Integrating consumption and reserve offer strategies for large consumers in co-optimised electricity markets

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Abstract

In this paper we present the development of a simulation model for large consumers to optimise their consumption and reserve offers in a security constrained electricity market. We utilise the New Zealand grid, which has security constrained generation and transmission which can influence marginal nodal pricing. To illustrate this influence we use a series of small optimal power flow models as well as illustrating how these may influence a large integrated consumer (who offers interruptible load). Our simulation model has been successful and determining periods during which a large consumer may reduce their consumption (demand response) in order to reduce the energy price. We expect this approach to be extensible to other markets although we note that information surrounding the underlying market structure will heavily influence the viability

1 Introduction

Electricity Markets have become prevalent in a multitude of countries and jurisdictions. In most countries the structure is for privately held companies to compete with one another in order to serve a largely short term inelastic load. This approach has led to some notable failures, such as California in summer 2000 but has also been linked with increased efficiency of investment and operations. Electricity markets provide topical areas of research, as even small increases in efficiency can lead to large economic benefits.

It is widely accepted that electricity markets can not operate efficiently without demand side participations. Many researchers are currently focusing upon the retail space and in particular the introduction of smart grids utilizing smart metering and appliances. Whilst this will eventually yield substantial benefits, more immediate gains can be made by ensuring large industrial consumers participate in the electricity market effectively. These users many of whom are exposed to spot markets already experience time of use pricing. Furthermore, due to their scale any improvements in their energy use can have a large impact on the company's bottom line. This impact, coupled with the greater proclivity towards capital expenditure when a clear benefit can be proven, makes them ideal targets for intelligent load consumption and demand side participation.

We will concentrate on the New Zealand electricity market (NZEM), however the basic methodology developed in this paper applies in any electricity market. The NZEM is a uniform price auction across a 250 node network split between two major AC networks connected by a single HVDC cable. As New Zealand is an island country all consumption must be met domestically. This leads to an increased focus upon both short and medium term planning as local supply shortfalls can be catastrophic.

A further peculiarity of the NZEM is that the market has co-optimised dispatch between energy and reserve. Market participants are able to specify offers for both primary (6s/FIR) and secondary (60s/SIR) instantaneous reserves subject to technology constraints. [1] Both energy and reserve offers follow so called hockey stick type curves [2] with large tranches of low priced offers with a steeply increasing tail. Therefore, at the margin price is sensitive to demand in both markets and an extensive knowledge of how price is formulated is required. In this market sufficient security is procured to cover the failure of the largest source of supply, either generation or HVDC transmission, within the current trading period.

Nodal pricing has been thoroughly studies previously in [3, 4, 5, 6, 7, 8] although the interaction of energy and reserve prices has received less attention with [4, 7, 9, 10, 11, 12, 13] providing a good overview. The papers demonstrate the mechanisms by which the energy and reserve prices are intertwined.

These interactions can lead to units being dispatched in non-intuitively, for example out of merit order, and adds to the complexity of the optimal power flow problem that determines nodal prices. In this paper we will describe the specific security requirements for New Zealand[1]. We will then demonstrate how energy and reserve prices can be coupled together and how the macro and micro considerations can be important. Any participant seeking to evaluate their impact upon the market would need to take into account these interactions.

To assist with evaluating this impact on nodal prices, we will utilize a full representation of the New Zealand grid dispatch model called vSPD [14]. vSPD or vectorised Scheduling Pricing and Dispatch is a formulation of the

System Operator's grid dispatch model (SPD) by the New Zealand Electricity Authority. This formulation includes all energy and reserve constraints along with the full transmission network and can be used to simulate the final pricing solution for each trading period using publicly available data. Although using vSPD can lead to computationally expensive simulations, other, more simplified models fail to capture nodal prices accurately.

We will use this formulation to develop an optimization model for large consumers of electricity in terms of their consumption and interruptible reserve offer (provided they are eligible to offer reserve). We note that we have not considered the case of aggregators who may offer reserve on behalf of a company, such added complexity remains an open problem.

2 Interaction of Energy and Reserve Offers

In this paper we present the utilization of a fully detailed optimal power flow dispatch software used in New Zealand to provide price distributions attached to each level of consumption of a large consumer of electricity.

