SHORT-TERM HYDRO BIDDING UNDER UNCERTAINTY

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University of Auckland, EPOC

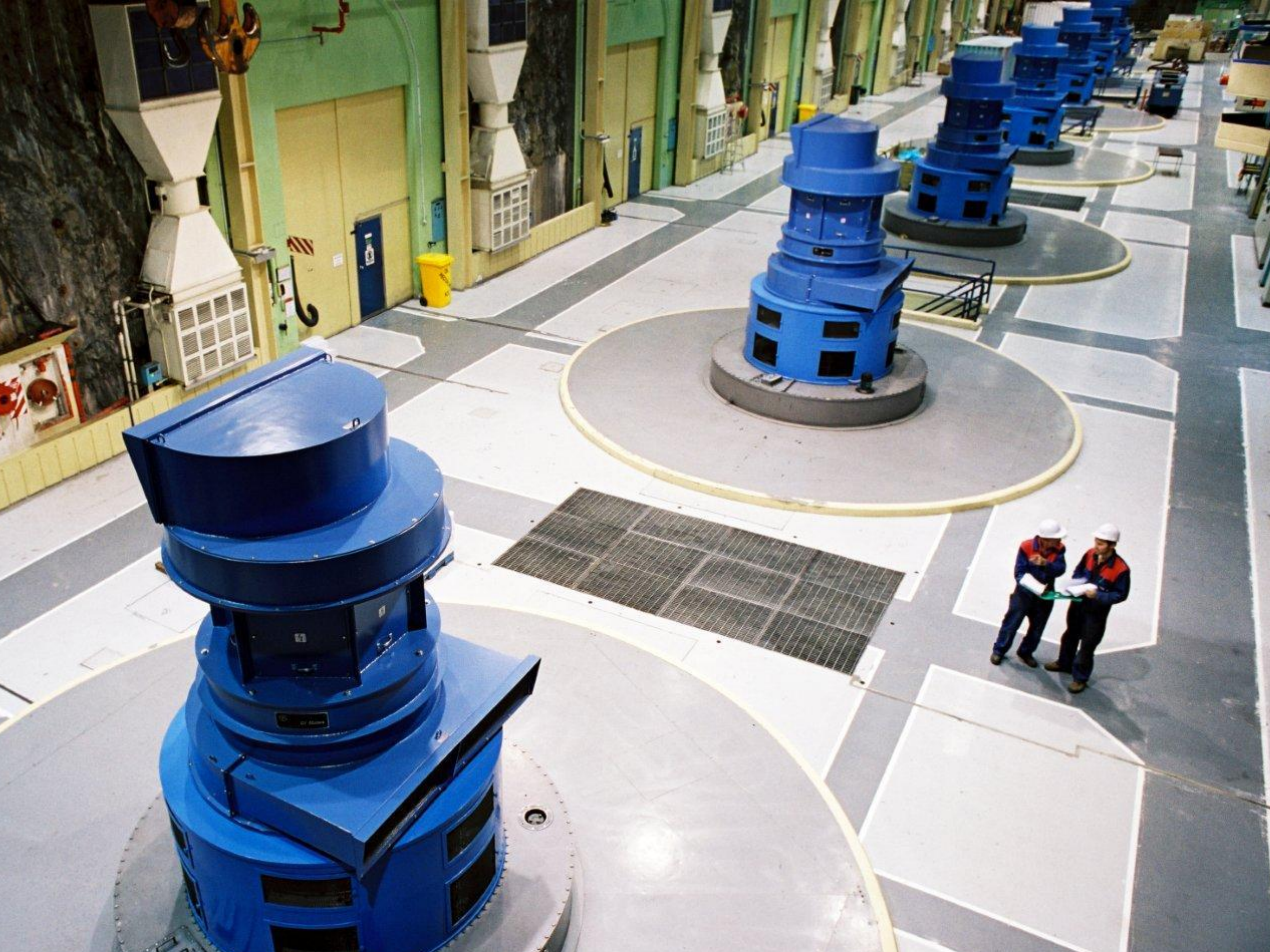
- 2010 - Worked as a Transportation Analyst with BECA Engineering simulating crowd flow for the 2012 London Olympics
- 2011 - Graduated in operations research at Engineering Science, University of Auckland
  - Honours Project: Investigating the operational effects of Tekapo A and B asset transfer
- 2012 - Worked as Wholesale Market Analyst for Mighty River Power
- 2013 – Began PhD with Gaspard Monge Program for optimisation and operations research (PGMO) , Meridian Energy and EDF

My Thesis

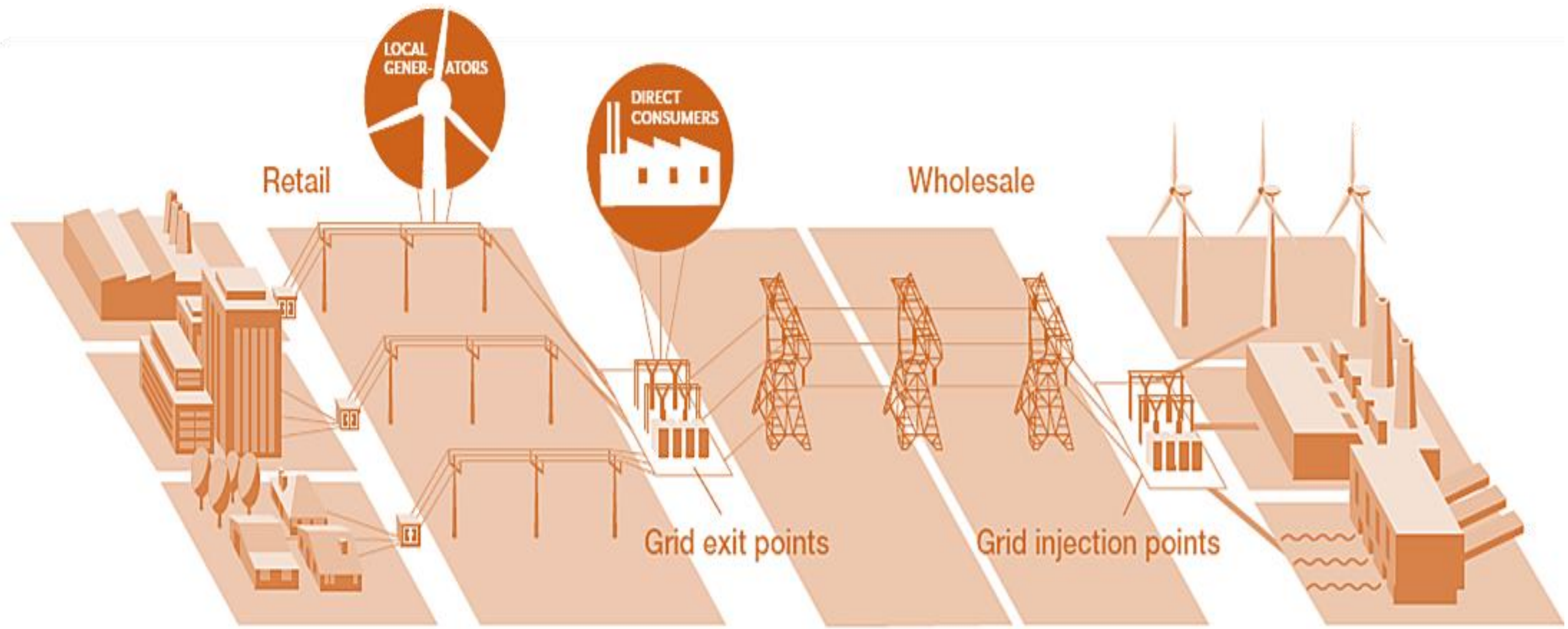
- Short-term hydro power bidding and scheduling
- Short-term: Intra-day to intra-week planning horizon
- Focus areas:
  - Price variation
  - Head-water variation
  - Strategic behaviour
- Investigating within New Zealand and French context
  - We want to see how significant head effects is in short-term operation
  - Offer behaviour (2 settlement market in France and single settlement in NZ)

Outline

- Electricity Sector
  - Electricity Supply Chain
  - Electricity Market Structure
- Electricity Markets
  - How does it function
  - Economics of supply and demand
  - Impact of transmission lines
- Hydro – electric Production
  - Hydro electricity and cascaded river systems
  - Modelling river chains
- Hydro bidding problem
  - Problem description
  - Solution techniques
- Summary of Frontier of research space

