Investigation of electricity load shifting under various tariff design using ant colony optimization algorithm

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ABSTRACT

A price-based program through a time of use tariff (TOU) program is one of the initiatives to offer sufficient benefit for both consumers and generations sides. However, without any strategy for implementing optimal load management, a new tariff design structure will lead to the miss perception by electricity consumers. Therefore, this study offers an investigation toward appropriate TOU tariff design to reflect load profiles. Concurrently, the ant colony optimization (ACO) algorithm was proposed to deal with the load shifting strategy to determine the best load profiles and reducing the consumers' electricity cost. The sample load profiles data is obtained from various residential houses, such as single-story, double-story, semi-D, apartment, and bungalow houses. The significant comparison between baseline flat tariffs to several TOU tariffs has shown an improvement in the percentage of cost saving for approximately 7 to 40%. Furthermore, the identified load management was observed where the maximum load shifting weightage was set up to 30% to reflect the consumers' effort towards energy efficiency (EE) program. The previously proposed TOU design was identified to be a suitable structure that can promote balancing of EE and demand response (DR) program effort in most consumers' houses category in Malaysia.

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1. INTRODUCTION

Residential contributes a majority of Malaysia's electrical energy consumers. The majority of electricity consumers in most countries are residential sector [1], [2]. In Malaysia, residential contribute 21% from 54% building energy consumption [3]. For several residences, depending on the culture, the number, and status of the residents, the number of possible existing appliances or devices could vary [4]. With the increasing demand for electrical energy, the energy generation cost will increase and affect the provider to increase the tariff cost. Thus, the demand response (DR) program is introduced to help reduce energy generation emission and costs due to its flexible management of price signals to the consumers. Customers are committed to reducing or diverting electricity consumption from periods with low generating capacity in response to signals from service providers called aggregators or can even temporarily change their normal consumption patterns using on-site standby generated energy [5]. Interactions between utilities and end-users can be generated with the help of DR to move the distribution network from a vertically controlled structure to a collaborative environment where it is not only governed by generational actions, but user actions and responses also influence it [6].

Furthermore, with an advanced metering infrastructure (AMI) installed, such as a smart meter from Tenaga Nasional Berhad (TNB) in Malaysia, consumers can apply demand side management (DSM) strategy if time of use (TOU) tariff is offered [7]. The smart meter data will provide three critical applications: load analysis, load forecasting, and load management. Considered the impact of external benefits and established an advanced system dynamics simulation model: price-based program and incentive-based program [8]. Demand side management strategy focuses on the symbiosis of the energy generation values and consumers' satisfaction by managing power consumption and peak demand by optimizing the appliance's operation on the user side [9]. Several DSM strategies can be proposed. Such as forecasting of residential energy, using direct load control [10], using optimization and artificial intelligence [11], incentive-based demand response program [12], load shifting [13], energy management systems (EMS) [14], photovoltaic systems (PV) integration [15].

Regarding the previous study that proposed the TOU structure in Malaysia [14], the authors have designed multiple time zones TOU tariff structures to benefit residential consumers. For TOU operation, pre-determined rates for specific days or weeks. Customers are informed of these tariffs' days or even months ahead. The tariffs rate may offer a higher price during peak periods to reflect the generation cost of the wholesale market [16]. Instead of dynamic price for the liberalized electricity market, time of use (TOU) pricing is fixed for the regulated market, reflecting long-term electricity power system cost for the monopoly system. In the overall view of tariff design that has been offered, different prices based on time of day, day of the week, and more closely always reflected the cost of producing electricity while considering the allowable range of profit concurrently [17]-[19]. In addition, the TOU tariff design also assists the authority in performing a better program for the demand response and promoting peak demand mitigation for the generation tension rectification. However, to the best of our knowledge, no study benchmarked the established TOU structure from the other countries and compared it to the proposed TOU [20]. Thus, this study will observe the real, local residential load profiles to suit several types of TOU design worldwide. Meanwhile, the optimization algorithm is adopted as the engine for optimal load shifting strategy to find the best load curve to reduce electricity cost.