The need for utilization of such detailed software arises from the nuances that eventuate from losses and congestion in a transmission network as well as interactions of energy and reserve. While nodel pricing and the effects of transmission are very well understood, less information is available on the interaction of energy and reserve. Furthermore, this interaction depends on the specific reserve requirements that are different in various jurisdictions. Below we will start by outlining the requirements of reserve procurement in New Zealand. We will then proceed to demonstrate how energy and reserve prices interact on a number of simplified situations. Subsequently we will present empirical results that demonstrates this interaction in New Zealand over the 2008 to 2012 years. The last sections are dedicated to the description of the demand side bidding software.

2.1 Reserve Procurement in New Zealand

New Zealand operates a co-optimised electricity network with primary (6s, FIR) and secondary (60s, SIR) reserve co-optimised with the energy dispatch. This reserve is procured on an island basis, to secure against the largest risk setter dispatched such as generation units, or specific transmission lines. This ensures that N-1 security is maintained in the event of an unexpected disconnection of the major units within the system with the largest of these being the three North Island CCGT units, as well as the receiving end of the HVDC interconnection. Losses and transmission congestion are not taken into account when dispatching reserve, with each island operating as a single zone in this respect. Reserve may not be transferred between zones (islands) although proposals are being considered to change this [15].

The New Zealand reserve market is capable of handling multiple technology types with Interruptible Load (IL), Partially Loaded Spinning Reserve (PLSR) and Tail Water Depressed Spinning Reserve (TWDSR) all viable options. IL is provided by large industrial companies who are connected to the grid via relays or through the services of an aggregation company. PLSR and TWDSR are procured from generation units with the most significant contribution from Hydro units, although some thermal units also contribute. This dispatch is constrained by three constraints colloquially known as the inverse bathtub constraints [16, 17].

These three constraints constrain the combined dispatch of energy and reserve. The proportionality constraint defines a minimum ratio between the dispatch of energy and reserve, this prevents the case where a unit may be dispatched for its full reserve capabilities, without being dispatched for energy. This proportionality value is a piecewise linear value which takes into accounts different configurations of units in a particular station. The capacity constraint limits the total amount of reserve which may be dispatched from a particular station. Units cannot ramp instantaneously and stringent technical requirements, such that reserve must be delivered within a certain space of time must be met. Finally, the combined dispatch constraint limits the total amount of energy and reserve dispatched from a station. A unit cannot be dispatched for greater than its total capacity for logical reasons.

In the New Zealand market this is leads to, in essence, two considerations as to how reserve impacts the wholesale market. The first consideration is the combined dispatch of energy and reserve from generation units, a situation considered in [10]. The second is the effect of reserve availability on the dispatch of the risk setting unit which can lead to interesting implications.

2.2 Interactions of Energy and Reserve in OPF

In this section we remind the reader of the interactions of energy and reserve prices through the OPF model. This concept is the focus of [10, 11]. We revisit this in the context of New Zealand that has its particular reserve requirements. To fathom the impact of these reserve requirements we lay out a simplified version of the OPF problem. We ignore losses (although they are present in vSPD) as they have been investigated thoroughly [3] and they make no essential difference to the points we make in this work. Consider the OPF below where firms bid in (step function) supply stacks as well as reserve stacks.

$$
\begin{array}{rll}
[POPF]\min & p_g^T g + p_r^T r & \\
\text{subject to} & Mg + Af = d & [\pi] \\
& r + g \leq G & [\epsilon] \\
& r - Kg \leq 0 & [\kappa] \\
& Er - g \geq 0 & [\lambda^1] \\
& Hr - Bf \geq 0 & [\lambda^2] \\
& r \leq R & [\omega] \\
& |f| \leq F & [\tau^{\pm}] \\
& Lf = 0 & [\alpha] \\
& r, g \geq 0 &
\end{array}
$$

