Electricity Market Modelling

Economic Dispatch and Hydro-thermal Scheduling

Tony Downward

Energy Centre / Electric Power Optimization Centre
Outline

Capacity Investment
- Generation Technologies
- Load Profile
- Load Duration & Screening Curves

Economic Dispatch & Pricing
- Wholesale Market
- Transmission

River-chains & Hydro-storage
- Hydro Resources
- Hydro Risk Curves
- Hydro-thermal Scheduling
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Capacity Investment
Generation Technologies

There are several different types of plants, using different fuels. These plants all have roles to play in order to maintain a reliable and efficient system.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Fixed Cost</th>
<th>Variable Cost</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>High</td>
<td>(see next lecture)</td>
<td>Hydro storage is expensive and best sites for run-of-river hydro have been built already. Rather difficult to get environmental approval.</td>
</tr>
<tr>
<td>CCGT</td>
<td>Medium</td>
<td>Most efficient thermal plant</td>
<td>Can operate in peak and shoulder periods.</td>
</tr>
<tr>
<td>OCGT</td>
<td>Low</td>
<td>Low efficiency gas plant</td>
<td>Typically only operates during peak demand</td>
</tr>
<tr>
<td>Geothermal</td>
<td>High</td>
<td>Very Low</td>
<td>Constant output</td>
</tr>
<tr>
<td>Wind</td>
<td>High</td>
<td>Very Low</td>
<td>Intermittent output</td>
</tr>
<tr>
<td>Solar</td>
<td>Very high</td>
<td>Very Low</td>
<td>Intermittent output</td>
</tr>
<tr>
<td>Coal</td>
<td>Medium-low</td>
<td>Medium</td>
<td>Moratorium on new coal in NZ</td>
</tr>
<tr>
<td>Diesel</td>
<td>Low</td>
<td>Very high</td>
<td>Used in some remote places or as backup</td>
</tr>
</tbody>
</table>
Capacity Investment

Load Profile

The load profile is cyclical:

– Daily cycles: morning and evening peaks.
– Yearly cycles: additional power usage during winter for lighting/heating. (In some places, summer demand may increase due to air conditioning.)
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- Daily cycles: morning and evening peaks.
- Weekly cycles: lowest usage during weekends.
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If we sort observed loads from highest to lowest we can construct a load-duration curve which specifies how often the load exceeds a certain value.
Capacity Investment

Load Duration Curve

If we sort observed loads from highest to lowest we can construct a load-duration curve which specifies how often the load exceeds a certain value.

North Island Load Duration Curve (2008)

- Baseload (Coal, Hydro)
- Peakers (OCGT)
Capacity Investment

Screening Curve

To procure the most cost effective mix of generation, a central planner would use screening curves. These would display the cost of generation as a function of total operating hours for each technology.
Outline

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In New Zealand, all power is traded in a real-time wholesale market. Bids are locked-in prior to dispatch. Each plant can offer a five-tranche offer-stack. Retailers or large industrials may submit bids. Transpower (the system operator) accepts power from plants so as to minimize the cost, while complying with the constraints imposed by the transmission grid.
Economic Dispatch & Pricing

Single-node Dispatch

Given the following offers:

- 100MW @ $10 (Hydro)
- 300MW @ $40 (CCGT)
- 200MW @ $60 (OCGT)
- 100MW @ $0 (Wind)

What is the optimal dispatch, if the demand is

(a) 450MW, (b) 550MW?

How much should consumers pay for the power?
Economic Dispatch & Pricing

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Economic Dispatch & Pricing

Single-node Dispatch

- For a single-node, it is clear how the system operator should decide who to dispatch.

Supply and Demand

- Market clearing price
- System MC
- Covers FC
- GT
- Old GTs

Hydro, coal, CC
An electricity transmission network consists of buses (nodes) and lines.

The buses are either grid exit points, GXPs (where power is taken off the grid), or grid injection points.

