Evaluation of the time-of-use tariff responsiveness for plug-in electric vehicle home charging in Malaysia

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ABSTRACT

Plug-in electric vehicles (PEVS) have become increasingly popular as a viable transportation option as owners can charge them at home. This will add much energy to the house if the users charge their PEVs at home. The PEV charging load will lead to extra energy demand on the distribution network, and the users will need to pay more for electricity if they use the current domestic tariff in Malaysia. This research aims to analyze the PEV charging costs using time-of-use (ToU) tariffs with different time segmentations and price elasticity. The effect of four residential load profile patterns has also been investigated in Malaysia as a case study. Four PEV charging scenarios were created, and the charging times were set according to Malaysian driving styles, with charging times starting at 6 PM, 10 PM, and 9 AM. The PEV and electric vehicle supply equipment (EVSE) are set to be homogeneous, and the EV was assumed to have a minimum state-of-charge of 20%. The main contribution of this paper is the selection of the ToU tariff segmentation, where the structure of the smallest time segmentation gave the lowest electricity bill per month compared to the Tenaga Malaysia Berhad (TNB) domestic tariff.

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1. INTRODUCTION

According to the International Energy Agency (IEA), vehicle numbers reached 10 million worldwide in 2020, increasing fuel demand and pollution [1]. Plug-in electric vehicles (PEVs) offer a solution, with 1 million in ASEAN, including Malaysia. Despite tax incentives since 2012 and further exemptions in 2022 [2], Malaysia still has fewer PEVs than other ASEAN countries. Increasing PEV ownership will raise electricity demand and impact the power system. By 2026, 35 million households globally are expected to use PEVs, resulting in 1 billion charging sessions, with 55% using wall box chargers and 45% using main plug chargers [3].

EV charging should be controlled to match electricity supply with demand to avoid harming distribution networks. Uncontrolled charging increases load demand [4]-[8], total harmonic distortion (THD) [9], accelerates transformer aging and loading [10]-[16] and causes voltage variations [7], [13], [17]. Studies show that time-of-use (ToU) tariffs positively impact PEV charging and user satisfaction with electricity bills. A coordinated charging algorithm based on optimal charging starting time under ToU tariffs reduces network power losses, enhances voltage profiles, [18], [19], and minimizes EV charging costs [20]. Limited research has explored ToU tariffs for PEV charging, but this study will apply ToU tariffs with two elasticity coefficients to household and PEV charging loads. Dynamic ToU pricing lowers PEV operating costs and electrical grid expenses, benefiting users financially [20]. Research indicates that randomizing PEV charging times during off-peak periods with ToU rates reduces peak loads [21]. Demand response strategies like ToU tariffs and real-time price (RTP) effectively mitigate peak demand [22], although residential ToU rates are challenging to determine due to price elasticity and weather [23], [24]. This ToU pricing scheme for residential can also be used to apply to the PEV home charging included in household loads. To date, limited research has examined price elasticity within the context of ToU tariffs for PEV charging requests. Limited research has explored ToU tariffs for PEV charging, but this study will apply ToU tariffs with two elasticity coefficients to household and PEV charging loads [25]. However, the research used price elasticity in the ToU tariff applied to only household loads in Malaysia [26]. To fill this gap, this research will use the same ToU tariff set by the two values of the elasticity coefficient and apply it to the household and PEV charging loads together. The aims of this paper are i) to analyze the PEV charging costs using ToU tariffs with different time segments and price elasticity and ii) to investigate the effect of residential load profile patterns in Malaysia as a case study. This paper can guide researchers and related bodies in Malaysia in implementing the ToU tariff when considering EV home charging. The remainder of this paper is organized as follows: the PEV charging coordination model is described in section 2. Section 3 provides the results and discussion regarding power demand and price for the PEV charging coordination. Finally, conclusions are made in section 4.

