Modelling Generation Investment under Wind Induced Uncertainty

with Markov Decision Processes

Speaker: Athena Wu
EPOC, University of Auckland

Supervisors: Prof. Andy Philpott
Dr. Golbon Zakeri

EPOC Winter Workshop 2012

Motivation

- Traditional capacity planning and investment are based on economic costs and their merit order
  - Combining LDC and Screening Curves
  - The solution provided are optimal assuming all generations are "dispatchable".

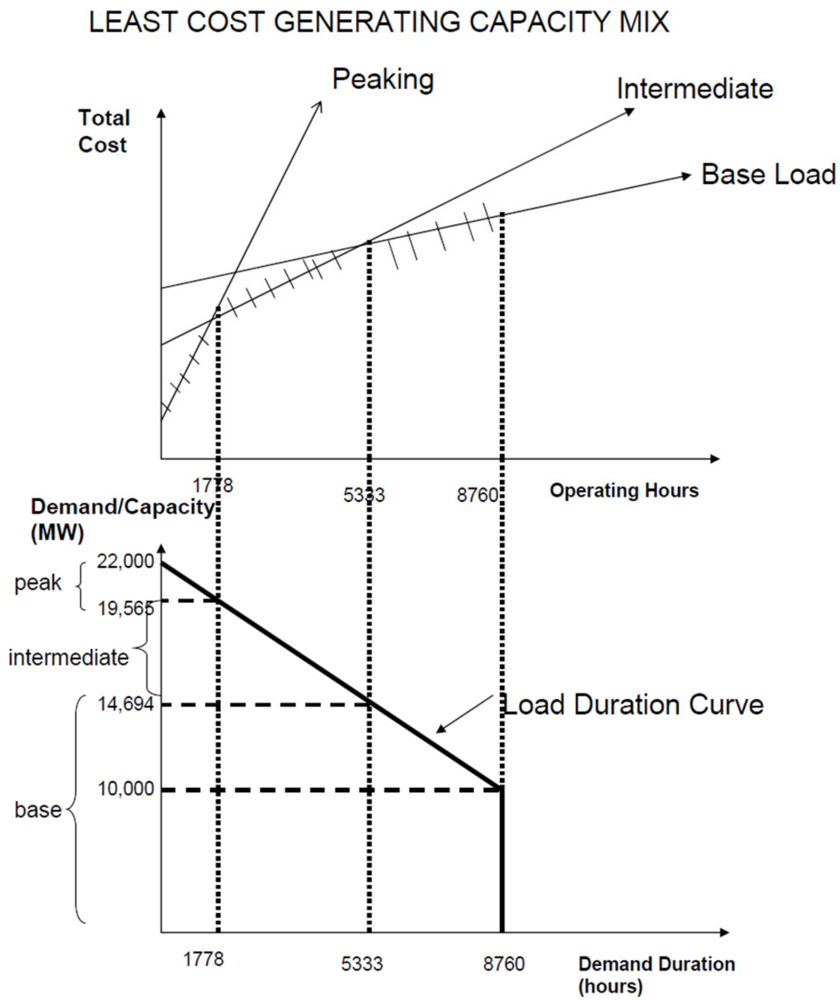
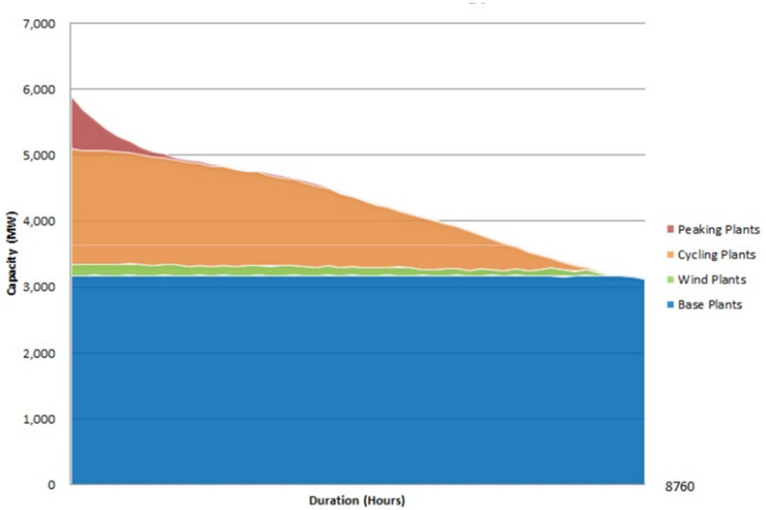
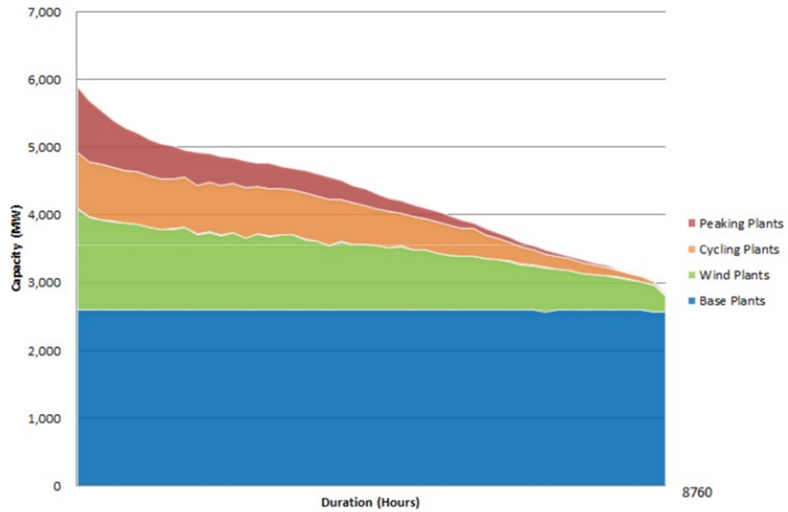