Here

- g is the vector of dispatched generation and r is the vector of dispatched reserve.
- f is the vector of flows.
- The objective is to minimize the sum of generation and reserve costs. p_g is the vector of generation costs and p_r denotes the vector of reserve costs.
- The first constraint energy balance at every node of the network. d denots the vector of nodal dmands, while M is a matrix that maps each tranche of offered generation to a node and A is the node-arc incidence matrix for the network.
- The second, third and sixth constraints comprise the reverse bath-tub constraints where the sum of generation and reserve must not exceed the unit capacity (denoted by the vector G), the reserve must be less than a specified proportion of generation (captured in matrix K), and procured reserve may not exceed the offered capacity of reserve denoted by R.
- The fourth constraint ensures that the sum of North Island reserve is larger than any unit generation dispatch as is the sum of South Island reserve. E is a mapping that takes the vector of reserves to the sum of North Island followed by the sum of South Island reserves.

- Similarly, the fifth constraint ensures that there is sufficient reserve is procured against any contingency set through transmission (failure). Constraints four and five set the (shadow) price of reserve.

- The rest of the constraints are standard ensuring transmission capacity and Kirchoff's law are complied with.

By taking the dual of the above we obtain

$$
\begin{array}{rcr}
[DOPF]\,\max & d^T + R^T\omega + G^T\epsilon + F^T(\tau^+ + \tau^-) & \\
\text{subject to} & M^T\pi + \epsilon - K\kappa + \lambda^1 \leq p_g & [g] \\
 & \omega + \epsilon + \kappa + E\lambda^1 \leq p_r & [r] \\
 & A^T\pi + \tau^+ - \tau^- - B^T\lambda^2 + L^T\alpha = 0 & [f] \\
 & \omega, \epsilon, \tau^{\pm}, \kappa \leq 0 & \\
 & \lambda^1, \lambda^2 \geq 0 &
\end{array}
$$

Here

- The first constraint, which links energy prices (π) and the security constrained dispatch of a generation unit (λ^1) is the first example of a macro type problem, here the total supply of reserve can limit a units dispatch.

- The second constraint, illustrates the micro considerations of an individual units dispatch, ϵ and κ both reflect constraints which may be binding upon the combined dispatch of energy and reserve.

- The third constraint is an uncommon addition, reflecting the role of reserve in an electricity market with zonal, security constrained transmission, an additional macro type constraint linked with aggregate reserve supply. Here, energy (π) and reserve prices (λ^2) are once again linked.

While is it evident from the dual that there is potential interaction between energy (π) and reserve prices (λ_1 and λ_2), we illustrate this by three examples below as outlined in Figure 1. These examples are inspired by and form the basis of, reserve constrained situations most frequently encountered in New Zealand. The first case is for a generation unit which is both the risk setter and the marginal generation unit. For the second case we examine the effect when a security constrained transmission network is used. Finally, we consider the case of an individual unit which can offer energy and reserve and how the dispatch constraints of this unit can influence the optimal solution.

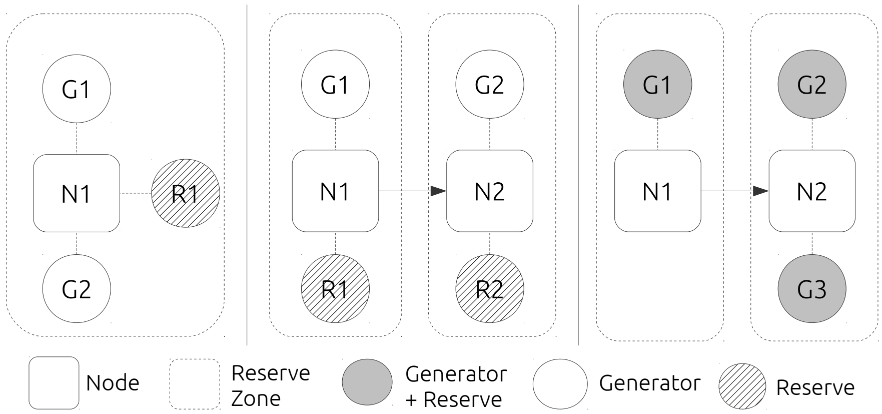

Figure 1: Depiction of the networks used in the three theoretical cases considered.

2.3 Case Studies

We consider three case studies as outlined in Table 1 and Figure 1. The full description of each example follows.

