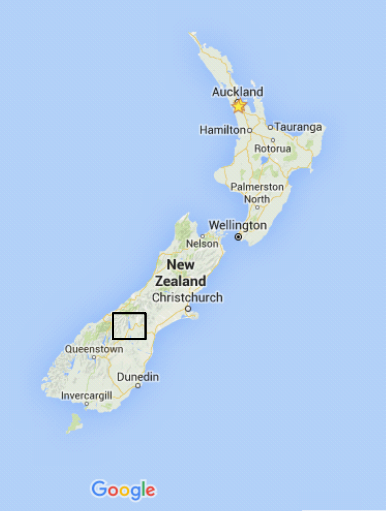
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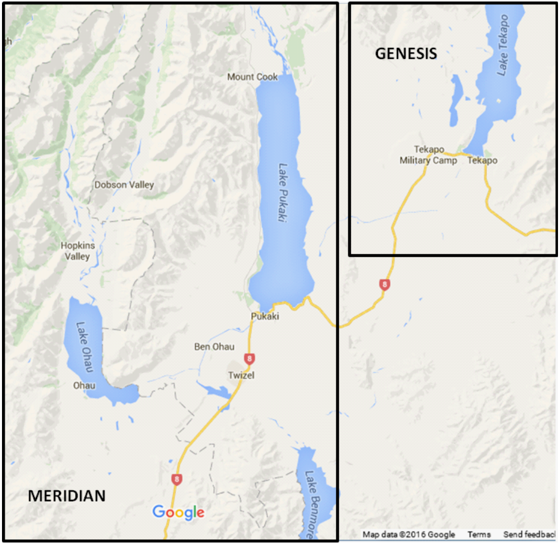
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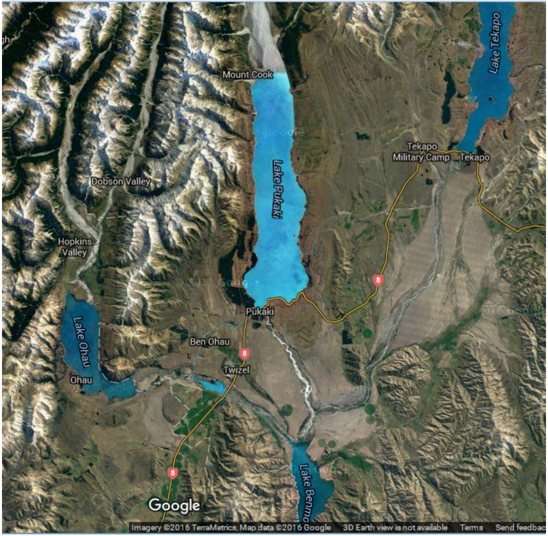
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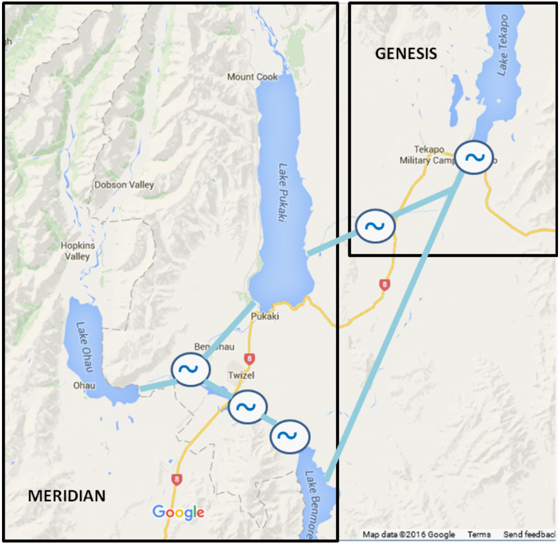
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Water transfer agreement

5.2 WATER MANAGEMENT AGREEMENT

Genesis Energy and Meridian Energy hold resource consents to take, transfer, discharge and use water via interconnected lakes, rivers and canals throughout the Waitaki River Catchment for the purpose of electricity generation.

A Water Management Agreement (WMA) between Genesis Energy and Meridian Energy was reached as part of the sale and purchase of the Tekapo Power Scheme to define the operational inter-relationships that exist between the two companies in the Waitaki Catchment.

5.2.1 THE PUKAKI SUPPLY FLOW

Under the WMA between Genesis Energy and Meridian Energy, Genesis Energy is required to supply Lake Pukaki with a pre-defined minimum volume of water each month. Genesis Energy is also required to contribute to a Fish and Game Minimum Flow during the months of June to September. However, during the reporting preiod, no additional flow was required from Genesis Energy.

Source: Tekapo Power Scheme: Environmental Report 2012-2013. Genesis Energy Limited.

Water transfer prices

- Ideally water should be traded between agents.
- If water cannot be traded between different agents on a river chain then there will be inefficiencies. The downstream agent might be prepared to pay the upstream agent to release more (above his otherwise optimal operating level).
- Without this incentive the socially optimal level of water release is not obtained.