The transmission lines carry power from the node where it’s generated to the node where the power is taken off the grid and distributed to consumers.
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Transmission lines have three important properties:
- thermal capacity (maximum amount of power that can be send);
- resistance (affects the power loss over a transmission line); and
- impedance / reactance (governs how power flows through the network).
The electricity grid is truly an AC system; finding the optimal power flow involves solving a highly non-linear and non-convex system of equations.

Approximations can be made, reducing this to a linear system.
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This approximation has the following constraints:
- node-balance \((\text{generation} + \text{inflows} = \text{load} + \text{outflows})\);
- loop flow (Kirchhoff’s law); and
- flows must comply with thermal limits.
Economic Dispatch & Pricing

Three-node Dispatch (two lines)
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

Demand = 80MW

- 100MW @ $60/MWh
- 100MW @ $40/MWh

Demand = 80MW
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

LOWEST COST DISPATCH $= 80 \times $40 = $3200$
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

LOWEST COST DISPATCH = 80 × $40 = $3200

Demand = 80MW

(0MW) $40

(0MW) $40

(80MW) $40

(80MW) $40

Demand = 80MW
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

Demand = 80MW

(100MW @ $60/MW)

MAX: 40MW

(100MW @ $40/MWh)

MAX: 200MW

Demand = 80MW
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

NEW LOWEST COST DISPATCH = $40 \times 40 + 40 \times 60 = 4000$
Economic Dispatch & Pricing

Three-node Dispatch (two lines)

NEW LOWEST COST DISPATCH = 40 × $40 + 40 × $60 = $4000

Demand = 80MW

(40MW) — $60

(40MW) — $40

(40MW) — (40MW)
Economic Dispatch & Pricing

Three-node Dispatch (loop)
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demand = 100MW

33.33

33.33

66.67

33.33

Demand = 100MW
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demand = 100MW

(100MW)
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demands = 200MW

0

100

100

(100MW)

100

Demand = 200MW
Economic Dispatch & Pricing

Three-node Dispatch (loop)

MAX: 20MW

(100MW @ $40/MWh)

MAX: 200MW

(100MW @ $60/MWh)

MAX: 20MW

Demand = 80MW
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demand = 80MW

(60MW)  

(0MW)  

20  

20  

40  

Demand = 80MW
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Power Exchange Market
With Loop Flows
Demand = 80MW

(20MW)

20 – 6.67

20 + 13.33

40 + 6.67

Demand = 80MW
This is not the lowest cost solution!
Economic Dispatch & Pricing

Three-node Dispatch (loop)

LOWEST COST DISPATCH = 70 × $40 + 10 × $60 = $3400
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demand = 80MW

(100MW @ $40/MWh)

(100MW @ $60/MWh)

MAX: 200MW

MAX: 200MW

MAX: 200MW

Demand = 80MW

(100MW @ $60/MWh)

MAX: 200MW

MAX: 200MW

MAX: 40MW
Economic Dispatch & Pricing

Three-node Dispatch (loop)

Demand = 80MW

MAX: 200MW

MAX: 40MW

MAX: 200MW

(40MW)

(40MW)
Economic Dispatch & Pricing

Three-node Dispatch (loop)

LOWEST COST DISPATCH = 40 × $40 + 40 × $60 = $4000

Demand = 80MW
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## River Chains / Storage