Figure 1 – Screening Curve example from Joskow 2006

Motivation

- However, the picture with high level of intermittent generation is very different





- Classical capacity planning models become problematic, as the dispatch facing high demand uncertainty is no longer according to merit order.
- Flexibility is the missing link

Motivation

- Alternative capacity expansion model that accounts for flexibility is required for an electricity system with higher wind generation

- **Today's talk:** Evaluating investment options using Markov Decision Processes (MDP)
  - A central planning model
  - Cost based investment planning

Overview

- Model Details
  - Modelling Demand Variation with Markov Chains
  - Finding Operating Policy using Markov Decision Processes
  - Modelling Investment options as a Mixed-integer Program
- Some Preliminary Results
  - Wind penetration with increase in demand variation
  - *and a comparison with screening curve results*
- Future Research

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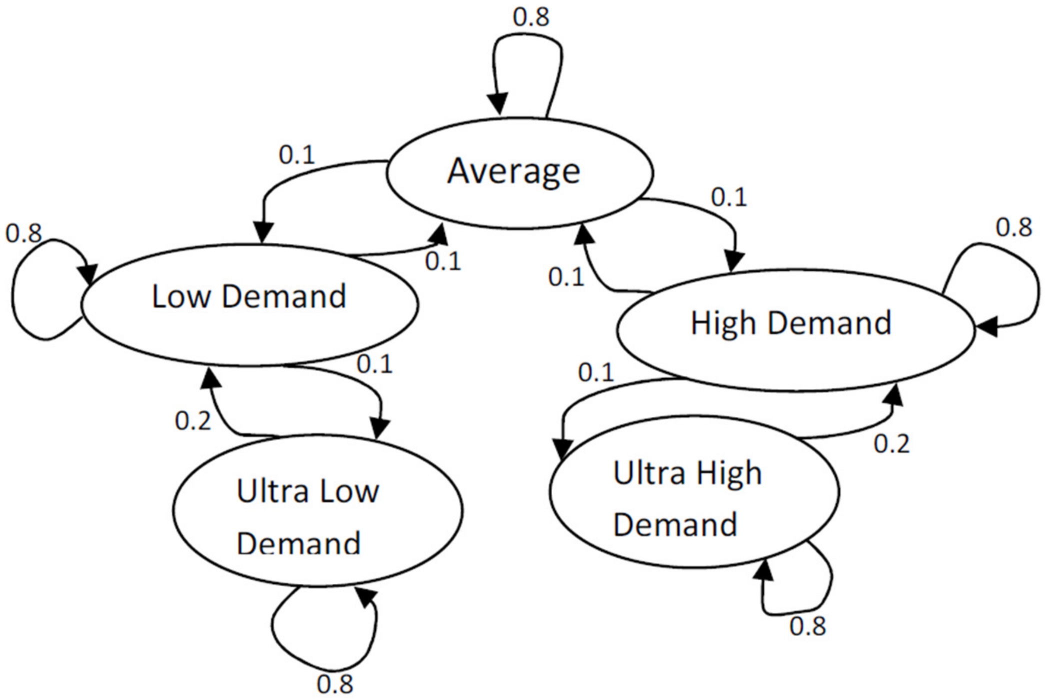
What's a Markov Chain?

