Mathematical model to determine optimal investment for solar power & EES for shifting the load

J. Khaiam, A. Downward

Department of Engineering Science

The University of Auckland

New Zealand

jkha088@aucklanduni.ac.nz

Abstract

Over the past decade, distributed generation has been gaining interest from the lines companies and consumers for mainly reducing the price of electricity and improving the energy reliability. The price of both solar panels and energy storage systems (EES) have dropped substantially in recent times. They will soon be serving an important role in distribution networks. Solar panels, installed on residential rooftops can only be used for load reduction during the day, however through a combination of solar panels and EES it is possible to shift load from peak to off-peak periods. If consumers use EES only, those who have fixed pricing contract with the distribution companies will have no load reduction or shifting; however, it can be used as a load shifter if the consumer use time of use pricing scheme. If all consumers have both EES and solar panel though this is not feasible in real electricity market, the distribution companies will hit new peak instead of peak reduction.

The main target of this paper is to derive a mathematical formulation for shifting the load from peak to off-peak by using solar panel and EES considering fixed price, time of use price, customer peak and coincident distribution peak.

Key words: Load-Shift, Fixed Price, Time of Use Price, Customer Peak, Coincident Distribution Peak.

1 Introduction

In this section we will provide some context around the current state of the electricity market in New Zealand and discuss several opportunities for using energy storage system (EES) and solar energy to shift load from peak to off-peak and incentivise the consumers with a cheap pricing scheme whereby both the consumers and the distribution companies have benefits.

1.1 Background

New Zealand electricity sector mainly comprised of four different part; Generation; Transmission; Distribution and consumer (commercial and residential). According to Ministry of Business, Innovation and Employment in New Zealand; there are five major electricity generation companies which generate more than 90% of electricity such as Meridian Energy (35%), Contact Energy (23%), Mercury Power (16%), Genesis Energy (14%) and Trustpower (6%). Several small companies meet the remaining demand of Electricity in New Zealand. Transpower New Zealand limited (TPNZ) which is a state-owned enterprise is responsible for transmitting electricity in New Zealand. Transpower performs two responsibilities: They provide the infrastructure of electric power transmission, which enable customers to have access on electricity generation from different sources; and as system operator manage the real-time operation of national grid and the physical operation of the electricity market.

New Zealand electricity is traded on the wholesale market. There are at present 30 retailer companies which purchase electricity from the generation companies and sell it to the consumers. In any case, five fundamental retailers hold most of electricity retail market; these are Contact Energy, Genesis Energy, Mercury Energy, Meridian Energy and Trustpower. These organizations are likewise the primary electricity generation organizations in New Zealand, and are often referred as gentailers. distribution companies have benefits.

1.2 Distribution Generation

The concept of distributed generation is to generate the electricity closer to the demand centres. Specifically, distributed generation is an electric power source connected directly to the distributed network, or on the customer side of the meter. According to the International Energy Agency (IEA), several major factors contribute to an increased interest in distributed generation.

- Time of use pricing tariff;
- Reliability of the network for example hospitals;
- Perceived environmental friendliness
- Substitute for grid investments

Electricity demand is cyclic, with daily, weekly, and seasonal variations; this creates peak and off-peak period. To avoid building additional peaking capacity in the electricity system, energy storage can be used. This has been used commercially in several systems around the world (e.g. pumped hydro storage in XX), however it has only recently appeared in the New Zealand electricity system in the form of battery storage. As prices of battery storage technologies fall, opportunities arise for consumers and distribution companies to invest in order to reduce their costs. This has an additional benefit on the system as whole, since it helps to flatten the daily demand curve, thereby reducing peaks and the corresponding need for peaking plants and upgrading transmission assets.

Solar panel are devices that use to produce electricity from light. A solar panel is comprised of solar cells. Lot of small solar cells spread over a large area can work together to provide enough power to be useful [9]. At noon time the solar panel has highest efficiency if the sky is clear. Solar panel have made through different materials such as monocrystalline silicon PV panels, polycrystalline silicon PV panels, thick-film silicon PV panels, amorphous silicon PV panels etc [10].

1.3 Distribution pricing methodology

The Electricity network sector in New Zealand comprise four types of participant: Generators; transmission operators; distribution companies and retailers. However, residential consumers face a bill from the retailer that consists of two main charges: energy charges (this goes to the retailers for the energy that is purchased from the wholesale market); distribution charges (this goes to the distribution company for physically delivering the power, this includes both transmission and distribution costs).

