# Price Formation with 100% Renewables

# Problem Definition

The opinions and conclusions in this presentation are entirely the views of Energy Link and do not in any way represent the views or opinions of any parties for whom Energy Link has undertaken work that may be presented, directly or indirectly, herein.

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# Outline

1. Our experience so far and our conclusions
2. Water values
3. 100% renewables without large-scale storage
4. 100% renewables with large-scale storage
5. The Price Formation Problem
6. Market power issues
7. A possible solution
8. Cost recovery for large-scale storage systems
9. Can the market deliver?

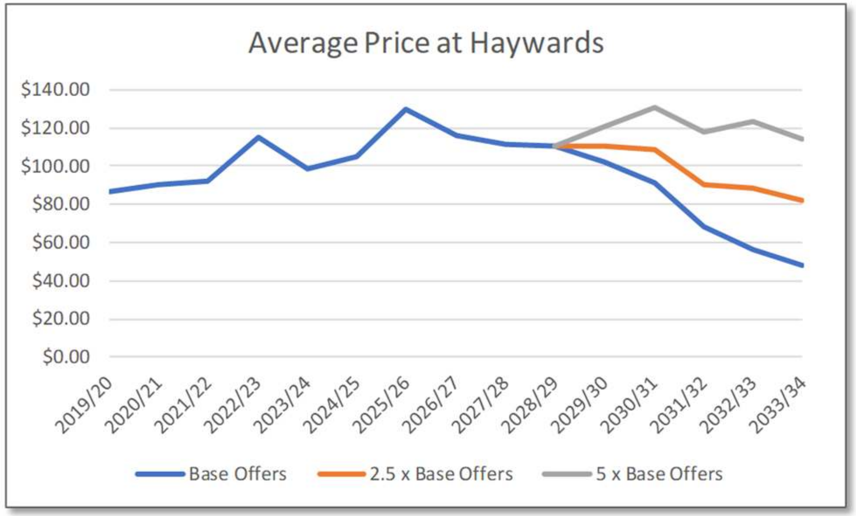
# Energy Link's Experience

- Our own interest is three-fold:
  - ➢ where will spot prices go in future?
  - ➢ will the market support new investment in future?
  - ➢ how quickly will the market get to 100% renewables?
    - this may resolve as the NZ Battery project proceeds

- Two key questions along the way are:
  - ➢ can the market serve demand without large-scale storage system(s) (LSSS)?
  - ➢ what happens to average prices and price distributions as we approach 100% renewables?

# Energy Link - High Renewables & ICCC

- Energy Link's High Renewables project (HRP) started in 2016 and results first included in our April 2017 Price Path
  - ➢ up to 99.98% renewables in 2035
  - ➢ HRP January 2019
    - price elasticity w.r.t. peaker offers start to fall after 90% is reached, and peakers have to raise offer prices to cover costs
    - windfarm capacity factors fall below theoretical levels from 96%




- ICCC base case 100% renewables 2018/19
  - ➢ over-build required, modest amounts of short-term storage (BESS), DSR[1] and SLR[2] dispatched, but these cause high prices which help to support investmentwindfarm capacity factors fall after 96% renewables is reached

| Annual Results Averaged Over 87 Inflows | BAU | 96.0% | 98.0% | 99.0% | 100.0% |
|---|---|---|---|---|---|
| DSR (MWh) | 39 | 3,959 | 4,713 | 4,952 | 8,191 |
| Non_Supply NI (MWh) | 0 | 536 | 722 | 832 | 3,707 |
| Non_Supply_SI (MWh) | 0 | 8 | 20 | 19 | 245 |

1. *Demand side response in tranches from $2,000 to $8,000*
2. *Supply of last resort (including non-supply at $10,000)*

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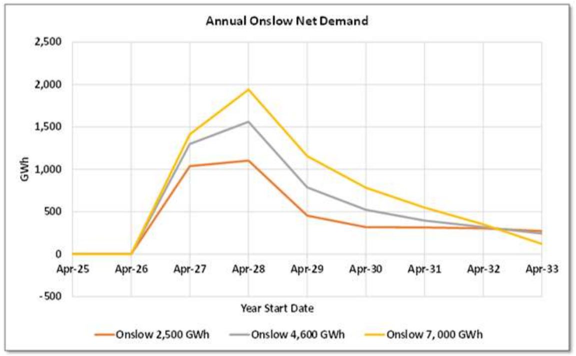
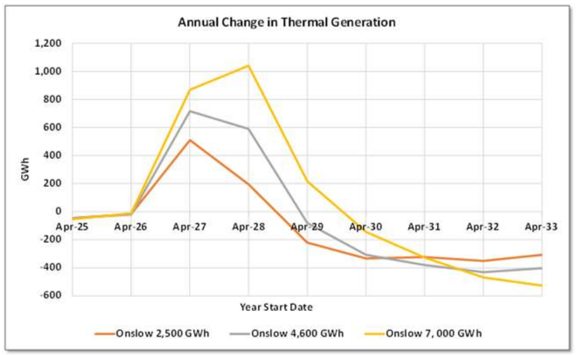
# Different Types of Modelled Demand