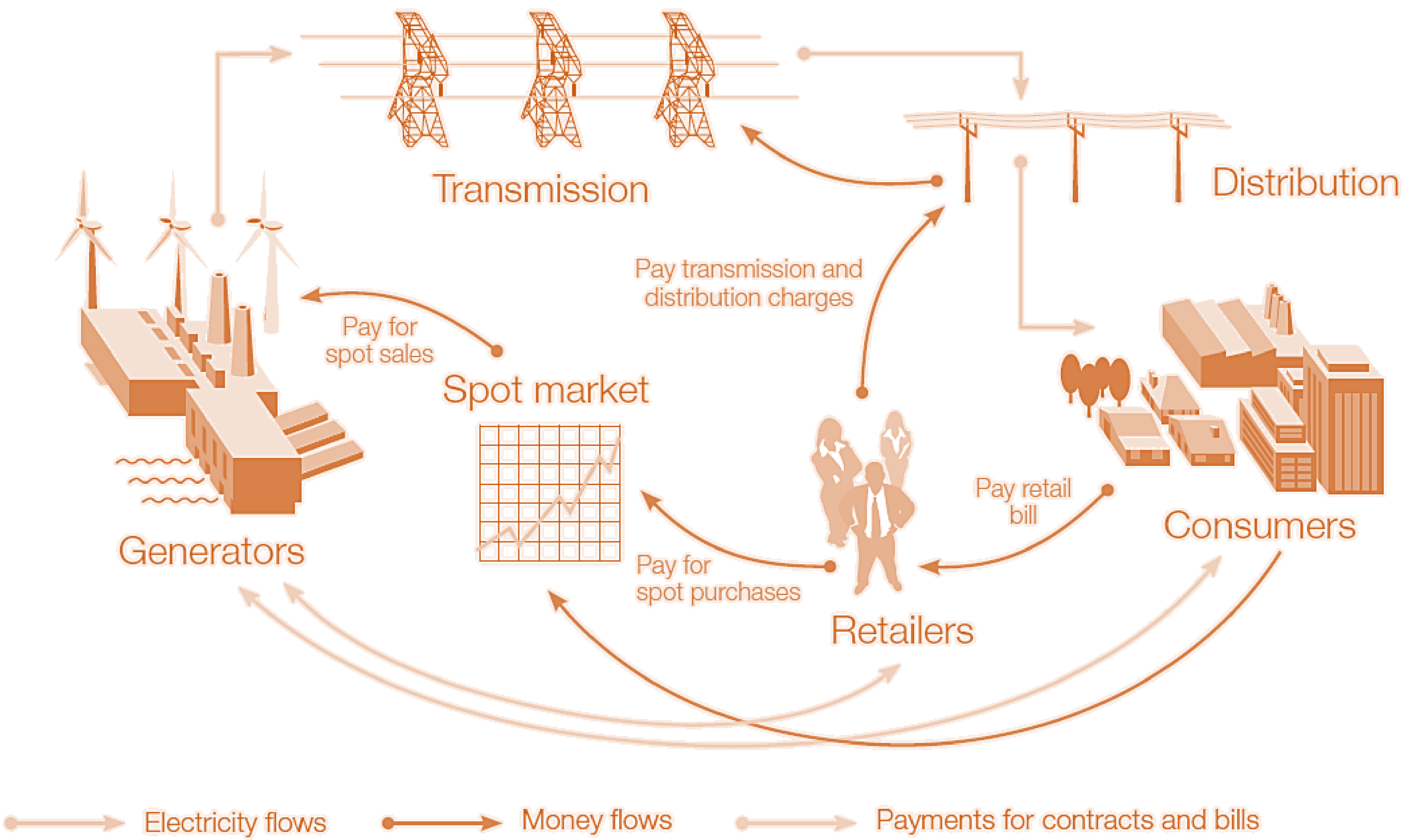


Electricity Supply Chain I



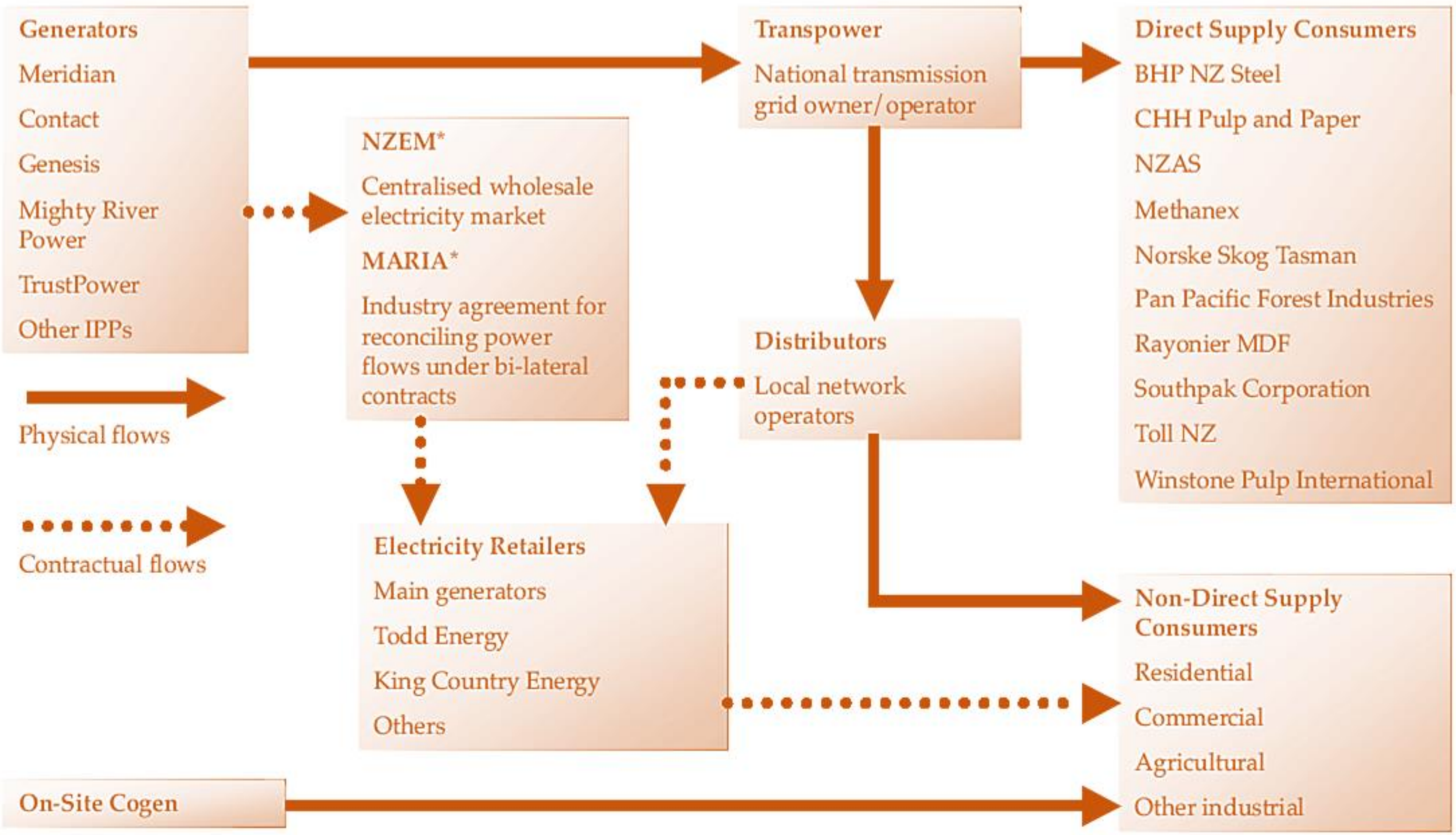
Source: Electricity Authority[2]

Electricity Supply Chain II

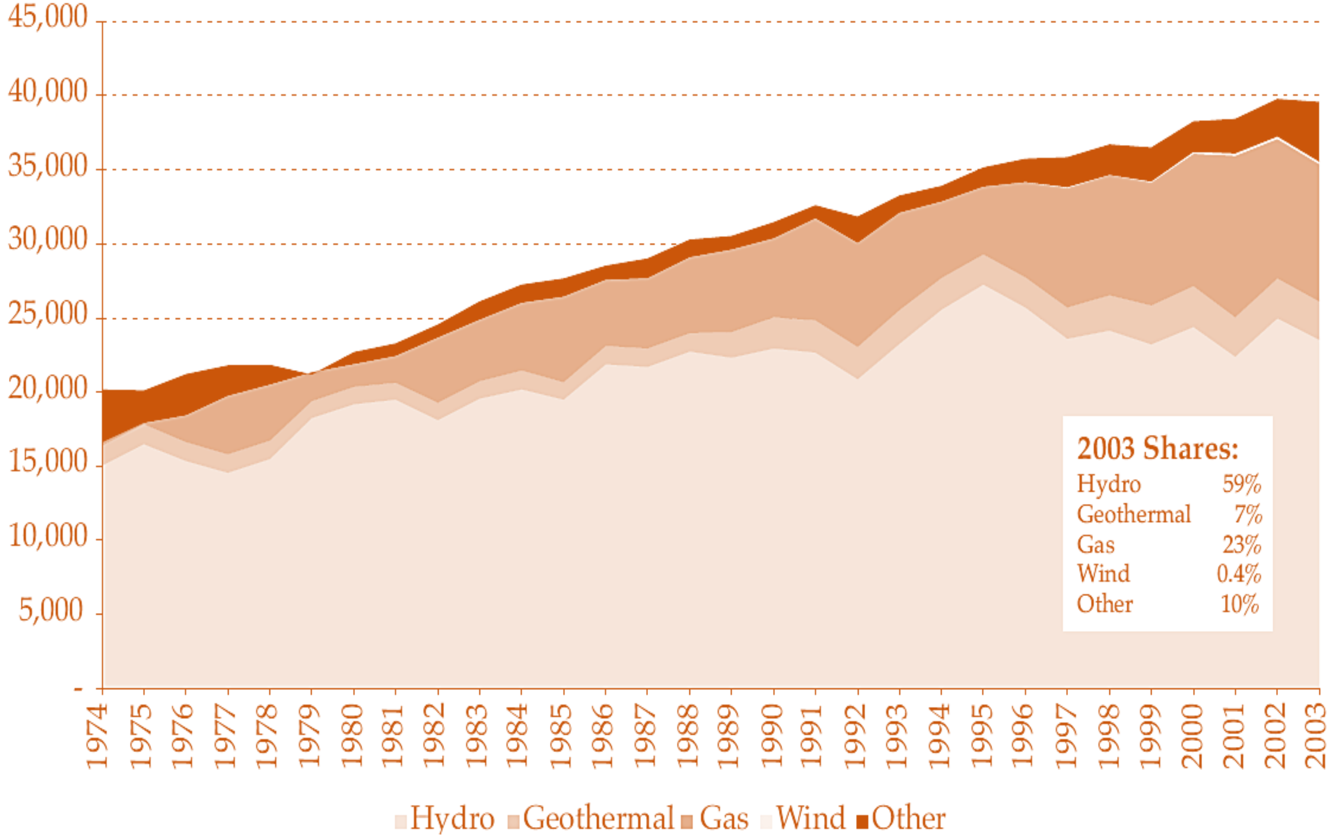


Source: Electricity Authority[2]