Hence, the paper is arranged as follows; a related study, such as a short briefing about the DSM, load shifting, and the optimization algorithm studies in section 2. Meanwhile, section 3 explains a method that has been used for the investigation, and section 4 analyzes the results and discussion for the finding of this study. Finally, the last section 5 will be the conclusion of the study.

2. DEMAND SIDE MANAGEMENT (DSM)

In this section, a brief overview of DSM will be explained. The current related studies have focused on residential consumers since the market has shifted to offer varieties of tariff designs for them. There is a load-shifting strategy that will be explained while the weightage of load management is introduced. On the other hand, the percentage of load management adjustment is explained in this section too.

2.1. DSM strategies

DSM is the selection, planning, and implementation of measures intended to influence the demand or customer-side of the electric meter. This paper pointed out that the DSM technique mainly relies on optimizing the load profile of the residential consumers to help them in referring to load management. According to prior research, energy efficiency (EE) and demand response (DR) are the most reliable, cost-effective, and efficient ways to influence the demand curve. Conventionally, there are six DSM strategies available in the DR program [21]. For example, Load shifting declines demand during on-peak hours by shifting load to off-peak hours. Strategic conservation generally reduces the general load profile based on seasonal changes. Meanwhile, Peak Shaving decreases peak demand during high consumption time. Valley Filling is deferring demand to lower consumption hours. Strategic Growth Load that is increasing the general load demand over the consumption profile. And, flexible load shaping has been presented as the consumption shaping by setting load limits at specific hours based on the requirement of the grid. Another researcher state that demand response (DR) is a flexible mechanism that enables consumer participation to demand modulation in response to a signal from the system operator [22]. The authors introduced critical concepts to reduce the electricity bill and decrease CO2 emissions by reducing the need for polluting peaking power plants. However, there were given implementation to achieve the DR program objective, the consumer must have to volunteer for the program, and some of the programs are mandatory.

2.2. Load shifting

Load shifting is a transfer process of electricity load from one period to another. For example, in reducing the energy cost in the peak zone, the load at the peak zone is shifted to the off-peak time zone, which has a lower cost of energy [23], [24]. The percentage of load shifting weightage depends on the type of load limitation, as illustrated by [25]-[27]. However, in this article, there were given demonstration the classification of appliance types for non-shift able and shift able due to load shifting strategy when dealing with TOU tariff structure. The first class is a non-shift able appliance with strict starting and ending time limits due to its non-flexible nature, such as television, fridge, and heater. For the second class, a shift able appliance is an appliance that cannot shift within a specified time limit if the available energy limit in a particulate time slot is less than the required energy, such as dishwasher, washing machine, and electric cooker, and clothes iron. The suggested load shifting weightage is 30% for the maximum setting [28]. Thus, Figure 1 shows the load shifting process where the dotted line represents the desired load reflecting tariff zones.

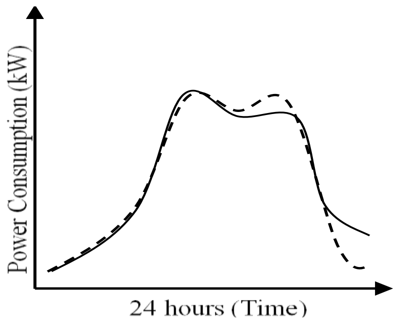


Figure 1. Illustration of load shifting strategy which is comparison of load profile before and after operation

2.2. Optimal load management

This study employs the ACO method to process many data and eliminate redundant information. ACO is widely recognized as a probabilistic approach for locating the approximate optimal solution [29]. The ant is finding the optimal new load profile that reduces energy cost with some percentage of energy reduction compared to the baseline profile. The rate of energy reduction results depends on the optimization algorithm performance.