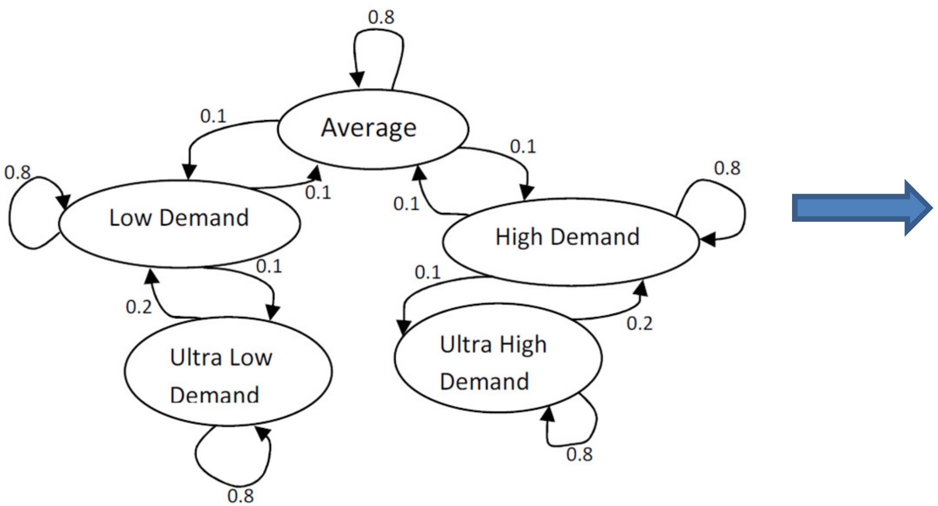
- A random process happens at discrete time intervals with state changes randomly between steps.



- The probabilities of next state changes are defined by transition matrices

Modelling Demand Variation with a Markov Chain Model

- Each period has a degree of variation from the period demand average (-2, -1, 0, 1, 2)



Base Case	-2	-1	0	1	2
-2	0.8	0.2	0	0	0
-1	0.1	0.8	0.1	0	0
0	0	0.1	0.8	0.1	0
1	0	0	0.1	0.8	0.1
2	0	0	0	0.2	0.8

- Demand variation transition matrices for the same period of day looks different depending on the wind scenario

High Wind Penetration	-2	-1	0	1	2
-2	0.6	0.3	0.1	0	0
-1	0.1	0.4	0.4	0.1	0
0	0.05	0.15	0.6	0.15	0.05
1	0	0.1	0.4	0.4	0.1
2	0	0	0.1	0.3	0.6

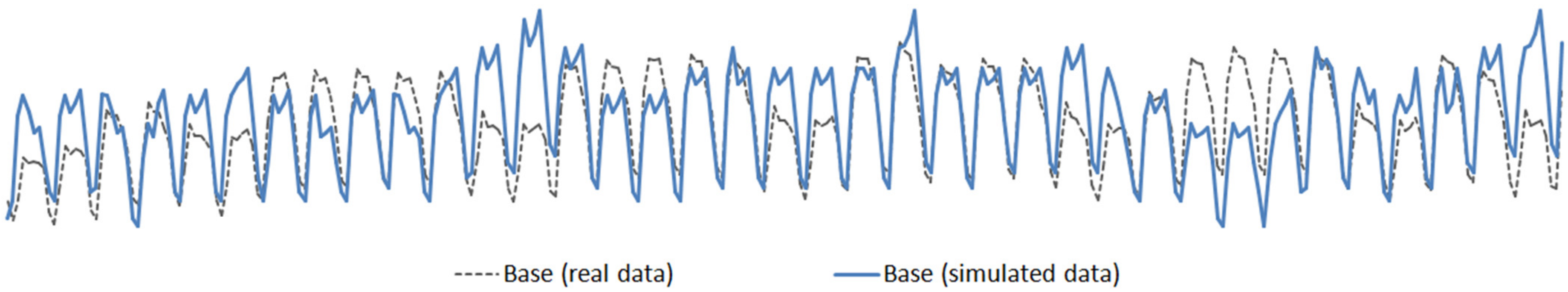
Modelling Demand Variation with a Markov Chain Model