NZ Electricity Market Structure



NZ Electricity Generation Portfolio



Wind & Others

Gas

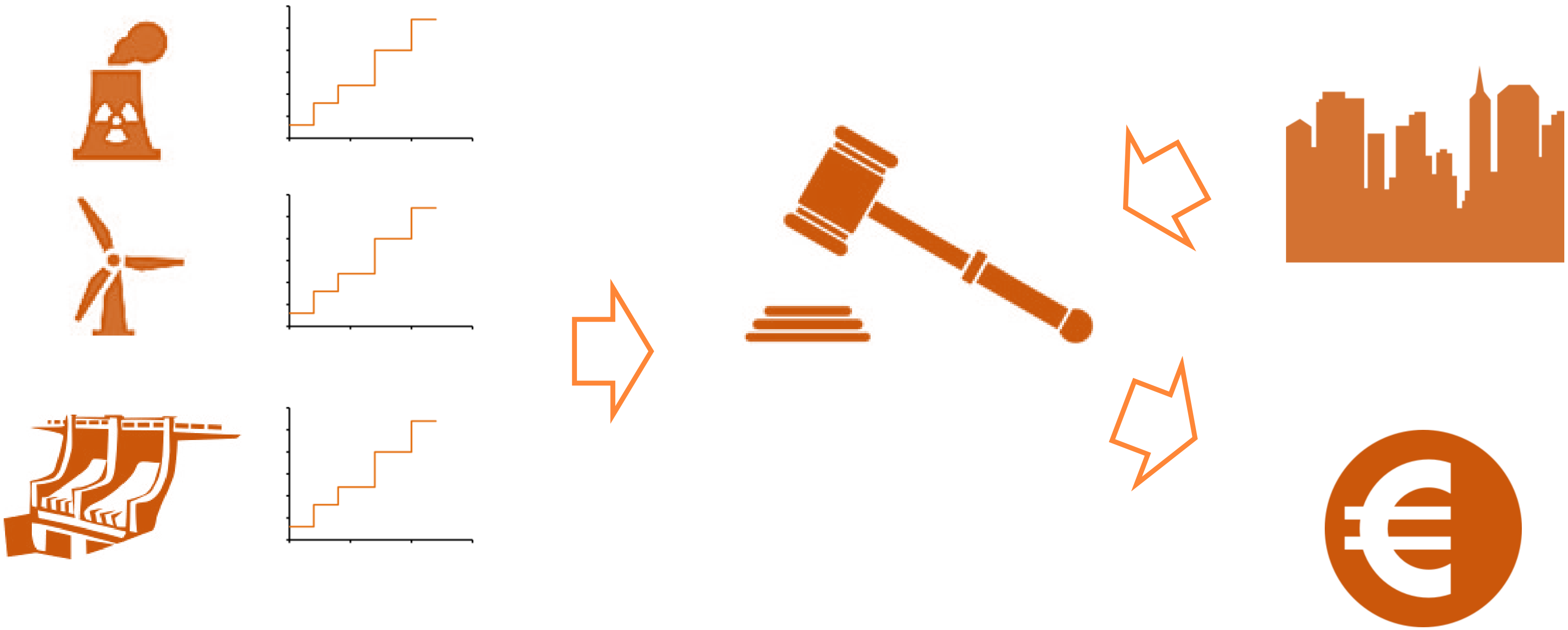
Geothermal

Hydro

Electricity Markets

- First introduced the 1980 in Chile and then followed by Great Britain and New Zealand in 1990's
- Currently Europe, New Zealand, Great Britain, Nordic countries, Australia and North America have decentralised their electric power systems
- Operate in a wholesale spot electricity markets to determine the price of electricity
- Electricity producer firms compete to supply electricity to the national grid
- To transparency in power pricing
- Attract capital needed for maintenance of assets and system expansion

How does it function?

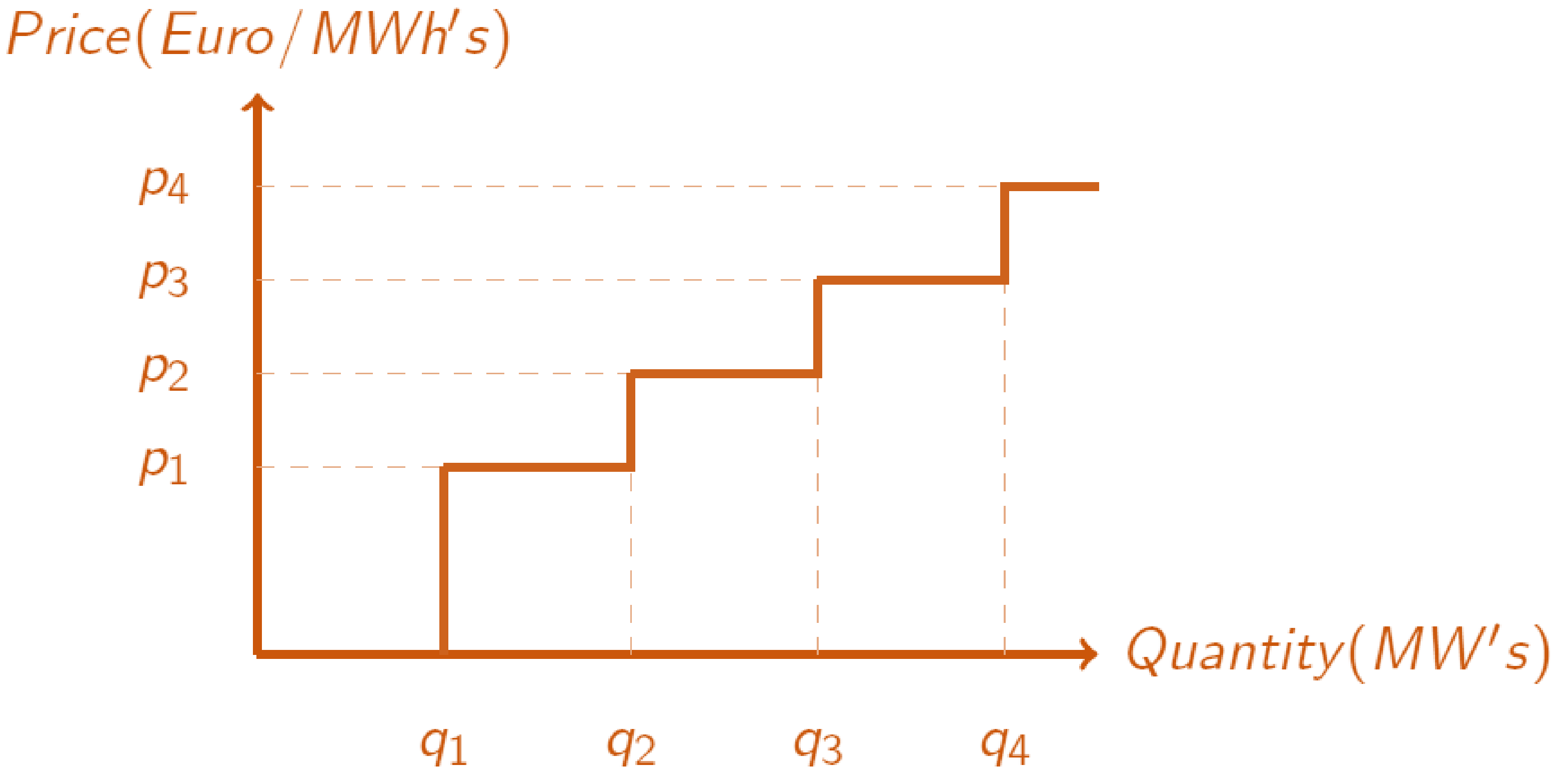


Generators submit an offer tranche to the Market operator

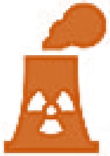
Market operator dispatches generators based on a merit order until load (demand) is met.

Dispatched generators are paid at the market clearing price

Offer tranche



Example I



G1:
200MW's @
€10/MWh's

G2:
350MW's @
€15/MWh's

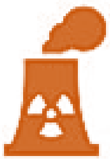
G3:
300MW's @
€20/MWh's

Generator 1 & 2 would be dispatched only because they are the cheapest to supply 550MW load.

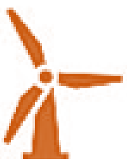
550 MW

€15/MWh's

Example II



G1:
200MW's @
€10/MWh's



G2:
250MW's @
€15/MWh's

G3:
300MW's @
€20/MWh's

All generators would be dispatched with G3 only dispatched for 50MW's to supply the 550MW load.

