

Statistical analysis of air-conditioning and total load diversity in typical residential buildings

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ABSTRACT

Electricity consumption by air-conditioners in residential buildings significantly affects the electrical grid. The stability of the grid can be improved by a precise prediction of air-conditioning (AC) variations. Therefore, more information about the electricity usage patterns specifically on AC load is important. This paper aims to determine the consumption patterns of AC and total load through a field measurement of 20 dwellings located in Kuala Lumpur and Selangor. Next, correlation and clustering are employed to identify the relationship between outdoor temperature and AC electricity consumption. The results revealed 75% of the occupants use the AC almost every day for about five to six hours per day at the rates of 0.93 kWh/day during day time and 3.43 kWh/day during night time. The correlation coefficient between the total daily AC consumption and the mean daily outdoor temperature ranged from -0.1 to 0.48. The variation of electricity consumption with time shows that AC electricity consumption increases with the increase of usage time. Lastly, the clustering process of AC usage pattern based on outdoor temperature displayed the uncommon behaviour from dwellings whereby high AC electricity consumption was recorded at low outdoor temperature.

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1. INTRODUCTION

As one of the fast-developing countries, Malaysia depends on fossil fuels such as coal and natural gas to propel most of the infrastructure and to generate electricity. According to the energy commission [1], Malaysia produced about 38000 ktoe for all types of fuel from 1993 to 2013. Meanwhile, the final energy demand in 2015 recorded a 27% increase from 40,845 to 51,807 ktoe [2]. However, fossil fuel is a non-renewable resource which deplete over time. It releases greenhouse gases (GHG) which are responsible for climate change and global warming.

Unlike fossil fuels, renewable energy (RE) provides alternative energy supplies with minimal or zero CO₂ emissions. Since Malaysia is a tropical country known for its agricultural industry, biomass, biogas, and solar are the main available RE resources besides hydroelectric [3]. However, the main issue pertaining to RE is sustaining the generation capacity. For example, solar energy production is influenced by the changing weather and is not always consistent. The power generation of RE can be unstable and does not concur with the demand for electricity. The major constrain is the infrastructure required to store

the harnessed energy and its distribution [4]. Hence, one way to overcome this issue is to collect more data about the usage patterns of the end user especially on air conditioning (AC) load as it uses more power and influences the load curve significantly. Ranjbar *et al.*, [5] stated that the air-conditioner is the highest contributor to the electricity usage in each dwelling sample, ranging from 28% to 46% of the total electricity usage. Various studies were carried out to link the occupant behaviour to the AC load and energy consumption. So far, many studies investigated physical environmental factors such as indoor temperature [6-9] and outdoor temperature [6, 8, 10]. For example, the AC usage pattern of residents in Kansai, Japan indicated that the AC operation rate was 80% at the outdoor temperature of 36°C and the indoor temperature of 27°C [6]. The study from Perez *et al.*, [11] mentioned that the precise prediction of AC variations can improve the stability of the grid.

The precise estimation of stochastic energy consumed by AC influenced by occupant behaviour, is essential to build and operate residential distributed generation systems in association with RE. Therefore, it is necessary to conduct research aiming to determine both AC and total dwelling's electricity consumption and its relation to the environmental factors such as outdoor and indoor temperature. The occupant behaviour towards the AC consumption may be different depending on the geographical location such as country or region. Thus, in this research, a field measurement of 20 selected dwellings was conducted to record the characteristics and consumption patterns of AC loads in Malaysian typical residential buildings and to determine the relationship between outdoor temperature and the AC electricity consumption.

2. RESEARCH METHOD

2.1. Target dwellings

Two major urban areas in Malaysia which are Kuala Lumpur and Selangor were selected as the measurement locations. To be specific the measurement was carried out in 19 dwellings from low-cost apartment buildings in Desa Rejang, Kuala Lumpur (3.1900°N, 101.7304°E) and a two-storey terraced house in Kajang, Selangor (3.0082°N, 101.8084°E). The dwellings were selected based on a voluntary basis and must be equipped with AC in one or more room. The number of family members in the selected dwellings ranges from 2 to 9 people. The total and AC electricity consumption of each dwelling were measured. The measured room represents living spaces equipped with frequently used AC's such as the living room (LR), bedroom 1 (BR1), bedroom 2 (BR2), and bedroom 3 (BR3). The dwelling compositions can be summarized into three groups for which 55% are dual income family, 40% are single income family, and only 5% were senior couples.

2.2. Overview of the measurement

The measurement profile is shown in Figure 1 such that the dwellings (represented by Dwelling ID) are sorted according to the increasing number of measurement days. Electricity usage of 20 dwellings was successfully measured for a minimum of 52 days to a maximum of 386 days. The total electricity consumption and total AC electricity consumption of all targeted dwellings were measured using the energy-monitoring devices (OWL) as shown in Figures 2(a)-(b), respectively. The details of the installation of the instruments are explained in [12, 13]. The ACs used in the selected dwellings was different in terms of brand, capacity and cooling mode among others. Although these differences would affect the results, we conducted questionnaire surveys in order to obtain detailed information about the dwellings and the AC used. The survey included number of occupants, dwelling compositions, income, home ownership, monthly electricity consumption and years stay, number of AC, type of room where the AC is installed, set time for AC, set point temperature, cooling mode, age of AC and energy star of AC.

