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Demand-side Management over a Finite Time Horizon in a Co-optimized Energy and Reserve Market

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   - Decomposition
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Motivation

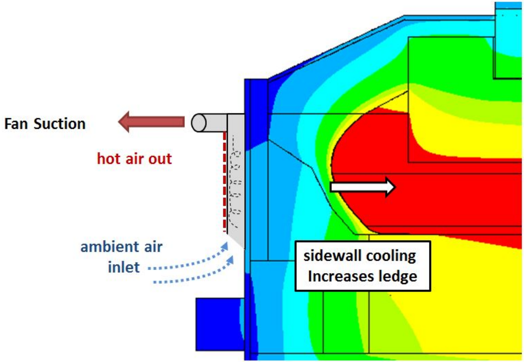
- In deregulated electricity markets, industrial consumers of energy may choose to purchase electricity from the wholesale market.
- The average wholesale prices is lower than the retail price, but with high volatility.
- In order to reduce the risk of high price fluctuations major consumers can use price-responsive consumption strategies.
- Our focus in this talk is on industrial demand response in the New Zealand Electricity Market (NZEM).

New Zealand Electricity Market

- NZEM works as a uniform pricing auction with locational marginal pricing, at 285 nodes.
- NZEM has a co-optimized energy and reserve market.
- NZEM has several large consumers that together use up to 35% of generated electricity.
- Large consumers have dispatchable demand and can offer Interruptible Load Reserve (ILR).
- New Zealand Aluminium Smelter at Tiwai point uses approximately one third of the total power of the South Island and 15% of the total power countrywide (up to 610MW).

Consumption Flexibility

- For aluminum smelters there are limitations on consumption.
- Shell Heat Exchanger is a new technology that is developed in UoA.
- SHE provides the cells with forced cooling/insulation equipment.



- SHE allows NZAS to respond to high and low prices of electricity via its flexibility in changing consumption levels in different time periods.

Strategic Demand Response

- We focus on tools to assist major electricity users with consumption and reserve offer decisions.
- Given the hockey stick nature of the stacks, response to price saves on the cut back part but also reduces price for the amount that is consumed.

- The primary formulation is a bi-level optimization problem.

Maximize [Consumer's Profit]

Subject to:

[Consumer's Consumption and ILR Constraints]

vSPD:

Maximize [Social Welfare]

Subject to: [Node Balance Constraints]

[Reserve Constraints]

[Network Constraints]

[Generation/Demand Constraints]

Bi-level Optimization

Strategic Consumer

- The single node equivalent is:

$$
\begin{aligned}
\text{Maximize} \quad & u(q^c) - q^c.\pi^e + q^{ILR}.\pi^r \\
\text{s.t:}\ & 0 \leq q^c \leq C^c \\
& 0 \leq q^{ILR} \leq C_r \\
& q^c - q^{ILR} \geq V \\
& \text{Max.} \quad \sum_{i \in I} p_i^c x_i^c - \sum_{j \in J} p_j^g x_j^g - \sum_{k \in K} p_k^r x_k^r \\
& \qquad \text{s.t.} \quad \sum_{i \in I} x_i^c = \sum_{j \in J} x_j^g - q^c \quad [\pi^e] \\
& \qquad\qquad R - \sum_{k \in K} x_k^r = q^{ILR} \qquad [\pi^r] \\
& \qquad\qquad \text{[Tranche and Bathtub Constraints]}
\end{aligned}
$$

Mixed-Integer Problem

Strategic Consumer

- We use KKT conditions of the dispatch problem, as well as big-M parameters to reformulate our bi-level problem to a MIP.
- We define our MIP in a generic form at time period t as below:

$$[\text{MIP}]_{t,v} \quad \max \Pi_t(\mathbf{x}_t) = vx_t - \mathcal{C}_t(\mathbf{x}_t)$$
$$\text{s.t. } \mathbf{x}_t \in \mathcal{S}_t$$

- Here $\mathbf{x}_t$ is a vector of decision variables at time t (in our model it consists of consumption and ILR), and x_t is the consumption level at time t.
- v is the value of consuming one unit of electricity, and $\mathcal{C}_t$ is the cost function at time t.

