Major Consumer Demand Response in a Co-optimized Electricity and Reserve Market

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EPOC Winter Workshop 2015

Outline

- SPD model.
- Dispatchable demand.
- Demand side participation - energy.
- Demand side participation - reserve.
- Previous work: BOOMER consumer.
- DEMON model.
- Sensitivity analysis.
- Stochastic version.
- Solve results.
- Reformulation challenges.

SPD Model

- Scheduling, Pricing and Dispatch model is run every half an hour.
- The generators offer quantities of electricity at given prices. The consumers put in consumption bids.
- Market clearing problem is solved to determine the prices and quantities to dispatch from each generator.

Dispatchable Demand

- Promotes competition in the wholesale market by enabling purchasers to compete with generators to set the price.
- Promotes the efficient operation of the wholesale market by improving the quality of information used to produce final prices.
- Promotes the reliable supply of electricity to consumers and the efficient operation of the industry by making existing demand response more certain.
- Provides financial compensation where the demand response has been impacted by the difference between the forecast price and the final price.[1]

[1] Electricity Authority - www.ea.govt.nz

Demand Side Participation - Energy

- 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.

Load Reduction Effects

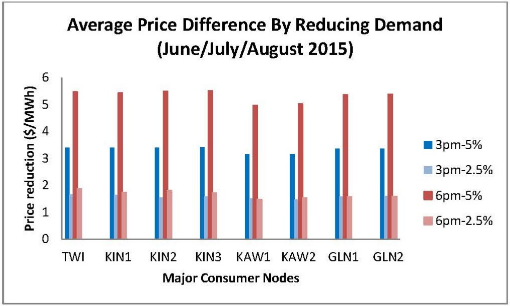

Figure: Simulation of Price Changes by Load reduction (5-2.5%) in Major Consumers' nodes for winter 2015

Load Reduction Effects

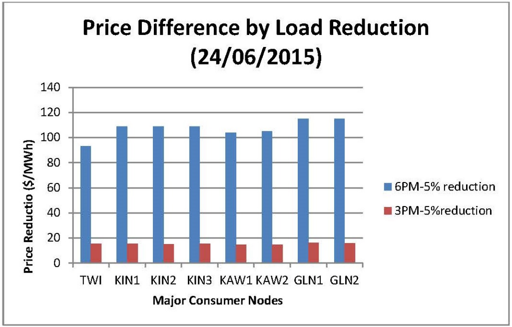

Figure: Price Changes by Load reduction (5%) in Major Consumers' nodes

Demand Side Participation - Reserve

- In NZEM reserve and electricity are co-optimized.
- Major consumers earn reserve revenue through offering in ILR.
- Also they can alleviate price spike by relaxing reserve constraints.

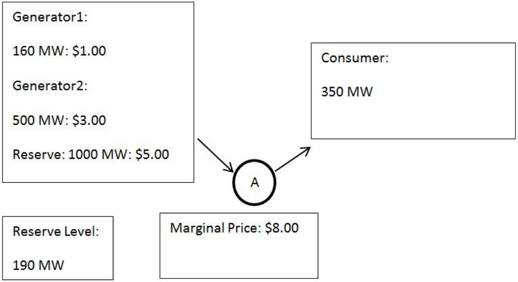

Figure: Procurement of reserve for N-1 Contingency

Demand side participation - Reserve

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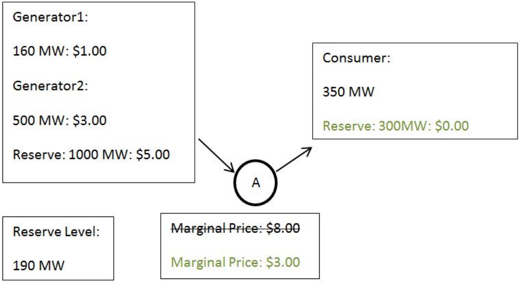

Figure: Procurement of reserve for N-1 Contingency

Reserve and Consumption Co-optimization Model

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- The model maximizes the profit for a major consumer.
- The output is an optimal electricity consumption bid and ILR offer.
- The model is a stochastic program that optimizes over full vSPD for multiple scenarios.

Previous Work: BOOMER-Consumer

- Uses simulation-optimization to tackle this problem.
- Select a set of offers from the generators (e.g. a historical period already provided by the EA).
- To deal with the uncertainty, have a distribution in mind for the load.
- Under different load scenarios, simulate what energy price would result for increments of consumption levels for the major consumer.