Distribution companies can have different tariff structures for their customers, which depend on several factors: whether the consumer is a commercial or residential customer; whether they are a low-user or a standard-user, and whether that have distributed generation (e.g. solar PV). The costs to the distribution companies are mainly capital costs (sizes of transformers, and capacities of distribution lines). The costs are based on the peak demands on the network. However, in order to recover these costs, the, current tariff structures the majority of consumption costs are based on the kWh used, rather than peak usage (kW). This lack of cost-reflective pricing may lead to uneconomic incentives for consumers. For example, installing solar PV may greatly reduce the kWh consumed, but the peak (which occurs PV panels are no longer producing energy) will stay the same. This leads to a reduction in revenue for the lines company, but not a reduction of costs. In order to maintain their revenue prices would need to rise, which would disproportionally affect the customers without solar PV. This would lead to increased incentives to install solar, and perpetuation of this cycle.

1.4 Principal of distribution pricing set by electricity commission

Taking consideration of generation, transmission, distributor and retailer companies Electricity Commission New Zealand prepare and execute distribution-pricing policy. According to Electricity commission, no subsidy will be provided to settle on the price of the electricity if the consumers install solar panel on to their roof to reduce the peak demand.

Recently, it has been proposed that distribution companies offer commercial and residential consumers different contracts according to both the amount of energy that they purchase, but also the peak capacity of electricity consumed. Each contract has fixed and variable charge components. We illustrate diverse contract types below:

- **Booked Capacity:** Consumers contract for a particular capacity, at a rate of daily rate.
- **Fixed cost/kWh plus Daily charge:** Most consumers have traditionally bought electricity at a flat rate. Peak and off-peak periods do not affect the price of the electricity.
- **Time of use:** With this tariff, certain periods of the day are charged at a higher rate (per kWh) rate. These periods are coincided with the periods of peak utilisation of the distribution network. This type of tariff helps distributors by incentivising consumers to shift load from peak to off-peak period, thereby reducing their cost. It is also a popular contract for commercial consumers, who benefit from lower prices in the periods that they consume the most power.

Load shifting, is also known as demand-site management. Put simply, load shifting is moving demand in the peak periods to off-peak or shoulder periods; this can be carried out in a number of ways; some of these are very simple which others require technologies such as battery storage. If an energy company offers time-of-use pricing, and there is a sufficient discount for consumption during the night, the consumers who are flexible in their consumption move activities with high consumption (such as running the washing machine and dryer) to the cheaper period.

However, for shifting the load from peak to off-peak, same energy source has considered such as thermal energy storage system. Using battery storage system and solar panel as an energy source are new concept. Large-scale battery storage system is available for storing the electricity, which are generated by large scale solar or wind generation in the existing power system. Even some sub-stations are using large-scale energy storage system as a back-up system.

2 Central Planning investment for battery and solar power for shifting the load from peak to off-peak

In the principal bit of the venture, utilizing the extreme limit of electricity generation plants is the fundamental objective. One of the primary focuses to create the load-shifting model is to design mechanisms to incentivise consumers to reduce the electricity request at peak time and moving the heap.

Electricity demand may vary from time to time. Peak period scan be distinguished in the morning when individuals are preparing to go to work or school and at the afternoon when the residential consumers return home. Without these morning and afternoon periods other sessions can be addressed, as off-peak period and electricity demand is moderately low at that period.

The idea of energy storage is when the electricity demand is low electricity will be stored into storage system whereas it will be discharged when the demand is high. There will be a certain limit, which will determine charging and discharging of the energy storage system. It means if the demand will be higher than electricity consumption limit, electricity will be discharging automatically from the storage system and supply it through the transmission network. Whereas if the demand is below that electricity consumption limit, electricity will be automatically starting to charge in to the storage system. Pre-determined electricity consumption data will fix the limit for the storage system.

For different reasons can be beneficial for both the consumer and the distribution company. If the consumer installed solar panel on their roof and utilized as an alternative source of producing electricity, the method can be applicable on them. In addition, if they do not have solar panel or they do not want to install, the client simply can buy battery storage system where they can store electricity at off-peak periods and discharge at peak period. In either way, they can be benefited and can be able to save the cost of electricity.