2.3.1 Marginal Risk Setting Generators

Here we consider the case of a single node market without transmission. Two generators both of whom are dispatched in the market, meet the demand. These are a low cost generator and an expensive peaker. Reserve is provided by a third plant (which does not offer energy). In this case the reserve price, $-\lambda^1$ is specified within the reserve offers by and takes on the marginal dispatched reserve price $p_{r,\text{marginal}}$. However, the nodal energy price, π_1 is not determined merely from the energy offer prices. In this situation, to meet an increase in demand, we must not only dispatch increased energy, but also, as the marginal plant is also the risk setter, we must procure additional reserves. Hence

$$\pi_1 = p_{g,\text{marginal}} - \lambda^1, \tag{1}$$

indicating the clearing energy price is the sum of the marginal energy offer and the reserve price.

Table 1: Case Study Results and Information

	A	B	C
	Demand Parameters		
d_1	350	50	50
d_2	-	300	310
	Offer Parameters (Price, Quantity)		
g_1	0.01, 400	0.01, 400	0.01, 300
g_2	100, 400	100, 400	1000, 50
g_3	-	-	10, 300
r_1	30, 400	30, 400	1, 300
r_2	-	45, 400	10, 50
r_3	-	-	0.01, 300
	Optimal Dispatch		
g_1	350	350	153.3333
g_2	0	0	6.6667
g_3	-	-	200
r_1	350	0	0
r_2	-	300	3.3333
r_3	-	-	100
	Optimal Prices		
π_1	30.01	0.01	0.01
π_2	-	45.01	670.0033
λ_1	30	0	0
λ_2	-	45	669.9933
κ_2	-	-	659.9933

2.3.2 Risk Constrained Transmission Networks

In the second example we use a two node model to illustrate how security can influence prices within a transmission constrained network. We use one generator and one reserve provider at each node. Generation and reserve are independent of each other and we assume that the parameters are chosen so that the bathtub constraints are not binding for this example. In this situation demand in node two is met through imported energy from node one. Transmission is the largest risk setter for node one and reserve, in node one, must be procured against the failure of transmission.

Here the reserve price $-\lambda^2$ is the reserve cost offered by the marginal reserve unit r_2. However, the clearing energy price for node two, π_2, is given by:

$$\pi_2 = \pi_1 - \lambda_2, \tag{2}$$

since in order to meet an increase in demand for node two, not only do we import more energy from node one (and must pay the energy price of that node), but also we must pay to procure further reserve covering the additional energy transported to node two.

2.3.3 Bathtub Constrained Unit Dispatch

For our final example we consider the case of the reserve dispatch being constrained by the co-optimisation between energy and reserve at a single unit. Three constraints exist which limit the joint dispatch of these two products known informally as the inverse bathtub constraints. We will consider only the most extreme of these three, the proportionality constraint which implements a ratio between the allowable energy and reserve dispatch, $r - kg \leq 0$. In this instance we set k to a value of 0.5 for illustrative purpose, Unit 3 is limited to 100 MW of reserve dispatch which is the intersection of the proportionality and combined dispatch constraints.

Note that neither the energy or reserve prices at node two may be found on the offer stacks, although at least they appear to be of similar orders of magnitude. The relationship between energy and reserve prices still holds and π_1 may be found on the offer stack at Node one. From the duals two simultaneous equations for the reserve price are required to be solved:

$$-\lambda_2 = p_{g,2} + k_{g,2}\kappa_{g,2} - \pi_1 \tag{3}$$

$$-\lambda_2 = p_{r,2} - \kappa_{g,2} \tag{4}$$

These may be used to determine the constraint charge, $\kappa_{g,2}$.

$$\kappa_{g,2} = \frac{p_{r,2} + \pi_1 - p_{g,2}}{1 + k_{g,2}} \tag{5}$$

Alternatively, the marginal energy price can be determined directly via:

$$\pi_2 = \frac{1}{1 + k_{g,2}} p_{g,2} + \frac{k_{g,2}}{1 + k_{g,2}} (\pi_1 + p_{r,2}) \tag{6}$$