BOOMER Consumer

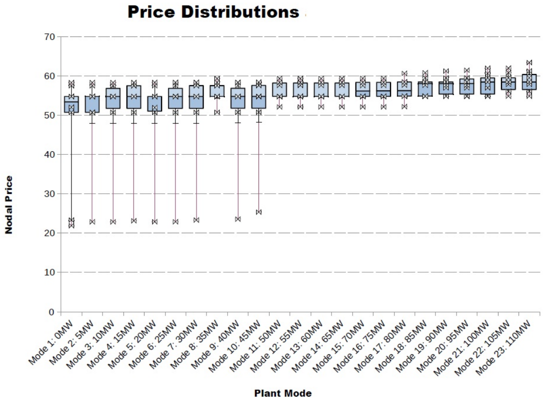

Figure: Price distributions are for optimal ILR offer, given a fixed consumption level.

Problems with BC

- Computationally very intensive.
- Only allows discrete consumption levels.

DEMON

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

Maximize [Consumer's Profit]

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Subject to:

[Consumer's Consumption and ILR Constraints]

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vSPD

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vSPD:

Maximize [Social Welfare]

DEMON

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

Maximize [Consumer's Profit]

Subject to:

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vSPD:

Maximize [Social Welfare]

Subject to: [Node Balance Constraints]

[Reserve Constraints]

[Network Constraints]

[Generation/Demand Constraints]

DEMON

- The single node equivalent is:

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

DEMON

$$\text{Maximize} \quad u(q^c) - q^c.\pi^e + q^{ILR}.\pi^r$$

DEMON

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DEMON

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$$

Single-level Reformulation

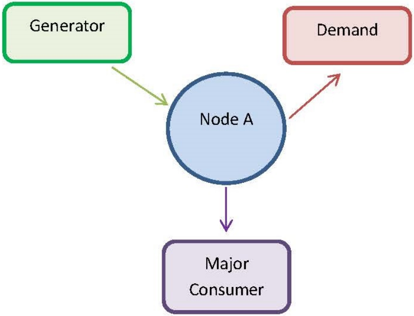
- At the first step the model is reformulated to a non-linear single level optimization problem.
- Then it is reformulated as a mixed integer program through different reformulations.
- For example, when using piece-wise linear reformulation without losses over a single period and a single scenario, the model consists of 6442 continuous and 2777 binary variables, and takes 0.01 seconds to solve.

Single Node Example : Sensitivity Analysis

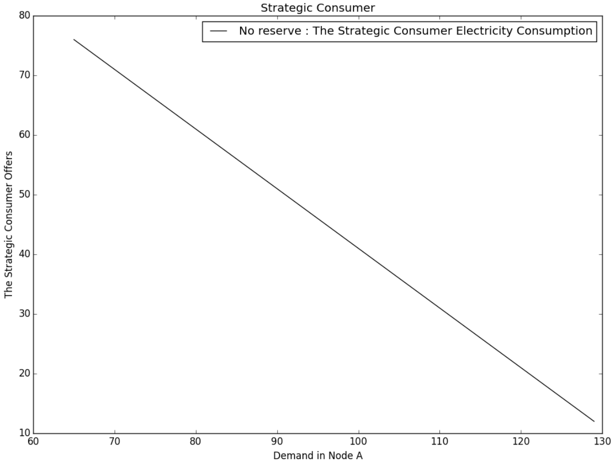
We will apply changes in demand in 'Node A' as a critical parameter in the model.

We plot the sensitivity analysis for these two cases:

- The strategic consumer offers in ILR.
- The strategic consumer does not offer in ILR.



Sensitivity Analysis: Strategic Consumer Electricity Consumption Bid



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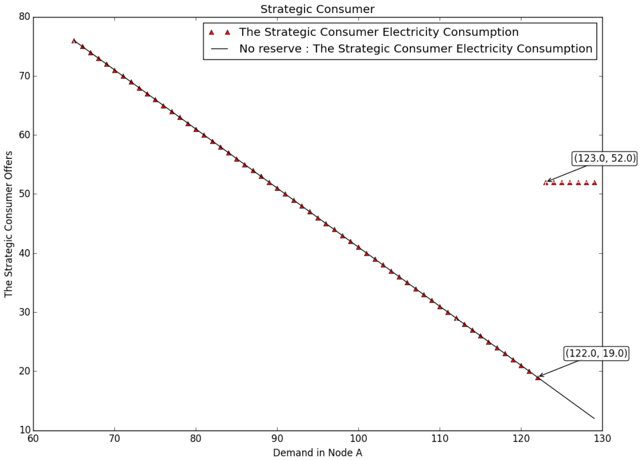
Sensitivity Analysis: Strategic Consumer Electricity Consumption and Reserve Offer