Competitive equilibrium under risk aversion: the bad news

- What risk-adjusted plan should a social planner adopt? Whose risk are they reducing?
- Suppose agents are risk averse, but regard bad events differently.
- A hydro plant faces risk when inflows are low and a thermal plant faces risk of being idle in high inflow periods.
- Here in general a competitive equilibrium corresponds to no risk-adjusted social plan.
- The bad news:
    1. Planned solutions no longer can be claimed to be market-like.
    2. Optimization models a poor benchmark for perfectly competitive markets.

Competitive equilibrium under risk aversion: the good news

- If risk markets are complete, and risk measures coherent and time-consistent, then a risk-adjusted social plan corresponds to a competitive equilibrium under risk.
- Completeness ensured by trades available in every risk. But sometimes only need some instruments to get close to completeness.
- The good news if markets (nearly) complete:
  1. Planned solutions can be claimed to be market-like.
  2. Optimization models a reasonable benchmark for perfectly competitive markets.

Examples of risk trading

- Contract for differences traded between a generator and a retailer reduces risk to both.
- Vertical integration between generator and retailer reduces risk even further.
- A hydro plant with inflow risk can trade risk with a thermal plant that has a risk of being idle in high inflow periods.
- Example: option contract with high exercise price P sold by thermal agent. When spot price exceeds P the thermal plant delivers an agreed amount of energy at price P for sale by hydro agent.

New Zealand example of risk trading

In October 2009, Meridian negotiated a swaption contract with Genesis, which operates to 2014. The terms state that Meridian is to pay Genesis a fixed premium of $2.6 million per month for the right to exercise an option during the winter period (April to October) at a fixed price.

New Zealand example of risk trading

'SWAPTION' AGREEMENT

In July 2014, Genesis Energy signed a 'swaption' electricity hedge contract to provide dry-year cover for Meridian Energy for four years from 1 January 2015. The 150MW swaption followed on from a previous agreement between Genesis Energy and Meridian Energy for 200MW, which expired in October 2014.

Source: www.genesisenergy.co.nz 2015InterimReport.pdf

New Zealand example of risk trading

Genesis to close last two coal-fired power units at Huntly

JAMES WEIR
Last updated 17:29, August 6 2015

RORY O'SULLIVAN/Stuff.co.nz

Prime Minister John Key is unsurprised by the news that Genesis Energy are to close the two remaining coal-fired units at Huntly power station.

Stuff.co.nz , August 6, 2015

New Zealand example of risk trading

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meridian

Meridian Energy signs swaption contract with Genesis Energy

28 April 2016 INVESTOR NEWS MEDIA RELEASES

Meridian Energy has signed a four year swaption contract with Genesis Energy to replace its current arrangement which expires on 31 December 2018.

The new agreement begins on 1 January 2019 and ends on 31 December 2022. The structure continues to allow for 100MW to be available year round, with an additional 50MW available from 1 April to 31 October in each year of the contract.

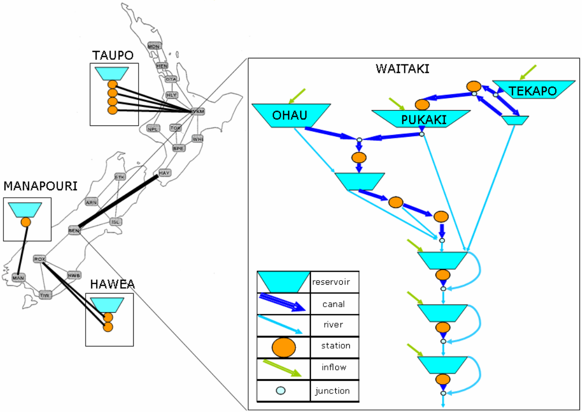
Source: www.meridianenergy.co.nz, April 28, 2016.

Summary

EPOC optimization models

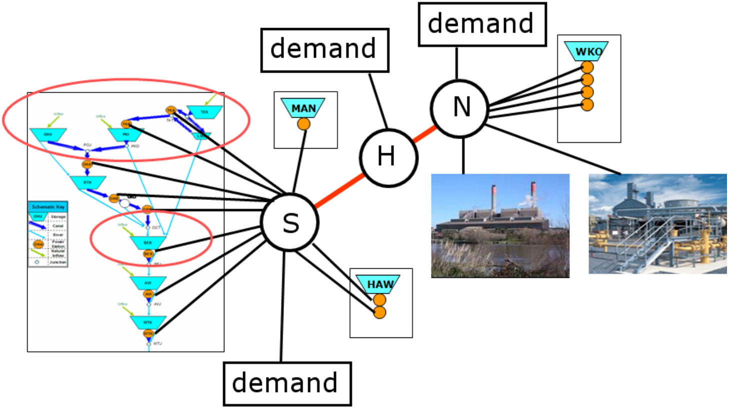
vSPD	285 node DC-Load flow model of the New Zealand wholesale electricity market. This is a GAMS version of SPD, the dispatch system used by the ISO. Given the same inputs, it yields identical dispatch and prices.
DOASA	SDDP model of the New Zealand electricity system, using an aggregated transmission network.

The main hydro catchments in New Zealand



Approximate network representation of New Zealand electricity network showing main hydro-electricity generators.