3 Empirical Assessment of Effects in the New Zealand Market

In this section we consider the evidence which exists for these constraints binding within the New Zealand market. These periods are important, for if no evidence exists then the development of models taking into account reserve considerations is not needed. The added complexity is not offset by a better realization of the problem and the subsequent actions should not differ from an energy only implementation. Based upon the theoretical models above we may make testable predictions about prices within the New Zealand electricity market. In particular, when reserve is constraining a generation unit we expect (7) to be valid.

$$| \pi_{Node} - p_{Node} - \lambda_{Node} | \leq tol \tag{7}$$

Whilst, when reserve is constraining transmission within the network we would expect (8) to be true.

$$| \pi_{Node,2} - \pi_{Node,1} - \lambda_{Node,2} | \leq tol \tag{8}$$

We introduce a tolerance, *tol*, to approximate the effect of losses along the HVDC cable. This tolerance is set to a nominally small value. We apply these two filters for the time period beginning 1st January 2008 and ending the 13th March 2013 for which data was available.

We note that New Zealand has two reserve prices. As such, there is no single reserve constraint but instead the cumulative reserve price, (FIR and SIR) is used. Furthermore, for the situations we have shown only the North Island cases. This is because reserve constraints are far more frequent in the North Island. Likewise, the South Island does not have any major CCGT units and as such the marginal risk constrained generator is not applicable in this situation. Figures 2 and 3 illustrate reserve constraining marginal generation and transmission respectively.

These constraints are quite common with 10.5% of all trading periods (9500) over the period assessed being constrained. Of these, the most constrained year was 2009 in which 4100 of these constrained periods occurred. Furthermore, as can be seen in Figures 2 and 3 reserve constraints appear to be occurring during periods in which energy prices are very high, ranging into the high hundreds to thousands of dollars per MWh. This indicates that reserve constraints heavily influence the highest spot prices, thus our focus upon their inclusion in our model of demand response for large integrated consumers.

We may take this one step further and calculate the impact of these energy and reserve constraints on a specific site, namely the one for which we will later develop our optimisation model for. This site, New Zealand Steel is a large consumer of energy who also provides Interruptible Load to the ancillary services market. The site is interested in the net price it pays for energy and is highly sensitive to high spot prices in that they reflect

