Uncertainty and sensitivity analysis applied on commercial tariff with off-peak tariff rider: a case study

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ABSTRACT

Commercial tariff with off-peak tariff rider (C1 OPTR) is one type of time-based electricity tariff. The C1 OPTR charges electricity consumers with different electricity rates instead of a flat rate tariff. This paper investigates the C1 OPTR tariff adopted recently by Universiti Teknologi MARA Cawangan Pulau Pinang (UiTMCPP) from its previous flat rate tariff. The investigation involves applying the uncertainty and sensitivity analysis to the average load factor (ALF) model of the UiTMCPP. The ALF model consists of two major factors, namely kilowatt-hour (kWh) and maximum demand (kW). The analysis aims to identify the most contributing factor between the kWh and kW to the uncertainty of the ALF in a systematic way using Monte Carlo simulation. The factor identified is important for improvement by UiTMCPP to ensure that the suitable target ALF can be easily achieved. Based on Sobol uncertainty and sensitivity analysis technique, 60,000 samples for the respective kWh and kW have been generated and executed to produce the output of the ALF model. The result of the uncertainty analysis shows that the ALF output is uncertain between 0.195 and 0.343. Furthermore, the applied sensitivity analysis discovers that the kW is the most contributing factor to the ALF output uncertainty, with the sensitivity index indicating 0.8853.

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1. INTRODUCTION

Tenaga Nasional Berhad (TNB) is the main supplier for electricity in Malaysia. TNB has classified their customers into 6 basic categories, depending on customer's business activities and supply voltage levels. The TNB customers are charged based on their categories in which each tariff differs. Details of the customer categories, schemes and tariffs are available in TNB booklets [1]. For commercial category, TNB also introduces an electricity tariff based on time of use (TOU). The TOU tariff separates the electricity consumption into peak and off-peak periods. The introduced TOU aims to decrease the consumer's maximum demand (kW) by transferring some of the demand into different hours especially within the off-peak period. In other words, the implementation of TOU is able to shrink the gap between peak and off-peak consumptions to gain a flatter electricity load profile. The impact of different types of TOU tariff has been studied and published in [2].

In the beginning, TNB commercial customers may only opt for two types of schemes, either medium voltage general commercial tariff (C1) or medium voltage peak/off-peak commercial tariff (C2). The C1 scheme provides a flat rate for electricity consumption (kWh) and kW at 0.365 RM/kWh and 30.3 RM/kW, respectively. In contrast, the C2 scheme provides two rates for the kWh consumptions. The enforced rates are 0.224 RM/kWh and 0.365 RM/kWh during off-peak (kWh-O) and peak (kWh-P) periods, respectively. The kW rate for C2, however, is fixed but higher as compared to the kW rate for C1. The kW rate for C2 is 45.1 RM/kW which is an addition of 14.8 RM/kW. Table 1 shows the comparison of C1, commercial tariff with off-peak tariff rider (C1 OPTR) and C2 tariff rates for the TNB commercial customers.

Table 1. A comparison of tariff rates for TNB commercial customers

Parameter	Medium voltage general commercial tariff (C1)	Commercial tariff with off-peak tariff rider (C1 OPTR)	Medium voltage peak/off-peak commercial tariff (C2)
$kWh-O$	0.365 RM/kWh	0.292 RM/kWh	0.224 RM/kWh
$kWh-P$	0.365 RM/kWh	0.365 RM/kWh	0.365 RM/kWh
kW	30.3 RM/kW	30.3 RM/kW	45.1 RM/kW

Later, TNB has enhanced the C1 scheme by introducing off-peak tariff rider known as C1 OPTR. The aim of the C1 OPTR scheme is to avoid high electricity demand during peak period. The main reason is that the high electricity demand during peak period, which is between 8.00 am and 10.00 pm, may require TNB to build up more power stations which result in an increase in the electricity cost [3]. Therefore, TNB provides a discount for kWh consumption during the off-peak period in order to motivate commercial customers to schedule their electricity consumption. As shown in Table 1, the difference between the C1 and the C1 OPTR is the kWh consumption rate during the off-peak period (kWh-O). The different rate value is 0.073 RM/kWh which is equivalent to 20% discount on the electricity cost for C1 OPTR scheme.