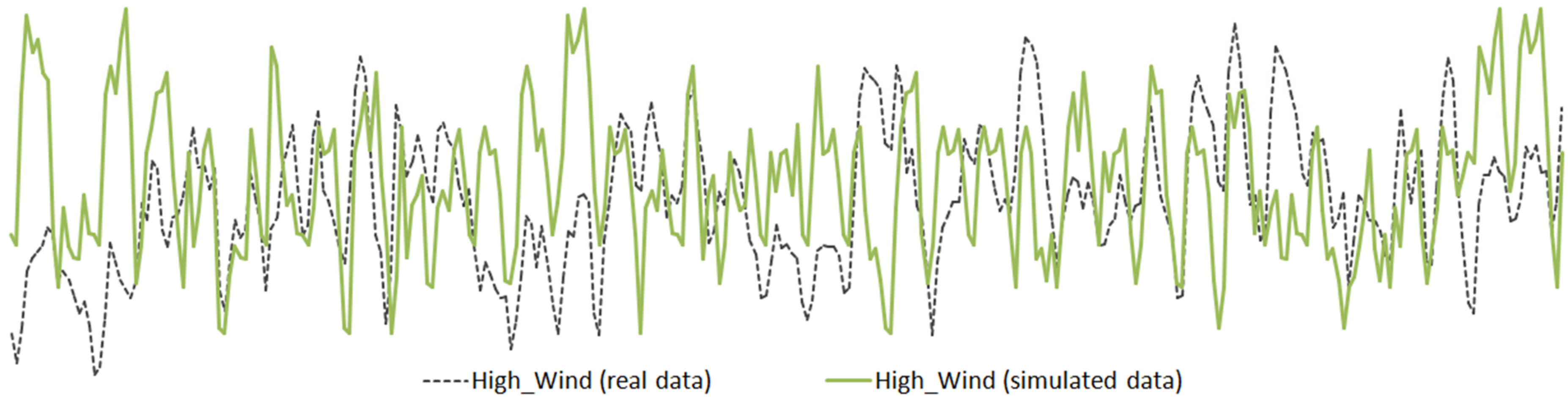
– Time-inhomogeneous Markov Chain

- 8 X 3-hour periods in a day

		1					2					3					4					5					6					7					8				
		-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2	-2	-1	0	1	2
1	-2	-	-	-	-	-	0.83	0.11	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	-	-	-	-	-	0.18	0.57	0.22	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	-	-	-	-	-	0.25	0.49	0.27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	-	-	-	-	0.01	0.20	0.68	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	0.02	-	0.16	0.82	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-2	-	-	-	-	-	-	-	-	-	-	0.85	0.09	0.06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	-	-	-	-	-	-	-	-	-	-	0.37	0.08	0.36	0.18	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	-	-	-	-	-	-	-	-	-	0.31	0.07	0.16	0.26	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	-	-	-	-	-	-	-	-	0.05	0.14	0.05	0.32	0.44	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	0.07	0.02	0.91	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.58	0.30	0.10	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.53	0.33	0.10	0.03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.30	0.51	0.18	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	0.47	0.44	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	0.46	0.49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.84	0.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.07	0.69	0.24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.11	0.56	0.33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	0.17	0.64	0.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	0.34	0.64	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.86	0.14	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.20	0.69	0.11	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.16	0.59	0.25	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.17	0.63	0.21	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	0.67	-	-	-	-	-	-	-	-	-	-
6	-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.85	0.13	0.02	-	-	-	-	-	-	-
	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.33	0.30	0.24	0.13	-	-	-	-	-	-
	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.11	0.29	0.27	0.31	0.03	-	-	-	-	-
	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	0.15	0.25	0.23	0.36	-	-	-	-	-
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	0.96	-	-	-	-	-
7	-2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.40	0.51	0.09	-	-
	-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.03	0.51	0.42	0.04	-
	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.25	0.36	0.39	-
	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.14	0.50	0.34	0.02
	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	0.09	0.46	0.45
8	-2	0.80	0.17	0.03	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-1	0.06	0.68	0.24	0.02	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0	-	0.24	0.55	0.21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	1	-	-	0.26	0.66	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	2	-	-	-	0.17	0.83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Simulated Demand with Markov Chain Modelled Variation