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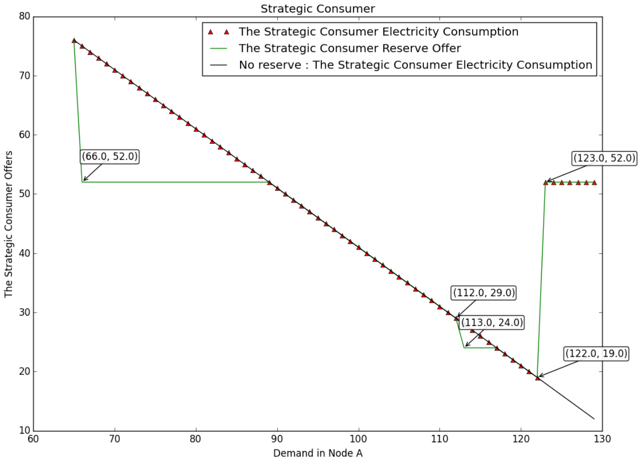
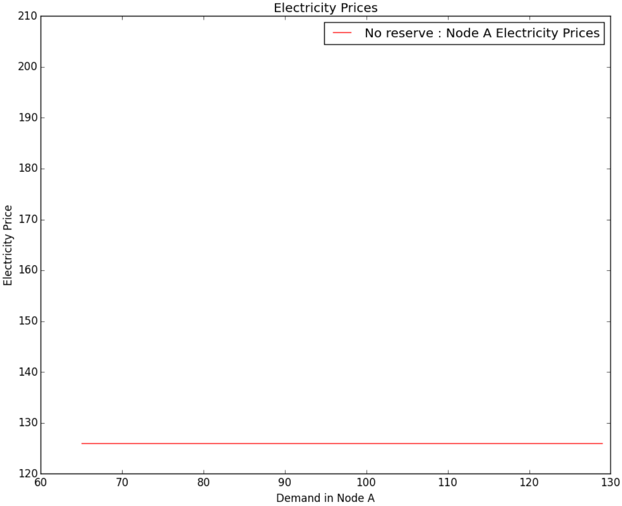
Sensitivity Analysis: Strategic Consumer Electricity Consumption and Reserve Offer



Sensitivity Analysis: Electricity Prices



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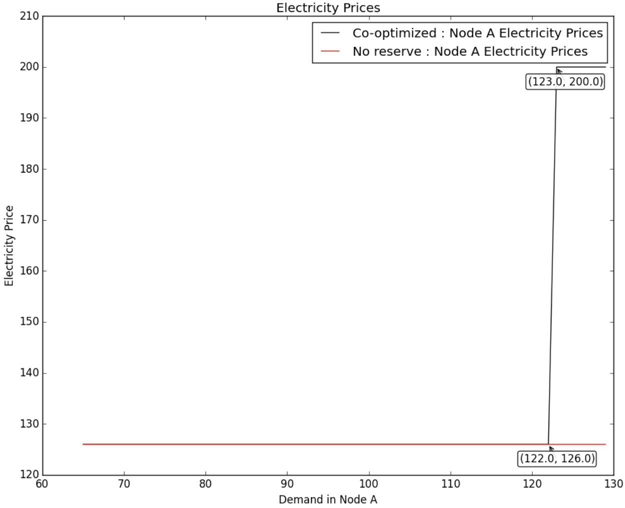
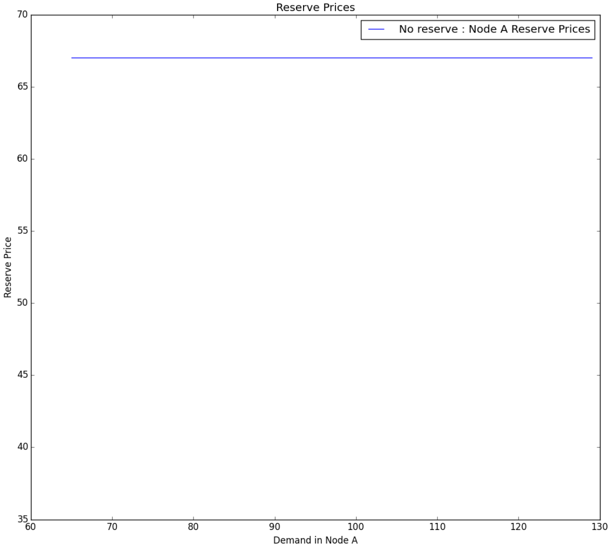
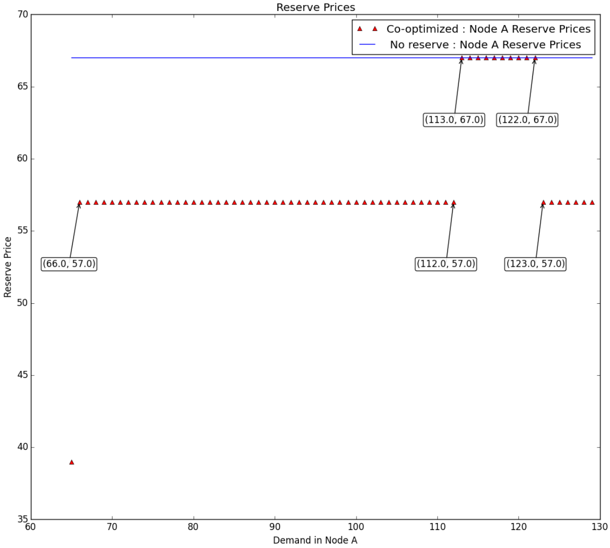