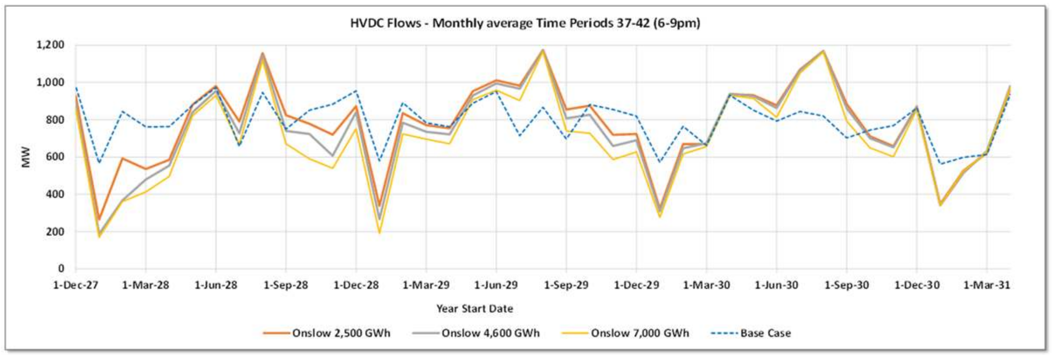
- DSR is assumed to be either bid as DCLS or offered as generation
  - it can be marginal and set the spot price
  - 100 MW in 2030 and 150 MW in 2050, offered at between $2,000 and $8,000
- DE is demand elasticity which reduces demand when spot prices rise
  - in the ICCC base case Tiwai remained, and DE included the Tiwai triggers in the Tiwai-Meridian contract
  - DE is neither bid nor offered and reduces prices from what they would otherwise be, so it can dampen investment signals
  - typically modelled as up to 10% of total demand
- SLR includes non-supply with scarcity price of $10,000
  - could also include emergency supply from a range of sources, as long as it can impact the price as either a DCLS or generator offer, at $10,000

# Energy Link – Adding Onslow PHES

- October 2020:
  - LSSS including Onslow PHES added to our *EMarket* model's capabilities
  - Energy Trader Forum presentation on Onslow with 1,300 MW capacity, 75% pumping efficiency[3], and three sizes: 2.5 TWh, 4.6 TWh, and 7.0 TWh of storage
  - gas peakers retained: Onslow increased renewables by about 2% by reducing spill
  - Onslow is a net consumer of energy, reduces price volatility, modest reduction in average price (the original build schedule was not adjusted), charges in summer
  - Onslow offers to generate, and bids to charge as a DCLS, based on its water value at the time: it can switch from pumping (charging) to generating (discharging) by 3-hour period






3. *"Evaluating the potential for a multi-use seasonal pumped storage scheme in New Zealand's South Island.", PhD thesis, Majeed 2019.*

# Energy Link* – NZ Battery

- NZ Battery Project early 2021:
  - any reference to Onslow can also be taken as a reference to any LSSS technologies
  - modelled impacts of Onslow in 100% renewables market, 5 TWh storage, 1,000 MW, 75% pumping efficiency
  - 2030 and 2050 modelled
  - DSR and SLR required in the North Is due to limited HVDC capacity (1,400 MW)
  - 2050, with higher demand, price distribution is especially sensitive to amount of plant built in the North Is – more on this later

* *As part of a team with Sapere Research and Chapman Tripp.*

# Energy Link – Carbon & Energy Finance Group

- We continue to explore 100% renewables with various configurations of storage

- Working on a project under the Carbon and Energy Finance Group[4] at the University of Otago to explore price volatility and investment at 100% renewables
  - ➢ literature search underway, 50% complete
  - ➢ few papers cover price formation directly, most focus on cost of supply and implicitly assume prices will reflect these costs

4. *https://blogs.otago.ac.nz/cefg/*

# Conclusions for the Energy-only Market

| | |
|---|---|
| 1 | A 100% renewables market without LSSS is not feasible<br>➢ having one or more large consumers willing to turn down by ~5 TWh in a year is unlikely<br>➢ over-building of renewables is required to cover dry years<br>➢ renewable capacity factors fall well below theoretical levels<br>➢ investment is supported by high prices due to DSR and SLR, which makes the market 'unstable' due to the 'missing money' problem, i.e.<br>• if more plant is built to reduce or eliminate DSR and SLR, average prices collapse and new investment is not supported<br>• this gets worse as demand rises<br>• the market fails to deliver secure supply |
| 2 | Hence, LSSS is required to support investment in renewables to get to 100% |
| 3 | But: "With near-zero marginal costs of variable renewable energy, prices will be determined based on the dynamic operational decisions of storage, along with consumers' willingness to pay for electricity."[5] |

5. *Ekholm, T. and V. Virasjoki (2021). "Pricing and Competition with 100% Variable Renewable Energy and Storage." The Energy journal (Cambridge, Mass.) 42(1).*

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# Water Values

- The hydro schemes with storage already use water values as their opportunity cost (SRMC)
  - water value is often said to be the 'expected future value of water in storage'
  - and hydro is often on the margin
- Water values were successfully applied to Onslow, BUT: we are really talking about 'energy-in-storage' values which can be applied to a variety of LSSS technologies
  - water value and energy-in-storage value are the same thing
- When the market is 100% renewable then storage systems will set the price in the majority of periods

# Water Values 101 – the Math

- A simplified model of the market with one thermal and one hydro generator
- **Deterministic (known) inflows**, weekly releases $r_t$ and spot prices $S_t$
- $Revenue = \sum_t (S_t \times r_t)$ for all weeks $t$ = 1, 2, 3, …, 52 in the year
- But $S_t$ could be a function of $r_t$ for larger generators, so
- $Revenue = \sum_t (S_t(r_t) \times r_t)$
- Using the method of Lagrange multipliers, we will maximise *Revenue* when $\frac{dS_t(r_t)}{dr_t} + S_t(r_t) = L$ where $L$ is a constant
- $\boldsymbol{S_t(r_t) = L}$ **expresses the principle that unconstrained generation is offered using a constant water value**
- $\boldsymbol{\frac{dS_t(r_t)}{dr_t}}$ **expresses market power, which may be zero for a smaller generator**