Stochastic Solution

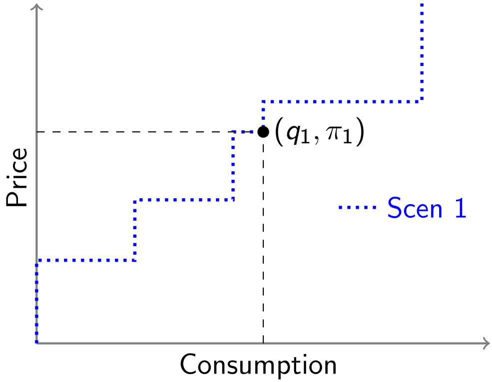


Figure: Optimal single scenario bid.

Stochastic Solution

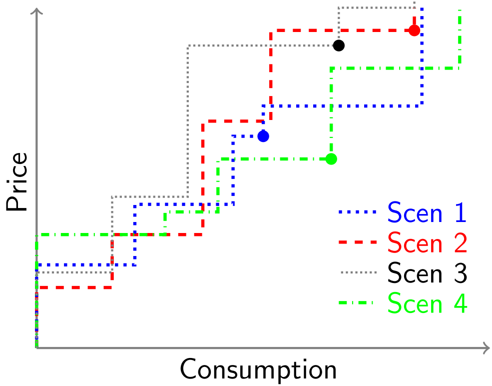


Figure: Optimal wait-and-see bids.

Stochastic Solution

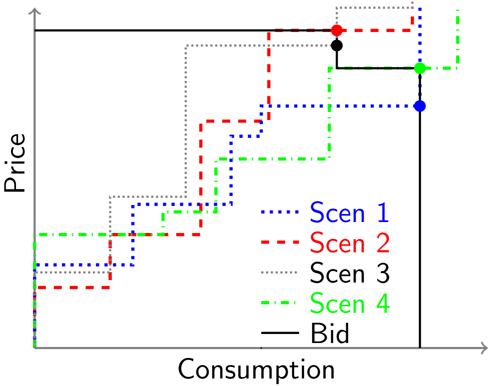


Figure: Optimal monotone bid.

Problem Size

Strategic Consumer

- The deterministic single stage problem ($[\text{MIP}]_t$) has over 15,000 constraints and 2000 binary variables.
- Using standard reformulation methods, we can solve a stochastic version $[\text{S-MIP}]_t$, where we optimize the strategic consumer's actions towards multiple scenarios and demand and generation offers.
- It takes about an hour to solve $[\text{S-MIP}]_t$ for 6 scenarios, which has over 100,000 constraints and 15,000 binary variables.

Bi-parametric Sensitivity Analysis Reformulation

Strategic Consumer

- The idea is to explicitly capture reserve and energy prices at the strategic node as functions of the actions of the strategic consumer, using the fundamentals of the simplex method
- We use sensitivity analysis on the right-hand sides of the two constraints that determine the nodal energy and reserve prices in the lower level problem for the major consumer.
- By employing an iterative algorithm, we define regions corresponding to optimal bases of the lower-level optimization problem (the OPF problem in our model)[1].

[1] Co-optimization of Demand Response and Reserve Offers for a Major Consumer, http://www.optimization-online.org/DB$_H$*TML*/2017/03/5932.*html*

Bi-parametric Sensitivity Analysis Reformulation

Strategic Consumer

- Utilizing this method we can solve our stochastic full-scale NZEM model for up to 22 scenarios in one hour.