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- Model Details
  - Modelling Demand Variation with Markov Chains
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  - *and a comparison with screening curve results*
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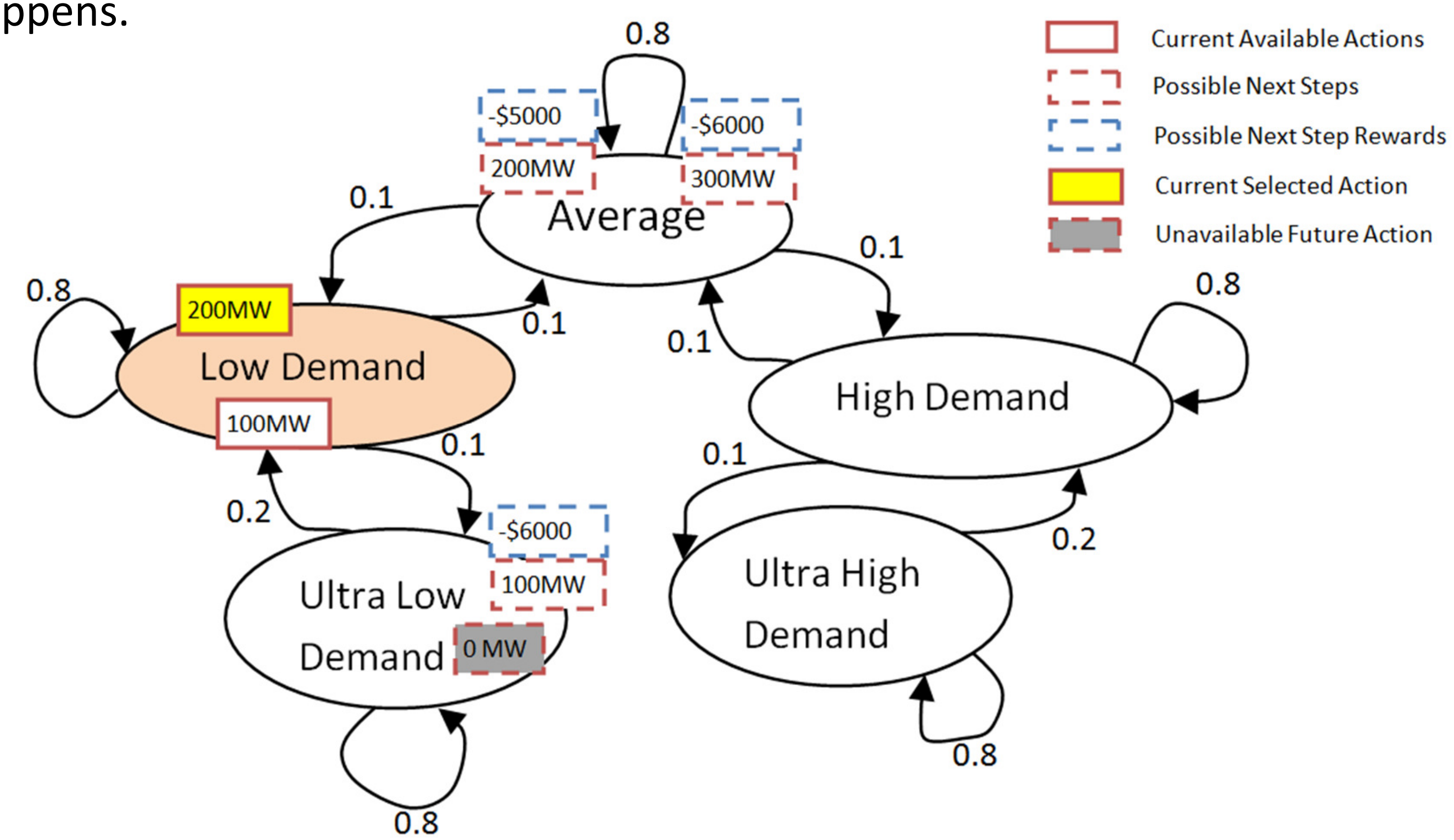
Short-term Operation as MDP

- Short-term operation of electricity plant can be modelled as an **average reward Markov Decision Process (MDP)**

- The Basic Idea of Average-reward MDP
  - To find an optimal policy for decision maker to operate in a Markov Chain environment that maximise the average reward per period in the long-run.