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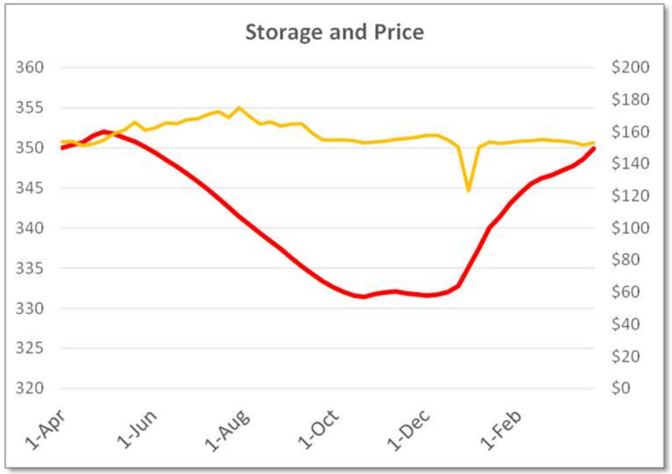
# Small Generator

- Storage reservoir is 500 GWh for large and small hydro generators (a small generator would in reality have a smaller reservoir)
- Demand is 1,747 GWh per annum (200 MW average)
- Hydro is 10 MW, with average inflows of 70 GWh per annum
- Thermal is 250 MW offered between \$20/MWh and \$200/MWh (linear "offer curve" a.k.a. "supply curve")
- Hydro aims to finish the year with end storage = start storage (so that next year can repeat!)
- Hydro offers have a spread of ±\$2.5 around the final water value




- Water value = \$152.89
- Average price = \$158.53
- Renewables = 4%
- Revenue = \$11.185 million
- If the weekly offer is increased or decreased in any week, then revenue may fall below this value
- Hence market power = 0
- If thermal offer prices are doubled, WV = \$305.56
- If thermal offer prices are halved, WV = \$76.01

**Conclusion: WVs are set by the cash costs of others that have higher cash costs; market power is nil**

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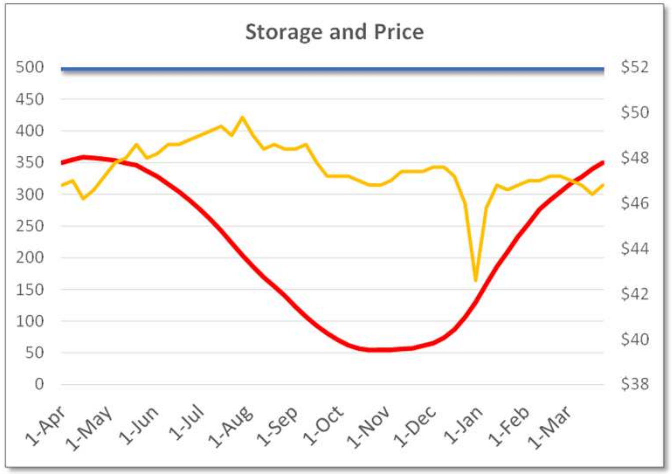
# Large Generator

- Hydro is 200 MW, with average inflows of 1,403 GWh per annum
- Thermal is 250 MW offered between $20/MWh and $200/MWh (linear offer curve)
- Hydro aims to finish the year with end storage = start storage (so that next year works out too!)
- Hydro offers have a spread of ±$10 around the final water value

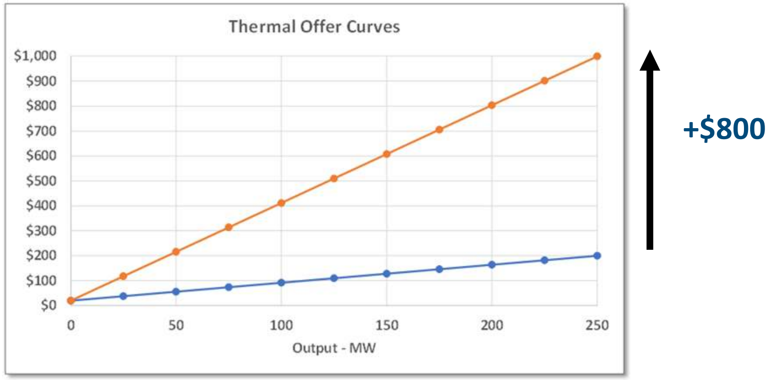


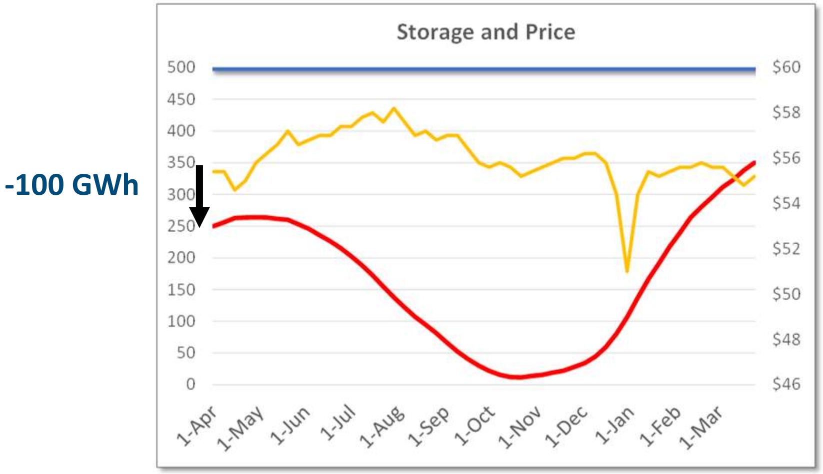

- Water value = $41.44
- Average price = $47.57
- Renewables = 80%
- Revenue = $66.739 million
- If the weekly offer is decreased in any week, then revenue <u>rises above this value</u>
- Hence market power > 0
- If thermal offer prices are doubled, WV = $95.21
- If thermal offer prices are halved, WV = $23.72

**Conclusions: WVs are set by the cash costs of others that have higher cash costs; market power > 0**

# Thermal Offer Variations

- Thermal offer curve can be made much steeper, e.g. $200 => $1,000
- What happens when storage starts 100 GWh lower than expected?