550 MW

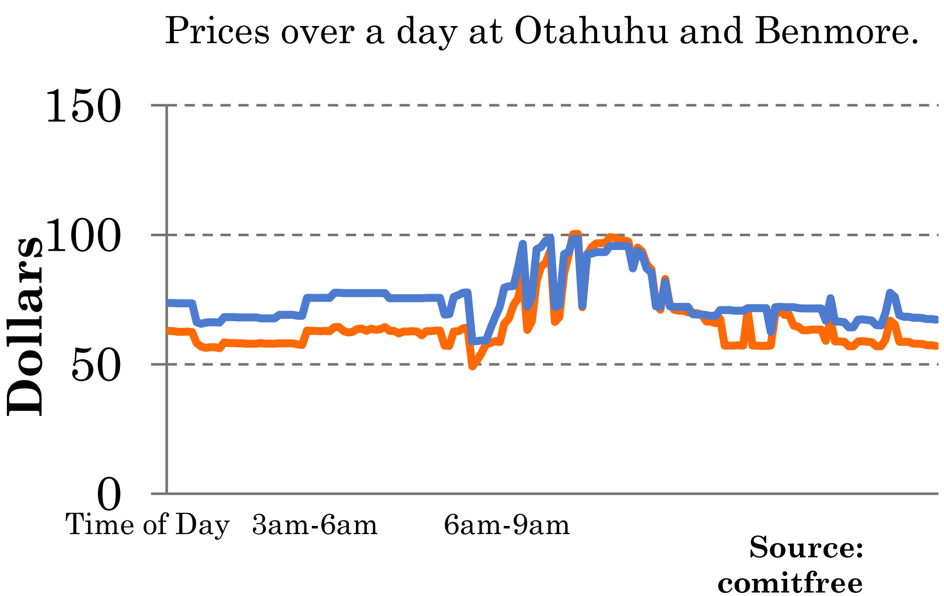
€20/MWh's

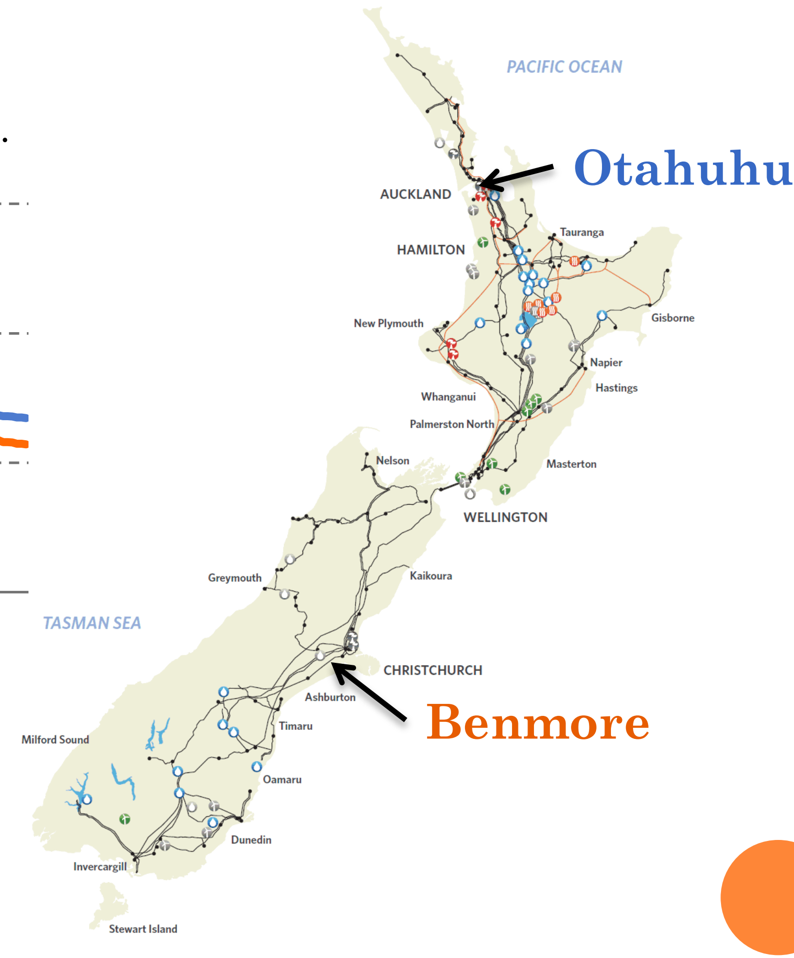
IMPACT OF TRANSMISSION LINES I

- Excess electricity generation cannot be stored
- Generation (supply) must match consumption (demand/load).
- Electricity can only transmitted through high voltage transmission lines.
- These transmission lines have a capacity (upper bound) on energy flow
- Not all of the cheap generation can be transported efficiently;

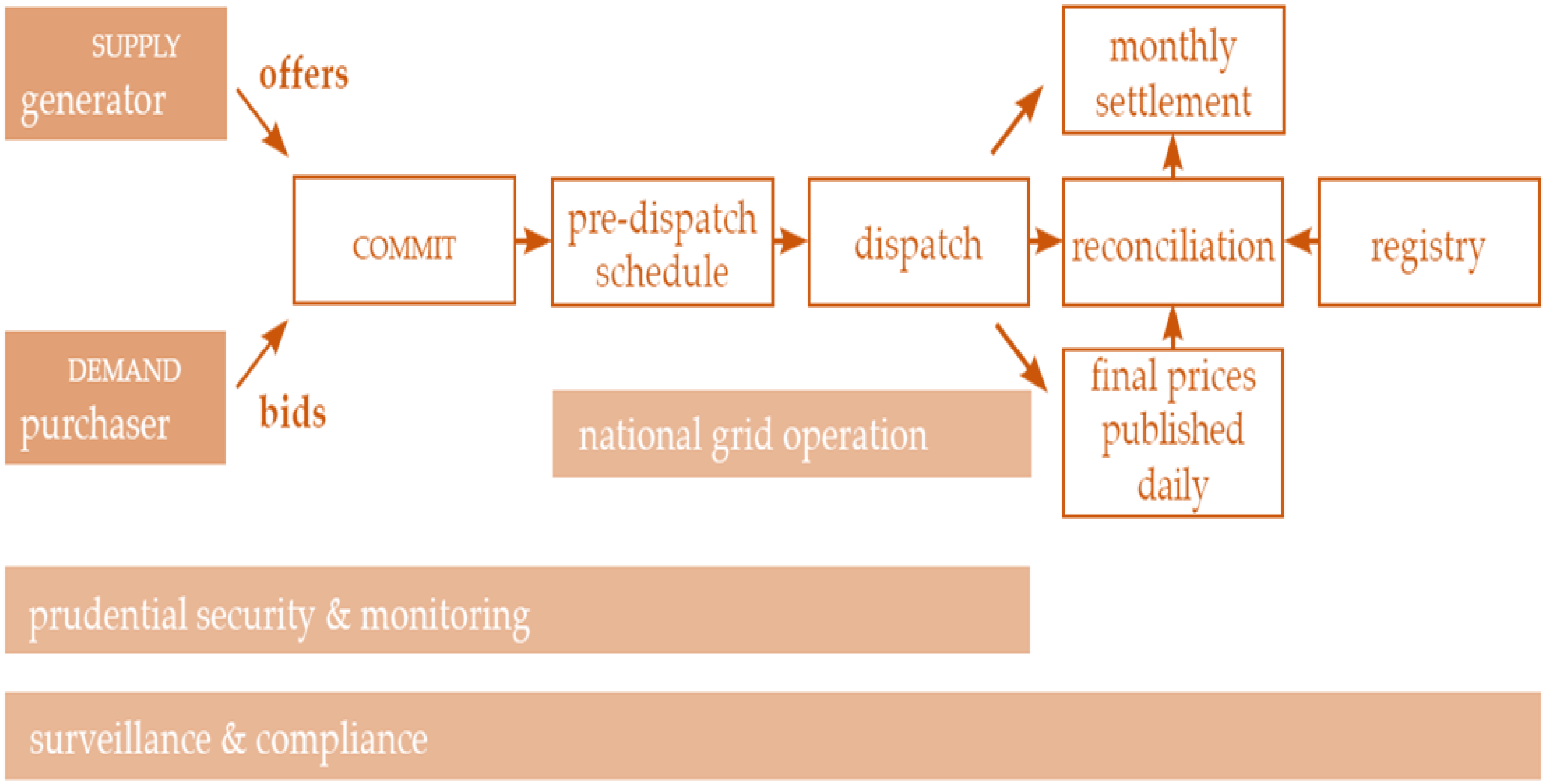
CAUSES LOCATIONAL PRICE DIFFERENCES

IMPACT OF TRANSMISSION LINES II





Schedule, Pricing, Dispatch



DAILY MARKET OPERATIONS

36 Hours

- Forecast price and schedule calculated every 2 hours by the TSO
- Agents submit revisable offers

