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The Optimal Charging Schedule of Energy Storage : Lessons from Data Networking

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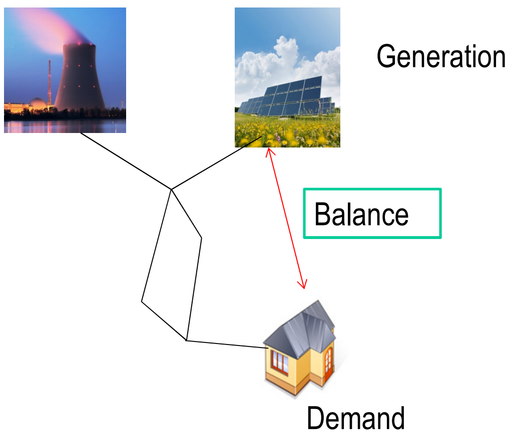
Supervised by: Dr. Lachlan Andrew & Dr. Hai Vu

Demand Management



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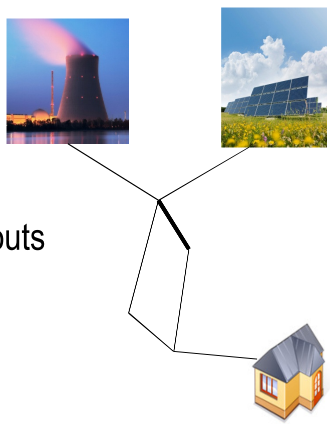
Demand Management

- Demand can change rapidly
- Peak demand has increased up to 30% from 1999 to 2010[1]
- Generators need to keep up with this demand

1.National Electricity Market, 2010, [online] Available: http://www.accc.gov.au/content/item.phtml?itemId=961581&nodeId=8d9cbc63c61c99def2e544adb08cad6d&fn=Chapter%201%20National%20Electricity%20Market.pdf

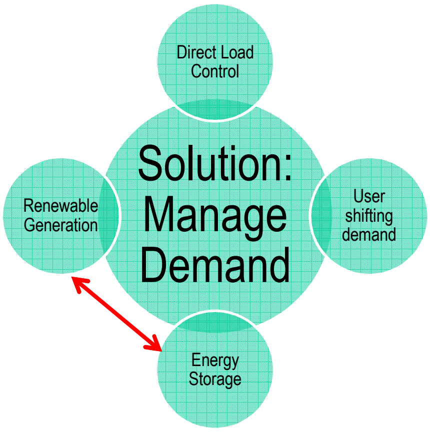
Results of increase in demand

- Increase in electricity prices
- Strain on the grid



- Possible blackouts

Demand Management



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Renewable Energy

- Renewable energy is intermittent
- Solar and wind generated affected by weather
- At times not able to keep up with committed generation

20% increase in South Australia[2]

2.South Australian Supply and Demand Outlook, Australian Energy Market Operator, 2011, [online] Available: http://www.aemo.com.au/en/Electricity/Planning/2011-South-Australian-Supply-Demand-Outlook/~/media/Files/Other/planning/SASDO2011/documents/SASDO2011%20pdf.ashx

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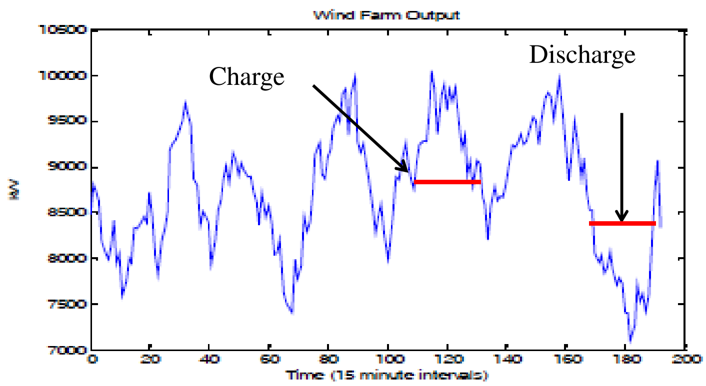
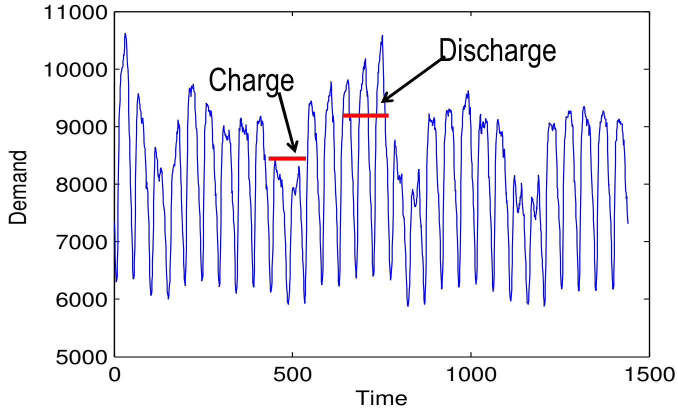
Energy Storage - Renewables