- $200 case: water value $41.44 => $51.14
- Increase of 23%

- $1,000 case: water value $164.82 => $211.39
- Increase of 28%

- The effect of the steeper thermal offer curve is to increase price volatility (somewhat dampened in this deterministic case)

**Conclusion: steeper thermal offer curve produces more volatile prices**

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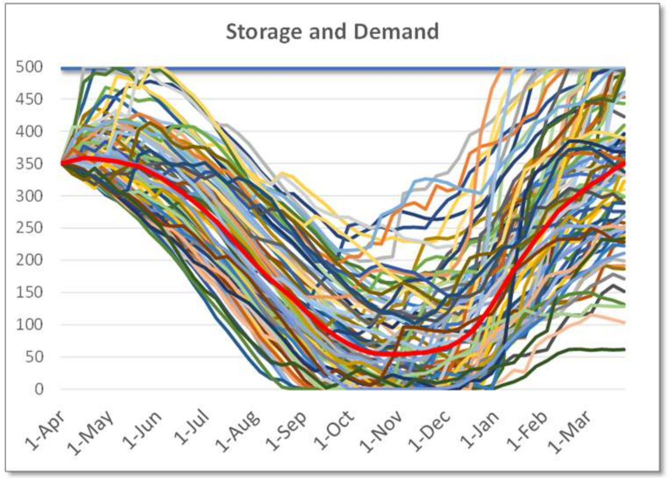
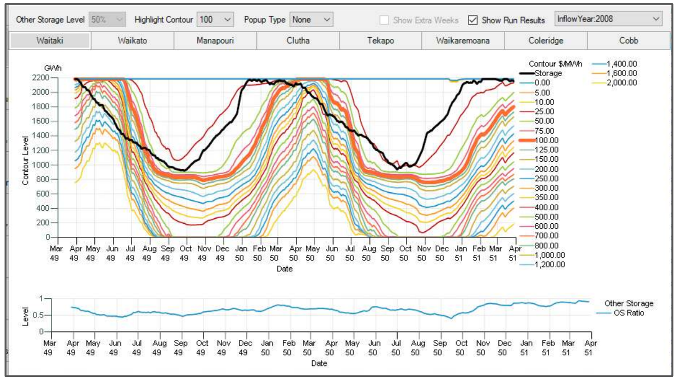
# Stochastic Water Values




- So far, we've used average inflows, but we get empty lakes if we don't account for uncertainty, shown here for 88 years of L. Pukaki inflow data

- Stochastic water values become a function of time, own storage and the storage in all other reservoirs, as shown at left

- Water value changes as these variables change
  - ➢ they are no longer equal to a constant, *L*, except for short periods, and are updated at least weekly

- As storage falls, probability of higher-priced thermal dispatch in future, or shortage, rises, and vice versa

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# 100% Renewables Without LSSS

- ICCC base case, NZ Battery no-storage base case and our own modelling:
  - over-build of wind and solar is required to cover dry periods
  - thermal offer curves that drive water values now, are replaced by DSR and SLR prices from $2,000 to $10,000 (scarcity pricing level)
  - new investment is supported by water values, and the small number of periods when DSR and SLR set prices
    - geothermal and hydros with storage benefit the most from this
    - wind and solar don't generate during calm, cold evening peaks in winter, especially when the lakes are low, so don't benefit to the same extent
  - the problem is that investment only happens if shortages occur
  - will consumers be happy with this?
    - probably not
  - will windfarm and solar developers be happy with capacity factors less than theoretical?
    - probably not

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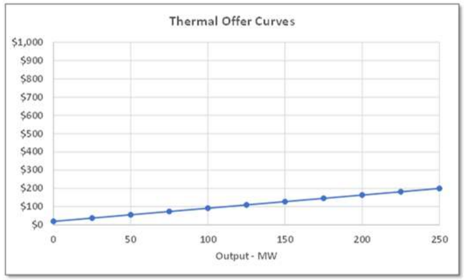
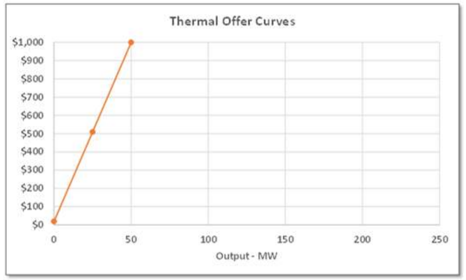
# 100% Renewables Without LSSS

- The underlying problem is that water values are supported by DSR and SLR (not thermal)
  - ➢ this is a very narrow & steep offer curve which makes prices more volatile & more sensitive to new builds




Wide & Flat

Narrow & Steep




- What could change or mitigate this problem?
  - ➢ larger scale demand response such as Southern Green Hydrogen (Meridian says 35% - 40% solution for dry years)
    - does this expose electricity prices to international $H_2$ prices? (if bid as DCLS)
    - or does this dampen investment signals by reducing demand?
    - what are the market power issues?
  - ➢ water values could be set by LCOE of new entrants: issues with this because LCOEs are not a short-term pricing signal; relationship between LCOEs and spot prices is complex due to GWAP/TWAP ratios varying significantly by generation type (wind, solar, geothermal, hydro)
  - ➢ voluntary contracting: an over-build large enough to virtually eliminate DSR and SLR will tank spot prices, so expect purchasers to choose not to contract => shortage of contracts to support investment
  - ➢ increasing or adding probabilistic scarcity pricing mechanisms (as opposed to scarcity pricing) such as the compensation payments during OCCs: who sets these prices?
  - ➢ move away from energy-only market and introduce new market mechanisms
  - ➢ ….?