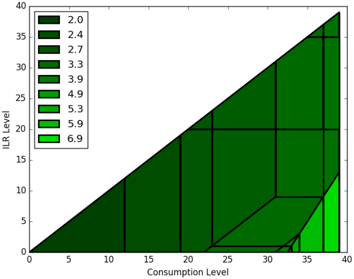


Figure: Energy Price Regions

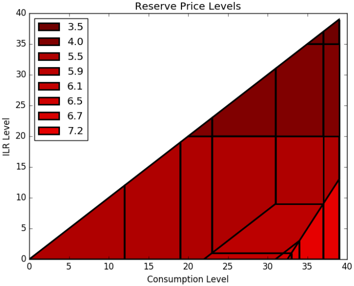


Figure: Reserve Price Regions

Stochastic Policy Simulation

Strategic Consumer

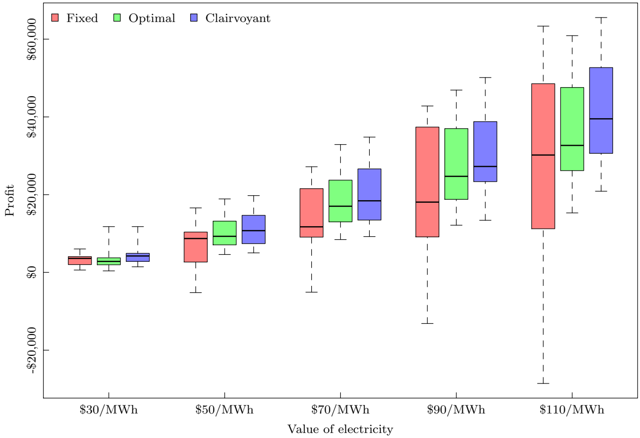


Figure: Winter peak profit for different values of electricity (u).

Planning Demand over a Horizon

Strategic Consumer

- Our strategic consumer of energy needs to solve their problem over a 1-2 months period (duration of a contract with their clients).
- In order to fulfill their contracts, there will be a total consumption goal over the time horizon.

Planning Demand over a Horizon

Strategic Consumer

- We optimize the consumption and ILR levels for the strategic consumer, given a total consumption level G over a time horizon $\mathcal{T}$.

$$
\begin{aligned}
\text{[MIP]} \quad & \max \Pi(\mathbf{x}) = -\sum_{t\in\mathcal{T}} \mathcal{C}_t(\mathbf{x}_t) + \sum_{t\in\mathcal{T}} v x_t \\
& \text{s.t. } \mathbf{x}_t \in \mathcal{S}_t && \forall t \in \mathcal{T} \\
& \sum_{t\in\mathcal{T}} x_t = G && [\hat{u}]
\end{aligned}
$$

- If we could price the total consumption constraint, the problem could be decomposed to each time period.
- Note that $\sum_{t\in\mathcal{T}} v x_t^* = vG$, where $\mathbf{x}^*$ is the optimal solution to [MIP].

Decomposing our MIP

- We define $[\text{U-MIP}]_{\hat{u}}$ as the problem with the total consumption constraint removed, and instead valued in the objective, with Lagrangian multiplier $\hat{u}$.

$$[\text{U-MIP}]_u \quad \max\ U(\mathbf{x}) = -\sum_{t\in\mathcal{T}} \mathcal{C}_t(\mathbf{x}_t) + \sum_{t\in\mathcal{T}} \hat{u}x_t - G\hat{u}$$

$$\text{s.t. } \mathbf{x}_t \in \mathcal{S}_t \qquad \forall t \in \mathcal{T}$$

- Using Lagrangian sufficiency theorem, we prove that with the additional condition $G = \hat{G}$ and $\hat{G} \in \mathcal{G}$, where $G := \sum_{t\in\mathcal{T}} x_t^*$, optimal solution of $[\text{U-MIP}]_{\hat{u}}$ solves [CM-MIP].

Utility-Consumption Curves

- We solve the $[\text{U-MIP}]_{t,u}$, $\forall u \in [0, u_{\max}]$, and plot (x^*, u).

Lemma

Let $\mathbf{x}^*$ be the optimal solution to $[MIP]_{t,u}$, for some t and u. $x^*(u)$ is monotone $\forall u \geq 0$.

Proof.

Let $\Pi(\mathbf{x}^*)$ be the optimal objective value of $[\text{MIP}]_{t,u}$. We define $[\text{MIP}]_{t,u'}$, for some $u' \geq u$, where $\Pi'(\mathbf{x}^{*\prime})$ is the optimal objective value of $[\text{MIP}]_{t,u'}$.

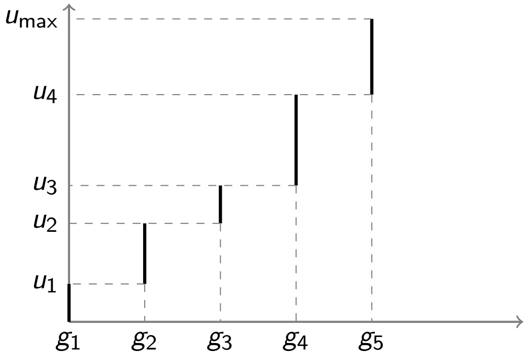
$$[\text{MIP}]_{t,u'} \max -\mathcal{C}(\mathbf{x}) + ux + (u' - u)x$$
$$\text{s.t. } \mathbf{x} \in \mathcal{S}$$