The previous findings for load shifting method by using various optimization algorithms. This thesis displays the particle swarm optimization (PS0) algorithm in the study condition with load shifting in dynamic pricing tariff. The results produced in the percentage of cost reduction is 10% [30], [31]. The condition of energy scheduling on the TOU program by using the Firefly algorithm was explained by [31]. The percentage of cost reduction, in this case, is 15%. Flattening the consumption peak of the TOU program with a shifting optimization algorithm, and the percentage of cost reduction is 11.8%. The following algorithm is an automated scheduling algorithm [12], [32], [33]. This project is generally done to study IoT-based automated HEMS load shifting with PV integration, and the percentage of cost reduction is 45% [33].

3. RESEARCH METHOD

In this section, the formulation and the adaptation method of the optimum load management for the various type of homes will be elaborated accordingly. The paper's main contribution is the implementation of the ACO algorithm under load management strategy to reflect appropriate TOU designs. Thus, the details flow of the research method is presented in the sub-section.

3.1. Formulation

The formulation of optimal strategies considers load shifting to get engage in optimization algorithm. Meanwhile, the TOU scheme tariff formulation is presented in (1). The simple TOU tariff scheme for residential consumers can be written as (1):

$$\mathrm{TOU}_{\mathrm{cost}}^{\mathrm{general}} = (\mathrm{OL_p} + \mathrm{OL_{op}})\mathrm{x}\ Zone_{\mathrm{p/op}}^{\mathrm{Price}} \tag{1}$$

where $Zone_{\mathrm{p/op}}^{\mathrm{Price}}$ presents the time zones prices for peak and off-peak. While, OL_p and OL_{op} are the optimal electricity consumption of the desired load curve after the load load shifting strategy is implemented, reflecting the base price of the two segments as presented in (2).

$$OL_p = \min \sum_{t=1}^{N=24} \frac{(P_{tBLP} - P_{tSLP})^2 \times TP_{TOU\ \&\ Flat}}{Wn} \quad (2)$$

$$OL_{op} = \min \sum_{t=1}^{N=24} \frac{(P_{tBLOP} + P_{tSLOP})^2 \times TP_{TOU\ \&\ Flat}}{Wn} \quad (3)$$

where:
N : Total number of the loads
P_{tBLP} : Baseline power consumption at particular tariff at peak time zone
P_{tSLP} : Load shifted (power consumption reduction) at particular tariff at peak time zone
P_{tBLOP} : Baseline power consumption at particular tariff at off peak time zone
P_{tSLOP} : Load shifted (power consumption increase) at particular tariff at off peak time zone
t : Time hourly
TP_{TOU} : TOU tariff price for peak time, off peak zones set by the utility
TP_{Flatt} : Flat tariff price set by the utility
Wn : Load shifting weightage applied

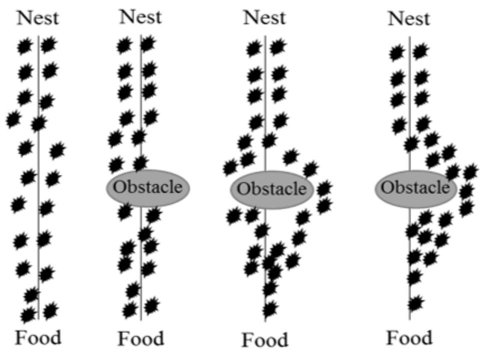
For the purposed of the apple to apple comparison of the accurate saving percentage, the total energy consumption (kWh) for baseline and after simulation was set to not more than ±5%. By this way, the optimization algorithm was not tie with the small searching area but it will contribute to a flexibility of optimum output finding for the load profile approximation [34]. Thus, the net total energy consumption (kWh) for baseline and after simulation is written by (4).

$$\sum E_T \approx \sum E'_T \quad (4)$$

In this study, the optimal solution for the load shifting strategy reflecting tariff structure has adopted ant colony optimization (ACO) algorithm to search for the best load profile with the output of electricity cost minimization. Details explanation of the ACO implementation is demonstrated below.