While it is clear that the C1 OPTR provides more advantage than the C1 scheme, commercial customers who plan to apply for the C1 OPTR scheme need to consider an average load factor (ALF). The ALF is a one-time baseline value (i.e. threshold) that will be used to compare with the customer's monthly load factor (LF) value. It is an important condition for the 20% discount eligibility [1]. If the LF value is greater than the ALF threshold, the customers are entitled for 20% discount. Otherwise, the customers are charged as C1 scheme. Therefore, the commercial customers should target the lowest possible ALF value in order to guarantee that the condition can easily be satisfied. However, the estimation of the ALF is determined based on the last 6 months of the customer's electricity load profiles and it is depends on the customer's business activities. For example, educational institutions depend on academic semesters where students are available in the institutions while the industries might depend on their product demands. Therefore, the estimation of a suitable ALF threshold with a confident level based on customer's activities is unique and worth to be performed. A technique known as uncertainty analysis can be the most suitable technique for the ALF estimation.

An uncertainty analysis is a technique that computes all possible outcomes that result from input or parameter uncertainties in a systematic way [4], [5]. The outcome from the uncertainty analysis shows the output boundaries as well as its probability distributions. The probability distribution outcome can be used as an indicator for the level of confidence. In general, a large area of the probability distribution within a specific target value indicates the high confidence level, and vice-versa. In this study, we have modelled ALF for UiTMCPP using electricity load profiles and applied the uncertainty analysis. The aim is to obtain a suitable target ALF threshold with confidence level. If the obtained confidence level is high, the margin between the future monthly LF and the ALF is also high, assuring the UiTMCPP to enjoy 20% discount for their future electricity bills.

Besides the uncertainty analysis, the sensitivity analysis is also essential since the latter is greatly related to the uncertainty analysis. Sensitivity analysis is how the input or model parameter uncertainty impacts the model outcome [6]. Therefore, we further apply the sensitivity analysis technique to computes the contribution of kW and kWh to the uncertainty of the output ALF. The result from the sensitivity analysis can be significant to prioritise the input factor [5], [7]. An input factor with the highest sensitivity index (main factor) indicates the most contributing factor to the uncertainty of the output ALF. The main factor should be the focus factor for further studies and exploration in order to achieve the target output ALF.

There are some research works on uncertainty and sensitivity related to electricity tariff and consumptions. The effect of TOU and kW tariffs on the power exchange between a commercial customer and the power system in the presence of solar panels and a battery has been studied in [8]. Furthermore, the sensitivity analysis has been performed on the load profile with respect to the effect of kW and battery characteristics. It is found that the kW rate affects the power exchange whereby the proper kW rate and battery size produce positive power flow from the power grid to the customer. Meanwhile, Ferreira *et al*. [9] proposed a TOU tariffs design based on a quadratically constrained quadratic programming considering the uncertainty in the price-elasticities of electricity demand. The stochastic optimization has also been deployed to the design to maximize the total economic welfare. It is found that the proposed design leads to increments in total economic welfare, as well as to improvements in the system load factor.

The performance and cost of a solar dish power plant under desert weather condition has been investigated using the sensitivity analysis [10]. The main objective of the applied sensitivity analysis is to investigate the effect of main economic variables on the levelized cost of electricity (LCOE) and net present value (NPV). The results of the sensitivity analysis indicate that LCOE and NPV are very highly sensitive to the solar dish collector cost. Besides, there is a study on the effect of weather condition on the energy consumption for office buildings. Kim *et al*. [11] has explored into the effect of local climate variations and occupancy rates of the electricity energy consumption of an office building. The local climate variables include temperature, humidity ratio, solar radiation, cloud type and wind speed for occupancy rates on both working and non-working days. The authors use the linear regression model and artificial neural network (ANN) approaches. The result has shown that the ANN approach is better than the linear regression for predicting electricity consumptions during working days. The sensitivity result reveals that the occupancy rate strongly dominates the electricity consumption in the building while temperature and humidity show small effect.

The study on the response of households to the TOU tariff has been conducted in Victoria, Australia [12]. The objective of this paper is to determine whether or not there is a shift in the consumption from peak to off-peak periods in response to the difference in peak and off-peak prices. The result from 6,957 Victorian households show that they respond weakly to the time varying rates while households in the lowest socio-economic areas do not respond at all.