2. RESEARCH METHOD

The paper aims to investigate the impact of the elasticity price on the total electricity price and power consumption in relation to the ToU tariff. The research activity was conducted by considering the residential areas. Subsequently, the relevant input data and information on PEVs, electric vehicle supply equipment (EVSE), price tariffs, and actual energy readings were acquired. The development of PEV charging scenarios was established considering Malaysia's driving and lifestyle patterns. A formula was derived to compute the power consumption associated with a PEV charging load, considering the energy price under a ToU. Finally, an analysis was conducted on the load profiles and overall electricity prices to determine which ToU tariff segmentation yields the lowest monthly electricity cost compared to the domestic and fixed-price tariffs.

2.1. Residential load profile

A single-story bungalow house was selected for this project as the house that has PEV charging. Figure 1 shows the different types of load profiles for four types of residential houses in Malaysia. The selected types of houses are single-story, double-story, semi-detached, and bungalow houses. The apartment or condominium type is not selected because the PEV charging port is usually installed in the parking lot and charges per service rate. Hence, these four houses were selected based on the assumption that they could be installed with an individual PEV charger or EVSE.

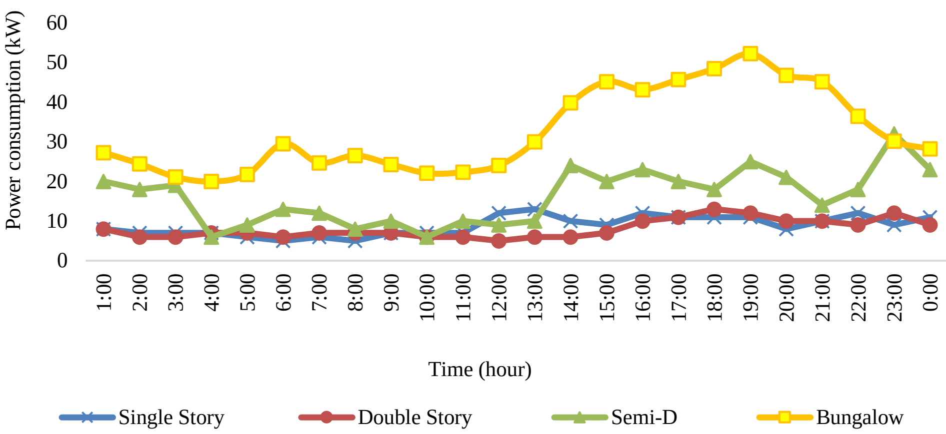

Figure 1. Power consumption profiles for different types of residential houses

2.2. Plug-in electric vehicles charging parameters

This study only focused on one type of PEV model, the Nissan Leaf New Range 2022. Using standard charging methods, the PEV indicates that it takes approximately 7 hours to charge the battery under minimal state-of-charge (SoC) conditions fully. This EV has a battery capacity of 40 kWh and charges at an input rate of 230 V/10 A, resulting in a charging load of 6.6 kW per hour. It came with its EVSE that could be installed at home [27]. Typically, the SoC of the PEV does not deplete entirely before initiating the charging process. According to the established standard, initiating the PEV battery's charging process is recommended when the SoC reaches a minimum of 20-30%. In this study, the battery's SoC will range from a minimum level of 20% to a maximum of 100%. This assumption is made to conduct research. In this regard, the standard charging process will require around seven hours to reach full capacity while drawing a charging load of 46.2 kW. The details of the temporal distribution of charges will be provided in the subsequent section.

2.3. Plug-in electric vehicle charging scenarios

Three charging times were selected based on the Malaysian driving styles: PEV and start charging at 6 PM, 10 PM, and 9 AM, 6 PM is chosen because people start charging their PEVs when they arrive home after work. 10 PM is chosen by assuming people charged their PEV during sleep time, and 9 AM is for people who stay home. For charging scenarios TC1, the users are assumed to charge their PEV daily. The total power consumption, PTC(n) in kW for all charging scenarios, starts at 6 PM, 10 PM, and 9 AM, as given in (1), with n representing all scenarios n=1, 2, 3, and 4. The other labels for the formula are represented in Table 1.