3.2. ACO implementation

ACO is inspired by the foraging behavior of ant colonies. Hence, ACO uses the element of the ant attribute to find the optimal path to the food source. In nature, ants communicate through pheromone, a chemical left by members of their colony that helps direct them to possible food sources [35]. The stronger the pheromone, the shorter the path to the food source. The ACO algorithm emulates this foraging behavior, where an ant represents a possible solution comprising a set of nodes visited by the ant in the path. Hence, when other ants choose the nodes, these ants will choose nodes with the highest pheromone level. Figure 2 shows the ant behavior in four situations. In this example, the nest is located at one end, and the food source is located at the other end. As shown in Figure 2(a), the ants leave the nest to search for food and return by moving randomly based on the pheromone scent. If there is an obstacle at the center of the pheromone trail Figure 2(b), the ants immediately react to search for alternative paths around the obstacle, as in Figure 2(c). In Figure 2(d), the ants have found the shortest path to the food source (the path with the highest level of pheromone), and this path is the optimal solution.



(a) (b) (c) (d)

Figure 2. The behavior of ants' nature (a) the ants leave the nest, (b) If there is an obstacle at the center of the pheromone trail, (c) the ants immediately react to search for alternative paths around the obstacle, and (d) the ants have found the shortest path to the food source

Thus, for the process of the ACO adaptation to the load management and reflecting the time segmentation of the TOU tariff pricing. The objective is to find the possible optimal solution for the electricity cost reduction for the residential load profile representing residential power consumption behavior.

3.2.1. Initialization

The ants represent a set of possible initial load profiles, N. The change in each electricity energy cost (called Cost) is represented as M. The fitness values will be used to update and gather more ants to proceed to the next step. In (5) shows the initial condition of the load arrangement. The initial constant parameters of the ants were set as follows: α=1, β=0, and ρ=0.3.

The convergence occurs when the group of ants is saturated to update any shortest route at some iteration. Hence, the optimal load profile and energy cost reduction result are presented. The best TOU tariff prices depends on two criteria, as stated in (2) and (3).

$$N=[n_{x1},n_{x2},n\ldots\ldots\ldots\ldots n_{xn}] \quad (5)$$

3.2.2. Generation of ant and calculation of the transition probability

The ants choose their solution (node) to the problem based on a probability rule. The ACO algorithm generates a new set of ants according to the desired nodes in each iteration. The probability of an ant to select a specific node is given by:

$$p\left(a_{ij}\middle|S_p\right)=\frac{r_{ij}^{\alpha}\times\eta_{ij}^{\beta}}{\sum r_{ij}^{\alpha}\times\eta_{ij}^{\beta}} \quad (6)$$

where:

$p(a_{ij}|S_p)$: Probability of Limit a_{ij} will be chosen in line with the partial solution S_p
a_{ij} : Limit from Node i to Node j
r_{ij} : Pheromone values at a_{ij}
η_{ij} : Heuristic value, which is typically the inverse of the cost of going through a_{ij}
α : Pheromone importance factor
β : Heuristic importance factor

The ants start to explore their node by randomly selecting the starting point in each system cycle. The ants can only visit each node once. The pheromone level is set as a low positive constant between any two nodes in the initial stage. The probability is calculated iteratively until the ants have reached all of the nodes, and the pheromone level is updated, simultaneously. In this step, the fitness value is calculated using the load shifting and price formulation as in (1)-(3) subject to the constraint (4) to determine the Cost M in the loop. The updated pheromone values are influenced by (2) and (3) and constraint too.

3.2.3. Updating pheromone

Once the ant has evaluated its solution and the corresponding fitness value has been calculated, it is used to update the pheromone, where the level of deposited pheromone has been identified. The increase of pheromone level in the trail as the ant continues to deposit will sharply limit the connecting nodes used by the ant. However, there is a possibility that the pheromone level will decrease, and this process is known as evaporation. The process of pheromone evaporation is updated according to the (7):

$$r_{ij}=(1-\rho)\times r_{ij} \quad (7)$$

where:

r_{ij} : Pheromone value at the limit from i to j
ρ : Pheromone evaporation factor

Likewise, the process of pheromone reinforcement is updated according to the following equation:

$$r_{ij}=r_{ij}+\sum\Delta r_{ij} \quad (8)$$

where:

r_{ij} : Pheromone value at the limit from i to j
$\sum\Delta r_{ij}$: Pheromone to be added to the trail by an ant, which is dependent on the length/cost of the path taken by the ants.