Energy storage

Energy Storage - Renewables



Energy storage- Manage Demand



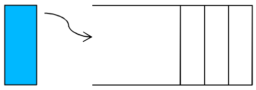
Outline

- Data Networking and Storage
- Model
- Tools to solve optimisation
- Structural Results
- Peak Shaving-Case Study
- Ongoing Work

Queuing and Storage

Queuing

- Packet arrivals and departures



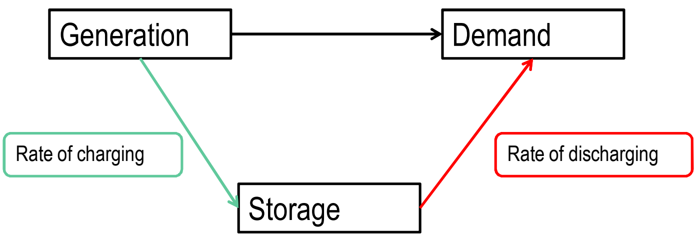
- Control arrivals –TCP congestion control
- Departure rate shaped by priority type QoS
- Optimal size of queues

Energy Storage

- Charging and Discharging power

- What rate to charge? and when?
- What rate to discharge and when?
- Optimal size of energy storage

Energy Storage System(ESS)



Storage schedule- Literature

- Alvin C. Fu, et al. "Optimal energy allocation and admission control for communications satellites". *IEEE/ACM Trans. Netw.*,2003.

- Balance energy consumption and demand for communication satellite
- Chooses how much demand to service for a given time slot
- Dynamic programming to optimise satellite energy allocation
- The optimal policy is a threshold policy

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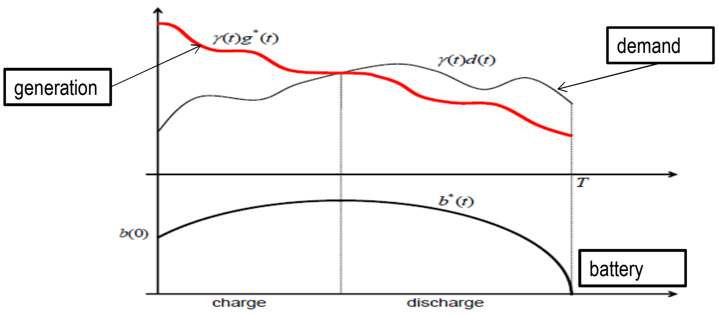
Structure of Optimal Policy-Literature

- K. Chandy, et al. "A simple optimal power flow model with energy storage," in *Decision and Control (CDC), 2010 49th IEEE Conference on, December 2010.*
  - ☐ Finds structural properties of charging schedule
  - ☐ Dynamic programing to solve optimisation



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Optimal Policy of ESS -Literature

- I. Koutsopoulos, et al. "Optimal energy storage control policies for the smart power grid," in *Smart Grid Communications,2011 IEEE International Conference* .
- Utility side optimal energy storage control
- Objective: Minimise long term average operational cost

$$\text{totalcost} = \min \sum_{t=1}^{\infty} \beta^{t} \text{cost(power drawn(t))}$$

- Inflation of electricity prices
- Uses Dynamic Programing to solve optimisation

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Research Question

- What is the long term optimal charging schedule for energy storage given arbitrary price increase?
  - ☐ How to optimise the use of energy storage?
  - ☐ What happens if we have rapid increase in prices?
  - ☐ How far into the future should we look ahead?
  - ☐ What is the structure of the charging schedule?