$\Pi(\mathbf{x}^*) = \Pi'(\mathbf{x}^*) - (u' - u)x^*$ and $\Pi(\mathbf{x}^{*\prime}) = \Pi'(\mathbf{x}^{*\prime}) - (u' - u)x^{*\prime}$
$\Pi(\mathbf{x}^*) \geq \Pi(\mathbf{x}^{*\prime}) \implies \Pi'(\mathbf{x}^*) \geq \Pi'(\mathbf{x}^{*\prime}) - (u' - u)(x^{*\prime} - x^*)$
If $x'^* \leq x^* \implies \Pi'(\mathbf{x}^*) \geq \Pi'(\mathbf{x}^{*\prime}) \implies \perp$ □

Utility-Consumption Curves

Price Maker Consumer

- If we solve the $[\text{U-MIP}]_{t,u}$, $\forall u \in [0, u_{\max}]$. We have the figure below:

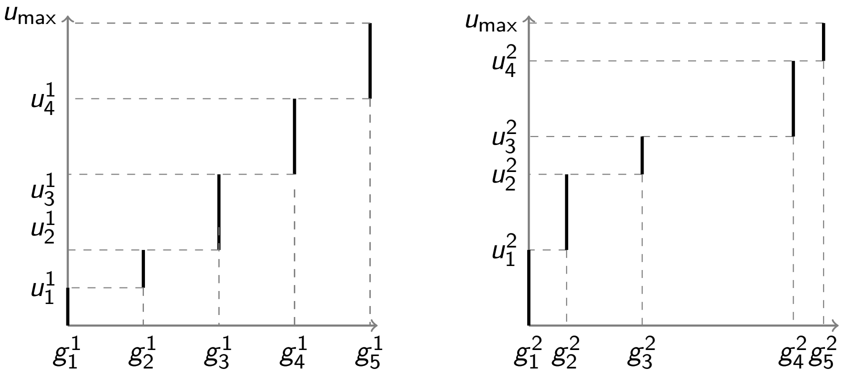


- Scott and Read (1996) used demand curves for release in a hydro-scheduling setting.

Aggregate Utility-Consumption Curves

Price Maker Consumer

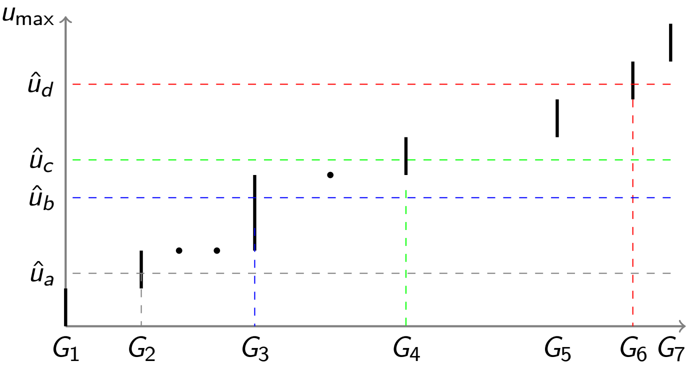
- First we build the U-C curve for each $t \in \mathcal{T}$. Assume we have $\mathcal{T} = \{1, 2\}$.



Aggregate Utility-Consumption Curves

Price Maker Consumer

- In the aggregate U-C curve, the points on the G axis determine the set of total consumption values $\mathcal{G}$ that obtain optimal policies.