What’s a Markov Decision Process?

- At each time interval, a decision needs to be made before the next random event happens.



- A cost or reward is associated with each (state transition, action) combination.
- The average reward is a combination of decision policy and MC transition matrix

Inputs for Average-reward MDP (1)

- **States**
  - time periods (x8), demand variation levels (x5), previous period's operating state (x N discrete levels)
- **Actions**
  - Available actions are dependent on previous operating levels (defined via ***flexibility matrix*** that restricts ramping)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1

Inputs for Average-reward MDP (2)

- **Transition probabilities**
  - MC transition matrices shown in previous section
- **Rewards**
  - Negative cost functions calculated using:
    - Demand: net of wind and base load
    - Fixed and variable costs of generation

Cost Type	*Base*	*Ramping*	*Peak*	Demand Reponse / Lost Load
Fixed Cost (ann. $k /MW)	400	200	100	0
Variable Cost ($/MWh)	30	70	150	3000

    - Each (state transition, action) pair has a reward calculated (another very large matrix)
    - Actions are restricted by flexibility matrix (20% ramping)
    - Any remaining demand is filled by peak (and/or lost load)

Solving the Average-reward MDP

- Decision variables are operating rules of ramping plants at each state
- The model can be formulated as a Linear Program

$$\max_{x} \sum_{i\in I, k\in K(i)} r_i^k x_i^k$$

s.t.

$$\sum_{k\in K(i)} x_i^k - \sum_{j\in I, k\in K(j)} p_{ji}^k x_j^k = 0 \quad ,\forall i \in I$$

$$\sum_{i\in I, k\in K(i)} x_i^k = 1$$

$$x_i^k \geq 0 \quad \forall i \in I, k \in K(i)$$

- For more details:
  - refer to: D. J. White, *Markov Decision Processes* 1994

Outputs from Average-reward MDP

- The **optimal reward** per period
- AND the **optimal decision policy** looks like this:

			Level of Previous Operation														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Periods	1	-2	-	-	4	4	4	4	4	5	6	-	-	-	-	-	-
		-1	-	-	5	5	5	5	5	5	6	-	-	-	-	-	-
		0	-	-	6	6	6	6	6	6	6	-	-	-	-	-	-
		1	-	-	6	7	8	9	9	9	9	-	-	-	-	-	-
		2	-	-	6	7	8	9	10	11	12	-	-	-	-	-	-
	2	-2	-	-	-	1	2	3	-	-	-	-	-	-	-	-	-
		-1	-	-	-	7	8	9	9	9	9	9	9	9	-	-	-
		0	-	-	-	7	8	9	10	11	12	-	-	-	-	-	-
		1	-	-	-	-	8	9	10	11	12	13	14	15	-	-	-
		2	-	-	-	-	-	9	10	11	12	13	14	15	-	-	-
	3	-2	4	5	6	-	-	-	6	6	6	7	8	9	10	11	12
		-1	4	5	6	-	-	-	10	11	12	12	12	12	12	12	12
		0	4	5	6	-	-	-	10	11	12	13	14	15	15	15	15
		1	-	-	-	-	-	-	10	11	12	13	14	15	15	15	15
		2	-	-	-	-	-	-	10	11	12	13	14	15	15	15	15
	4	-2	-	-	-	2	2	3	4	5	6	7	8	9	-	-	-
		-1	-	-	-	3	3	3	4	5	6	7	8	9	10	11	12
		0	-	-	-	7	8	9	10	11	11	11	11	11	11	11	12

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MDP based Mixed-integer Program for Investment Options

