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Optimizing Time of Use (ToU) Electricity Pricing in Regulated Market

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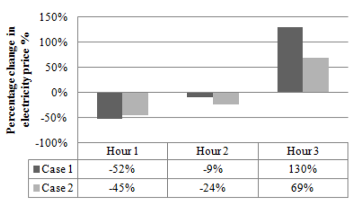
Graphical abstract



Abstract

Time-of-Use (ToU) electricity price for residential consumers is receiving lots of attention lately with the increment of smart meters usage among residential customers. ToU prices reflect the actual electricity cost and the rate is commonly set base on market price of electricity. Implementing ToU pricing system on a regulated electricity system such as in Malaysia is complicated due to non existence of electricity market. The electrical utility company or the regulator will need to determine the optimum ToU prices that would give the correct price signal so that customers will react accordingly. Many factors need to be considered such as impact on electricity generation cost, load profile, load elasticity and customers' satisfaction. This paper presents an optimization method to estimate the optimum ToU prices for given electricity demand profile and demand elasticity. The presented method able to reduce the gap between peak and off-peak demand and ensure the estimated ToU prices are fairly proportionate among hours i.e. summation of rate increments (from the fixed price) is equal to the summation of rate decrements. A simple system is used as a case study to demonstrate the application of the optimization method presented.

Keywords: Time of use pricing; optimization; load profile; peak and off-peak tariff

1.0 INTRODUCTION

ToU electricity tariff is a tariff for which the price of electricity is set at different levels for consumption at different times. In other words, customers are charged at different prices for electricity usage at different times. Conceptually, this ToU rate will be set at a higher price at time of high load demand and at low priceduring low load demand. ToU main goal is to influence the way electricity is used in the daily lives of consumers. If ToU is set correctly, it can reduce the peak load on the electrical system and therefore can avoid the use of expensive generation and ultimately, reduce operating costs to the utility.

For a regulated electricity system as practiced in Malaysia, ToU electricity rates are only offered to industrial and commercial customers [1-2]. For residential customers, they are still subject to a fixed tariff where everyone is subject to the same electricitytariff disregarding the time of electricity usage. Introducing ToU tariff for residential users is difficult because they have significantly different load profile from commercial and industrial users. Another constraint is the need for smart meterthat can record kWh consumption at all times (eg. every half hour) to replace the old meters at home. It will bring significant additional costs to the utility since the price is expensive. However, with the smart grid technologies that rapidly developed in many countries, the price of smart meters becoming more affordable. Therefore, in the near future all homes will be fitted with smart meters and ToU tariff implementation on residential customers will be possible.

The main problem faced by the utilities is to choose ToU tariff rate that can adjust electricity consumption pattern without changing the amount of electricity consumed in a day. In other words, if the ToU rates can be optimized, the utility can maintain the same income as fixed tariff and save their operation costs. Setting the ToU prices is complicated because it depends on many factors such as load profiles, load elasticity, consumer acceptance etc. The utility also need to be careful in setting the ToU prices during peak and non-peak. A disproportionate difference is not preferred and will lead to dissatisfaction among consumers, especially if the percentageprice increase is much higher than price decrease.

This paper presents a method to optimize ToU pricing to help the utility in setting the correct ToU prices, that would satisfies both utility and consumers need i.e. load profile more flat and fair ToU prices. The optimization problem is solved by using linear programming and it will consider load profiles and loadelasticities. Simple test system will be used to test the suitability of the method presented.

2.0 TIME OF USE PRICING (TOU)

ToU tariff is an electricity pricing scheme in which the consumer is charged base on the time the electricity is consumed within a day. 24 hours a day will be divided into several time blocks in which each block consist of defined duration in hours. The price of electricity in each block will not be the same. The purpose of setting different prices for each block is to reflect the electricity generation costs incurred by the utility to meet the demand at different times. Basically, the cost of generating electricity is very high at peak periods, average at mid-peak and low at off-peak periods. When demand was at its peak load, the utility has to provide the maximum amount an electric energy and using the highest number of generation capacity. Less efficient or expensive generators need to be used and transmission-line losses are also increased. For these reasons, the cost of electricity at peak load is very expensive

ToU seeks to influence the daily electricity consumption patternamong users. Generally, ToU will prompt consumers to cut electricity consumption at peak times and transfer it to other times by adjusting/shifting their electricity usage. In this way, users can reduce the cost of electricity bills for using more electricity when the price is low and reduce it when price is high. Therefore, users can still consume the same amount of electricity but with a lower electricity bill. This in turn, will create awareness among users to use electricity efficiently.