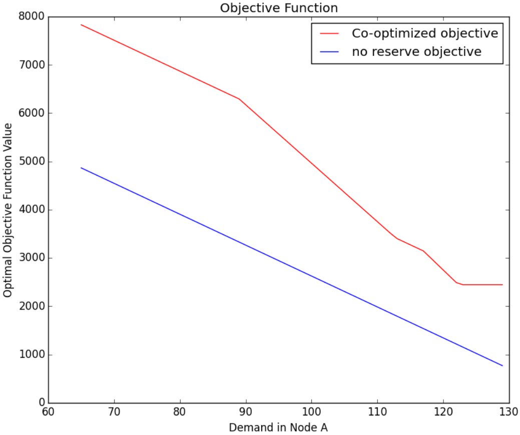
Sensitivity Analysis: Reserve Prices



Sensitivity Analysis: Reserve Prices

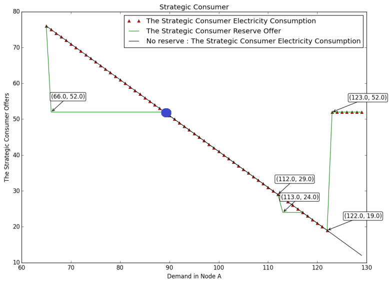


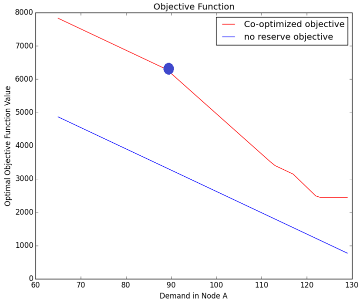
Sensitivity Analysis: Objective Function



NB. This is the profit maximization problem's objective function.

Sensitivity Analysis: Objective Function





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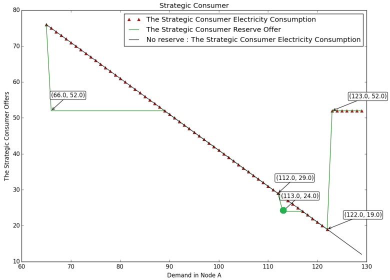

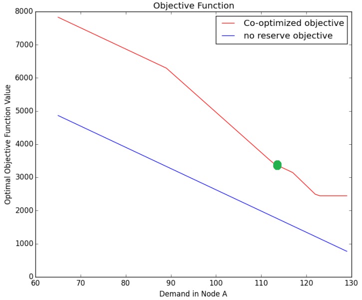

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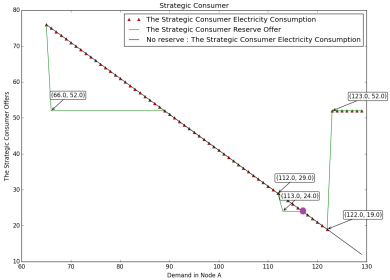

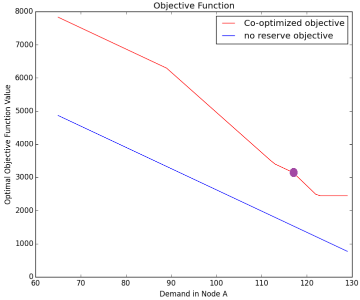

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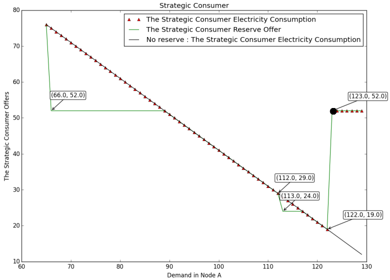