4 Hours

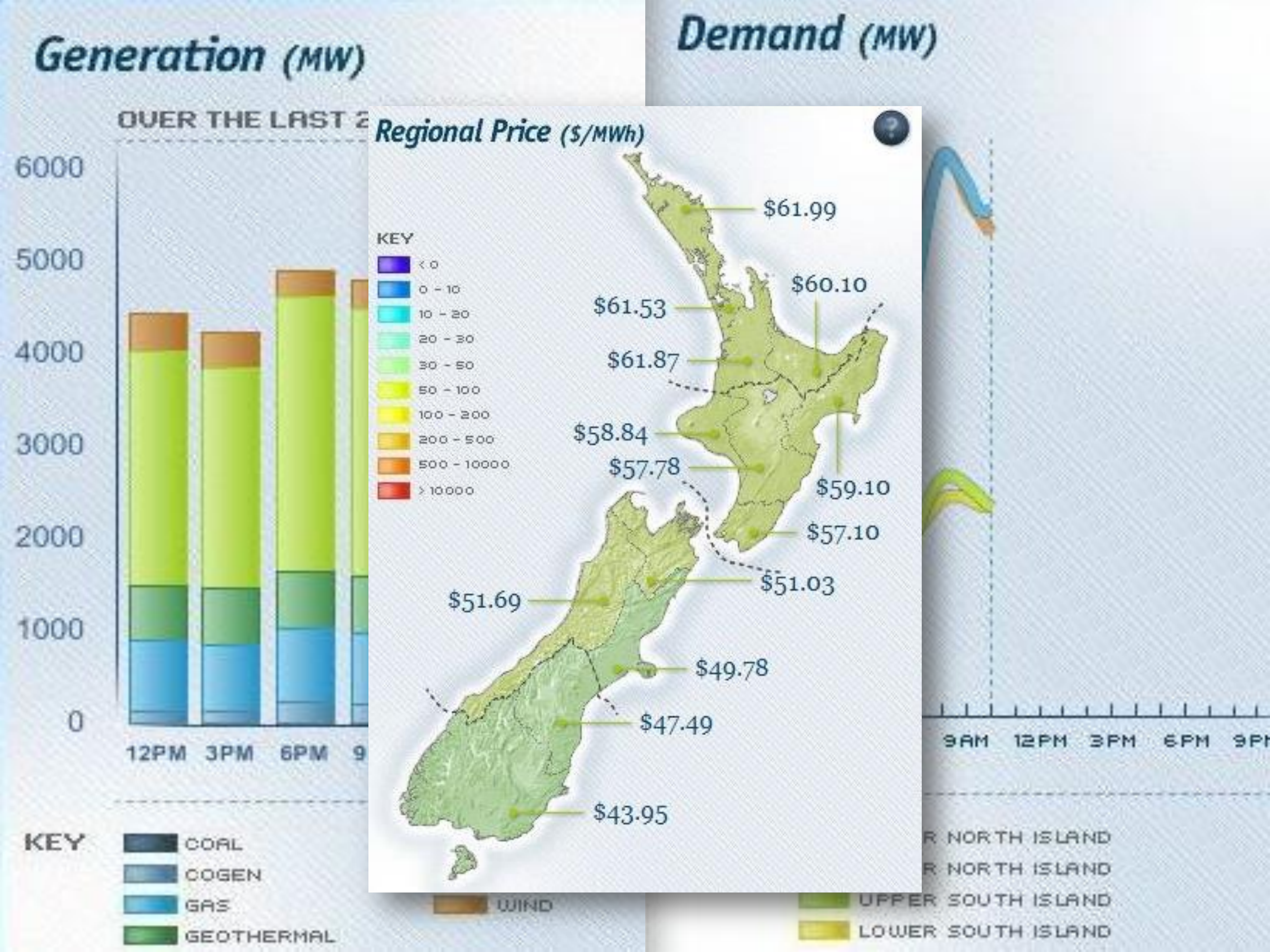
- Market clearing price calculated every 30 minutes by TSO
- Based on load forecast and generator offers

2 Hours

- Agents final offer (non revisable) to TSO
- Market clearing price is calculated
- Dispatch schedule finalised

Gate closed

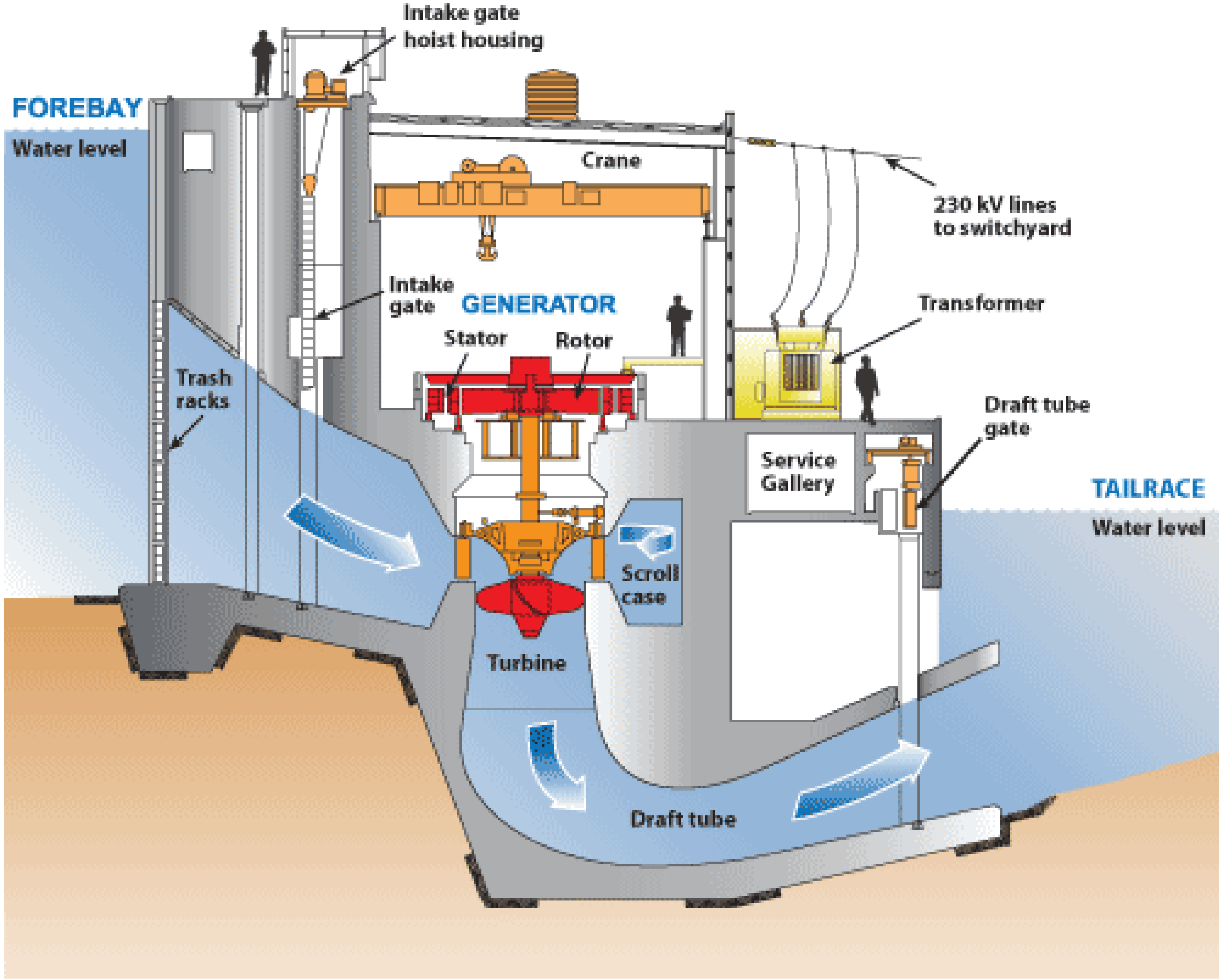
- Realtime management of production, reserves & frequency keeping by TSO
- Final price calculated noon the followind day
- Based on actual metered demand, reserve, final offers, and grid configuration


Generation (MW)
OVER THE LAST 2
6000
5000
4000
3000
2000
1000
0
12PM
3PM
6PM
KEY
COAL
COGEN
GAS
GEOTHERMAL
WIND
Demand (MW)
9AM
12PM
3PM
6PM
NORTH ISLAND
NORTH ISLAND
UPPER SOUTH ISLAND
LOWER SOUTH ISLAND
Regional Price ($/MWh)
KEY
< 0
0 - 10
10 - 20
20 - 30
30 - 50
50 - 100
100 - 200
200 - 500
500 - 10000
> 10000
$61.99
$60.10
$61.53
$61.87
$58.84
$57.78
$59.10
$57.10
$51.03
$51.69
$49.78
$47.49
$43.95

Hydro power production

- Hydropower is the most common form of renewable energy
- Globally provides 16 400 TWh per year
- Most economical form of large-scale electricity storage
- One of the most flexible form of generation asset
- Requires careful management of stock (water)

Mechanics of hydro power



Planning for tomorrow

- The challenge for hydro power producers is to plan for tomorrow
- **Uncertainties around:**
  - Reservoir inflows (i.e. snow melt and rainfall)
  - Scarcity of water reserves
  - Consumer demand
  - Unit outage
  - Grid congestion or transmission line outage
  - Price of electricity

Planning for tomorrow

How do we schedule this production in order to utilise the maximum value of water stock?

Optimisation!