Aggregate Utility-Consumption Curves

Price Maker Consumer

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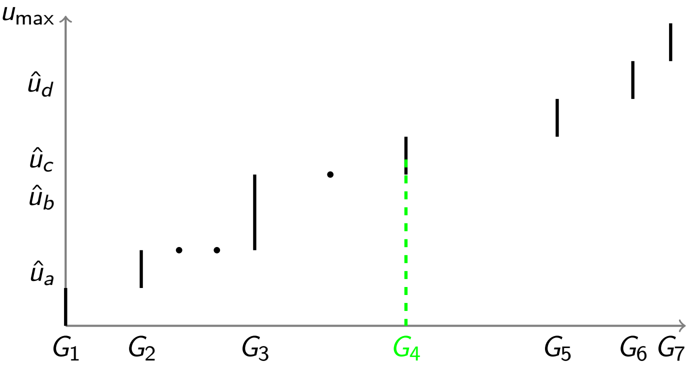
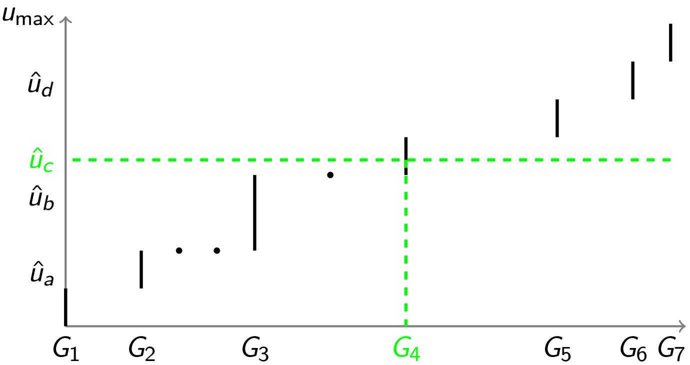


- We can choose from total consumption values in $\mathcal{G}$.

Aggregate Utility-Consumption Curves

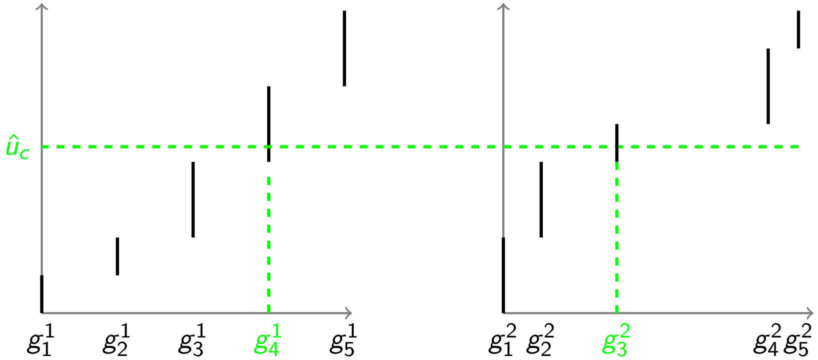
Price Maker Consumer

- In the aggregate U-C curve, the points on the G axis determine the set of total consumption values $\mathcal{G}$ that obtain optimal policies.



- After choosing the right $G \in \mathcal{G}$, we can look up our U-C curve and find the right $\hat{u}$ for our model.

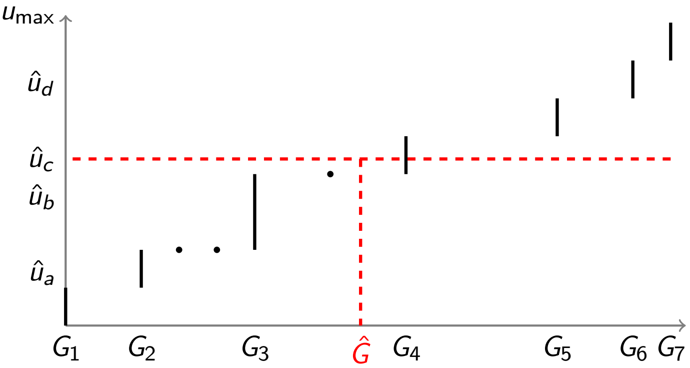
- Therefore we can solve each $[\text{U-MIP}]_t$ separately, given $\hat{u}$.



Utility-Consumption Curves

Price Maker Consumer

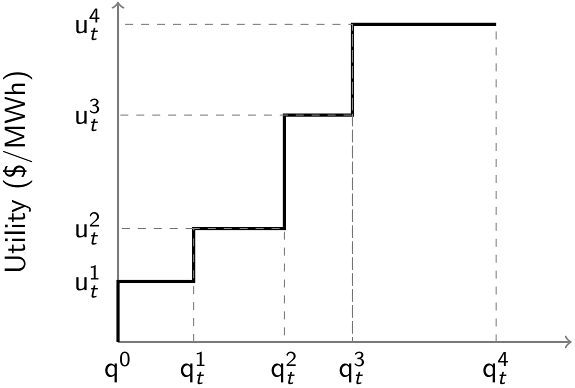
- But what if our designated total consumption $\hat{G}$ is not in $\mathcal{G}$?



Heuristics

Price Maker Consumer

- We define the U-C curve for $t \in \mathcal{T}$ as below:



- We connect the vertical lines with virtual horizontal lines, to make step functions.