$$\mathrm{P_{TC(n),6\,PM/10\,PM/9\,AM}} = \sum_{\mathrm{D}}^{\mathrm{N}}\left[\sum_{\mathrm{t}}^{24}\mathrm{P_{d(t,D)}} + \sum_{\mathrm{t}}^{7}\mathrm{P_{EV(t)}^{6\,PM/10\,PM/9\,AM}}\right] kW \quad (1)$$

Table 1. PEV charging scenarios for charging sessions in one month

Charging scenarios		PEV charging sessions (days)	6 PM	10 PM	9 AM
TC1	30	D=everyday	/	/	/
TC2	15	D_1=1, 3, 5 … (odd days) D_2=2, 4, 6 … (even days)	/	/	/
TC3	10	D_3=1, 4, 7, 10, 13, 16, 19, 22, 25, 28 D_4=other than D_1 in 30days	/	/	/
TC4	22	D_5=1, 5, 6, 11, 13, 15, 18, 21, 22 D_6=2, 9, 16, 30 D_7=3, 4, 7, 17, 19, 20, 28, 29 D_8=8, 10, 12, 14, 23, 24, 26, 27	Random charging time		

2.4. Electricity price analysis

This paper applies the suggested ToU tariff with two price elasticity values: $\alpha = -0.02$ (overall consumers in Malaysia) and $\beta = -0.27$ (residential customers) [26], [28] with four different segmentations. The study calculates the monthly electricity price using the Tenaga Malaysia Berhad (TNB) domestic tariff [29], a fixed-price (RM0.25), and eight different ToU structures, with total electricity costs for charging cases TC1, TC2, TC3, and TC4 calculated as in (2).

$$K_{fixed,T_C} = P_{TC(n)} \times 0.25 \quad (2)$$

In addition, the electricity price for one month using the ToU tariff for all charging scenarios is listed in (3). Table 1 also contains the other labels for the formula. S_T is the ToU structure for S1α, S1β, S2α, S2β, S3α, S3β, S4α, and S4β, t is time in hours (24 hours), Pd(t,D) is total household loads, PEV(t,D) is EV charging loads, and bg is the ToU block with g=1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12.

$$K_{TC(n),(S_T)}^{ToU} = \sum_{D}^{N}\left[\left(\left(\sum_{t}^{17} P_{d(t,D)}\right) \times ToU_{b_g}^{S_T}\right) + \left(\left(\sum_{t}^{7} P_{EV(t,D)}\right) \times ToU_{b_g}^{S_T}\right)\right] \quad (3)$$

3. RESULTS AND DISCUSSION

The results section will be divided into four parts: a baseline comparison of electricity price and price signal, the PEV charging effect on monthly power consumption, and a comparison of PEV charging effects on electricity prices between ToU, fixed price, and TNB residential tariff. The analysis of load profiles to determine the best price signal for the ToU tariff. The price signal serves as an indicator for selecting the appropriate ToU tariff for the corresponding load profile.

3.1. Baseline cases

This section examines the application of the ToU tariff to baseline power consumption, comparing it with the TNB domestic, a fixed price of RM0.25, and four ToU tariff structures: S1, S2, S3, and S4. From Figure 2, the fixed price results in the lowest electricity bill at RM 194.67 per month but is impractical for real-world generation. Therefore, this paper uses the fixed price as a baseline to compare with the ToU tariff, which, excluding the fixed price, reduces the electricity bill by 38%, from RM 328.99 to RM 204.94, using the ToU tariff S2. Hence, TOU tariff S2 gave the lowest price for baseline load consumption.