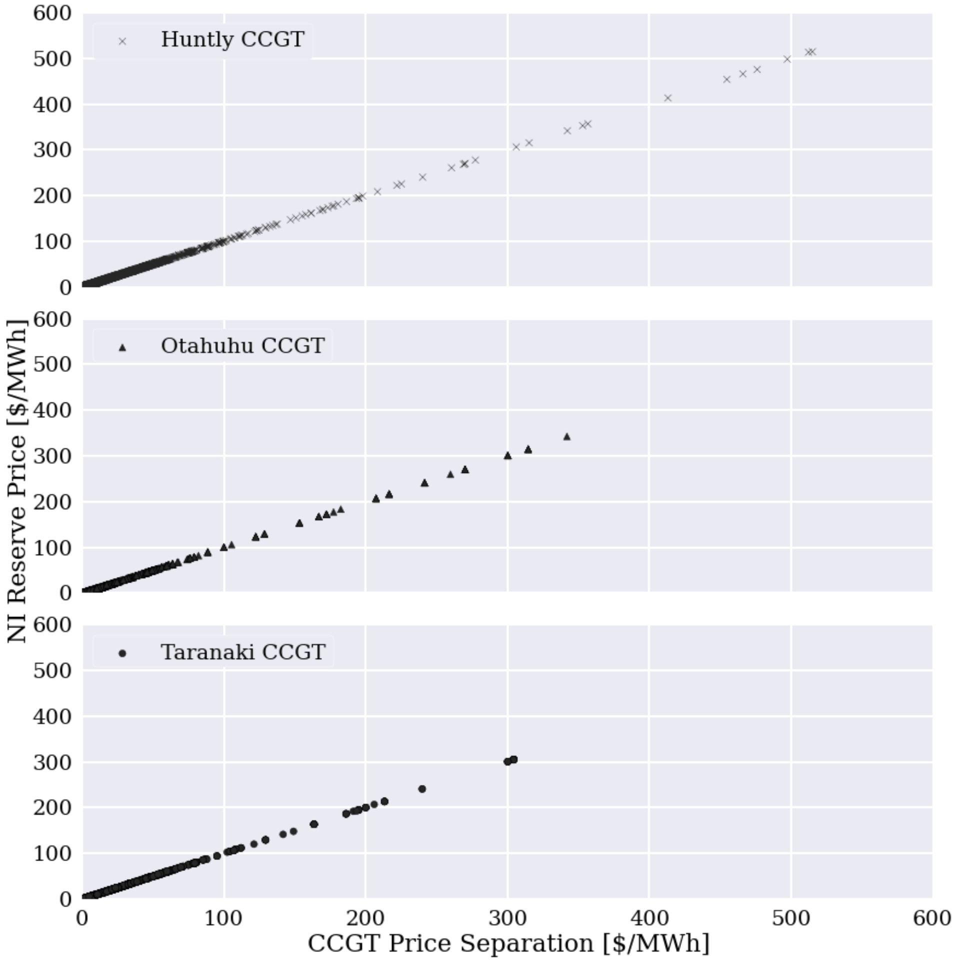

Figure 2: Influence of reserve constraints upon the output of the three major combined cycle units in the North Island as indicated by equation (7)

opportunities to reduce their total energy bill. This leads to a comparison between the effective and nominal prices for energy paid by the specific firm. This effective price is the total amount paid in a trading period, less revenues for reserve on a per MW of consumption basis in order to compare it with the nominal price of energy. Figure 4 shows that in a number of trading periods the effective price was far below the nominal price for energy and in certain cases negative. This negative price occurs due to the divergence between energy and reserve quantities for which the prices are paid, the site has some onsite generation which can be used to reduce their exposure to the wholesale electricity market. A naive optimiser, one seeking to mitigate exposure to high energy prices would erroneously act during these trading

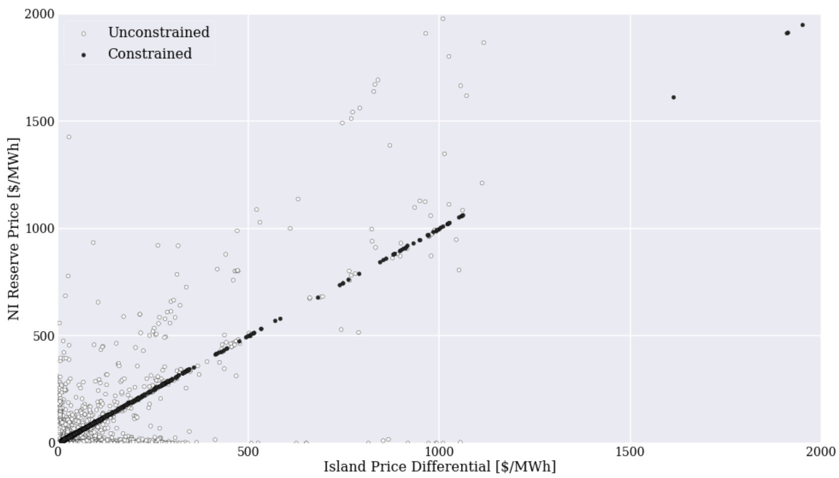

Figure 3: Instances of periods in which reserve constraints could be identified as acting upon the transmission link between the North and South Islands as predicted by equation (8)

periods as a certain degree of natural hedging occurs for this site. We wish to extend this, to take into account an active participant and in doing so optimise the individuals energy and reserve offers to the market. The model we use to accomplish this will be described in the following sections.

4 Boomer Consumer

Demand side participation is identified as a key feature leading to an efficiently functioning electricity market [18, 19]. The single signal initiating a reaction in demand side participation in a wholesale electricity market is the price of electricity. Due to the hockey-stick nature of the prices a small change in demand can result in a sharp drop in prices as seen in Figure 5. This would not only result in savings over the reduced load but also savings over the consumed load as the price has now dropped. It is therefore imperative that a large consumer is well informed regarding the impact of their consumption on wholesale prices.