Distribution Company involve with operations of electricity from national grid to the consumers end. Retailer companies act as an agent in between the distributor and consumer. Retailers buy electricity from the distribution company through spot market. In the spot market the price of the electricity, determines through bid system two hours earlier to transmit. After buying the electricity, the company transmit it through transmission lines, which is owned by Transpower and finally sell this to the consumer. The distributor company pays a certain transmission charge to Transpower. The charge mainly depends on time and volume (either on peak or off-peak period electricity will transmit or amount the electricity will transmit). The distributed companies want to take reduce peak consumption of electricity during off-peak period so that they can pay lower charge. In order to do so, the distributor company needs to shift load from peak to off-peak, store the electricity in battery storage system in off-peak period, and sell the electricity on peak period to the customers to maximize the profit. There are several benefits to store electricity in off-peak periods and sell it in peak period.

- Minimize the peak demand the of the electricity,
- Minimize the cost of providing electricity
- Optimize the use of transmission of electricity in order to supply substation(TPM)
- Reduce the need for high emission peaking plants

Battery storage system can be very useful for shifting load from peak to off-peak, but several things need to be considered and determined. Cost of the battery storage system is still expensive. Cost of the battery storage system need to be determined. After that comparison between battery cost and transmission, charge will determine the best option for the distributors. To avoid the transmission cost, commercially large solar power plant can install near sub-station. This would reduce the peak load on the national grid.

Retailers offer different contracts to the consumers based on the time of usage, demand and peak and off-peak period. Pricing contracts can be three types' peak, off-peak and shoulder. Each contract would have one fixed charge and three variable rates. These contracts are applicable for the consumers. For the distributor companies their costs are based on peak demand. Peak demand can be considered from different perspectives:

- Customer peak,
- Distribution peak
- Transmission peak.

Consumers who buy electricity from the retailers can be categorized into two subsections: Residential and commercial. According to the amount of usage of electricity per year residential consumer, have different options to choose among them. Almost all the retailer companies have divided their residential consumers into two groups' low user and standard user. The consumers who consume electricity below than 8000 kWh or 9000 kWh (Lower South Island) are considered as a low user and if they consume more than that are known as standard user. Meridian and Mercury energy have offered solar panel to the consumers to generate electricity by their own and offer a buy back rate of 8 cents/kWh and 12 cents/kWh respectively.

3 Load shifting model

In This section, we will demonstrate a model for shifting demand from peak period to off-peak period. Given a battery capacity and efficiency, solar panel efficiency, different pricing schemes and electricity demand of the substation that the distribution companies want to shift for, the model will output optimized peak demand with new pricing structures, while complying all constraints. We present the notation for this model below.

This model requires a database at the electricity demand of each hour of a substation and the solar radiation data to calculate the possible solar generation if the consumers install solar panel onto their rooftop.

Parameters

The set of time periods $\mathcal{T}$	$\{1,2,\ldots,24\}$
Network price	π_{network} ($ /kW)
Energy price	$\pi_{\text{energy}}\ (t)$ ($ /kWh)
Sellback price	$\pi_{\text{sellback}}(t)$($ /kWh)
Battery cost	π_{B} ($ /kWh /day)
Electricity purchased	$X_P(t)$
Electricity sold	$X_S(t)$

Original individual Electricity demand	$D_t\ (t)$
Battery efficiency	e_b
Energy of photovoltaic cell	$S(t)$
Photovoltaic cell efficiency	ϵ
Absorbed sunlight per m^2	$\sigma(t)$
Photovoltaic cell area	A_{ph}
Battery charge rate	$c(t)$
Battery discharge rate	$d(t)$

Variables

Net individual Electricity demand	$D_{net}(t)$
Maximum electricity demand	m
Battery capacity	C(kWh)
Battery Charge level	B_{level}
Battery charge rate per kWh installed	α

Constraints

This model has a number of constraints to consider different pricing schemes that are available for the consumers to purchase electricity, battery capacity, amount of solar energy produced through solar panel which is installed by the consumers

$$D_{net}(t) = D(t) - S(t),\ \forall t \in \mathcal{T}$$
$$B_{level}(t \bmod 24 + 1) = B_{level}(t) - d(t) + c(t) \times e_b, \quad \forall t \in \mathcal{T}$$
$$S(t) = \epsilon\sigma(t)A_{ph},\ \forall t \in \mathcal{T}$$

Net individual electricity demand and charged electricity in the battery must be equal to purchased electricity from the distribution company.

$$D_{net}(t) + c(t) - d(t) = X_P(t) - X_S(t),\ \forall t \in \mathcal{T}$$
$$m \geq D_{net}(t) + c(t) - d(t),\ \forall t \in \mathcal{T}$$
$$c(t), \qquad d(t) \leq \alpha C,\ \forall t \in \mathcal{T}$$

Electricity amount sold or purchase and charge and discharge rate at time t, are greater than 0.