ToU pricing has been implemented in other countries such as in [4-5]. Studies on the impact of ToU pricing on consumer demand response is presented in [6-15]. Researchers in [6,7] had studied the optimum utilization of demand response program by using an economic load model and observed with different scenarios for price. This study also claimed that optimum ToU program could be improving the load curve characteristics with lower cost of customer electricity consumptions. Elasticity values, energy prices, customer participation and the periods of the off peak, mid peak and on peak will affect the load characteristics.

Ref. [8] suggested that the ToU rates should consider the stakeholders of the government, electrical power company and consumer. In order to realize the goal of power load control, power companies are allowed to adjust the price with the prerequisite of price fixing by government. Game theory has been established where the government and the power company has set or obtain a price for ToU pricing model while for electricity consumption are by consumer.

Work in [9] also proposed the ToU pricing models and methods in China which is included the ToU price for electricity. There consist of four method which are ToU pricing model based on user response(model I), pricing model based on the user response and customer satisfaction(model II), pricing model based on the linkage between the generation side and the demand side (model III) and lastly ToU pricing based on game theory (model IV). This research stated that the power company focusing on different subject of price due to the different between the models. Different accuracy of the price is one of the factors affecting the model. Thus, investigating data of the user response is affecting the accuracy of the pricing Model I and Model II while forecast of electricity demand are influences Model III. For the Model I, II and III, affected the price of power load and user have fewer concerns without a view to the government regulation effect on the power supply where game between the power company and the customers. Thus, valuable supplement for the former models is to involve the government, power companies and the customer for Model IV.

Work in [10] presenteda method that can improve grid reliability and reduce costs by finding the optimal price for electricity. In order to calculate the price of electricity during different periods of the day used an iterative linear programming was formulated based on optimization problem. Demand response can improve system reliability, reduce electricity prices, reduce price volatility and improve system reliability. This study demonstrates to reducing the peak power the effect of the demand response strategy has been applying. Thus, the peak load reduction and demand elasticity are necessary to consider the performance of demand response programs. [11] developed a demand response model for residential customers with PHEV penetration that reflects the customer behaviors in response to variable electricity prices. Results show the impacts of ToU pricing schemes on distribution feeder with different load shapes that will reduce the peak demand.

In [12],ToU pricing in inequality models is studied. For this case, there have three purposes which are for regulatory bodies in jurisdictions to assess market power, to forecast future ToU prices and examine welfare changes in electricity markets. In this study, cross price are effects the ToU models which are simulate consumer prices using monthly demand function. This study consists of three slots of ToU price (i.e. on peak, mid peak and off peak). ToU pricing are able to reduce their overall consumption when customer shift their consumption to mid peak and off peak period.

Ref. [13, 14] presented an econometric model for ToU pricing that is implemented in industrial companies and analyzed the response of consumers. It is found that the customer do participated by decreasing their energy consumption during peak hours and increasing it during off peak hours. Researchers in [15] studied two different structures of ToU scheme in which ToU is divided into ToU in demand and in energy. ToU in demand consists of flat energy and variable energy term. Whereas, ToU scheme in energy composed of variable energy and constant demand term. This structure is implemented in small and medium commercial and industries companies. Ref. [16] proposed aToU model and analyze the ToU scheme with different fixed price between seasons to reflect the differences in supply costs according to period of time.

3.0 PRICE ELASTICITY

Price elasticity is among important factor to be considered when setting the ToU prices. Price Elasticity is defined as the sensitivity of demand with respect to the price. Elasticity have two different coefficients consists of self elasticity and cross elasticity. Self demand elasticity determines the percentage change in electricity demand divided by the percentage change in the electricity price. Price elasticity can be used to interpret how consumer demand responds to price changes. The sign will always be negative, so it is common to consider only the absolute value when analyzing the own price elasticity.

In scientific literature, there are two types of price elasticity coefficients are often used, namely: own-price elasticity and elasticity of substitution. Own-price elasticity is one factor that tells useful information about how our customers adapt to the increase in electricity prices and adjust electricity usage. Own price elasticity usually has a negative value indicating a reciprocal relationship between demand and price. In this paper, we only focus on own-price elasticity, because of the importance of this paper is to estimate how changes in the price of retail electricity will have an impact on electricity demand change. For simplicity, this paper uses the word '*price elasticity*' instead of '*own-price elasticity*'.