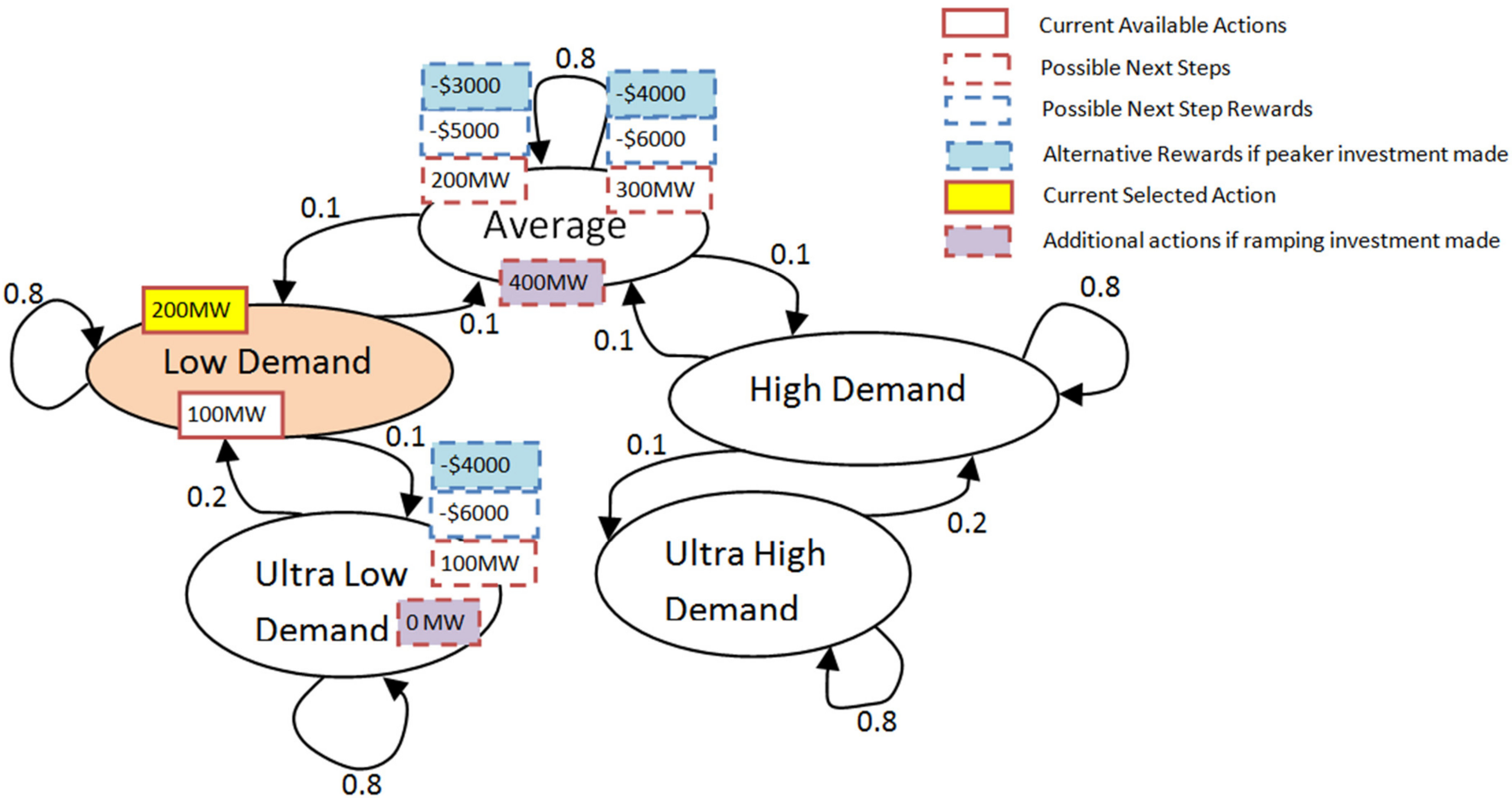
- The linear program used to solve for optimal operation policy can be augmented by binary variables defining investment actions, leading to a mixed-integer program.
- Two types of Investment Options :
  - Ramping plant options gives ***multiple flexibility matrices***

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
7	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-	-
10	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-	-
17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1
19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1	1
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	1

  - Different peaking plant options generates ***multiple reward matrices*** for all (state, action) combinations – *too big to show…*

MDP based Mixed-integer Program for Investment Options



MDP based Mixed-integer Program for Investment Options

- The formulation gets a bit more complex…

$$\max_x \sum_{h\in H} \sum_{i\in I, k\in K(i)} r_i^k(h) x_i^k(h) + \sum_{g\in G} T_g z_g$$

s.t.