Despite several research works, those works can be considered different from this study in a way that this study applies both the uncertainty and sensitivity analysis for the C1 OPTR scheme as in the case of UiTMCPP. Thus, the main contribution of this paper is the quantification of the uncertainty and sensitivity of the ALF model output due to the uncertainty of kW and kWh input factors. As the methodology for this study is based on Monte Carlo simulations which require a very high number of samples for input factors [13], [14], the uncertainty and sensitivity analysis has been performed using Google colaboratory high-performance computing. The Google colaboratory is an open source, cloud-friendly notebook environment based on Python code and supports uncertainty and sensitivity libraries [15], [16].

2. RESEARCH METHOD

2.1. UiTMCPP electricity scheme

Universiti Teknologi MARA Cawangan Pulau Pinang (UiTMCPP) is an educational institution located in Permatang Pauh, Pulau Pinang, Malaysia. Since the establishment of UiTMCPP in 1996, the institution adopted C1 scheme from TNB. With the C1 scheme, UiTMCPP needs to pay electricity tariff (new tariff rate started in 2014) at RM0.365 for each kWh consumption and of RM30.3 for kW. The electricity is used to cater for several academic buildings, hostels, halls, and the library. Besides, it is also used to drive many high-power machines and equipment in several laboratories since the UiTMCPP offers electrical, mechanical, civil, chemical engineerings including hotel and tourism programs.

2.2. Average load factor (ALF)

The ALF is a one-time calculated value prior to the enrollment to the C1 OPTR scheme. The ALF value will be used to compare with customer LF. As mentioned previously, if the LF in particular month is less than the ALF value, no discount is eligible, and vice-versa. The ALF and LF are calculated using (1) and (2), respectively.

$$ALF = \frac{Total\ energy\ consumption\ in\ kWh\ for\ previous\ 6\ months}{(Highest\ Maximum\ demand\ in\ kW \times total\ hours)\ for\ previous\ 6\ months} \tag{1}$$

$$LF = \frac{Total\ energy\ consumption\ in\ kWh\ for\ the\ current\ month}{(Maximum\ demand\ in\ kW \times total\ hours)\ for\ the\ current\ month} \tag{2}$$

As shown in (1), the minimum dataset (kWh and kW) required to calculate ALF value is six months. Thus, the ALF model for UiTMCPP has been based on the actual electricity bills for the year 2020.

2.3. Uncertainty and sensitivity analysis

The aim of the uncertainty analysis is to computes the propagation of inputs and parameters uncertainties to the model outputs, whereas the sensitivity analysis quantifies the contribution of those inputs and parameters to the uncertainties [5]. The uncertainty and sensitivity analysis can broadly be classified into local and global techniques.

The local uncertainty and sensitivity analysis, such as Morris technique, is a simple technique whereby only one input factor is varied at a time while other factors are being fixed at their nominal values. The varied input factor, however, is only explored around its nominal value. The local uncertainty and sensitivity analysis technique is suitable for screening purposes whereby a few important among many input factors need to be identified. The drawback of the local analysis is that it is unable to computes the interaction contribution among input factors [17].

In contrast, the global uncertainty and sensitivity analysis, such as Sobol technique, is based on varying all input factors simultaneously within their respective factor spaces. The global analysis can compute the interaction contribution among the input factors. The global analysis, however, requires a high computational cost due to a complete exploration within the factor spaces. In this paper, we choose a global uncertainty and sensitivity analysis based on Sobol' technique. The Sobol' technique is a variance-based technique that decomposes the output variance into components that compute the importance of the single model input factors [5], [18], [19]. The Sobol' technique has been proven to be one of the most robust and popular techniques applied in many study areas [20]-[22].