After the pheromone levels have been updated, a counter is used to measure the maximum iterations. The ants move from one node to other nodes during the process, and the transition probability is calculated accordingly.

3.2.4. Convergence

The pheromone levels are updated until the maximum iteration is reached, and the ants will take a similar trail. The optimal load profile reflecting the minimum cost of the electricity is gained when the values of pheromone level have achieved maximum iteration. As for the ACO method presentation, when the criterion for the best Cost M is fulfilled, Cost M has converged. In this stage, the minimum electricity cost is obtained. Suppose the criterion for Cost M is not fulfilled. In that case, a list of new possible optimum settings for the ants will be generated, and the whole procedure is repeated based on Figure 3 accordingly.

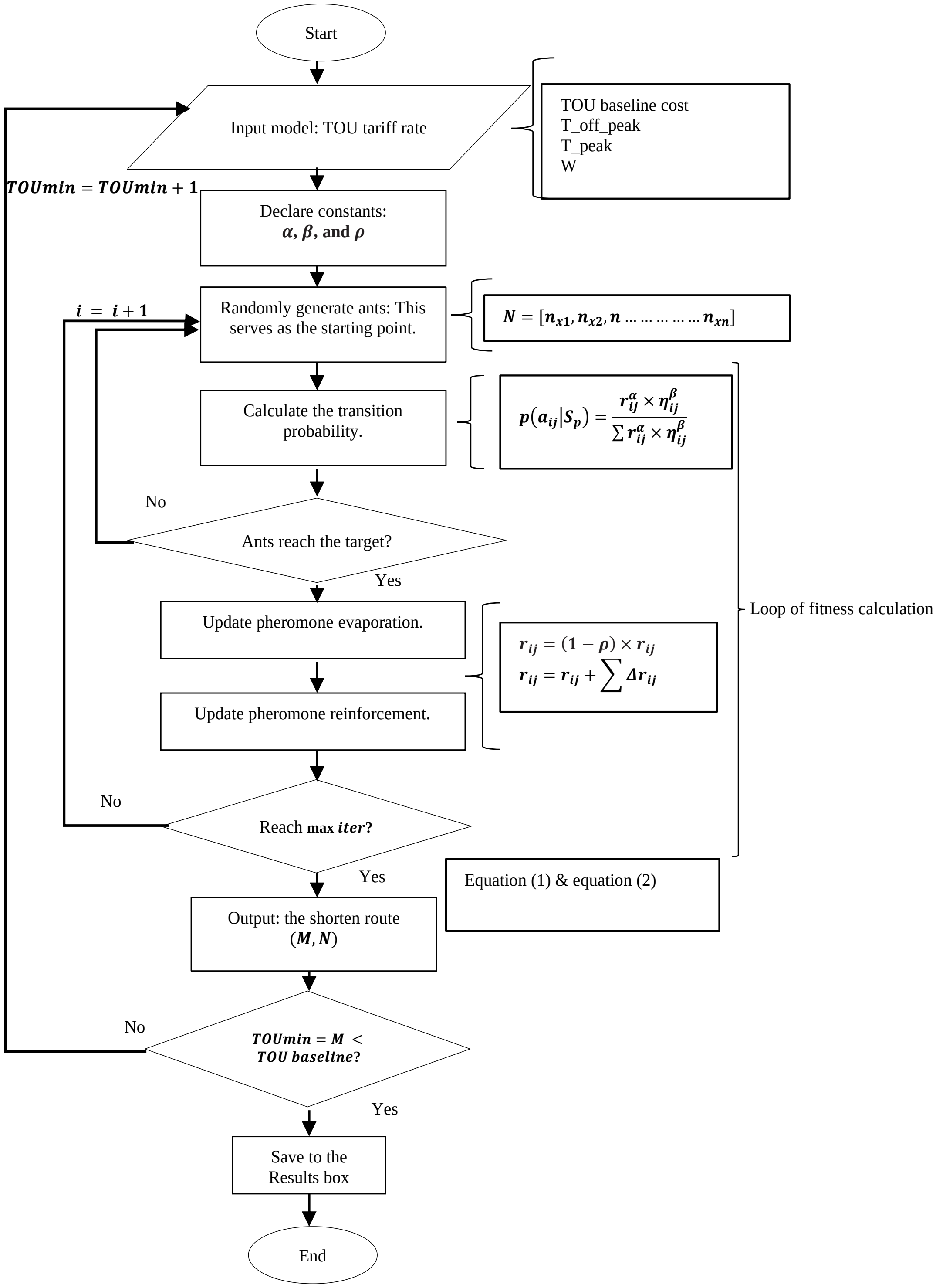


Figure 3. Steps involved in the ACO algorithm to minimize the electricity cost of residential consumers

4. RESULTS AND DISCUSSION

4.1. Case study

The load profiles based on types of houses have been collected from Tenaga Nasional Berhad (TNB) smart meter. The state of Melaka is the first state completed with the smart meter installation since 2019. Figure 4 demonstrates average load profiles from many houses that reflect each home type. The six-month load profile data was processed and massaged to establish a baseline for the simulation process to investigate and validate the best TOU tariff price structure that benefits residential consumers in Malaysia. Setting conditions for the home activities are selected from the typical situation mix of working and non-working residents.