Apply mathematical models and techniques to efficiently manage the water

Hydro scheduling

- Overarching research space that encapsulates this resource planning Problem

- **Long-term:** Planning horizon up to 25 years and usually related with investment decisions

- **Medium-term:** Planning horizon up to 5 years and associated with monthly production plans for contract position

- **Short-term:** Planning horizon up to 1 week and associated with hourly production plans for real-time operation and market participation

River chains I

- Represent a series of reservoirs and hydro stations which are physically connected by rivers and tributaries. It can be mathematically abstracted via a graph where:

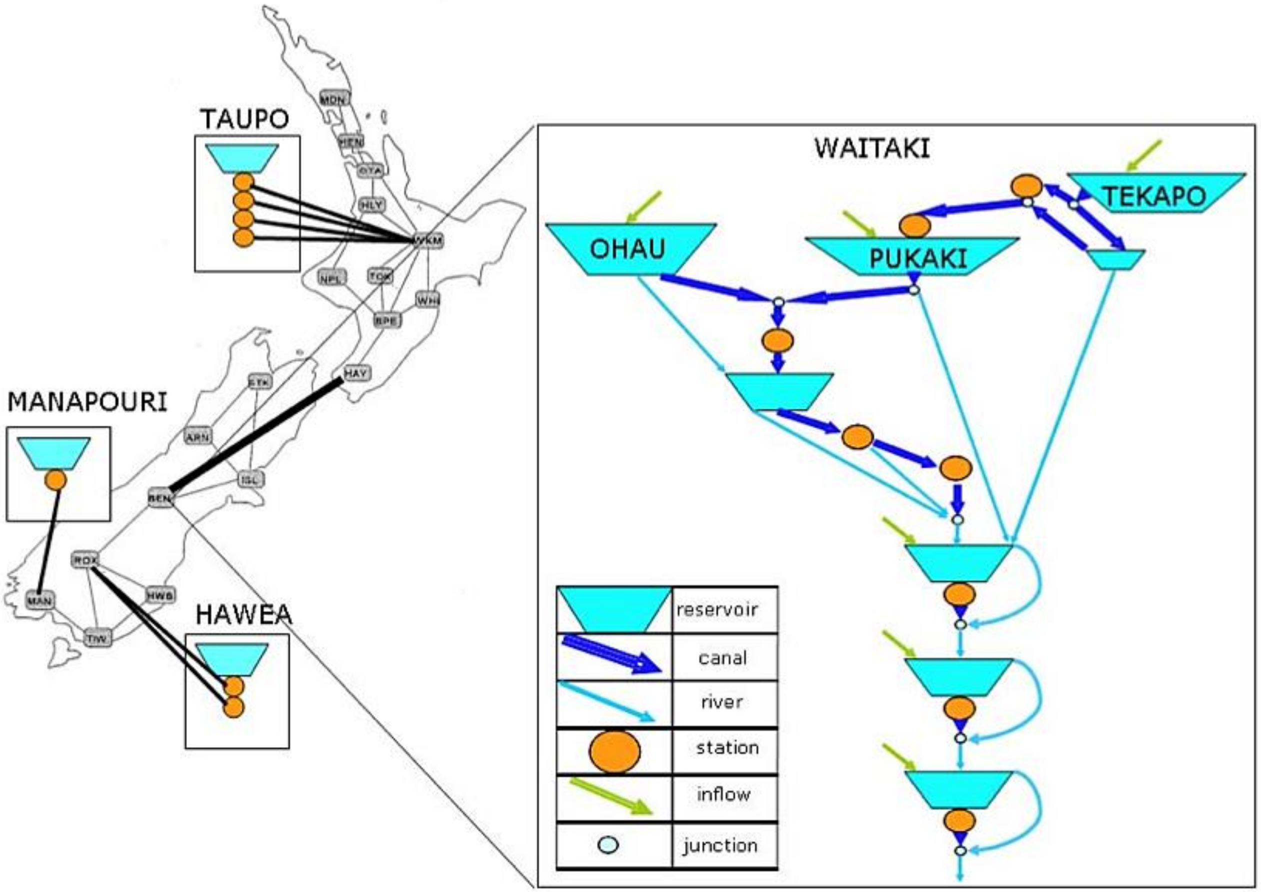
- **Arcs:** Flow of water between two connected nodes (i.e. rivers and tributaries)

- **Reservoir node:** Physical storage of water in lakes and dams

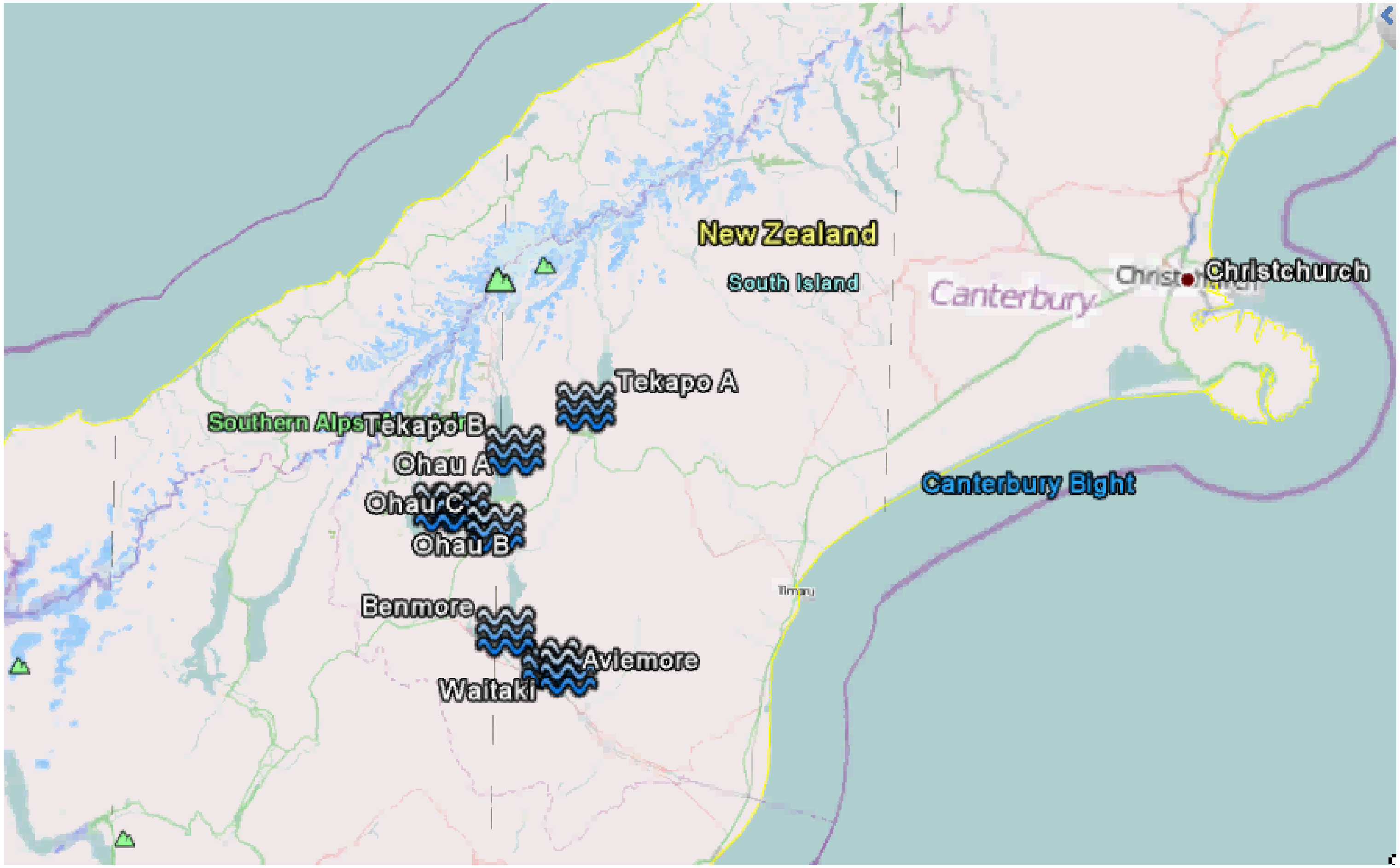
- **Station node:** Physical power production at a station

- **Junction node:** Convergence & divergence of arcs in the network

River chains II



River chains III



Modelling river chains

- River chains can be represented as a network optimization problem where:

Maximize Value of the water stock

Subject To:

1. Conservation of reservoir storage

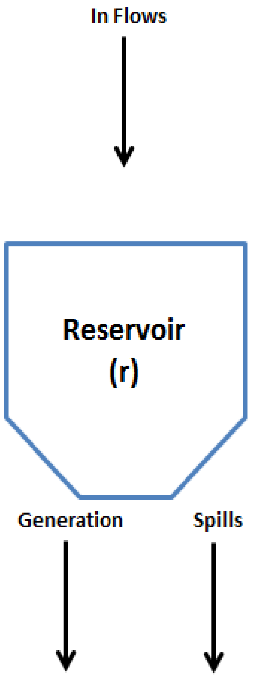
2. Delay of Flows across the Network

3. Generation, reservoir and flow capacities

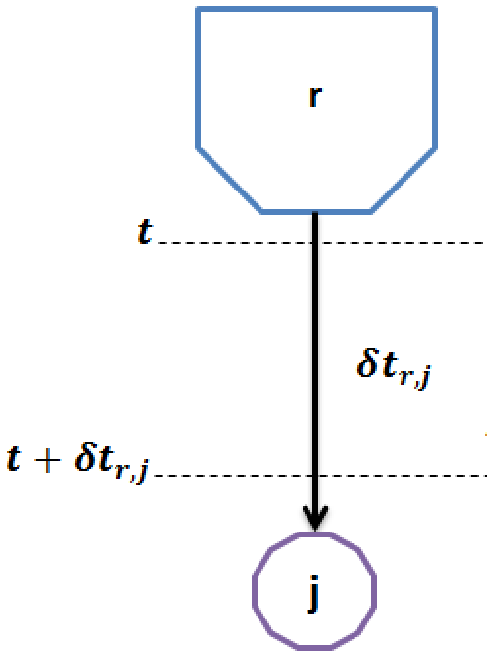
4. Market regulations and operations

Constraint 1 and 2

Conservation of reservoir storage



Delay of flow



Hydro bidding

- *Electricity generators in countries like New Zealand, Great Britain, Nordic countries, Australia and North America mostly operate in wholesale electricity market to determine the price of electricity*

- Challenge to hydropower producers in these markets is supplying offers which maximise the monetary value of the water.