4.0 ToU PRICES OPTIMIZATION METHOD

By referring to Figure 1, the thick line represents the actual demand, P_d^{actual} , which varies over time. At certain hours, the demand is at its peak. The dotted line represents the average demand, P_d^{ave} which is the desired flat demand profile (load profile).

$$P_d^{ave} = \frac{1}{24} \times \sum_{houri=1}^{24} P_{d,houri}^{actual} \qquad (1)$$

The difference between the actual demand and the average demand in *hour i*is given by:

$$P_{d,houri}^{diff} = P_{d,houri}^{actual} - P_d^{ave} \qquad (2)$$

The objective of ToU pricing is to minimize the difference between the actual demand and the average demand. Since the difference can be negative value (for the case actual demand is lower than the average demand), in the presented method the difference is squared. The objective function is written as follows;

$$Min\left\{\sum_{houri=1}^{24} \left(P_{d,houri}^{actual} - P_d^{ave}\right)^2\right\} \qquad (3)$$

Price elasticity at hour i is given by:

$$\epsilon_{houri} = \frac{\%\Delta P_{d,houri}}{\%\Delta Price_{houri}} \approx \frac{\Delta P_{d,houri}/P_{d,houri}}{\Delta Price_{houri}/Price_{houri}} (4)$$

$$\Delta P_{d,houri} = \frac{\Delta Price_{houri}}{E_{houri}} (5)$$

where; $E_{houri} = \frac{Price_{houri}}{\epsilon_{houri} \times P_{d,houri}}$

In this case, the change if price is the price difference between the ToU price (at a particular hour) and the fixed tariff price. From the concept of price elasticity, the electricity consumer will react to the electricity price change (from the current fixed price). Thus, the change in price at hour i is given by;

$$\Delta Price_{houri} = ToU_{houri} - fixedtariff \qquad (6)$$

Assume that the actual demand changes as ToU is introduced, thus;

$$P_{d,houri}^{actual} = P_{d,houri}^{actual,old} + \Delta P_{d,houri} \qquad (7)$$

$$P_{d,houri}^{actual} = P_{d,houri}^{actual,old} + \frac{\Delta Price_{houri}}{E_{houri}} \qquad (8)$$

Substitute eq. (8) into eq.(3);

$$\text{Min}\left\{\sum_{houri=1}^{24} \alpha + \beta \Delta P_{d,houri} + \gamma\left(\Delta P_{d,houri}\right)^2\right\} (9)$$

Where: $\alpha = \left(P_{d,houri}^{actual,old} - P_d^{ave}\right)^2$ (10)

$$\beta = 2\left(P_{d,houri}^{actual,old} - P_d^{ave}\right)/E_{houri} \qquad (11)$$

$$\gamma = (1/E_{houri})^2 \qquad (12)$$

To ensure fair ToU pricing, the summation of electricity price increment (from the fixed price) must equal to the summation of price decrement. Thus the objective function in (9) is subjected to the following equality constraint;

$$\sum_{houri=1}^{24} \Delta Price_{houri} = 0 \quad (13)$$

Solving the optimization problem would yield the following equations:

$$\lambda = \frac{\sum_{houri=1}^{24} \beta/_{2\gamma}}{\sum_{houri=1}^{24} 1/_{2\gamma}} \quad (14)$$