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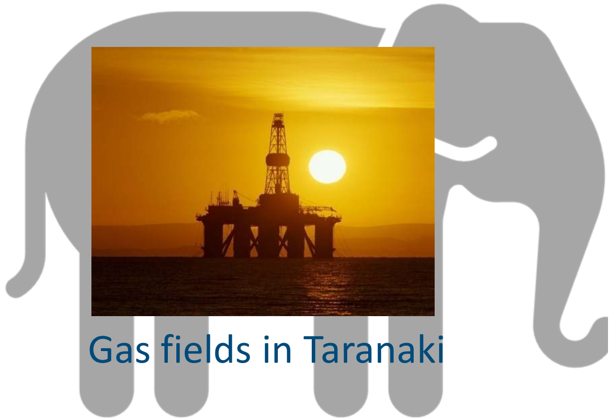
# From the NZWEA Conference 2021

## We have massive & diverse storage today

Hydro lakes

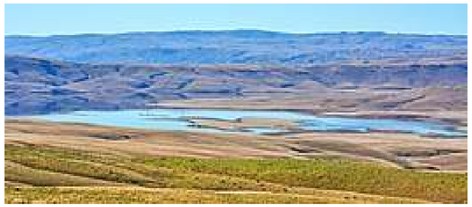
Coal stockpile at Huntly



Gas fields in Taranaki

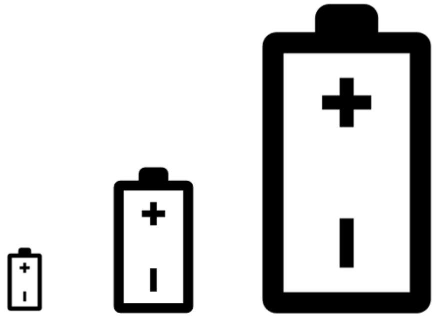
## We will need massive & diverse storage in 2050

Hydro lakes



Pumped storage

Green hydrogen



Chemical batteries of all sizes

and more…

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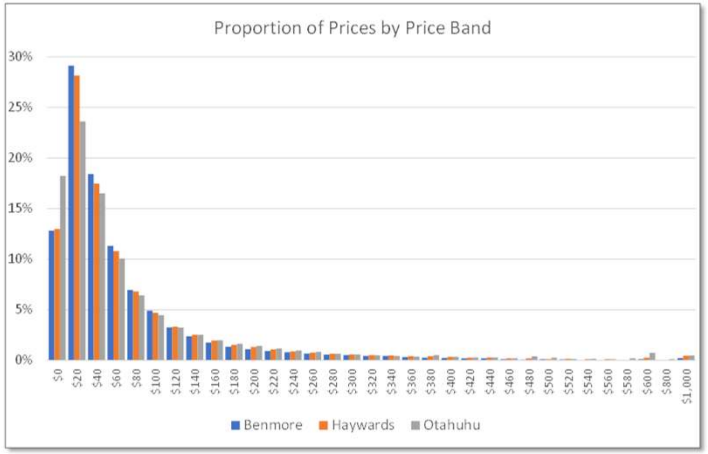
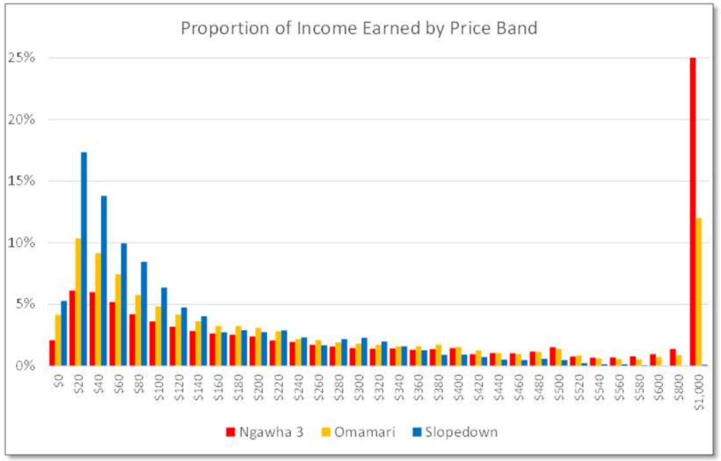
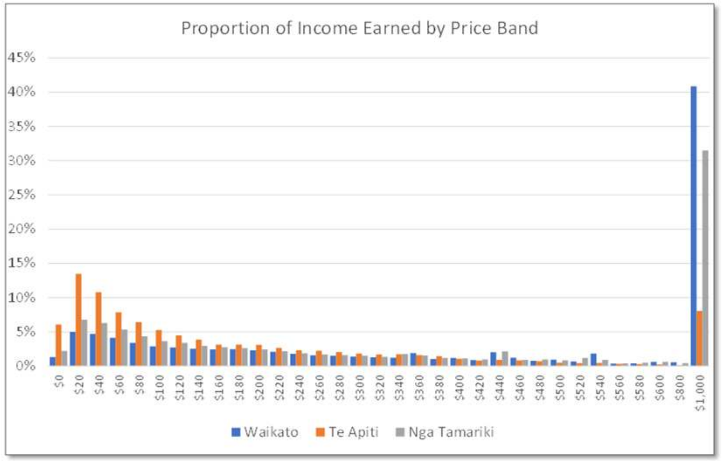
# 100% Renewables With LSSS