On the other hand, to verify the best of several TOU tariff designs, the study case is classified as demonstrated in Table 1. It is observed that the ratio of each tariff design was different, except for Case C1 and Case 4. However, the arrangement of the time segmentation for the peak and off-peak is other for C1 and C4. The time zones for C1 were four segments instead of C4 having only two segments.

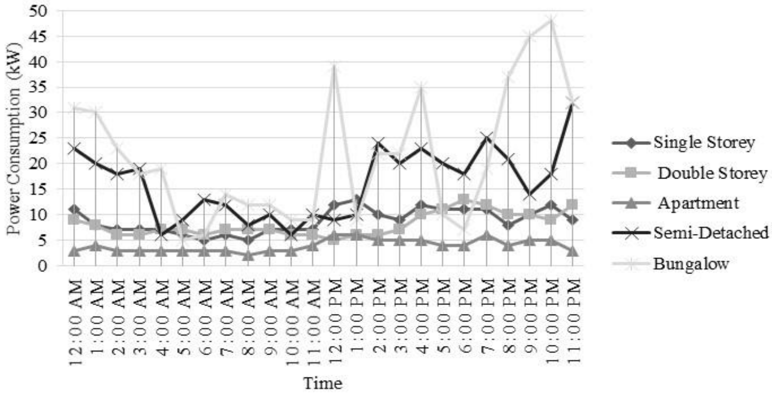


Figure 4. Baseline load profile from various types of houses in Melaka

Table 1. Cases of study for TOU tariff design

Cases	C1 [38] From previous study of Malaysia TOU design	C2 [37] United Kingdom	C3 [38] Columbia	C4 United State	C5 [39] Bangladesh	C6 [40] China
Peak hours (AM/PM)	0800-0900 & 2100-2200	1600-2000	1600-2100	0800-1100	1700-2300	1300-1700
Off-Peak hours (AM/PM)	2300-0800 &1000-2100	2100-1600	2200-1600	1200-0800	0000-1700	1800-1300
Ratio	4:20	5:19	6:18	4:20	7:17	5:19

4.2. Energy and cost reduction

Regarding Table 2 for the minimum energy reduction percentage to reflect simulation desired formulation, it was observed that the best case is C1 which is an average of 13.2% energy reduction only. In comparison, the worst is case C4, with an average of 25.2%. Instead, the consistency and stability of the result are also the criteria of a good TOU design. Case C1 percentage of energy reduction difference was only 2.1% from maximum and minimum energy reduction. Meanwhile, the worst-case inconsistency was C2, with a 21.3% energy reduction difference. It was investigated that some instances of TOU tariff design suit to double storey load profile to produce a minimum requirement for the energy efficiency (EE) solution when dealing with the TOU tariff. Thus, it can be summarized that the EE program effort will increase for more luxury houses depending on floor area.