Consider a mathematical model $f()$ in which the output variable Y is a nonlinear deterministic function of its k input factors:

$$Y = f(x_1, x_2, x_3 \dots, x_k) \tag{3}$$

where $x = [x_1, x_2, x_3 \dots, x_k]$ are the uncertain input factors of the mathematical model. It is assumed that the input factors are not only independent but also random variables. The output expected value $E(Y)$ and variance $V(Y)$ are provided by:

$$E(Y) = \int f(x_1, x_2, x_3, \dots, x_k)\, dx \tag{4}$$

$$V(Y) = \int [f(x_1, x_2, x_3, \dots, x_k) - E(Y)]^2\, dx \tag{5}$$

the expected value of Y conditional on x_i is given by:

$$E(Y|x_i) = \int f(x_1, x_2, x_3, \dots, x_k)\, \frac{dx}{dx_i} \tag{6}$$

the first order sensitivity index of the model is defined by:

$$S_i = \frac{V[E(Y|x_i)]}{V(Y)} \tag{7}$$

further, the total order sensitivity index of the model is defined by:

$$S_{Ti} = 1 - \frac{V[E(Y|x_{-i})]}{V(Y)} \tag{8}$$

where x_{-i} represents the total input factors excluding x_i.

The effect of a single parameter on the output variance is indicated by first order index. In contrast, the total order index shows the effect of the first order and interaction involving that parameter (second and higher order effects) on the output variance. If the first order is about similar to the total order indices, the model has mostly no interaction effects [23], [24]. To assist in computing the S_i and S_{Ti} indices, the SALib sensitivity analysis library has been installed in Google colaboratory notebook. The library is one of the popular libraries for the uncertainty and sensitivity analysis for Python environment [16].

2.4. Implementation of uncertainty and sensitivity analysis

The flowchart for applying the uncertainty and sensitivity analysis is shown in Figure 1. Firstly, kWh and kW are defined as the investigation input factors. Their values of uncertainties for performing the sensitivity analysis must be based on previously recorded data or expert views [6], [25]. In our case, the input factor uncertainties are based on UiTMCPP electricity bills from January 2020 to September 2020. Based on the bills, the recorded maximum and minimum values for kWh and kW are tabulated in Table 2. It is assumed that the probability of each input factor is a uniform distribution. The uniform distribution means that the probability for input factors to occur within their minimum and maximum values is the same. The uncertainty and sensitivity analysis has been implemented in Google colaboratory notebook. Besides, SALib package has been imported into the notebook to simplify the process of estimating the sensitivity indices. While the package has several sensitivity analysis techniques, this paper applies the sensitivity analysis based on a Sobol's sensitivity technique.

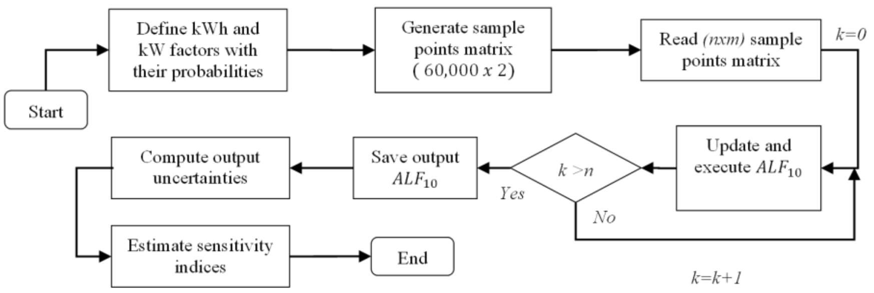


Figure 1. Uncertainty and sensitivity analysis flowchart

Table 2. Input factor uncertainties

Factor	Minimum	Maximum	Distribution
kWh	458,750	1,058,277	Uniform
kW	1,389	4,054	Uniform

A high accuracy result for the sensitivity analysis is achieved by using a high number of sample points since the applied sensitivity analysis is based on Monte Carlo simulation approach. The SALib package provides a function to generate systematic sample points by providing the number of input factors. With two input factors (kWh and kW), the function generates 60,000 sample points within the boundaries of factor spaces. For opting C1 OPTR scheme, the ALF needs to be calculated for a period of the previous 6 months including the current month as shown in (1). Since the focus of the ALF model in this study is on October 2020, the ALF for the October (ALF_{10}) can be written as (9).

$$ALF_{10} = \frac{\sum_{m=5}^{10} kWh(m)}{\max(kW(m)) \times 24 \times \sum_{m=5}^{10} days(m)} \quad (9)$$

Where m is the month, and $days(m)$ is the number of days of m^{th} month. The days are a constant value since the total number of days from May 2020 to October 2020 is 184 days. In equation (9), there are two main factors that affect the average load factors which is the total energy consumption (kWh) and kW, for $m = 5$ to 10. It is important for consumers to identify the most influencial factor between these two factors to the output ALF_{10}. The most influencial factor is the target factor for consumer to act toward achieving a specific ALF target.