- LSSS is storage that is sufficiently large, in total energy terms, to manage all, or at least the majority of, the dry-year problem
  - could be smaller storage systems that achieve this in aggregate
- Lake Onslow is an obvious example, but others are possible
- Storage solves problems:
  - reduces the degree of renewable over-build required
  - eliminates DSR and SLR entirely with a much greater degree of certainty than over-building without storage
  - supports windfarms and solar to achieve theoretical capacity factors
  - reduces price volatility by raising prices when supply is plentiful (charging), and depressing prices when supply is not plentiful (discharging)

# Price and Revenue Distributions




- Demand[7], LSSS in the South Is, much smaller-scale BESS in the North Is, HVDC 1,400 MW constrains often
- Less than 0.5% of all prices exceed $1,000 in the North Is, 0.2% in the South Is

| Generator | Ngawha 3 Geothermal | Nga Tamariki Geothermal | Te Apiti Windfarm | Omamari Windfarm | Slopedown Windfarm | Waikato |
|---|---|---|---|---|---|---|
| Market Premium (GWAP/TWAP-1) | 0% | 2% | -40% | -37% | -11% | 34% |
| Revenue Earned at Prices > $500 | 38% | 38% | 11% | 18% | 1% | 47% |

*7. NZ Battery modelling*

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# Price and Revenue Distributions

- Key insights:
  - ➢ LSSS's impact in the North Is limited by the capacity of the HVDC link
    - creates more prices due to DSR and SLR dispatched during winter peaks when demand is high, it is calm across the country, and the sun has set
    - geothermal and hydro with storage benefit from these high prices much more than windfarms (and solar by implication)
    - but windfarms and solar still earn significant revenue from DSR and SLR prices
    - reliance on over-building renewables means the market needs more windfarms and solar to be built to reduce the dispatch of DSR and SLR
    - BUT building more would reduce revenue and destroy the investment
  - ➢ In the South Is
    - Slopedown is not nearly so reliant on high prices due to the consistent presence of the LSSS
    - DSR and SLR hardly feature

# Is Storage the Whole Answer?

- South Is LSSS won't solve all problems in the North Is unless the HVDC link is upgraded beyond 1,400 MW
  - ➢ additional storage in the North Is is highly desirable
  - ➢ or further upgrades of, and greater redundancy, for the HVDC link

- BUT:  LSSS has water values, and storage in general has energy-in-storage values => what drives them if DSR and SLR are eliminated?

# The Price Formation Problem at 100%

**The core problem is that the market loses a relatively wide & flat offer curve, in the form of the thermal fleet (including its large stored energy reserves), complete with competition between thermal generators. The "flatness" is assisted by the fact that the gas market is much bigger than the demand for gas to generate electricity, i.e. scale lowers costs.**

- DSR and SLR are left to replace it, and they represent a narrow & steep offer curve, with a fundamental concern that consumers may not be willing to make these resources available at any (realistic) price, and certainly not non-supply
- In addition, DSR and SLR are typically not able to provide long-term energy reductions required to get through dry years, although Southern Green Hydrogen might be feasible as part of the dry year solution

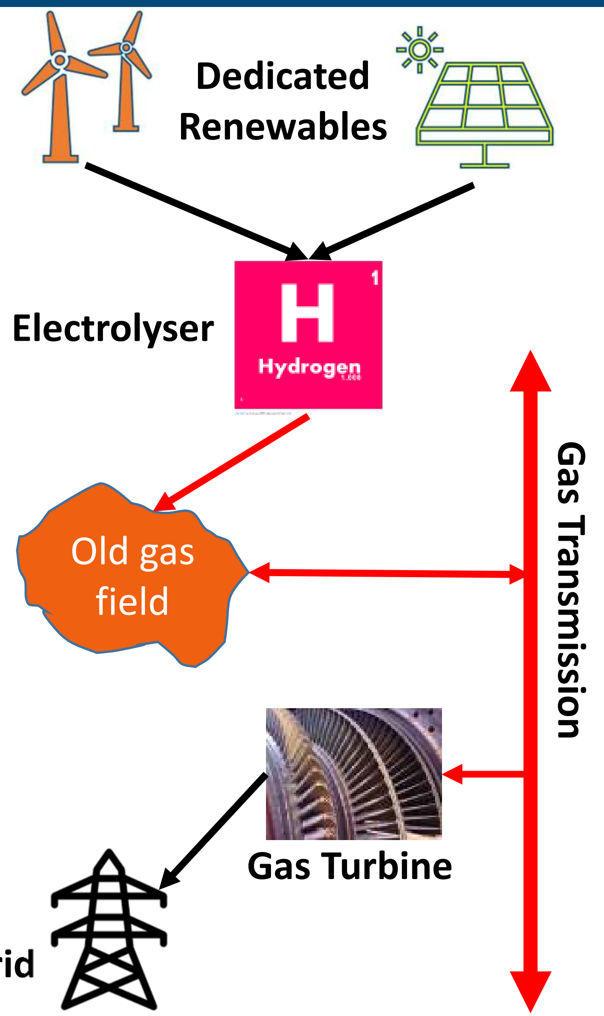
- Additional storage reduces price volatility
- But then electricity is an input cost as well as an output, introducing a circularity which might fail as an input into water values, i.e. it is not a replacement for the wide & flat thermal offer curve