$$X_P(t), X_S(t), c(t), d(t) \geq 0, \quad \forall t \in \mathcal{T}$$

Objective Function

The objective function of this model is to shift load from peak period to off-peak period considering network peak price and battery capacity and incentivise consumers by offering them difference pricing schemes,

$$\text{Minimise} \sum_{t \in \mathcal{T}} \left(\pi_{\text{energy}}(t)\, X_P(t) - \pi_{\text{sellback}}(t) X_S(t)\right) + \pi_{\text{network}} m + \pi_{\text{B}} C$$

4 Result

To demonstrate how this model works, we have considered electricity demand of Henderson (HEN0331) substation, Auckland. We have considered 18300 houses in the Henderson substation with an average residential consumption of 6983 kWh [21]. We have considered average solar energy [22] produced through the solar panel of every houses of Henderson substation (though this is not feasible in reality) with a 20% efficiency.

Fixed Price	30 ¢ / kWh		
Time of Use Price	Peak Period	7 a.m. – 10 a.m. 6 p.m. – 10 p.m.	26 ¢ / kWh
	Shoulder	10 a.m. – 6 p.m.	20 ¢ / kWh
	Off-Peak	10 p.m. – 7 a.m.	16 ¢ / kWh

Table1: Different pricing schemes with a different time zone

To shift load from peak period to off-peak period and get the maximum benefit from the battery, we have considered different pricing schemes (fixed price and time-of-use price) and constant network peak charge. We have considered following pricing tariff at different period of the day. To avoid the complexity of model initially, we have considered 5 kW of EES with 87% efficiency. To describe the model, in this paper we have considered the electricity demand of the month of July, as this is the coldest month in New Zealand with a less solar energy availability and highest peak demand.

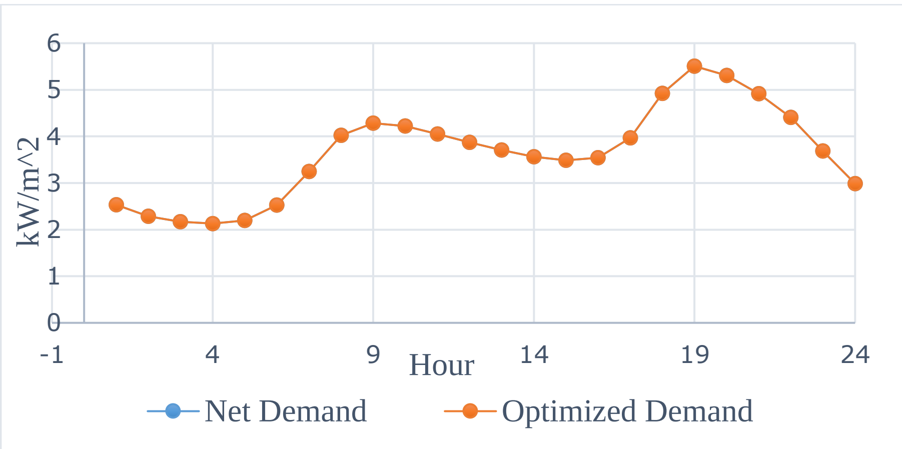

Figure 1: Demand curve without solar energy (Fixed)

If the consumer with fixed pricing contract with the distribution companies does not have solar panel but have EES then there is no benefit of using EES (Figure 1). However, even if they installed solar panel onto their rooftop but they are with fixed contract; there is no benefit to use EES.

However, the consumer with TOU pricing contract can shift the peak demand as electricity will store in EES at off-peak period (after midnight and midday) and discharge at peak period (afternoon) (Figure 2).

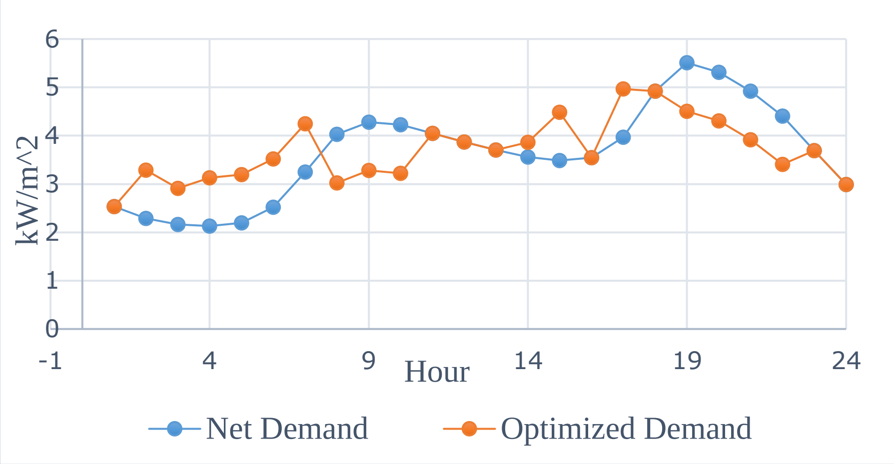

Figure 2: Demand curve without solar energy (TOU)