### Summary of Resources

<table>
<thead>
<tr>
<th>Hydro Scheme</th>
<th>Capacity</th>
<th># Reservoirs</th>
<th># Stations</th>
<th>Owner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waikato</td>
<td>1,050 MW</td>
<td>8</td>
<td>9</td>
<td>Mercury</td>
</tr>
<tr>
<td>Tongariro</td>
<td>360 MW</td>
<td>1</td>
<td>2</td>
<td>Genesis</td>
</tr>
<tr>
<td>Tekapo</td>
<td>185 MW</td>
<td>1</td>
<td>2</td>
<td>Genesis</td>
</tr>
<tr>
<td>Waitaki</td>
<td>1,550 MW</td>
<td>6</td>
<td>6</td>
<td>Meridian</td>
</tr>
<tr>
<td>Clutha</td>
<td>760 MW</td>
<td>2</td>
<td>2</td>
<td>Contact</td>
</tr>
<tr>
<td>Manapouri</td>
<td>850 MW</td>
<td>1</td>
<td>1</td>
<td>Meridian</td>
</tr>
</tbody>
</table>
Within a river chain there are a number of interconnected reservoirs. Some of the reservoirs are large with weeks of storage, whereas others may have less than a day of storage. Therefore these electricity generators need to manage their water over multiple time-scales.
River Chains & Hydro-storage

Time-scales

Within a river chain there are a number of interconnected reservoirs. Some of the reservoirs are large with, weeks of storage, whereas others may have less than a day of storage. Therefore these electricity generators need to manage their water over multiple time-scales.

- Hourly: ensure that generators are operating at efficient levels, and the plants are ready to respond to contingency events (reserve).
River Chains & Hydro-storage

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- **Hourly:** ensure that generators are operating at efficient levels, and the plants are ready to respond to contingency events (reserve).
- **Daily:** ensure that water is positioned correctly within the river chain so that maximum generation can be achieved during peak periods.
River Chains & Hydro-storage

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- Hourly: ensure that generators are operating at efficient levels, and the plants are ready to respond to contingency events (reserve).
- Daily: ensure that water is positioned correctly within the river chain so that maximum generation can be achieved during peak periods.
- Seasonally: ensure that the overall amount of water in the reservoirs is sufficient to meet future demand.
River Chains & Hydro-storage

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- Daily: ensure that water is positioned correctly within the river chain so that maximum generation can be achieved during peak periods.
- Seasonally: ensure that the overall amount of water in the reservoirs is sufficient to meet future demand.

For all of these time-scales, the key risks are that water could get spilled or that a reservoir becomes effectively empty.
River Chains & Hydro-storage

JADE model of River Chains

JADE model network.

Huntly = 500 MW coal, 430 MW CCGT, 50 MW OCGT
NZ Controlled Storage and Risk Curve

Updated 17 Feb 2019

Nominal NZ Full (Lakes Taupo, Tekapo, Pukaki, Hawea, Te Anau & Manapouri)
River Chains & Hydro-storage
Simulated Trajectories

NZ Actual Controlled Storage and Risk Curve

Update: 11th December 2018

Actual storage courtesy of NZX Hydro
Nominal NZ full
(Lakes Taupo, Tekapo, Pukaki, Hawea, Te Anau & Manapouri)

Transpower NZ
In a system with a significant proportion of hydro-electric generation, such as New Zealand, it is critical to manage the storage carefully. This is done through water valuation.

Put simply, we should value water at the opportunity cost of water in future periods. Let us first consider two extreme situations.
River Chains & Hydro-storage
Hydro-thermal Scheduling

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Put simply, we should value water at the opportunity cost of water in future periods. Let us first consider two extreme situations.

– What should the value of water be if the reservoir is full?
– What should the value of water be if the reservoir is empty?

It is non-trivial to estimate the marginal water value for any other reservoir levels, since this will depend on: the time of year, projected future inflows, costs of other plants or demand response, etc.
Consider a single-node system, with three generators
– a hydro plant (700MW);
– a gas plant (400MW, w/ SRMC: $50/MWh); and
– a coal plant (250MW, SRMC: $80/MWh), and a VOLL of $1000/MWh.

Suppose we consider two periods (each one-hour long) with a constant demand of 1000MW.
Hydro-thermal Scheduling

Stylised Example

Consider a single-node system, with three generators
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– What should we do if we start with 1500MWh? What is the marginal water value?
Hydro-thermal Scheduling

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– What should we do if we start with 1500MWh? What is the marginal water value?
– What should we do if we start with 200MWh? What is the marginal water value?
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Suppose we consider two periods (each one-hour long) with a constant demand of 1000MW.