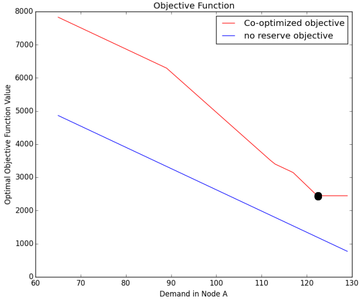

Stochastic Version

- Due to uncertainty the model is solved over several scenarios.
- Maximizes expected profit.
- In addition to previous constraints, the monotonicity constraints are enforced.
- The output is a monotonic electricity bid and an ILR offer curve.

Stochastic Version: Example

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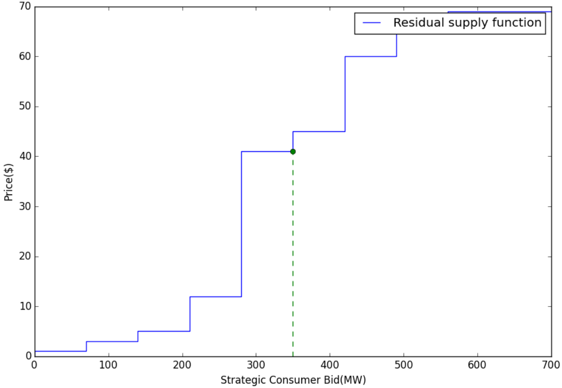
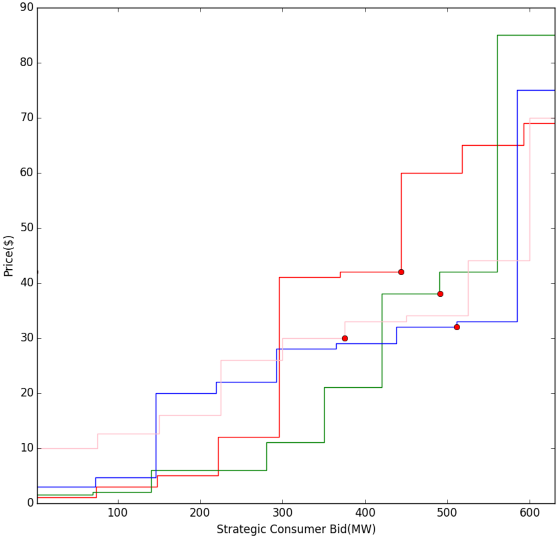
- Optimal bid for one scenario.



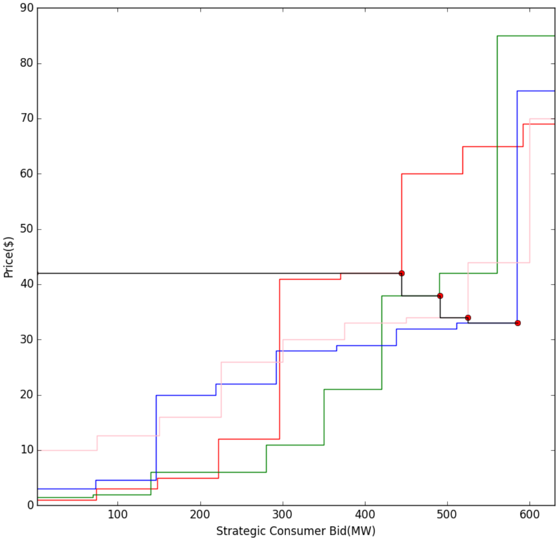
Stochastic Version: Example

- The optimal demand curve



Stochastic Version: Example

- The dispatchable demand curve



Solve Time Issue

- We have implemented the mixed integer model in python.
- We used gurobi as the solver.
- The stochastic model, when monotonicity is enforced can be solved for up to 5 scenarios.
- Thus far we have observed that the solve time increases with the number of congested lines.
- for the 5 scenario case, it can take up to 1500 seconds to solve.
- As this is clearly inadequate, we are looking at reformulations.

MIP Reformulations

To enhance the solve time the non-linear model is transformed into a mixed integer program through these reformulations:

- Big-M
- Piece-wise linear
- Disjunctives

Each of these reformulations may be beneficial in different aspects, e.g. more scenarios or tranches.

The challenge is to come up with the best reformulation for DEMON specifications.


Questions?