On the other hand, Table 3 represents the best monthly cost reduction in five different houses. On average, the best TOU tariff design that reduces the maximum monthly cost is case C4 with approximately 23.57%, while the lowest cost reduction is case C1 for around 18.12%. Thus, even though C4 has produced better results by 5.45% more cost reduction compared to C1, but the trend of the results computed from the simulation shows inconsistency to handle various load profiles from different types of houses. Furthermore, it was observed that Case C1 has a lower maximum and minimum cost reduction difference for around 2.99% only, while case C4 contributes 14.36%.

In conjunction, Figure 5 compares the two findings. It was verified that TOU tariff design such as case C1, able to compute with demand response program rather than EE solution, would be applied more like other cases. The condition would be described if the consumer conducts load shifting at 30% load management weightage without any EE program, the consumer will enjoy only 4.92% of cost reductions on average. The monthly electricity bills are reducing 16.23~19.22% with an average of 18.12%, with some effort consumer to apply for minimum energy efficiency program at average 13.2% energy reduction. Nevertheless, the monthly bills will increase if the consumers do not take the energy reduction effort for the other cases.

Table 2. Percentage of energy reduction compared to baseline

Type of house	Energy reduction (%)					
	C1	C2	C3	C4	C5	C6
Single storey	12.8	19.9	24.2	25.6	22.3	23.7
Double storey	13.0	9.3	15.5	19.2	11.9	11.9
Apartment	14.7	24.2	22.7	29.5	24.2	24.2
Semidetached	12.6	21.4	20.6	21.9	20.6	22.2
Bungalow	13.1	30.6	30.4	30.2	31.4	30.8
Minimum	12.6	9.3	15.5	19.2	11.9	11.9
Maximum	14.7	30.6	30.4	30.2	31.4	30.8
Average	13.2	21.0	22.6	25.2	22.0	22.5

Table 3. Monthly cost reduction compares to flat tariff

Type of house	Monthly cost reduction (%)					
	C1	C2	C3	C4	C5	C6
Single storey	18.42	16.53	22.66	24.05	22.21	23.21
Double storey	16.23	7.23	11.42	15.41	10.62	8.90
Apartment	18.70	21.15	24.48	27.36	24.14	24.53
Semidetached	19.22	22.43	18.28	21.28	20.86	21.27
Bungalow	18.02	29.54	29.30	29.77	31.29	30.97
Minimum	16.23	7.23	11.42	15.41	10.62	8.90
Maximum	19.22	29.53	29.30	29.77	31.29	30.97
Average	18.12	19.38	21.23	23.57	21.82	21.77

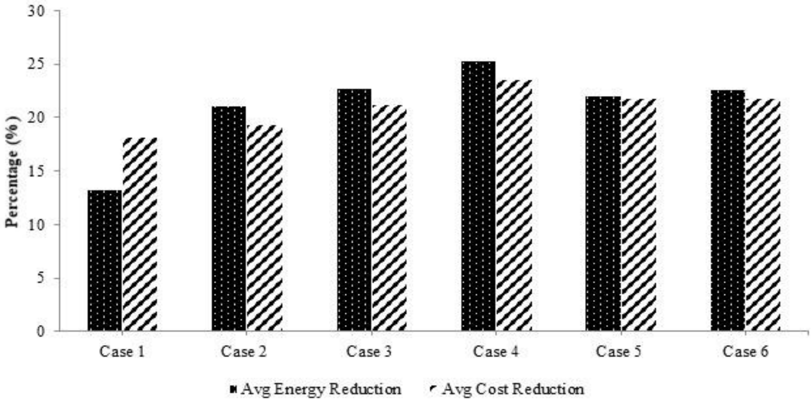
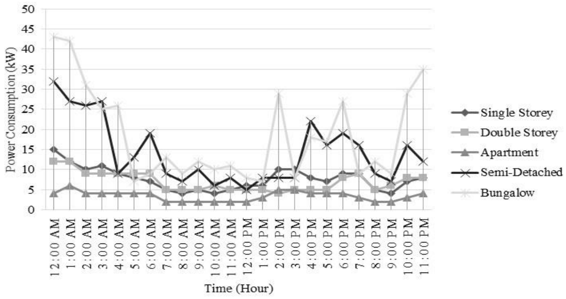