$$\Delta P_i = (\lambda - \beta)/_{2\gamma} \quad (15)$$

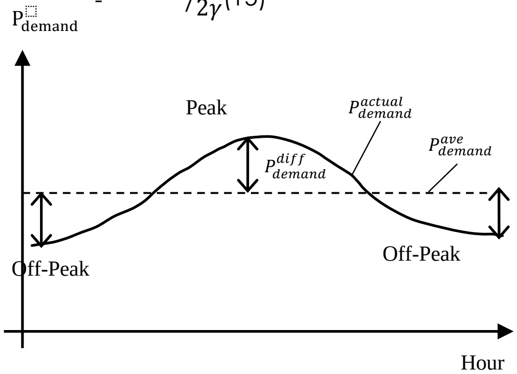


Figure 1 Actual and average demand of electricity consumer

5.0 CASE STUDY

5.1 Test System

The system consists of 3 generators supplying demands of residential customers. Table 1 shows the cubic fuel cost model for each generator in the system where P_i is the generation output of generator G_i.Each generator has different generation cost function. The maximum power output for each generator is fixed to 150MW. The demand of the customers is shown in Figure 3. To simplify the problem, only 3 hours electricity demand is considered (instead of 24 hours). Demand in Hour 1 represents off-peak consumption which commonly occurred between 12am and 8am. Hour 2 represents medium-peak consumption which commonly occurred between 8am and 6pm while Hour 3 represents peak electricity consumption which occurred between 6pm to 12am. It is assumed that the price elasticity (self) of each hour is given in Table 2.

5.2 Base Case- System With Fixed Tariff

In regulated market, there is no hourly market price since all generators belong to the utility and no competition. Thus the hourly cost here is the cost incurred by the utility for generating MW power, transmission and other services to meet the required demand. In this test system, the generators are optimally dispatched to minimize the overall electricity generation cost in meeting the hourly system demand shown in Figure 3. The generation output and generation cost for 3 hours for the test system is given in Table 3. As expected the results show that the hourly generation cost depends on system demand i.e. the generation cost increases as system demand increases. Thus the generation cost per kWh is calculated as follows;

$$\frac{RM(5323 + 5694 + 9058)/h}{250MW + 270MW + 420MW} = 21.36\ cents\ /kWh$$

In Malaysia, the residential customers are charged at fixed tariff. For discussion purpose, it is assumed that the tariff is set at generation cost per kWh.

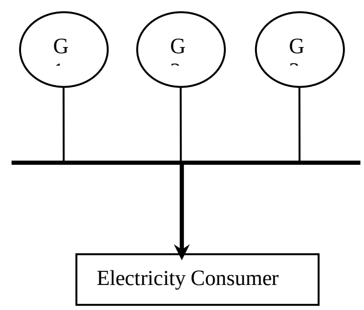


Figure 2 Test system

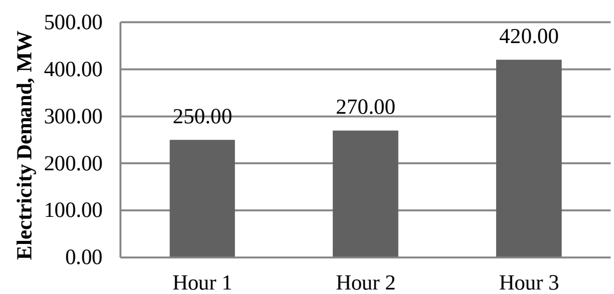


Figure 3 Electricity demand of the test system

Table 1 Generation cost data of the test system

Generator	Fuel input (RM/h)
G1	$500 + 15.1P_1 + 0.012P_1$
G2	$400 + 15.5P_2 + 0.015P_2$
G3	$200 + 17.0P_3 + 0.050P_3$

Table 2 Price Elasticity of Electricity Consumer

Hour	*Elasticity, ϵ*
1	-0.005
2	-0.019
3	-0.002

Table 3 Generation output of each generator and total generation cost for each hour

Time		Hour 1	Hour 2	Hour 3
Electricity Demand		160.00 MW	270.00 MW	420.00 MW
Generation Output (MW)	G1	138.40	148.20	150.00
	G2	97.39	105.23	150.00
	G3	14.22	16.57	120.00
Total Generation Cost		RM5323.18	RM5693.96	RM9057.50

5.3 Case 1- With ToU Pricing (Without ToU Optimization)

In this case, ToU pricing is used to adjust the electricity demand. It is assumed that the electricity consumers will response to the price change according to the price elasticity in each hour as given in Table 2. By using the elasticity factor given in equation (4), the suggested ToU prices in each hour is given in the 3rd row of Table 4.

5.4 Case 2- With ToU Pricing (With ToU Optimization)

In case 2, the ToU prices are optimized such that the summation of electricity price increment equal to the summation of price decrement. By applying equation (1)-(15), the ToUprices is given in the 4th row of Table 4.