To calculate the output ALF_{10} with the input matrix of 60,000×2 sample points, we have written python codes to automatically read the row of the matrix, update the input factors and execute the expression (9). This process has been repeated for all the 60,000 rows of the matrix. The generated output ALF_{10} has been mapped with the sample point matrix using SALib package to compute the output uncertainties and estimate sensitivity indices. The result of the uncertainty and sensitivity analysis will be described next.

3. RESULTS AND DISCUSSION

The sensitivity analysis based on Sobol' technique has been applied to the ALF expression to apply the C1 OPTR scheme. The ALF expression has been based on UiTMCPP energy consumption from January 2020 to September 2020 since the target month for the sensitivity analysis is for October 2020. As the sensitivity analysis is highly related to the uncertainty analysis, two types of analysis results are presented. The first is the result of the uncertainty analysis and the second is the result of the sensitivity analysis.

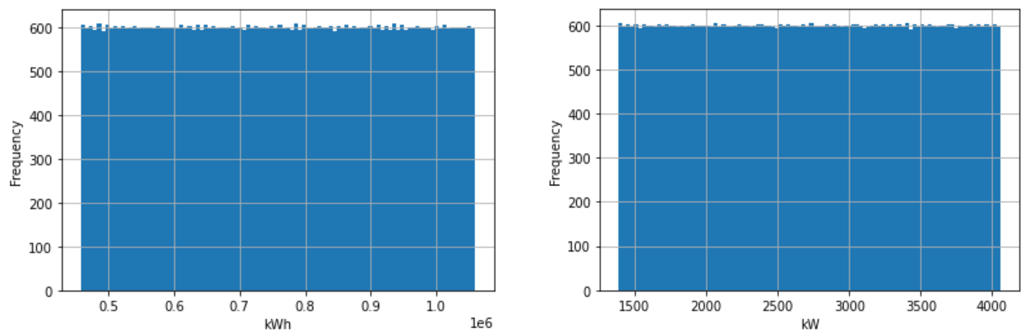
3.1. Uncertainty analysis

The range of uncertainties for kWh and kW is determined based on electricity bills dated January 2020 until September 2020. The recorded ranges of uncertainties for the kWh and kW are 458,750≤kWh≤1,058,277 and 1,389≤kW≤4,054, respectively. Using the SALib package, 60,000 sample points have been generated for each kWh and kW factor. Figure 2 shows part of the generated sample points where by the first column represents the kWh samples and the second column represents the kW samples.

```
[787970.24041748   1929.18951416]
[548144.80352783   1752.21685791]
[525677.17791748   1752.21685791]
[548144.80352783   2428.87701416]
[548144.80352783   2428.87701416]
[525677.17791748   1752.21685791]
[525677.17791748   2428.87701416]
[847908.30352783   3084.71685791]
[825440.67791748   3084.71685791]
[847908.30352783   3761.37701416]
[847908.30352783   3761.37701416]
[825440.67791748   3084.71685791]
[825440.67791748   3761.37701416]
[997790.05352783   2418.46685791]
[675558.92791748   2418.46685791]
```

Figure 2. Generated sample points dataset (1st column is kWh samples, 2nd column is kW samples)

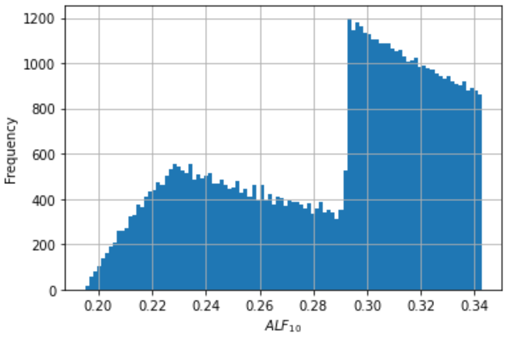
Furthermore, Figure 3 shows the input factor histogram with the bins set to 100 for Figure 3(a) electricity consumption, kWh and Figure 3(b) maximum demand, kW. It can be seen that the sample points are distributed in a uniform way indicating that their probability of occurrence within their respective range is the same. The generated sample points are automatically inputted to expression (9) to determine the output ALF. When the execution is completed, a 60,000 ALF outputs have been generated. Figure 4 shows the ALF_{10} output. The histogram and cumulative density function of the ALF_{10} output is shown by Figure 4(a) and Figure 4(b), respectively. Details of the histogram result in Google colaboratory show that the output ALF values are uncertain, which is between 0.195 and 0.343.