In the preceeding sections we have demonstrated that unintuitive pricing situations can and do arise as a function of transmission as well as reserve constraints. To accurately capture the impact of various load levels on the nodal prices we have developed a software that utilizes vSPD [14] to simulate

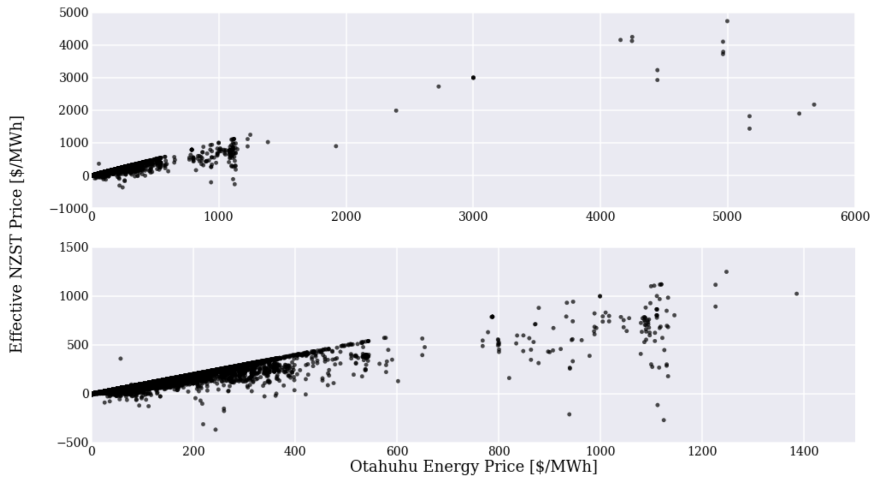

Figure 4: Effective price paid by New Zealand Steel per unit of spot market consumption of energy, taking into account site wide energy and reserve elements.

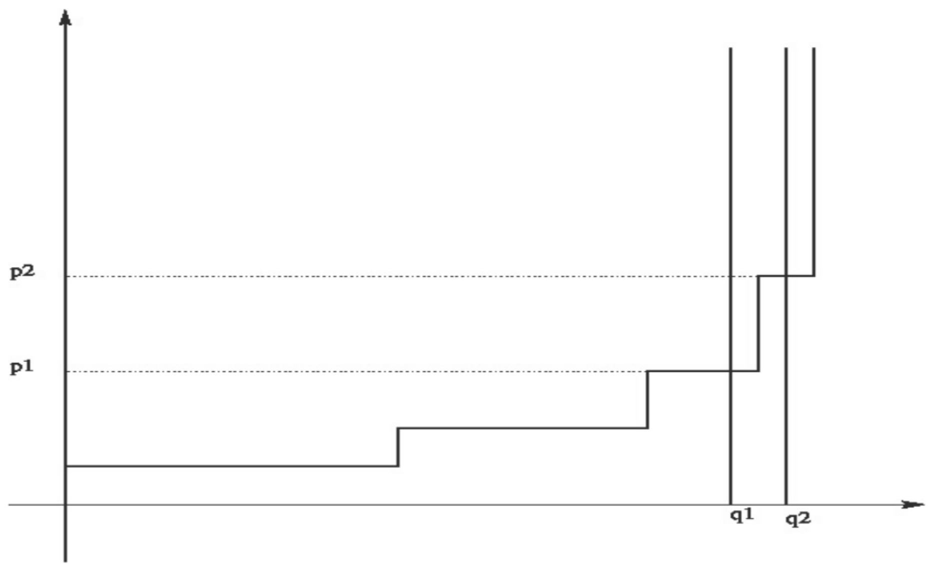

Figure 5: Price Distributions over different modes of operation as determined using Boomer Consumer

nodal prices for each operating (i.e. consumption) level for a large consumer, for varying levels of "rest of New Zealand" demand. In particular

- Given a trading period under scrutiny, several "similar" historical periods are identified as base scenarios. These periods are selected based on similarity of time of day and day of the week, as well as time of year and hydro-lake levels (which is of particular importance to New Zealand).
- Supply offers from these base scenarios, as well as most recently published offers (which are often only a few hours old) are used to produce base scenario nodal prices.
- The overwhelming component of uncertainty in the outcome of a nodal price is the overall amount of consumption in New Zealand. To represent this we sample from a log-normal distribution of demand in each of the North and South Islands ***Geoff to fill in the parameters and the justification here.
- For each of the identified historical periods, and each operating (i.e. consumption) level vSPD is run for varying NZ demand scenarios and nodal prices are recorded. This provides a distribution of prices corresponding to operating levels such as depicted in Figure 6.