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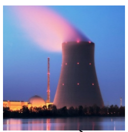
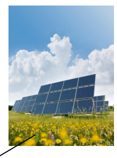
Objective

$$\text{Min} \sum_{t=1}^{\infty} \gamma(t) \text{Cost}(\text{generation}(t))$$

$\gamma(t)$ = time varying prices

Model for Long-term Charging Schedule

- Model:

$$\text{Min} \sum_{t=1}^{\infty} \gamma(t)\text{Cost}(\text{generation}(t))$$

convex

Subject to:

generation(t) = battery(t) – battery(t-1) + demand(t)

B≤ battery(t) ≤ 0

generation(t) ≥ 0

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But we can't solve for infinite horizon

- Cost per stage unbounded
- Increasing prices- $\gamma(t)$ grows rapidly
- Total cost does not converge
  - Total cost = ∞
- Can't get the minimum cost
- Need to reformulate the model

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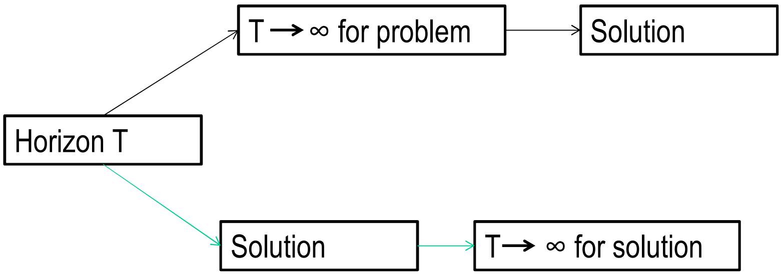
Solution Approach



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Reformulated Model

$$\text{Totalcost} = \min \sum_{t=1}^{T} \gamma(t)\text{Cost}(\text{generation}(t))$$

Subject to:

generation(t) = battery(t) – battery(t-1) + demand(t)

B≤ battery(t) ≤ 0

generation(t) ≥ 0

battery(T) = bf,

Where ‘bf∈ [0,B]’ is the terminal battery level

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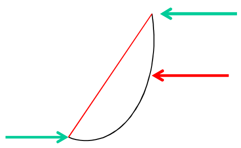
Convexity

- Our generation cost is Convex



⟶ Local optimum is also global optimum

- Can use "Lagrange duality" to find structure

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Lagrange Duality

- Augment weighted sum constraints with objective

L(x,λ) = objective(x) + λ * constraints

- The dual function is given by the lower bound of L(x, λ)
- Primal: minimise with respect to x
- Dual : maximise with respect to λ

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Lagrange Duality

- If problem is convex:

solution of primal = solution of dual

- Optimal solution satisfies the KKT conditions

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KKT(Karush-Kuhn-Tucker) conditions

- Stationarity : $\nabla L(x,\lambda) = 0$
- Complementary slackness:
  - λ * constraints(x)= 0
  - where $\lambda \geq 0$
- Feasibility: λ & x must be "in bounds"

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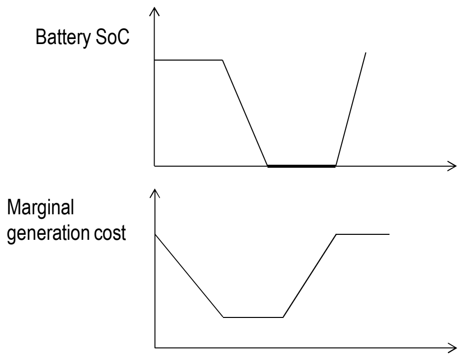
Optimal policy of model

- Marginal generation is the change in total cost when the amount of generation increases by a unit amount



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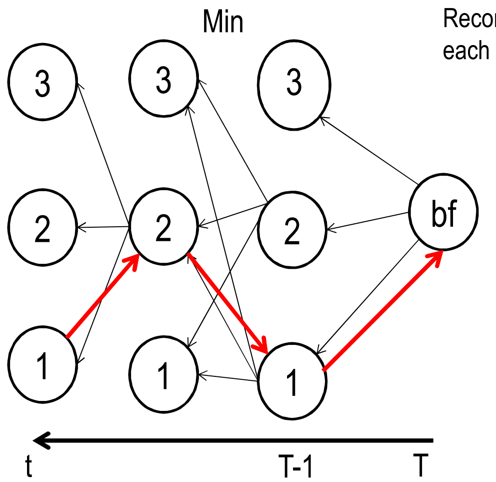
Dynamic programing(DP)

- Finds the minimum cost by breaking down a large problem into multiple sub problems
- Finds tail sub problem first
- Extend problem: Find optimal policy backwards
- Path based on the sum of the present cost and expected future cost

Dynamic Programming



Record the cost at each recursion

Routing- Bellman-Ford

- Uses Dynamic Programming to get shortest path
- Routers are viewed as nodes in a network graph
- Advertises its path metrics to other neighbouring routers
- Shortest path: Own path metric & received path metric