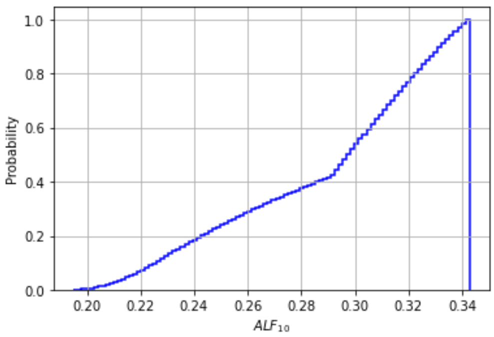
(a) (b)

Figure 3. Input factor histogram, (a) kWh and (b) kW

Ideally, the main target during the application of C1 OPTR scheme is to obtain the lowest possible ALF value. The lowest ALF value creates a high margin between the target ALF value and the future LF. However, the probability to obtain a single lowest ALF value, which is 0.195, is extremely small. In this study, we assume that the range target ALF is 0.29 or below. Thus, the cumulative density function (CDF) of the same ALF output has been plotted as Figure 4(b). It is shown that the probability to obtain the ALF output for 0.29 or below is 0.41. The CDF result indicates that based on the previous electricity consumption from January 2020 to September 2020, UiTMCPP has the probability of 41% to obtain the ALF output value of less than 0.29.



(a)



(b)

Figure 4. ALF_{10} output (a) histogram with bins of 100 and (b) cumulative density function

3.2. Sensitivity analysis

The output of the ALF_{10} expression depends on the kWh and kW input factors. As the kWh and kW values are uncertain, these factors propagate through the ALF_{10} expression to produce output that is uncertain as well. The output uncertainties can be contributed by the single input factors (kWh or kW) and/or interaction between these factors. It is important to identify the input factor that contributes the most to the uncertainties of the output ALF_{10} for factor prioritization. Table 3 shows the numerical result of the sensitivity analysis performed in Google colaboratory. The first order index for kWh and kW is approximately 0.11 and 0.89, respectively. Since the kW index is greater than kWh index by almost 8 times, the kW input factor is the most contributing input factor to the uncertainty of the output ALF_{10}.

The total order sensitivity index is the first order index including the interaction effects with other input factors. The sensitivity indices between the first order and total order for kWh are about a similar index value indicating no interaction effect between kWh and kW. The similar result (no interaction effect) is also shown by the similar sensitivity indices between the first order and total order for kW.

Table 3. Sensitivity indices for kWh and kW

Factor	First order	Total order
kWh	0.11243567	0.11449996
kW	0.88534833	0.88764376

4. CONCLUSION

C1 OPTR scheme is one of the TOU electricity tariffs that provide a lower electricity tariff during off peak to eligible TNB's commercial customers. The customers may save 20% in their electricity bills with a condition that their monthly LF exceeds the ALF. This paper presents the studies on the ALF model for UiTMCPP and applies the model with the uncertainty and sensitivity analysis. The applied uncertainty and sensitivity analysis is based on Sobol's technique using Monte Carlo simulation. The aim of the applied uncertainty is to measure the uncertainty of the output ALF due to the uncertainties in the input factors namely the kWh and kW. The uncertainty result shows that the output ALF is uncertain, between 0.195 and 0.343. The probability to obtain 0.29 or below for the target ALF is 41%. Additionally, the sensitivity analysis is applied to identify the contribution of the kWh and kW to the uncertainty of the output ALF. The applied sensitivity analysis reveals that the kW factor is more sensitive as compared to the kWh factor. The sensitivity index for the kW factor is about 3 times higher than the kWh factor. The interaction between the kWh and kW, however, shows no contribution to the uncertainty of output ALF.

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