Figure 5. Average energy and cost reduction for all cases

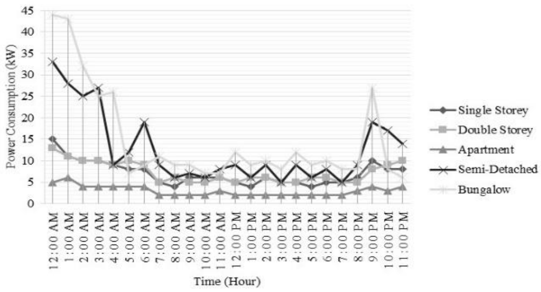
4.3. Best load profile

Figure 6 shows the tabulated optimal load profiles for commercial C1 cases. Figure 6(a) shows the best load profiles for Case C1 that has adopted the TOU tariff proposed appropriately for the Malaysia electricity residential consumers. Unless the load curve was close to the baseline profile, the observation was made, and it was identified that the short load shifting had occurred. For example, peak demand in the afternoon shifted from started at 12:00 PM to 14:00 PM. In this process, the ACO algorithm finds the best allocation of the lower price makes a short, successful load shifting strategy. Thus, it proves that reducing the energy consumption is minor exercise for Case C1.

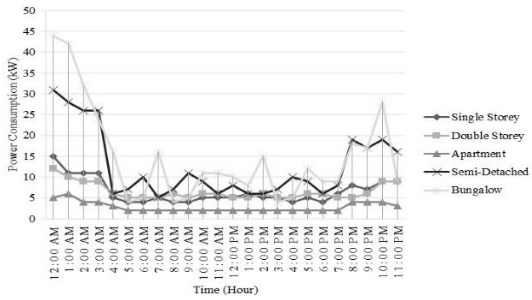
On the other hand, for Cases C2 and C4, the proposed method of the algorithm has been performed to make a load shifting strategy for the load profile with the suggestion of an energy efficiency program that should be applied concurrently. The investigation found that instead of the demand response program by consumers to do shifting for the appliances, the EE solution should be used, such as minimizing the peak load when dealing with those types of TOU tariff design. As a result, as presented in Figures 6(b) and (c), most loads have moved from 21:00-23:00 PM to 00:00-02:00 AM while the total power peak demand reduced to 44 kW.



(a)



(b)



(c)

Figure 6. Tabulated load profile for the (a) Case C1, (b) Case C2, and (c) Case C4

5. CONCLUSION

In this study, the best TOU tariff design was compared and investigated based on the real residential consumers in Melaka, Malaysia. The optimal TOU designs that impact cost reduction with minimal energy reduction effort. The formulation and optimization algorithm such as ACO have advanced the investigation of the study while giving a fast response for the arrangement of the load shifting strategy. The proper optimization process for the load profile able to reduce the cost of electricity among residential consumers while the minimum load shifting weightage is needed. Thus, the findings of this study are essential in promoting the demand response program in the residential sector and improving the effectiveness of the electricity market. For future recommendations, the appropriate peak and off-peak price could be designed to simultaneously reflect consumers' and energy providers' satisfaction. The price signal in the regulated electricity market through the TOU tariff should be focused on enhancing the market opportunity for the best design of the alternative tariff in supporting the future demand-side management program.

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