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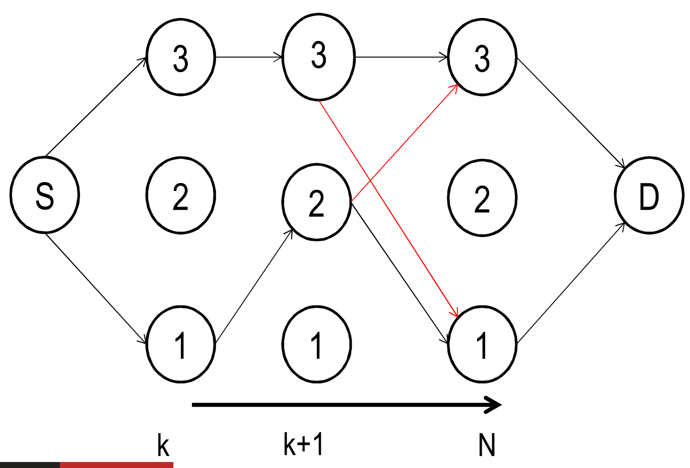
Routing- Bellman-Ford



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Viterbi – Application of DP

- Viterbi find the most likely path for a sequence of events
- Used in detecting sequential error codes and for speech and character recognition
- A finite state machine that finds the maximum likely noiseless path
- Finds the sequence of symbols closest to the received symbols recursively

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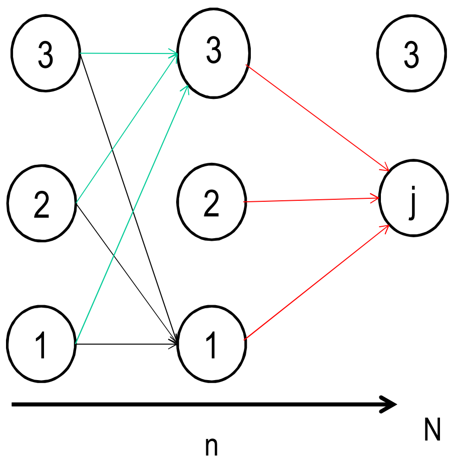
Viterbi



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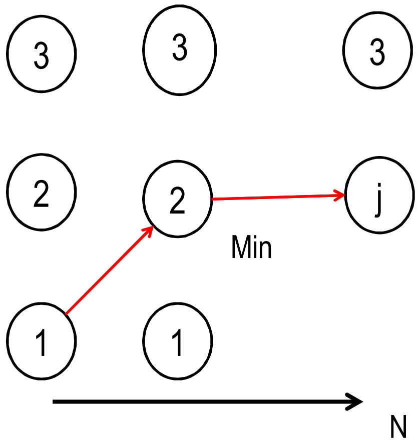
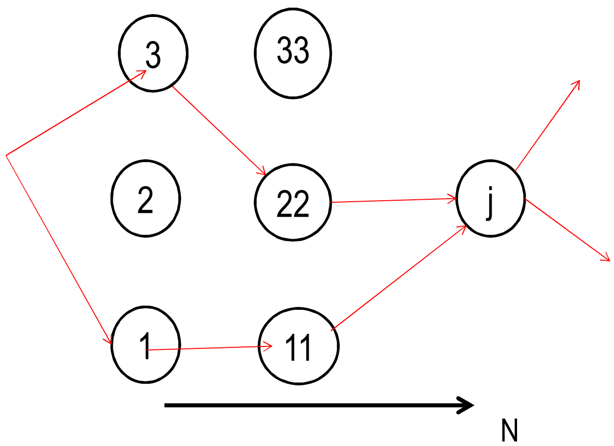
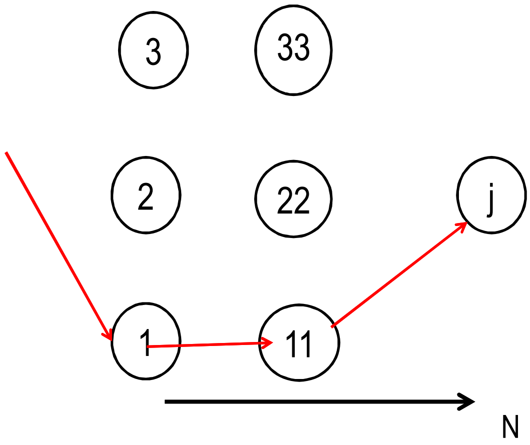
Viterbi