- ***Hydro bidding under uncertainty:*** *Producing optimal offer policies to a market that maximises the value to the producer while meeting the operational constraints of their river chain.*


Price
Quantity

Hydro bidding

- Take a price taker assumption (perfect market competition):
  - The offer of the hydro producer does not affect the price
  - The hydro producer is maximising their profit

- Formulate the hydro bidding problem as a stochastic optimisation problem;

- With main source of uncertainty is market clearing price

- Price is represented as a Markov chain

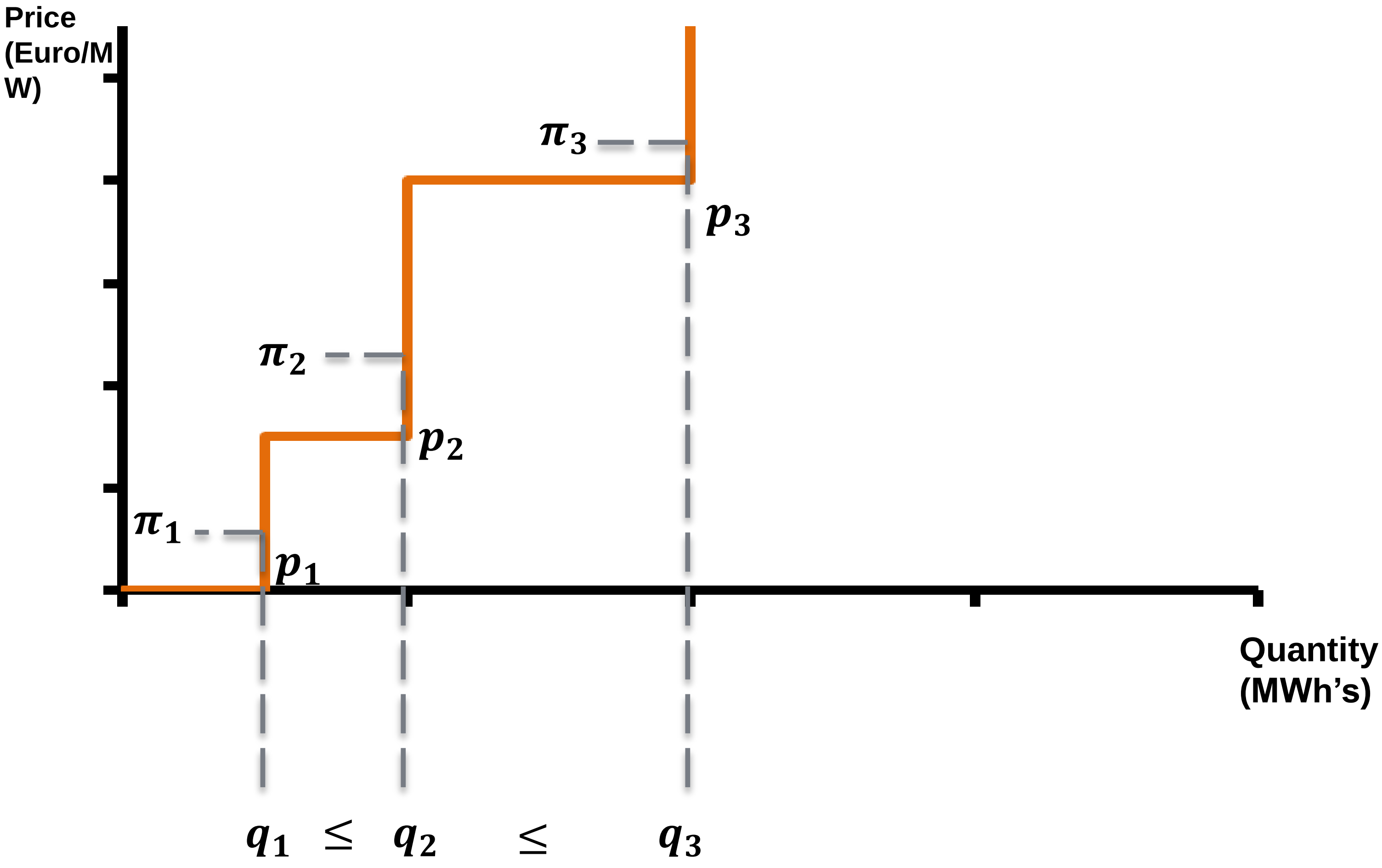
Formulation – single stage

Formulation – single stage

- Random variable is market price
- Market price represented by $\boldsymbol{n}$ discrete states
- Market clearing price is a random variable $\boldsymbol{\pi}$
- Each state has a price interval
  - **Price States =** $\{[\boldsymbol{p1}, \boldsymbol{p2}), [\boldsymbol{p2}, \boldsymbol{p3}), \ldots, [\boldsymbol{p_n}, \ \boldsymbol{p_{n+1}})\}$
- Each price intervals has an average price
  - $\boldsymbol{\pi_i} = \mathbb{E}[\boldsymbol{\pi} \mid \boldsymbol{p_i} \leq \boldsymbol{\pi} \leq \boldsymbol{p_{i+1}}]$
- Each average price has an associated probability
  - $\mathbf{Pr}[\boldsymbol{p_i} \leq \boldsymbol{\pi} \leq \boldsymbol{p_{i+1}}]$
- Quantity variables for each price state
  - $\boldsymbol{Q}(\boldsymbol{\pi}) = \begin{cases} \mathbf{0} \\ \boldsymbol{q_i}, \boldsymbol{p_i} \leq \boldsymbol{\pi} \leq \boldsymbol{p_{i+1}} \end{cases}$

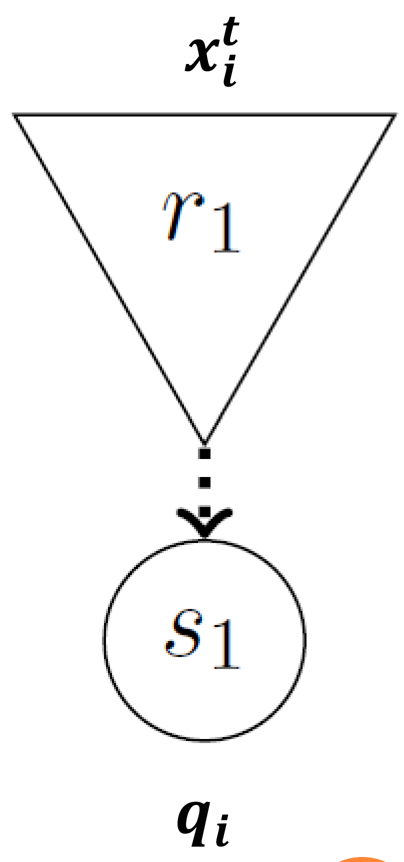
FORMULATION – SINGLE STAGE

$$\textbf{Max}\ \mathbb{E}[\pi Q(\pi)] = \sum_{i=1}^{n} q_i \pi_i Pr[p_i \leq \pi \leq p_{i+1}]$$