Large Consumers Reserve and Consumption Co-optimization Model- Single Node

$$
\begin{aligned}
\text{Min.} & \pi_d y_d - \pi_r y_r \\
\text{s.t.} & 0 \leq y_d \leq C_d \\
& 0 \leq y_r \leq C_r \\
& y_d - y_r \geq V \\
& \text{Max.} \quad \sum_{i \in I} p_i^c x_i^c - \sum_{j \in J} p_j^g x_j^g - \sum_{k \in K} p_k^r x_k^r \\
& \qquad \sum_{i \in I} x_i^c = \sum_{j \in J} x_j^g - y_d \qquad [\pi_d] \\
& \qquad - \sum_{k \in K} x_k^r = y_r - r \qquad [\pi_r]
\end{aligned}
$$

Large Consumers Reserve and Consumption Co-optimization Model- Single Node

$$0 \leq x_i^c \leq q_i^c \qquad [\nu_i^+, \nu_i^-] \quad \forall i \in \mathcal{I}$$

$$0 \leq x_j^g \leq q_j^g \qquad [\mu_j^+, \mu_j^-] \quad \forall j \in \mathcal{J}$$

$$0 \leq x_k^r \leq q_k^r \qquad [\zeta_k^+, \zeta_k^-] \quad \forall k \in \mathcal{K}$$

$$\sum_{k \in \mathcal{K}^c} x_k^r \leq \sum_{i \in \mathcal{I}} x_i^c - V \qquad [\theta]$$

$$\sum_{k \in \mathcal{K}^g} x_k^r \leq B \sum_{j \in \mathcal{J}} x_j^g \qquad [\phi]$$

$$\sum_{k \in \mathcal{K}^g} x_k^r + \sum_{j \in \mathcal{J}} x_j^g \leq W \qquad [\phi']$$

Large Consumers Reserve and Consumption Co-optimization Model- Big-M Reformulation

$$\text{Max.} \quad ut * y - (-d\pi + \sum_i \nu_i q_i + p_i x_i)$$

$$\begin{aligned}
\text{s.t.} \quad & 0 \le y \le C & & \\
& d = \sum_{j \in \mathcal{J}} x_j - y & & [\pi] \\
& 0 \le x_i \le q_i & [\nu_i] \quad & \forall i \in \mathcal{I} \\
& -\pi + \nu_i \ge -p_i, & & \forall i \in \mathcal{I} \\
& p_i - \pi + \nu_i \le M z_i & & \forall i \in \mathcal{I} \\
& x_i \le q_i(1 - z_i) & & \forall i \in \mathcal{I} \\
& q_i - x_i \le q_i z_i' & & \forall i \in \mathcal{I} \\
& \nu_i \le M(1 - z_i') & & \forall i \in \mathcal{I} z, z' \in \{0, 1\}
\end{aligned}$$

Large Consumers Reserve and Consumption Co-optimization Model- Piece-wise Linear Reformulation

$$
\begin{aligned}
\text{Max.} \quad & ut * y - pq(t) + dp(t) \\
\text{s.t.} \quad & 0 \leq y \leq C \\
& d + y = q(t) \\
& p(t) = \pi
\end{aligned}
$$

Large Consumers Reserve and Consumption Co-optimization Model- Disjunctive Reformulation

$$
\begin{aligned}
\text{Max.} \quad & ut * y - w \\
\text{s.t.} \quad & 0 \leq y \leq C \\
& d = \sum_{j \in \mathcal{J}} x_j - y & [\pi] \\
& 0 \leq x_i \leq q_i & [\nu_i] \quad \forall i \in \mathcal{I} \\
& -\pi + \nu_i \geq -p_i, & \forall i \in \mathcal{I} \\
w = & -d\pi + \sum_i \nu_i q_i + p_i x_i \\
w = & \sum_{l=p}^{P} \sum_{k=0}^{9} 10^l k \hat{\pi}_{k,l}
\end{aligned}
$$

Large Consumers Reserve and Consumption Co-optimization Model- Disjunctive Reformulation - Continued

$$y = \sum_{l=p}^{P} \sum_{k=0}^{9} 10^l k z_{k,l}$$

$$\sum_{k=0}^{9} \hat{\pi}_{k,l} = \pi \qquad \forall l \in \mathcal{L}$$

$$\sum_{k=0}^{9} z_{k,l} = 1 \qquad \forall l \in \mathcal{L}$$

$$z_{k,l} \in \{0, 1\} \qquad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}$$

$$\hat{\pi}_{k,l} \leq \pi^u z_{k,l} \qquad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}$$

$$\hat{\pi}_{k,l} \geq \pi^l z_{k,l} \qquad \forall l \in \mathcal{L}, \forall k \in \mathcal{K}$$