- What should we do if we start with 1500MWh? What is the marginal water value?
- What should we do if we start with 200MWh? What is the marginal water value?
- What should we do if we start with 600MWh? What is the marginal water value?
Hydro-thermal Scheduling
Marginal Water Values

Marginal Water Value

Storage at end of period (MWh)

$ / MWh

Period 2
Hydro-thermal Scheduling

Marginal Water Values

Marginal Water Value

$ / MWh

Storage at end of period (MWh)

0 500 1000 1500 2000

Period 2  Period 1
Hydro-thermal Scheduling

Marginal Water Values

Marginal Water Value

![Graph showing marginal water values over storage at the end of the period (MWh). The x-axis represents storage in MWh, ranging from 0 to 2000, and the y-axis represents cost in $/MWh, ranging from 0 to 1200. The graph includes three periods: Period 0 (gray), Period 1 (orange), and Period 2 (blue). The marginal water value is highest in Period 1, with a peak at around 500 MWh.]
Hydro-thermal Scheduling

More Realistic Scenario

In reality, future inflows are random, so we cannot be sure how much water we will have in the future, so we must consider the expected (average) opportunity cost, associated with using water now.

Typically, these models are run over a year, with a weekly time-step.

Figure 5.3 shows the convergence of the terminal marginal water value for the current scenario of the NZEM. Note how in the legend that Iterations 14 and 15 are coloured blue and red respectively but in Figure 5.3 a pink line is seen. This means the lines are directly on top of one another and the 1D approximation of the marginal water values are identical (implying convergence) for iterations 14 and 15.

The convergence of this criterion implies that the policy of the of the problem has converged. This is because the marginal water values for a given set of reservoir levels informs the hydro-thermal scheduling decision.

To summarise this section so far all three criteria have converged. The convergence of these criteria implies convergence of the infinite-horizon SDDP algorithm. The rest of this Section discusses how variation of the user chosen parameter $J$, (insignificantly) affects our three convergence criteria.

5.4 Expected Terminal Future Cost-To-Go Update Frequency

We chose to cache stage 1 cuts for 500 iterations of SDDP before determining the $\hat{\delta}$ to shift the new stage 1 cuts down by (then update $V_T^{(x)}$). As $J$ is the number of iterations of SDDP to run per 'outer loop' this means we have been setting $J = 500$. This choice for $J$ was chosen from the supervisor of this project's specialised knowledge of JADE and SDDP. Choices such as caching the stage 1 cuts for 200 or 1000 iterations of SDDP (or anything in-between) before determining the $\hat{\delta}$ may result in faster convergence of $\hat{\delta} \rightarrow \Delta$. Inspection on how the convergence of the other two criteria with the different choices of $J$ is also of interest.

The infinite-horizon model was run with $J = 100, 200, 320, 400, 500, 615, 800, \text{ and } 1000$. The total number of iterations pf SDDP was kept constant at 8000 iterations. Hence the number of iterations of the outer loop ($I$) also varied.

5.4.1 Terminal Future Expected Cost-To-Go Integral Convergence

The terminal cost integral converged for all cases. Recall from 5.2 that this implies the expected future terminal cost-to-go function has converged. However, the value of the terminal marginal integral for each case was different. This was expected because of initial (bad) values for $\hat{\delta}_i$ shift the expected future terminal cost-to-go function to different heights.
JADE output

End-of-year NZ Hydro Storage (GWh)

Scenario 1: Status Quo at Huntly

Scenario 2: Coal Shutdown

Scenario 3: Huntly Shutdown
Summary

Mathematical modelling and optimisation is used throughout the planning and operations of electricity systems.

In order to make the right decisions, we need to consider both long-, medium- and short-term uncertainties, around demand, and hydrology.

This afternoon, we will run interactive simulations of the economic dispatch model, and also consider hydro storage. These simulations will be in Labs 2 and 3 on Level 0, OGGB.