5 ILR Offer consideration

Geoff to write an explanation that for each fixed level of demand we optimize a reserve stack (and put a nice grid, undoubtedly mention prize collection)!

6 Conclusions

In this paper we present the development of a simulation model which seeks to optimise the combined energy and reserve offer for a particular large consumption site. Such large consumer sites are the most viable options for immediate demand response action and potential exists to integrate this behaviour in currently established markets without major market changes. We utilise the New Zealand market, a security constrained market which has some interesting pricing considerations which we outline through the use of a simplified OPF model. These models explain price dynamics across a significant number of periods in the New Zealand market and must be taken

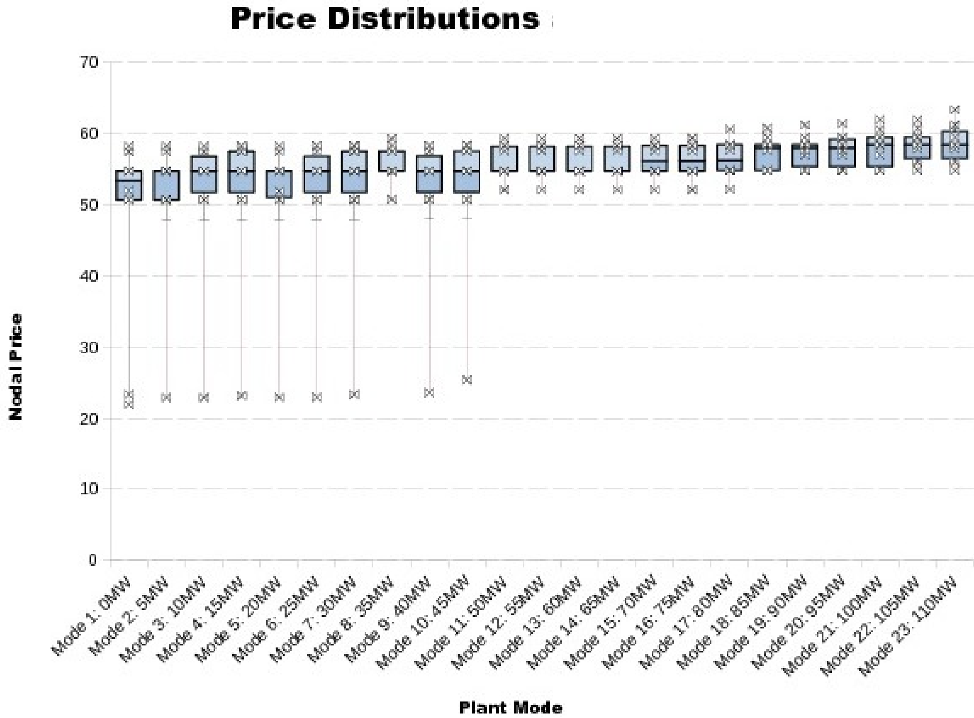

Figure 6: Price Distributions over different modes of operation as determined using Boomer Consumer

into account when attempting to evalute a particular sites impact upon the market.

The model presented is able to assess the likely impact of different levels of demand response across a wide variety of scenarios. It utilises the hockey stick type nature of electricity offer curves, along with the reserve consideratons of the NZ grid, to recognise that small changes in consumption can result in major changes in price. Initial results seem promising, however it remains to be seen whether this model is able to ex ante assess the periods when effective demand response may occur. The model is sensitive to the input parameters, with small deviations in system load having a major impact upon the ability of the site to influence price.

We conclude that such a model is an effective method of optimising demand response and reserve offers for large consumers. We expect that such models will play an extended role as demand response becomes more prevalent in countries throughout the world. In addition there exists scope to extend this model for aggregation providers capable of offering load reduction, a potential method of integrating smart appliances and metering technology.

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