$$\sum_{k\in K(i)} x_i^k(h) - \sum_{j\in I, k\in K(j)} p_{ji}^k x_j^k(h) = 0 \quad ,\forall i\in I, \forall h\in H$$

$$\sum_{i\in I, k\in K(i)} x_i^k(h) = 1,$$

$$x_i^k(h) \le \left(\sum_{g\in G} z_g U_g \right)_i^k, \forall i\in I, k\in K(i), \forall h\in H$$

$$z_g \in \{0,1\} \qquad \sum_{g\in G} z_g = 1$$

$$w_g \in \{0,1\} \qquad \sum_{h\in H} w_h = 1$$

$$x_i^k(h) \le w_h, \forall i\in I, k\in K(i), \forall h\in H$$

$$x_i^k(h) \ge 0 \quad \forall i\in I, k\in K(i), \forall h\in H$$

- *For more information, look out for coming paper on our EPOC website.*

Overview

- Model Details
  - Modelling Demand Variation with Markov Chains
  - Finding Operating Policy using Markov Decision Processes
  - Modelling Investment options as a Mixed-integer Program
- Some Preliminary Results
  - Wind penetration with increase in demand variation
  - *and a comparison with screening curve results*
- Future Research

Scenarios and Assumptions

- **Case 1: Base**
  - Very minimal wind energy and the demand variation caused by wind is not significant enough from the normal demand variation caused by loads/users

- **Case 2: High Wind Penetration**
  - Growth in wind generation is able to satisfy the growing energy demand (i.e. the net LDC after deducting wind requires the same energy as Base Case)
  - The penetration of wind, however, increased the variation of demand by 25%

- Common Assumptions
  - Plan for investment for intermediate and peaking demand only
  - Ramping operate at 50 discrete levels; Peakers operate at continuous levels
  - Flexibility constraints for ramping plant is 20% of invested capacity
  - Fixed and Variable costs of plant types are as below:

Cost Type	*Base*	*Ramping*	*Peak*	Demand Reponse / Lost Load
Fixed Cost (ann. $k /MW)	400	200	100	0
Variable Cost ($/MWh)	30	70	150	3000

The Impact of Increasing Wind Variation on Investments

- MIP results for the two cases:

1. *Base Case (wind contribution low, have minimal effect on demand variation)*

	Theoretical Results				50 Simulations of 2920-period (one year) sequences				Dmd Response
Model	Base	Ramping	Peak	Cost per Period	Average	s.e.	Min	Max	Average (hrs)
Screening Curve	4,217	776	656	$ 153,935	$ 235,554	$ 7,938	$ 213,200	$ 253,869	405
MDP model	4,217	**600**	**840**	**$ 195,042**	$ 193,208	$ 6,739	$ 173,873	$ 204,980	135

2. *Higher Wind Penetration (wind sequence adds 25% variance on demand)*

	Theoretical Results				50 Simulations of 2920-period (one year) sequences				Dmd Response
Method	Base	Ramping	Peak	Cost per Period	Average	s.e.	Min	Max	Average (hrs)
Screening Curve	4,183	994	528	$ 173,664	$ 344,371	$ 20,880	$ 310,057	$ 402,543	1,439
MDP model	4,183	**700**	**840**	**$ 220,050**	$ 223,107	$ 8,828	$ 203,548	$ 241,666	9

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  - Not enough capacity planned
  - Results in high number of demand response hours

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  - Not enough capacity planned
  - Results in high number of demand response hours
- MDP model investments & policies perform much better in simulation
- MDP tend to invest in less 'Ramping' and more 'Peaking' plants

Comments on the Results

- Wind changes the picture, traditional capacity planning methods needs to be challenged

- MDP is one way to take generation flexibility into account, and get insights of supply mix required to supplement a system with more intermittency

- With higher wind penetration and the increased demand variability caused, more flexibility is required to supply the system reliably – peakers are not valued enough

- How do we price flexibility in a pool market?

Future Research

- Locational Model
  - Generation as well as transmission planning
  - Spatial dependence of wind
- Time-staged Investment
  - GEMSTONE (Girardeau-Philpott)
- Hydro (New Zealand context)
  - The current MDP model is for a generic thermal dominated system
  - What if we can use hydro as peaker to supplement wind?
    - Merit order dispatch won't work
    - Need to price flexibility into dispatch model too