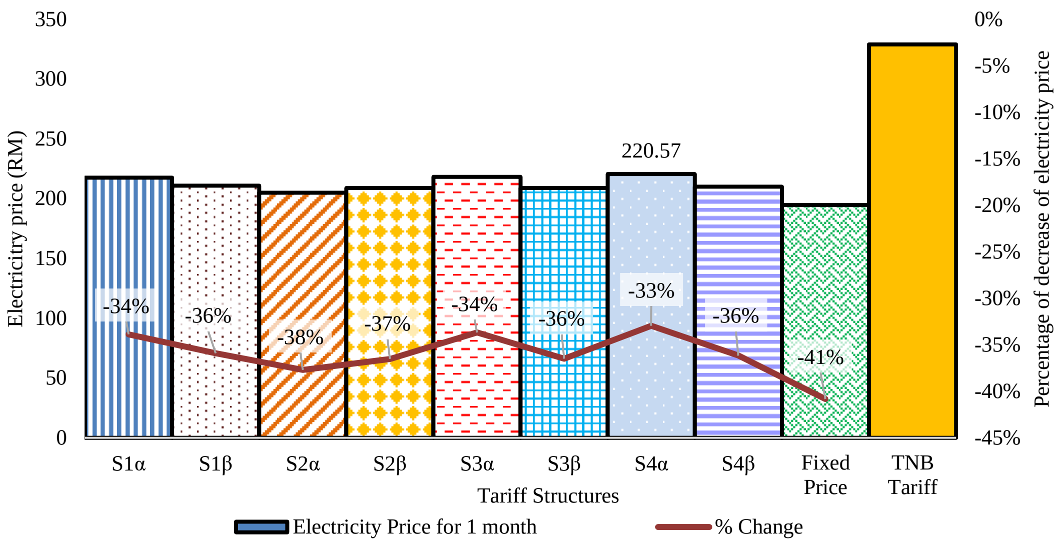

Figure 2. Electricity price comparison for baseline loads consumption

3.2. Plug-in electric vehicles charging effect on power consumption

This section discussed the effect of the PEV charging activity on power consumption. 4 PEV charging scenarios were applied, with TC1, TC2, and TC3 having 3 different charging times, and for TC4, the charging times were randomly applied in one month. As shown in Figure 3, TC1 has the highest total power consumption, 2164.676 kW, with a 28% increase. Followed by TC4 with 2135.201 kW, a 27% increase; TC2 with 1471.676 kW, a 19% increase; and the lowest case, TC3, with 1240.676 kW, a 16% total power consumption increase. Subsequently, TC4 shows that while power consumption has increasingly spread throughout time, it still contributes to the second-highest total power consumption.

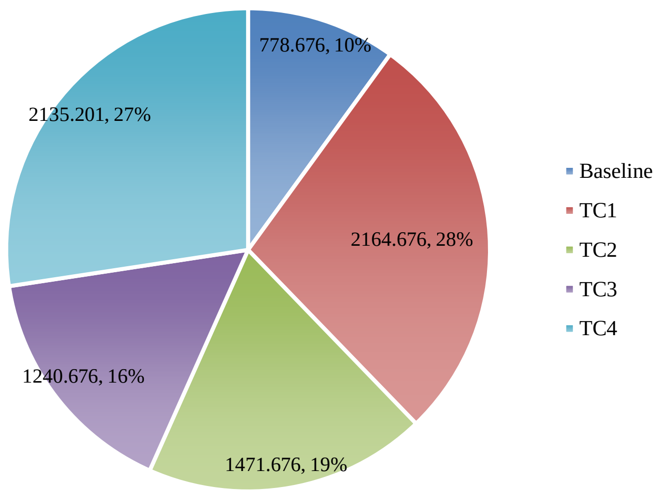

Figure 3. The increase percentage according to PEV charging scenarios

3.3. Plug-in electric vehicles charging effect on electricity price

Dynamic prices like the ToU tariff were chosen because the hourly or segment-based variations allow for selective electricity use. This section compares the TNB residential, fixed-price, and ToU tariffs under various PEV charging scenarios. Figure 4 shows the TNB domestic tariff's baseline electricity price applied to various PEV charging scenarios, with the total bill for September and October 2021 at RM328.99. TC4 has the highest bill with a 235% increase, followed by TC1 at 231%, while TC3 has the lowest increase at 79% compared to the baseline. Figure 5 compares the fixed and ToU prices for different charging times and scenarios (TC1, TC2, TC3, TC4). Charging EVs at 6 PM under S3 resulted in the lowest price increases for TC1 (219.7%), TC2 (109.9%), and TC3 (79.3%). Charging at 10 PM, S1 provided the lowest price increases across all scenarios, with TC1 at 151.1%, TC2 at 75.6%, TC3 at 50.4%, and TC4 at 171.2%. Charging at 9 AM, S1 again yielded the lowest price changes for TC1 (96.2%), TC2 (48.1%), and TC3 (32.1%).