The DOASA model



New Zealand model has seven state variables corresponding to seven storage reservoirs.

Shortage Costs

Energy deficit in any stage is met by load shedding at an increasing shortage cost in three tranches. This is equivalent to having three dummy thermal plant at each location with capacities equal to 5% of load, 5% of load and 90% of load, for each load sector, and costs as follows

	Up to 5%	Up to 10%	VOLL	North Is	South Is
Industrial	$1,000	$2,000	$10,000	0.34	0.58
Commercial	$2,000	$4,000	$10,000	0.27	0.15
Residential	$2,000	$4,000	$10,000	0.39	0.27

Load reduction costs (NZD/MWh) and proportions of load that is industrial, commercial, and residential in each island.

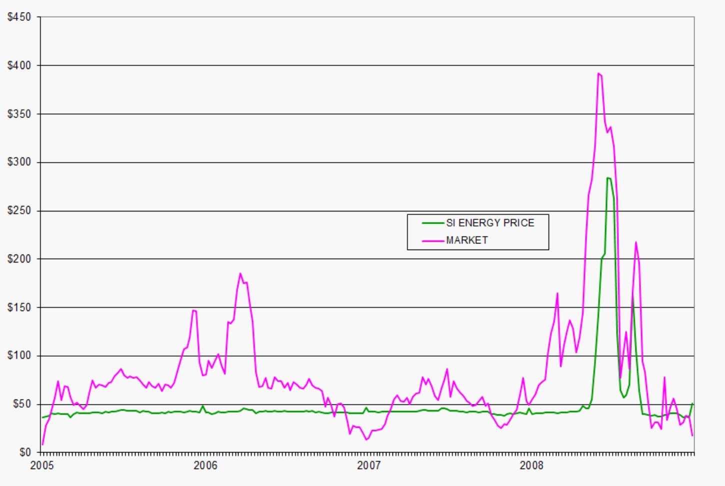
Modelling assumptions and caveats

- No spinning reserve;
- No extra costs for SRMC apart from fuel, and no fuel take-or-pay contracts or supply constraints;
- No snowmelt model or coal stockpiles;
- No contracting;
- Outages modelled using POCP database;
- 300 cuts per solve;
- Rolling horizon with resolve every 4 weeks.

South Island storage

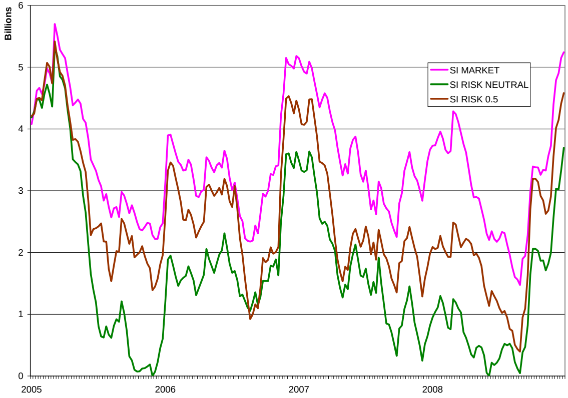
Simulated and actual South Island storage trajectories in market (pink) and counterfactual (green) 2005-2008.

South Island prices



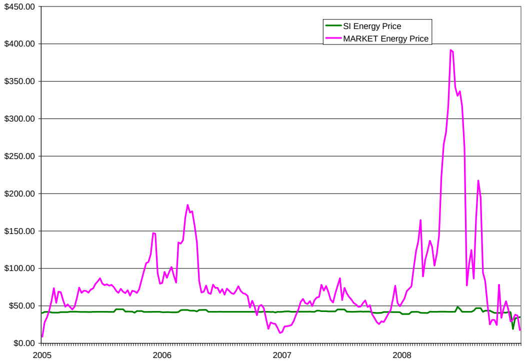
South Island weekly average prices in market (pink) and counterfactual (green)

Risk-averse storage trajectories



South Island storage trajectories for varying levels of risk aversion.

Risk-averse average prices



Weekly average South Island prices from risk averse model with $\lambda = 0.5$ (green) compared with historical Benmore prices (pink).

The change in fuel cost

	Annual thermal fuel cost ($M)		
	MARKET	λ=0	λ=0.5
2005	451.79	349.27	377.99
2006	490.99	444.62	432.03
2007	492.51	441.56	447.70
2008	508.49	435.27	424.19

Annual fuel cost for different levels of risk aversion. The risk neutral solution ($\lambda = 0$) incurs load shedding cost of $95M in 2008. The risk-averse solution ($\lambda = 0.5$) incurs no load shedding.

Conclusions

- El Nino effects have been less dramatic in New Zealand than South America. Dry winter shortage risk virtually ignored for last 8 years.
- Competitive equilibria need not be welfare maximizing. Suboptimality in many examples is not shown to be an artifact of imperfect competition, but of incompleteness in the market design.
- Including trade in specific instruments in the equilibrium model completes the market, and recovers the social optimum.
- The extent to which we complete the market will depend on transaction costs.
- Benchmarking the main use of SDDP-type models in the NZEM.

Summary

This is the end

THE END

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