- This step-wise function has the same attributes as a supply function for a generator in the dispatch model.
- We view each time period as a node, and the total consumption value is the demand.
- We introduce [HEU], where we minimize utility $\times$ consumption.

$$
\begin{aligned}
\text{[HEU]} \quad \min \quad & \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}_t} u_t^i x_t^i \\
\text{s.t.} \quad & \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}_t} x_t^i = G && [\hat{u}] \\
& 0 \leq x_t^i \leq q_t^i - q_{t-1}^i && \forall i \in \mathcal{I}_t, \forall t \in \mathcal{T}
\end{aligned}
$$

Modelling Uncertainty

- We model stochasticity by defining scenarios $\omega \in \Omega_t, \forall t \in \mathcal{T}$.
- We will maximize expected utility $\mathbb{E}_{\omega \in \Omega_t, t \in \mathcal{T}} \, U(\mathbf{x})$.
- Using Lagrangian sufficiency theorem, we prove that we can use the same decomposition method for the stochastic model with some adjustments*.

- We use backward induction to aggregate the expected U-C curves, using the following algorithm:

- For $t = T$: $\boldsymbol{u}_T(q) = \mathbf{E}_{\omega \in \Omega_T} u_T^{\omega}(q)$.

- To aggregate the curves in backward induction, we use the intuition from the price taker model $(\mathcal{C}'(\mathbf{x}_t^{\omega}) = \mathbf{E}'_{\nu \in \Omega^{t+1}}[C_{t+1}^{\nu}(g_{t+1}^{\omega})] = u_t^{\omega})$.

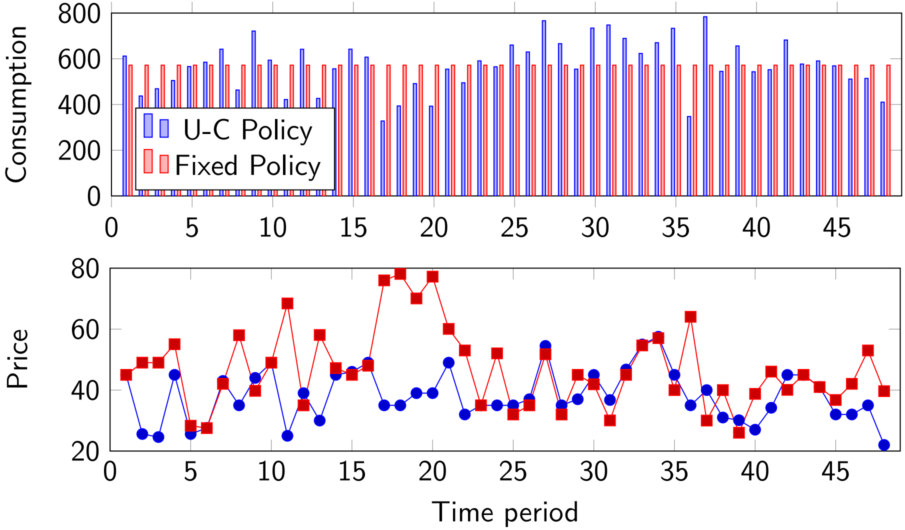
- For $t \neq T$: if $u_t^{\omega}(\hat{q}_t) = \mathbf{E}_{\omega \in \Omega_{t+1}} u_{t+1}^{\omega}(\hat{q}_{t+1})$, we aggregate the consumption levels $q = \hat{q}_t + \hat{q}_{t+1}$ to build the U-C curve for time t and scenario ω $(u_t^{\omega}(q))$.
- For $t \neq T$: $\boldsymbol{u}_t(q) = \mathbf{E}_{\omega \in \Omega_t} u_t^{\omega}(q)$.

Case Study

- We implemented this approach for a large consumer of electricity in South Island.
- We simulated the optimal policies, using historic data of winters 2016 and 2017.
- We simulated our policy for 200 sample paths, which resulted in %14 reduction in average cost.
- For the monthly scheduling the time horizon consists of 1440 trading periods.

	Expected cost	Average Price
Standard U-C Policy	42321019.1	62.6
Fixed Policy	50998360.2	82.4

Table: Monthly Scheduling Comparison



Consumption
800
600
400
200
0
U-C Policy
Fixed Policy
0
5
10
15
20
25
30
35
40
45
Price
80
60
40
20
Time period

Questions?

- Thank you.