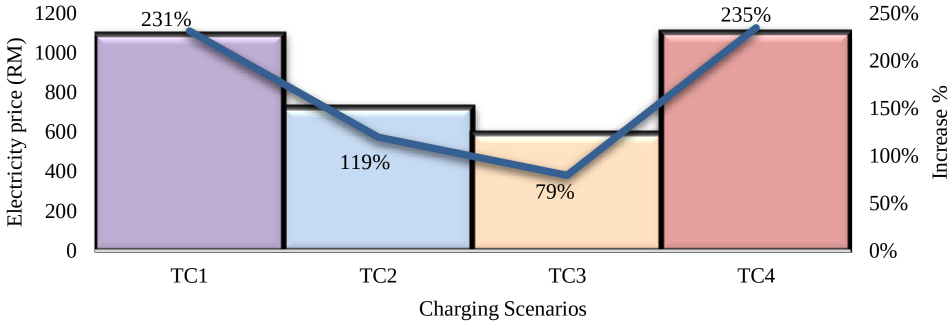

Figure 4. Electricity price using TNB domestic tariff for different charging scenarios

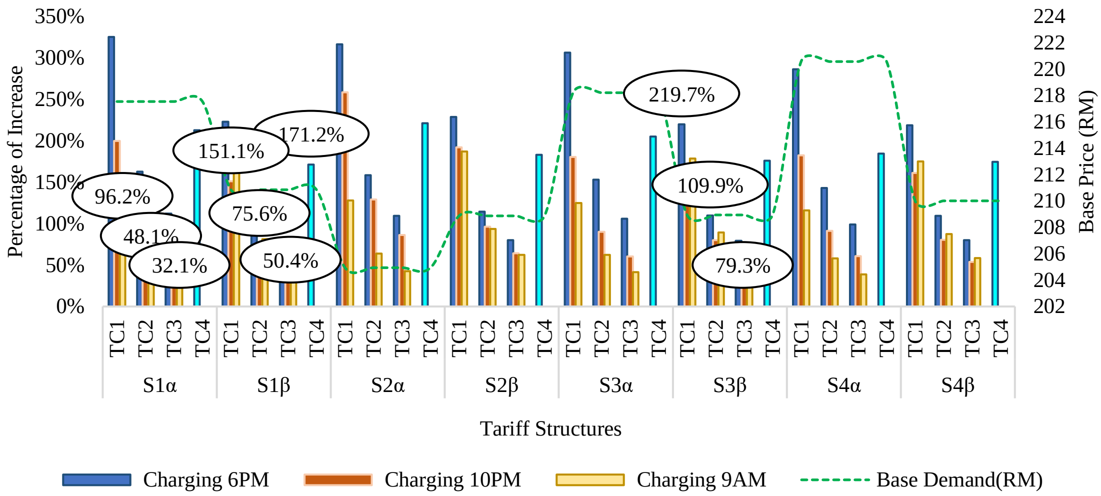

Figure 5. PEV charging a percentage increase when using the ToU tariff

Figure 6 shows how different PEV charging times and scenarios power demand profiles, comparing ToU tariff structures (S1, S2, S3, S4) with distinct price elasticity coefficients for TC4. TC4's random charging times confirm S1's efficiency, contrasting with S4's high costs during peak hours (9 PM to 10 PM). Table 2 shows that the lowest monthly electricity bill for bungalows is achieved by charging PEVs at 10 PM and 9 AM using structure S1, which has only four price segments per day. Structure S1 is the best ToU tariff for residential PEV charging. For baseline loads, the optimal ToU structures vary single-story (S3α), double-story (S2β), semi-detached (S4α), and bungalow (S2α). Most houses respond well to a price elasticity of $\alpha = -0.02$, representing Malaysian consumers. The TC4 charging case results for other house types are like those for bungalows.