Viterbi-Convergence



Viterbi-Convergence



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- **Structural Results**
- Peak Shaving-Case Study
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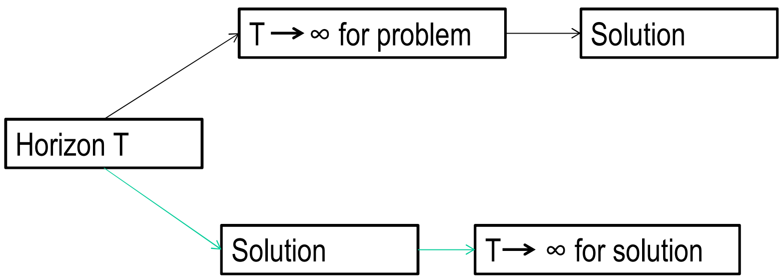
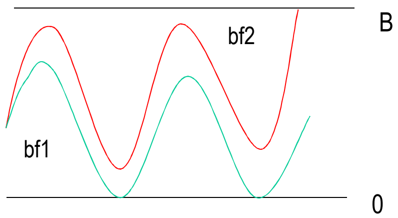
Solution Approach



First Key Result

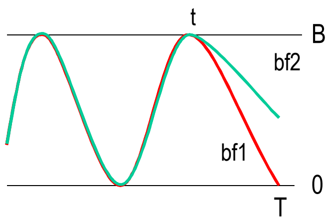
- The structure of the charging schedule is well defined



- bf1 < bf2
- Monotonic in the terminal battery level “bf”.

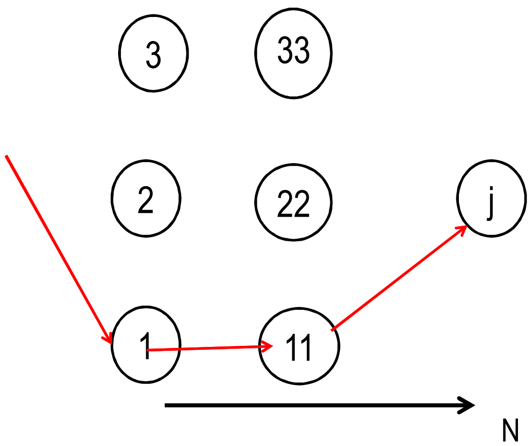
Key Result

- If all optimal paths converge at some time t, then any point before t will follow the same path

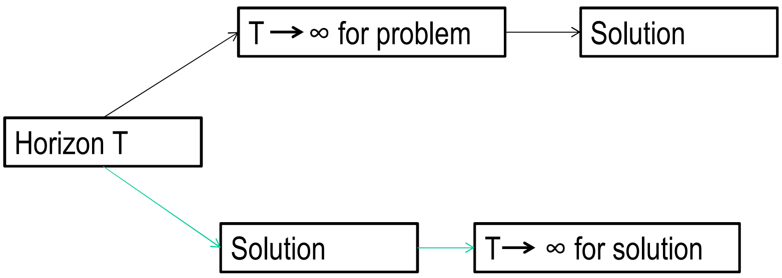


- ☐ DP states that any point having a common convergence point and initial state will have the same optimal path
- ☐ Same as Viterbi algorithm

Viterbi-Convergence



Solution Approach



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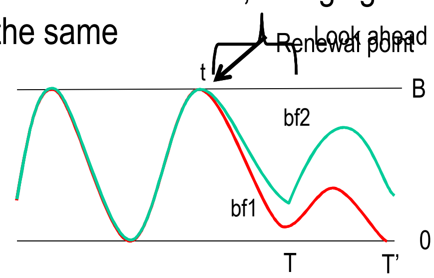
Second Key Result

- Even if the horizon is extended, charging schedule till “t” will be the same



- bf1 =0 saturating above
- bf2 =B saturating below

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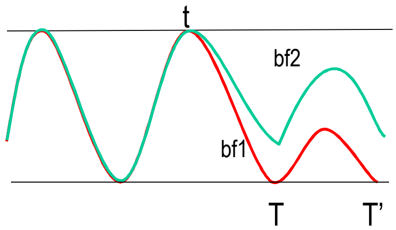
What do the results mean

- The price & demand beyond the look ahead will not affect the charging before time "t"
- Time "t" is called a renewal point for the battery