5.5 Comparisons and Discussion

Table 4 shows the results for all three cases. The base case shows the prices used at present for which the price has not changed in the three hours (constant prices). Case 1 shows ToU based electricity price calculated using the consumer price elasticity data. For this case, there is no constraint on the pricing of electricity generated, so there is a significant difference between the price at hours 1 and 2. If calculated in terms of the percentage difference from the original price (shown in Figure 4), the percentage difference is high for 3 hours ie 130% respectively while only -52% and -9%, only to hour 1 and hour 2. The difference is disproportionate and will lead to less favored dissatisfaction for consumers because higher percentages increase than decrease. Case 2 shows ToU price calculated using the method set out optimization. This method takes into account the rate of price increases and decreases balanced. The results displayed in Figure 4 show the percentage difference is respectively -45%, -24% and 69% for 1 hour, 2 hours and hours 3. The price of this case is unfair because the percentage increase is equal to the percentage reduction.

As discussed in the previous section, ToU is to change consumption load profiles to be horizontal so that the cost of electricity generation by the utility can be saved on an hourly basis. Figure 5 shows the load profile in the case of a horizontal one is perfect. Although the two cases are not as good as the first case, the load profile is better than the base case. Similarly, the cost of generation for each case is shown in Figure 6. The cost of electricity generation at 3 in the case of 1 and 2 are lower than the base case.

6.0 CONCLUSION

This paper presented a simple method for ToU price optimization. It can be considered as a first step for the utility to estimate the ToU prices, which are reasonable and acceptable to consumers. The presented method taking into account the price elasticity, load profiles and ToU rate of balance between peak and non-peak hours. This method is applied on a simple test system the results show that the ToU rates can be optimized while taking into account the requirements of the utility (i.e. more flat load profile) and the requirements from consumers (i.e. ToU rates peak and non peak time is balanced). Further work needs to be done to include other factors such as cross elasticity and practical residential load profiles.

Table 4 Electricity pricing of the cases for each hour

Case	Hour 1	Hour 2	Hour 3
Base Case	21.36 cents	21.36 cents	21.36 cents
Case 1	8.69 cents	19.19 cents	53.36 cents
Case 2	10.32 cents	15.36 cents	38.40 cents

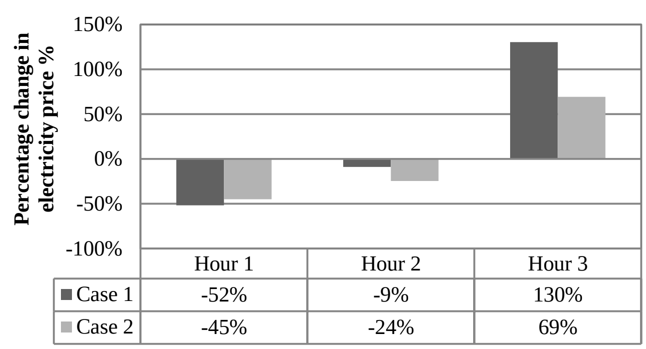
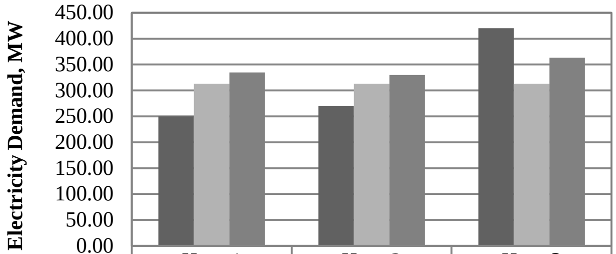
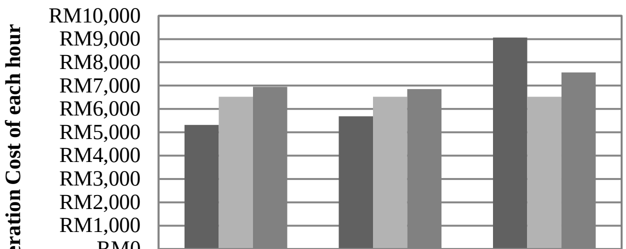


Figure 4 Percentage change in electricity price



	Hour 1	Hour 2	Hour 3
Base Case	250.00	270.00	420.00
Case 1	313.33	313.33	313.33
Case 2	334.94	329.96	363.21

Figure 5 Electricity demand for each case



	Hour 1	Hour 2	Hour 3
Base Case	RM5,323	RM5,694	RM9,058
Case 1	RM6,522	RM6,522	RM6,522
Case 2	RM6,952	RM6,852	RM7,572

Figure 6 Generation cost for each case

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