$$\mathcal{L} = \{p, p+1, ..., P\}$$

Large Consumers Reserve and Consumption Co-optimization Model- Network

$$
\begin{aligned}
\min \quad & \sum_{n\in\mathcal{N}} \pi^d_n y^d_n - \pi^r_n y^r_n \\
\text{s.t.} \quad & 0 \le y^d_n \le C^d_n \quad \forall n \in \mathcal{N} \\
& 0 \le y^r_n \le C^r_n \quad \forall n \in \mathcal{N} \\
& y^d_n - y^r_n \ge V_n \quad \forall n \in \mathcal{N} \\
& \sum_{t_c\in\mathcal{T}_c} M^c_{n,t_c} x^c_{t_c} + \sum_{i|ni\in\mathcal{A}} f_{ni} - \sum_{i|in\in\mathcal{A}} f_{in} = \\
& \sum_{t_g\in\mathcal{T}_g} M^g_{n,t_g} x^g_{t_g} - y^d_n \quad [\pi^d_n](\forall n \in \mathcal{N}) \\
& -\sum_{t_r\in\mathcal{T}_r} M^r_{n,t_r} x^r_{t_r} = y^r_n - r \quad [\pi^r_n](\forall n \in \mathcal{N}) \\
& \sum_{ij\in\mathcal{A}} L_{k,ij} f_{ij} = 0 \quad [\lambda_k](\forall k \in \mathcal{L})
\end{aligned}
$$

Large Consumers Reserve and Consumption Co-optimization Model - Continued

$$-K \leq f_{ij} \leq K \quad [\eta_{ij}^{+}, \eta_{ij}^{-}] \quad (\forall ij \in \mathcal{A})$$

$$0 \leq x_{t_c}^{c} \leq q_{t_c}^{c} \quad [\nu_{t_c}^{+}, \nu_{t_c}^{-}](\forall t_c \in \mathcal{T}_c)$$

$$0 \leq x_{t_g}^{g} \leq q_{t_g}^{g} \quad [\mu_{t_g}^{+}, \mu_{t_g}^{-}](\forall t_g \in \mathcal{T}_g)$$

$$0 \leq x_{t_r^c}^{r} \leq q_{t_r^c}^{r} \quad [\zeta_{t_r^c}^{+}, \zeta_{t_r^c}^{-}](\forall t_r^c \in \mathcal{T}_r^c)$$

$$0 \leq x_{t_r^g}^{r} \leq q_{t_r^g}^{r} \quad [\zeta_{t_r^g}^{+}, \zeta_{t_r^g}^{-}](\forall t_r^g \in \mathcal{T}_r^g)$$

$$\sum_{t_r^c \in \mathcal{T}_r^c} M_{n,t_r^c}^{r} x_{t_r^c}^{r} \leq \sum_{t_c \in \mathcal{T}_c} M_{n,t_c}^{c} x_{t_c}^{c} - V_n \quad [\theta_n](\forall n \in \mathcal{N})$$

$$\sum_{t_r^g \in \mathcal{T}_r^g} M_{n,t_r^g}^{r} x_{t_r^g}^{r} \leq B_n \sum_{t_g \in \mathcal{T}_g} M_{n,t_g}^{g} x_{t_g}^{g} \quad [\phi_n](\forall n \in \mathcal{N})$$

$$\sum_{t_r \in \mathcal{T}_g^r} M_{n,t_r}^{r} x_{t_r}^{r} + \sum_{t_g \in \mathcal{T}^g} M_{n,t_g}^{g} x_{t_g}^{g} \leq W_n \quad [\phi'_n](\forall n \in \mathcal{N})$$

Large Consumers Reserve and Consumption Co-optimization Model - Continued

$$p^c_{t_c} = \sum_{n\in\mathcal{N}} M^c_{n,t_c}\pi^d_n + \nu^+_{t_c} - \nu^-_{t_c} - \sum_{n\in\mathcal{N}} M^c_{n,t_c}\theta_n, \quad \forall t_c \in (\mathcal{T}_c)$$

$$p^g_{t_g} = \sum_{n\in\mathcal{N}} M^g_{n,t_g}\pi^d_n - \mu^+_{t_g} + \mu^-_{t_g} + \sum_{n\in\mathcal{N}} M^g_{n,t_g}(B_n\phi_n - \phi'_n), \quad \forall t_g \in \mathcal{T}_g$$

$$p^r_{t^c_r} = \sum_{n\in\mathcal{N}} M^c_{n,t_c}\pi^r_n - \zeta^+_{t_r} + \zeta^-_{t_r} - \sum_{n\in\mathcal{N}} M^r_{n,t^c_r}\theta_n, \quad \forall t_r \in (\mathcal{T}^c_r)$$

$$p^r_{t^g_r} = \sum_{n\in\mathcal{N}} M^c_{n,t_c}\pi^r_n - \zeta^+_{t_r} + \zeta^-_{t_r} - \sum_{n\in\mathcal{N}} M^r_{n,t_r}(\phi_n + \phi'_n), \quad \forall t_r \in (\mathcal{T}^g_r)$$