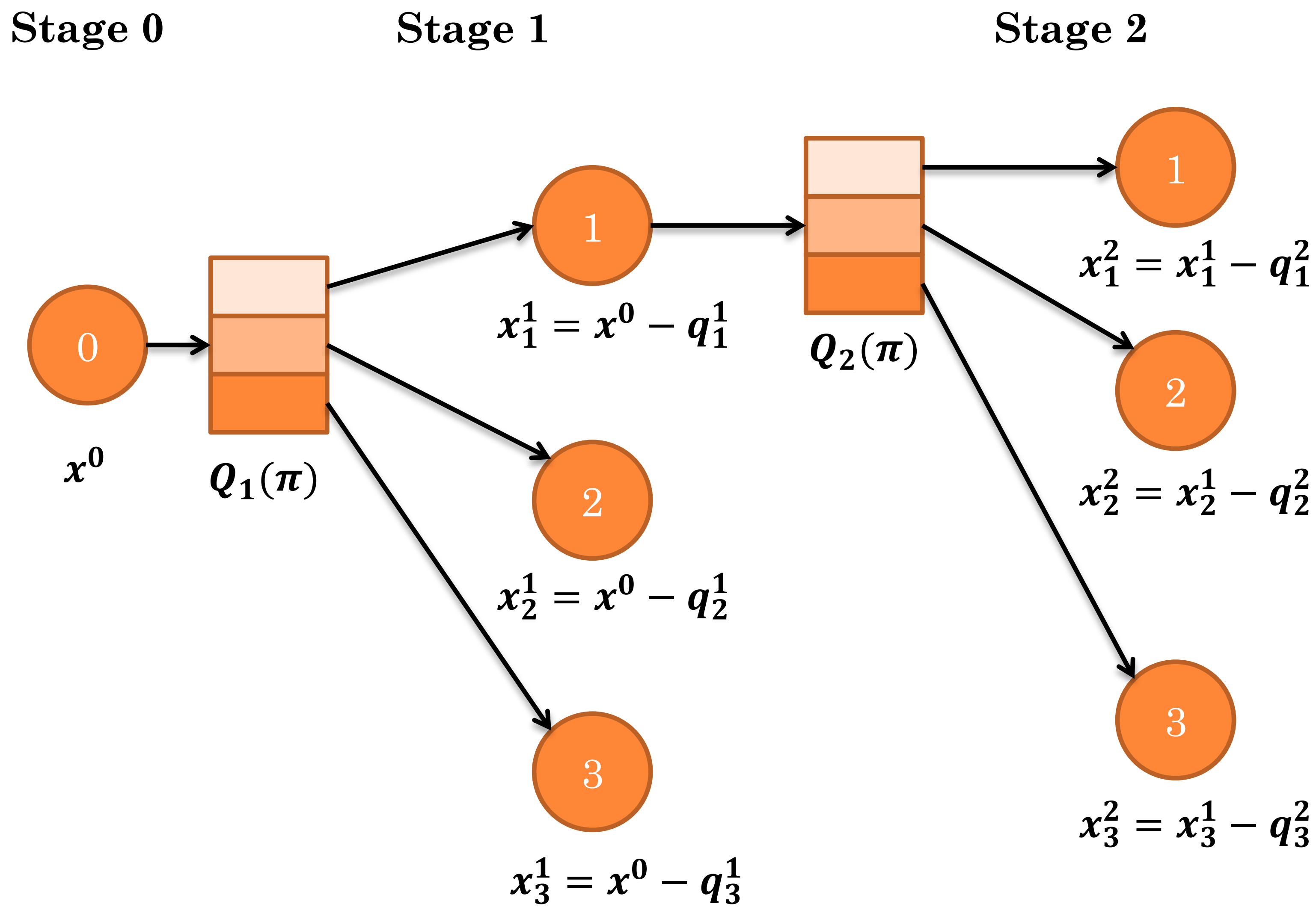


Formulation – single stage

- Maximising expected profit
  - $\mathbf{Max}\ \mathbb{E}[\boldsymbol{\pi Q(\pi)}] = \sum_{i=1}^{n} \boldsymbol{q_i \pi_i Pr[p_i \leq \pi \leq p_{i+1}]}$
- Conservation of reservoir storage
  - $\boldsymbol{x_i^{t+1} = x_i^t - q_i^{t+1}}$ $(t = stage\ index)$
- Storage bounds
  - $\underline{\boldsymbol{x}} \leq \boldsymbol{x_i^t} \leq \overline{\boldsymbol{x}}$
- Monotonic offers
  - $\boldsymbol{q_1^t \leq q_2^t \leq\ \dots\ \leq q_i^t \leq \overline{q}}$



Formulation – Two Stage

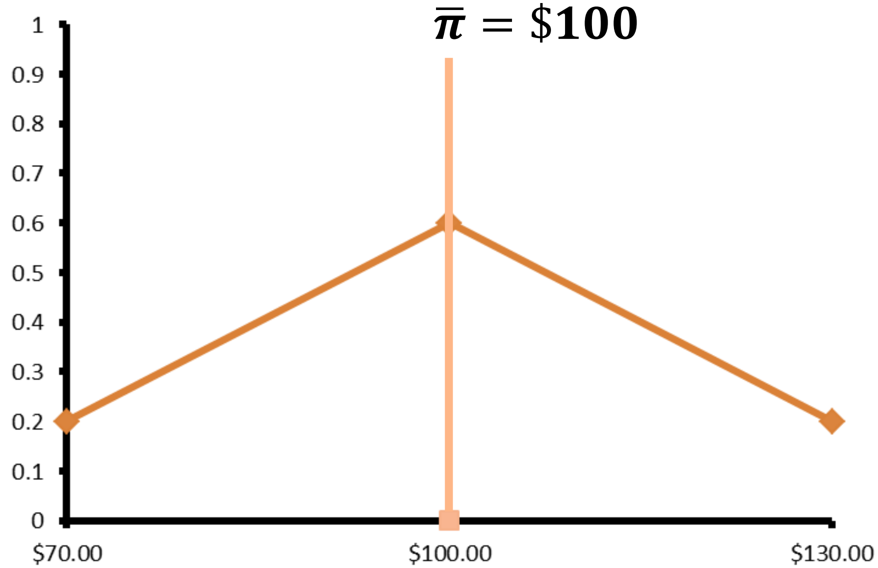


EXAMPLE #1

State (i)	π_i	Probability	Cumulative Probability
1	$ 70.00	0.2	0.2
2	$ 100.00	0.6	0.8
3	$ 130.00	0.2	1

Stage 0	Stage 1	Stage 2
0	30	70
		70
		70
	70	30
		30
		30
	70	30
		30
		30

$\overline{\pi} = \$100$



$x_0 = 100 \qquad \overline{q} = 70$

Comparison with EVP

Expected Value of Perfect Information (EVP)

Stage 0	Stage 1	Stage 2
		50
	50	50
		50
		50
0	50	50
		50
		50
	50	50
		50

Max $\mathbb{E}[\boldsymbol{\pi Q(\pi)}] = \$\mathbf{10,000}$

Stochastic Hydro bidding

Stage 0	Stage 1	Stage 2
		70
	30	70
		70
		30
0	70	30
		30
		30
	70	30
		30

Max $\mathbb{E}[\boldsymbol{\pi Q(\pi)}] = \$\mathbf{10,240}$

Example #2

State (i)	π_i	Probability	Cumulative Probability
1	$ 70.00	0.2	0.2
2	$ 80.00	0.6	0.8
3	$ 130.00	0.2	1

$\bar{\pi} = \$88$

<table>
<tr><th>Stage 0</th><th>Stage 1</th><th>Stage 2</th></tr>
<tr><td rowspan="9">0</td><td rowspan="3">30</td><td>70</td></tr>
<tr><td>70</td></tr>
<tr><td>70</td></tr>
<tr><td rowspan="3">30</td><td>70</td></tr>
<tr><td>70</td></tr>
<tr><td>70</td></tr>
<tr><td rowspan="3">70</td><td>30</td></tr>
<tr><td>30</td></tr>
<tr><td>30</td></tr>
</table>

$x_0 = 100 \qquad \bar{q} = 70$

Challenges

- Curse of dimensionality
- Simulating stochastic prices
- Implementing large river chains
- Solution integrity
- Computation time, solving a large optimisation problem with many integer variables

Decomposition techniques

- Separate each time stage problem in to a sub-problem

- Each sub-problem is making the decision trade-off between maximizing the value of water now versus in the future

- The future value of water is approximated by a function called Bellman function

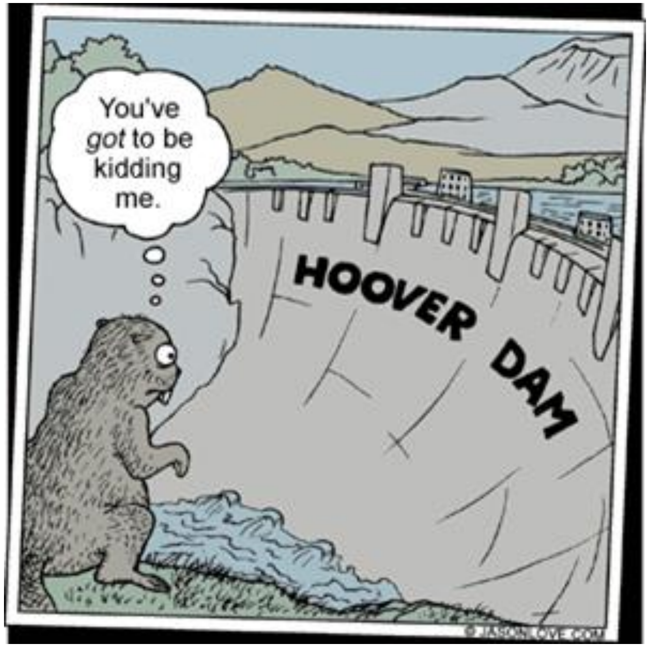
- Solve using recursive based algorithms
  - dynamic programming
  - approximate dynamic programming

Stag wise (sub-problem) formulation

$$
\begin{aligned}
V(x, p_i) = \text{Max} \quad & p_i q(t) \\
& + \textstyle\sum_{j=1}^{N} \rho_{ij}(t) V(x(t+1, j), p_j) \\
\text{s.t.} \quad & \\
& x(t+1, j) = x - A \cdot u(t) + \omega(t) \quad j = 1, \ldots, N \\
& q(t) = \eta^{\top} \cdot u(t) \\
& q(t) \in \mathcal{Q} \\
& u(t) \in \mathcal{U} \\
& x(t+1, j) \in \mathcal{X} \quad j = 1, \ldots, N \\
& V(x(t+1, j), p_j) \in \mathbb{R}
\end{aligned}
$$

Approximating the Bellman function

- In reality the Bellman function may not be continuous or convex;
- The innovation is using novel methods to accurate approximate this Bellman function
- The aim of my time in France is to identify novel approaches to represent the Bellman function shape in a concave and non-concave setting.



Thank You

Questions?

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