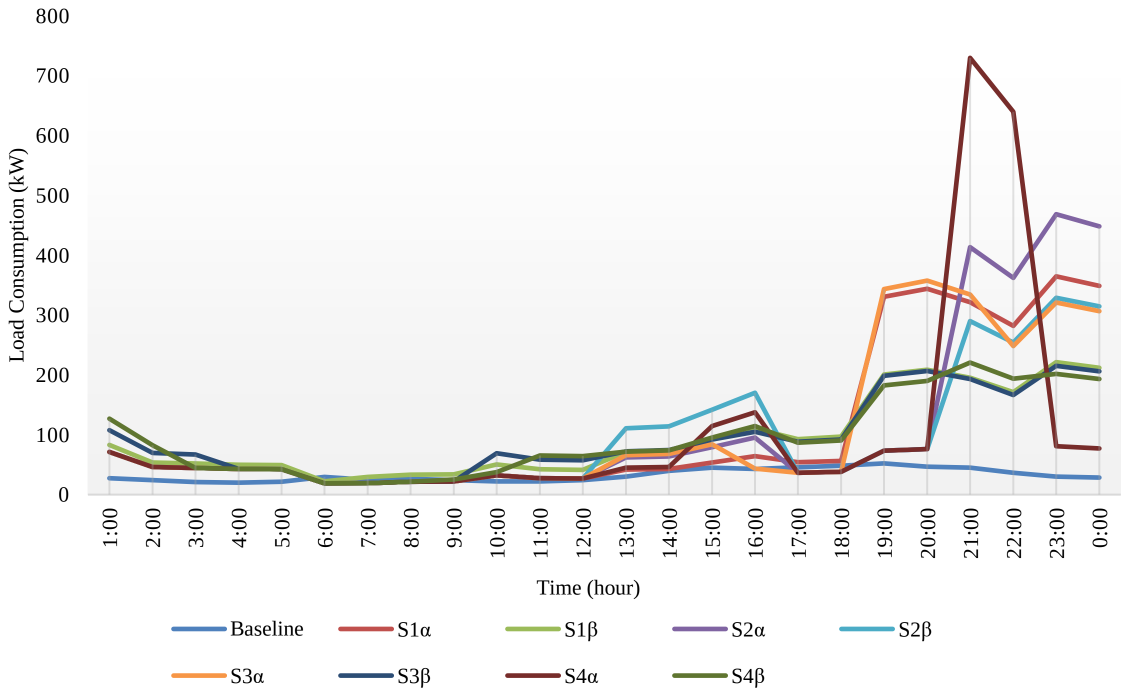

Figure 6. Comparison of load consumption for TC4

Table 2. Price elasticity comparison for different types of houses

Type of houses	Baseline	Electricity price (RM)	Charging 6 PM	Electricity price (RM)	Charging 10 PM	Electricity price (RM)	Charging 9 AM	Electricity price (RM)
Single-story	S3α	56.99	S3β	515.64	S1β	374.85	S1α	266.42
Double-story	S2β	50.1	S3β	509.68	S1β	369.89	S1α	263.83
Semi-detach	S4α	99.63	S3β	564.09	S1β	423.78	S1α	323.16
Bungalow	S2α	204.94	S3β	667.98	S1β	529.45	S1α	426.79

4. CONCLUSION

This paper focuses on the impact of using different types of electricity prices, the TNB domestic, fixed-price, and ToU tariff, on the total electricity bills and the power demand when the electric vehicle charging loads are added to the existing household loads. The results show that all charging scenarios respond more to the ToU tariff with price elasticity $\beta = -0.27$, except where EV charging starts at 9 AM. This implies that the price structure of the ToU with a price elasticity coefficient $\beta = -0.27$ is appropriate for residential loads. Reducing the temporal segmentation of the ToU price structure in Malaysia is advisable. In the future, it is recommended to analyze different types of residential housing available in Malaysia, such as apartments and terrace houses. The apartment house also has an EVSE on the parking lot. A price comparison can be made with the current charges provided by the residential management. The PEV charging coordination integration of a PEV home charging station with a solar panel can also be considered.

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