Alternatives include:

- work to make the DSR offer curve significantly wider & flatter; or
- find one or more renewable supply-side solutions with a wide & flat aggregate offer curve

# Supply-side Solutions

- Biomass for thermal generation – is the resource available?
- First Gas recently released a feasibility study concerning conversion of the natural gas supply chain to $H_2$, powered by electricity
  - ➢ this included using a depleted gas field for $H_2$ storage for dry years; and
  - ➢ gas turbines to burn $H_2$ during dry periods and peaks
  - ➢ but wholesale electricity is the major cost => potential for circularity
    - could be eliminated by directly connecting to renewable generation, or PPAs with new renewable generation
    - effectively, we create storage with its own electricity supply at a **fixed price**
    - this would result in a wider & flatter offer curve similar to today's thermal, especially given that there would be other users from whom to recover costs, i.e. when replacing natural gas for most gas users

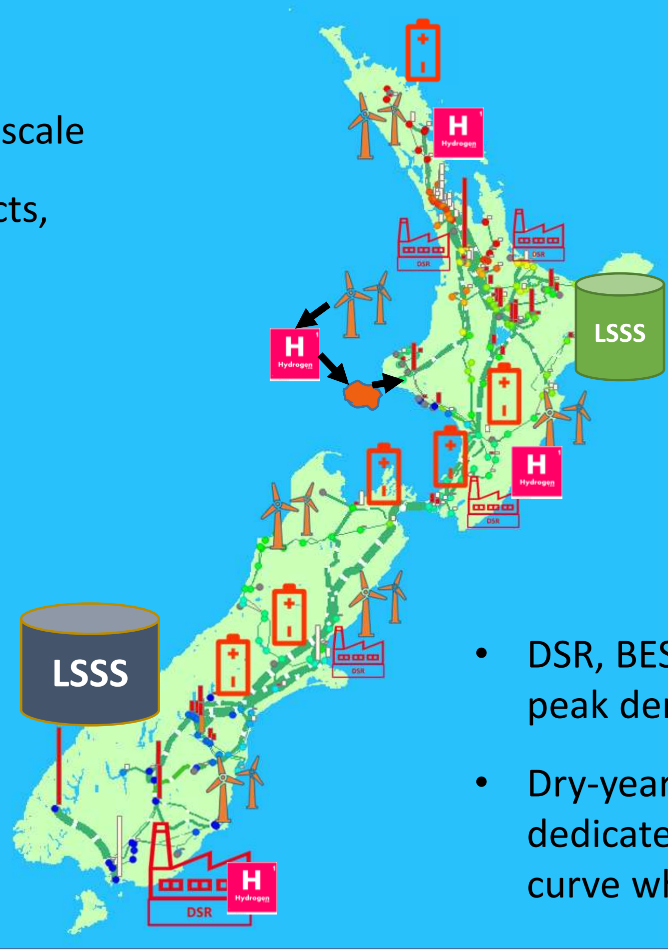


# A Possible Solution?

- LSSS (dry-year scale) mostly likely has to be infrastructure provided by government, like the grid, roads, potable water, …
- LSSS in both islands
- Highly developed DSR over a wide range of prices
  - mainly short-term but possibly with dry year element as well
- Supply-side solutions such as green $H_2$ with LSSS, and captive supply
- Water and energy-in-storage values based on wide & flat offer curves composed of offers from supply-side solutions and DSR

# A Possible Solution?

- LSSS provides the buffer for dry years
- LSSS could include $H_2$ storage on a large scale
- $H_2$ costs “anchored” to renewable projects, either physically or by PPAs




- DSR, BESS, small-scale $H_2$ storage, help to meet peak demand
- Dry-year capable DSR and large-scale $H_2$ with dedicated supply provide the wide & flat offer curve which, along with LSSS, stabilise prices

# Market Power with LSSS

- We saw how large hydro generators with storage have market power
  - this will increase as water and energy-in-storage values dominate pricing
  - *“strategic storage operation always results in a lower use of the storage capacity than non-strategic operation. The under-utilization of storage capacity is more pronounced in an oligopolistic generation market and particularly high if the total storage capacity is concentrated with a single strategic generator”*[7]
- Negative impacts can be reduced by ensuring that new LSSS is independent of existing large hydro, so that water values are formulated for the benefit of consumers

7. *Schill, W.-P. and C. Kemfert (2011). "Modeling Strategic Electricity Storage: The Case of Pumped Hydro Storage in Germany." The Energy journal (Cambridge, Mass.) 32(3): 59-87..*