[Orthogonality Conditions]

Reserve and Consumption Co-optimization Model - Piecewise Linear Reformulation

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$$
\begin{aligned}
\text{Min.} \quad & \sum_{n \in \mathcal{N}} y_n^d \pi_n^d - y_n^r \pi_n^r & \\
\text{s.t.} \quad & 0 \leq y_n^d \leq C_n^d & \forall n \in \mathcal{N} \\
& 0 \leq y_n^r \leq C_n^r & \forall n \in \mathcal{N} \\
& y_n^d - y_n^r \geq V_n & \forall n \in \mathcal{N} \\
& q_n^c(t_n^c) + y_n^d = q_n^g(t_n^g) & \forall n \in \mathcal{N} \\
& q_n^{rg}(t_n^{rg}) + q_n^{rc}(t_n^{rc}) + y_n^r = r & \forall n \in \mathcal{N} \\
& q_n^{rc}(t_n^{rc}) \leq q_n^c(t_n^c) - V_n & \forall n \in \mathcal{N} \\
& q_n^{rg}(t_n^{rg}) \leq B_n q_n^g(t_n^g) & \forall n \in \mathcal{N} \\
& q_n^{rg}(t_n^{rg}) + q_n^g(t_n^g) \leq W_n & \forall n \in \mathcal{N}
\end{aligned}
$$

Reserve and Consumption Co-optimization Model - Piecewise Linear Reformulation

$$p_n^c(t_n^c) = \pi_n^d - \theta_n \qquad \forall n \in \mathcal{N}$$
$$p_n^g(t_n^g) = \pi_n^d + B_n\phi_n - \phi_n' \qquad \forall n \in \mathcal{N}$$
$$p_n^{rc}(t_n^{rc}) = \pi_n^r - \theta_n \qquad \forall n \in \mathcal{N}$$
$$p_n^{rg}(t_n^{rg}) = \pi_n^r - \phi_n - \phi_n' \qquad \forall n \in \mathcal{N}$$

- And the linear objective function will be :

$$= \sum_{n\in\mathcal{N}} [pq_n^g(t_n^g) - pq_n^c(t_n^c) - p_n^{rg}(t_n^{rg})r + pq_n^{rc}(t_n^{rc}) + pq_n^{rg}(t_n^{rg}) - r\phi_n - r\phi_n' + W_n\phi_n' - V_n\theta_n] - \sum_{ij\in\mathcal{A}} [\eta_{ij}^+ + \eta_{ij}^-]K_{ij}$$

$$= A$$

Reserve and Consumption Co-optimization Model - Maximizing Utility

The objective function is a profit maximization which has a parameter u as the utility of consuming one unit of energy.

$$
\begin{aligned}
&\sum_{n \in \mathcal{N}} (u - \pi_n^d) y_n^d + y_n^r \pi_n^r \\
&= \sum_{n \in \mathcal{N}} u y_n^d - (\pi_n^d y_n^d - y_n^r \pi_n^r) \\
&= u \sum_{n \in \mathcal{N}} [q_n^g(t_n^g) - q_n^c(t_n^c)] - A
\end{aligned}
$$

Load Reduction Effects

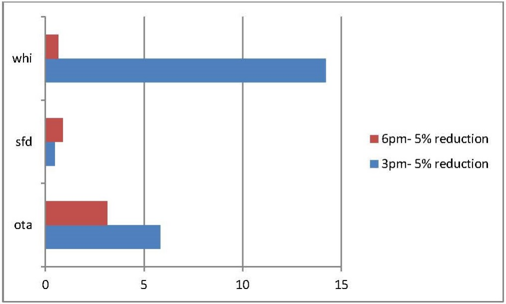

Figure: Simulation of Thermal generation Changes by Load reduction (5-2.5%) in Major Consumers' nodes for winter 2015

Downward, A., Tsai, Y., Weng, Y., & Zakeri, G. (2013). Multi-node offer stack optimisation over electricity networks. Paper presented at 47th Annual Conference of the ORSNZ, Hamilton, New Zealand. 24 November - 27 November 2013.