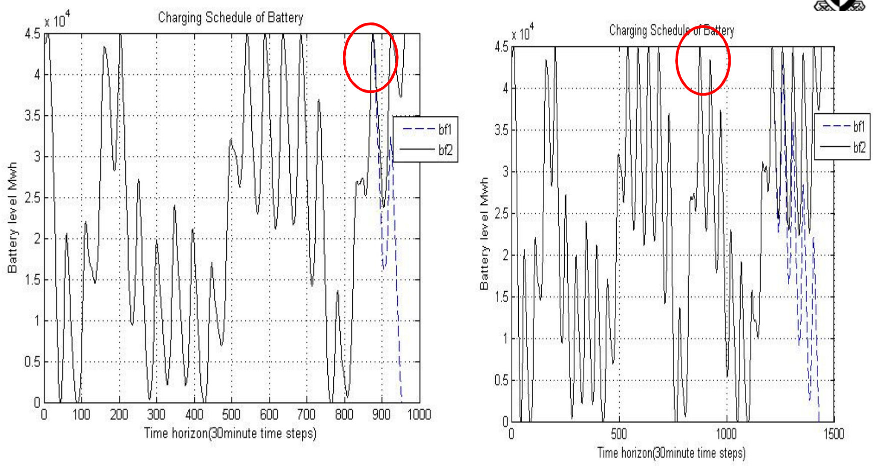


Numerical results

- Using DP we have proved that renewal points exist
- NSW demand data from Australian Energy Market Operator(AEMO)[3] for the month of March 2012

Price increase per year	20%	20%
Battery Capacity	45MW	45MW
Number of Days	20	30

Renewal points- Numerical example



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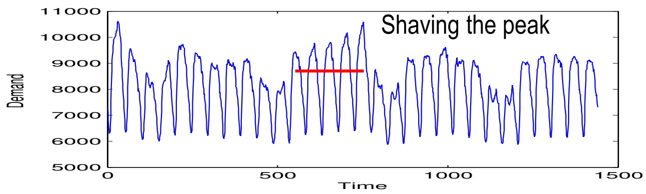
Peak Shaving-Case Study

- Generation has to satisfy demand
- By shifting peak demand to low demand periods
- Store energy during low peak periods and supply during peak demand periods



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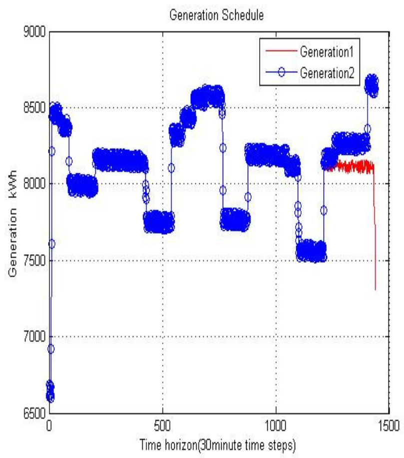
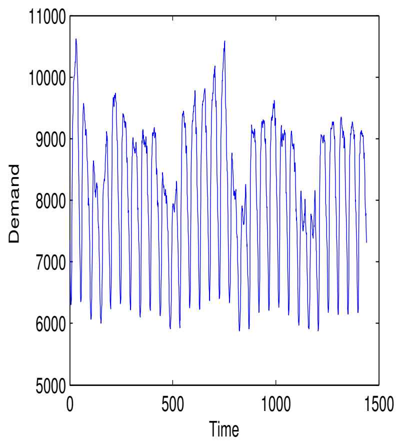
Results for peak shaving





Price increase per year	20%
Battery Capacity	45MW
Number of Days	30

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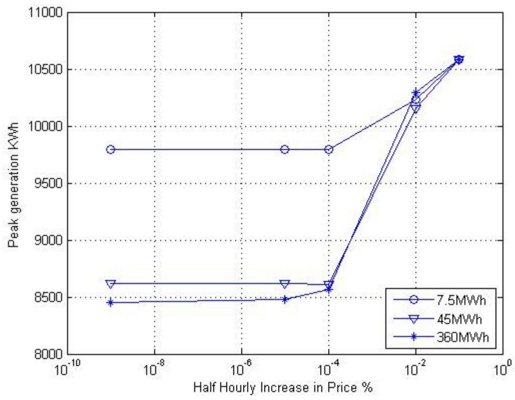
Peak shaving with rapid price increase



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Ongoing Research

Theoretical

- Model of fully efficient storage
- Structure of fully efficient energy storage
- Model of storage with inefficiencies

Numerical

- Structure of Fully efficient energy storage
- Structure of Inefficient energy storage
- Peak shaving for both models

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Summary

- Presented a model for an energy storage system
- Alternative formulation to solve the infinite total cost problem
- Found structural properties of the formulate model
- Use dynamic programming to solve the problem
- Applied the results to a case study on peak shaving

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QUESTIONS?

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