In figure 2, electricity demand has the highest peak at around 7 pm; however, the EES got charged in the early morning & midday, and discharged it at the afternoon which creates reduced new peak around 6 pm. Moreover, optimized demand creates new peak around 11 am, still it is lower than original peak demand.

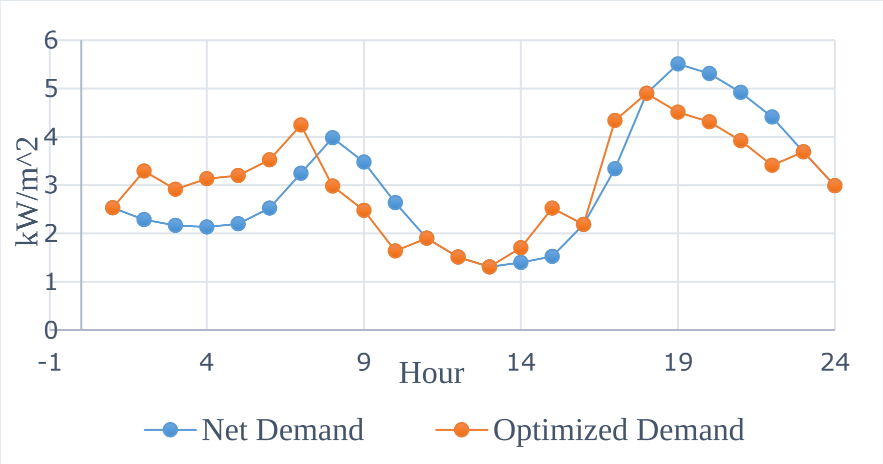

Figure 3: Demand curve with solar energy (TOU)

If the consumer has solar panel with a TOU pricing contract, will have the optimum load shifting from peak to off-peak period (Figure 3). Though the reduced peak demand would be same in both cases for with and without solar panel, but it reduced the morning peak as well significantly.

5 Conclusions

In this project we have developed a preliminary model which automatically shift load from peak to off-peak for consumers based on pricing schemes and availability of solar energy and EES. The model has been demonstrated and solved using open solver; the Solver-Studio plugin for Excel is used to manage the data.

Now, through the model we have only analysis and calculated load-shifting of the month July, nevertheless, we need to analyse summer time demand data as well; whereas at midday period, we will have maximum output from solar panel which will not only meet the demand of that certain period, but also will excessive energy will charge EES at the same time and discharge at evening peak. We have considered here constant network peak charge to simplify the model. Furthermore, we need to increase the network peak charge to see whether this will increase the price of the energy as well as capacity of EES or not. We have considered Henderson substation which is a residential area but need to consider industrial area such as Penrose substation as they have different demand profile than residential area. We need to analyse demand data of other parts of New Zealand like Christchurch, wellington as they have different solar energy production and demand profile than that of Auckland.

6 References

K. Purchara, R Belmans, Kuleuven, L. Exarchakos,A.D. Hawkes, Distributed generation and the grid integration issues." *Imperial college London.*

Bruce Dunn, Haresh Kamath, Jean-Marie Tarascon (18 November). "Electrical Energy Storage for the Grid: A Battery of Choices." *Science*, Volume 334, Issue 6058, pp. 928- (2011).

Hussein. A. Attia (19-21 December 2010). "Mathematical Formulation of the Demand side management (DSM) Problem and its Optimal Solution Electrical Power and Machines." *14th International Middle East Power Systems Conference, Cairo University, Egypt, December 19-21, 2010, Paper ID 314.*

R. Lily Hu, Ryan Skorupski, Robert Entriken, Yinyu Ye (Nov 2015), "Mathematical Formulation of the Demand Side Management (DSM) Problem and its Optimal Solution." *IEEE Transactions on Smart Grid, Vol. X, No. X.*

Andreas Poullikkas (August 2013), "A comparative overview of large-scale battery systems for electricity storage." *Renewable and Sustainable Energy Reviews,* Volume 27, Pages 778-788.