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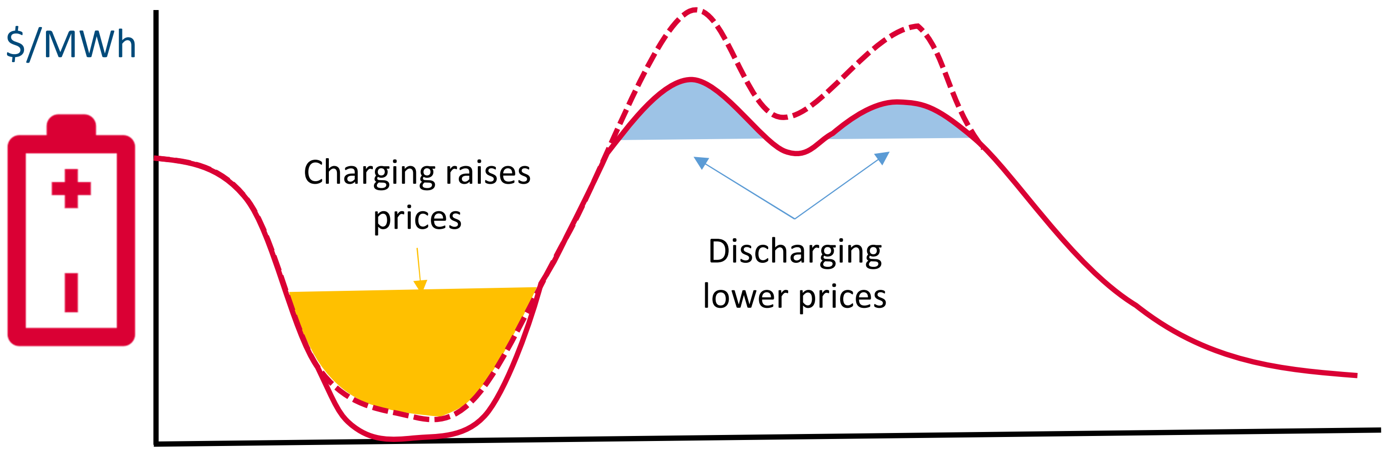
# Cost Recovery for LSSS




- LSSS cost recovery may impact on price formation
- A major issue for all storage solutions is that they reduce volatility by arbitraging between periods of low and high spot prices
  - makes it difficult if not impossible to recover all costs by trading the market
- LSSS modelling shows that this net revenue falls well short of recovering all costs
  - trading revenue is also highly variable depending on prices, and on ending and starting storage differences

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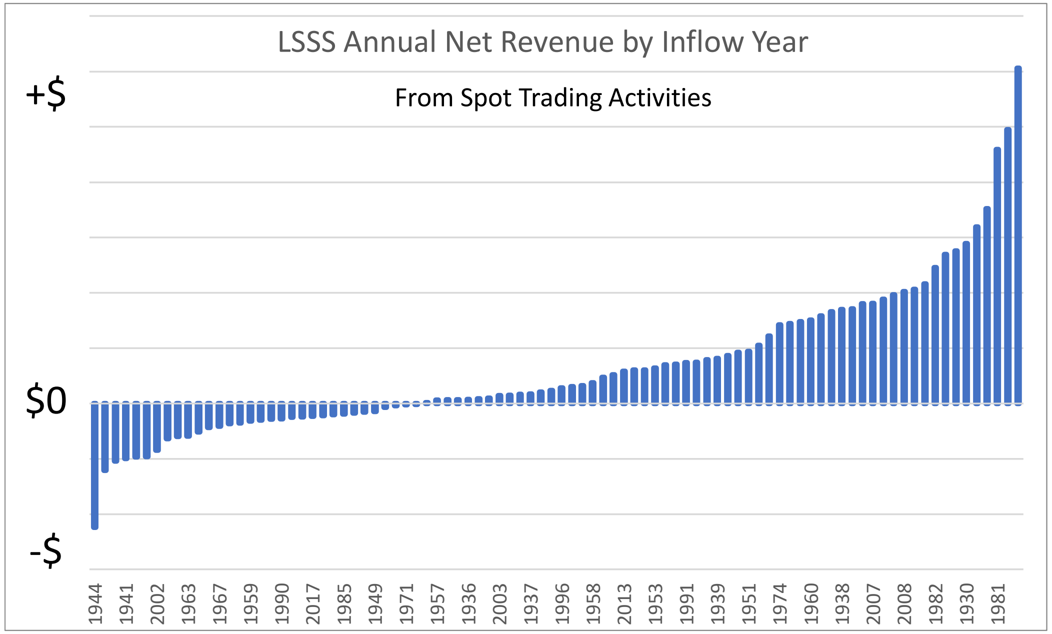
# Cost Recovery for LSSS

- Fixed costs could be recovered by levies on all consumers or all generators
  - would not effect spot prices
- A causer-pays approach could be implemented using a fixed HVDC-like charge levied on hydro generators as causers of the dry year problem
  - would become a cost for hydro generators which might or might not be passed on to consumers, especially as demand grows and hydro share of market shrinks
- Choice of cost-recovery mechanism will be critical, just as it is for the grid
  - depending on the mechanism, cost-recovery may or may not impact price formation

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# Can the Market Deliver?

| | |
|---|---|
| ✘ | • Large-scale, environmentally sensitive infrastructure that may be required to support the market, e.g. LSSS South plus LSSS North.<br>• The scale and nature of the investment probably requires government involvement. |
| ✓ | • Large-scale $H_2$ storage solution:  market has already delivered the Ahuroa Gas Storage Facility, and Genesis plans more gas storage<br>• First Gas is investigating an $H_2$ LSSS using depleted gas field<br>• Market could deliver, if it is technically feasible |
| ✓ | • Supply-side solutions such as $H_2$ with captive supply and storage, e.g. First Gas study |
| ✓ | • DSR:  Transpower's Demand Response Program shows that demand response can be contracted<br>• But can it be bid as DCLS? |
| ? | • DSR: Will Southern Green Hydrogen require direct government support? |
| ✓ | • In future, we will have millions of small batteries in EVs, homes and businesses which could provide mainly short-term storage if the pricing and infrastructure supports it<br>• It will need to be easy for consumers to set up and operate, i.e. highly automated networks |
| ✓ | • Medium-sized grid-scale storage, primarily chemical batteries, e.g. Meridian battery proposal |
| ✓ | Wide & flat aggregate offer curve which contributes to stable water values and supports new investment<br>• combination of $H_2$ (and other) with captive supply and storage<br>• possibly also additional pricing signals such as OCC compensation payments (energy-only augmentation) |