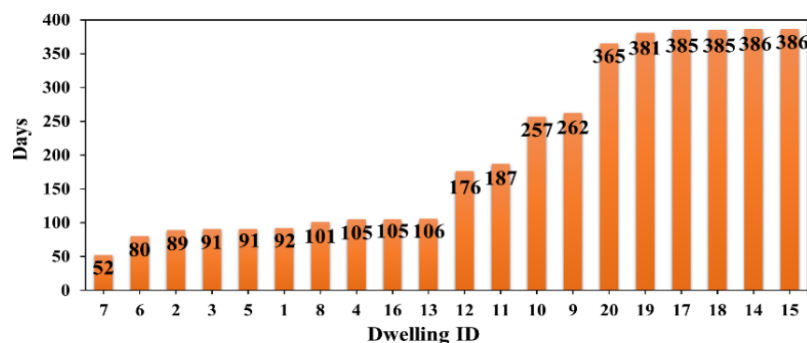


Figure 1. Measurement profile for each dwelling

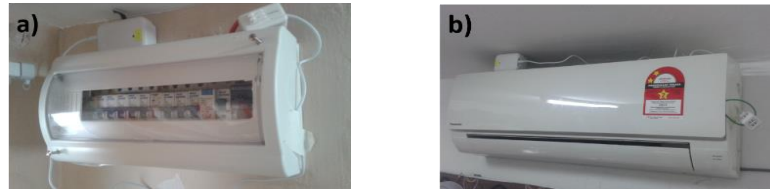


Figure 2. OWL installed at, (a) Circuit breaker, (b) Air-conditioner

2.3. Cluster analysis

Cluster analysis is the process of grouping the observations into clusters whereby the objects in the same cluster have high similarity while objects in different clusters have low similarity. Among various clustering methods, K-means is the most widely used method [14-18]. It is capable of clustering a large number of sample quickly and efficiently and highly popular in load curve clustering [19-21]. The K-means method identifies k number of centroids, then assigns each data point to the nearest cluster while keeping the centroids as small as possible. It uses the Euclidean distance formula as shown in (1) to find the correlation between two objects by examining the root of square differences.

$$dist(x, y) = \sqrt{\sum_{i=1}^n (x_i - y_i)^2} \quad (1)$$

where x_i and y_i are the attributes of a given object and i varies from 1 to n . In this research, the K-means cluster is applied in SPSS to cluster all hourly AC data of each targeted dwelling within the same period recording the outdoor temperature.

Firstly, the number of clusters was specified in advance. The data is standardized and rescaled by using the z-score formula in (2). In this context, x represents the score, μ represents the mean and σ represents the standard deviations. Next, the z-score results were used as the basis for the trace or input cluster. Then the clustering process began by grouping the data within its minimum distance and a data point became part of a cluster if it was the closest from its cluster centre.

$$Z = \frac{x - \mu}{\sigma} \quad (2)$$

3. RESULTS AND DISCUSSION

3.1. AC usage frequency

Figure 3 provides an overview of the ratio of AC usage days to the total measurement days in all 20 targeted dwellings. The data obtained with less than 30 minutes of AC usage in a day were filtered out, while the rest were included for analysis. In Figure 3, the highest ratio was 0.9 which corresponded to 10 dwellings for which the residents used AC almost every day. In addition, Figure 4 shows the daily hours of AC usage for all 20 targeted dwellings. The figure indicates that most of the residents used AC for five to six hours per day. This result is similar to a field survey conducted in China which found that the residents kept the AC running for eight hours per day [22].

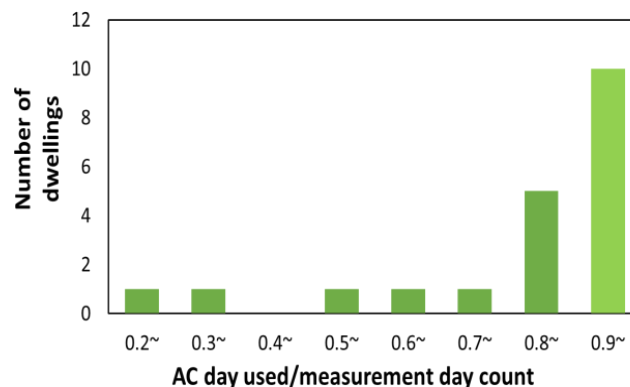


Figure 3. Ratio of AC usage days to total measurement days

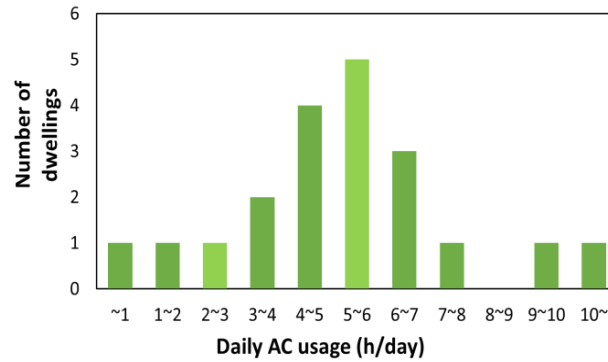


Figure 4. Daily hours of AC usage

3.2. Total daily and AC usage of each dwelling

Figure 5 shows the total energy consumption and the total AC energy based on two time slots, day time and night time. The time slot for day time is from 6:00 to 18:00 and for night time is from 18:00 to 6:00. The total energy consumption and the total AC energy consumption from 20 targeted dwellings were shown in Figure 5(a)-(b), respectively. The daily averages of the total energy consumption are 5.4 kWh/day (day time) and 8.4 kWh/day (night time). Meanwhile, the daily average of total AC consumption is much lower which are 0.93 kWh/day (day time) and 3.43 kWh/day (night time). Essentially, the AC energy consumption averages during night time and day time accounted for about 41% and 17% of the total energy consumption, respectively was used by AC. This indicates that most of the residents used AC at night rather than during the day. According to Kubota *et al.*, [23], the detailed daily usage patterns of cooling appliances in Malaysia showed that most of the residents installed AC in their bedrooms to be operated at night when they sleep.

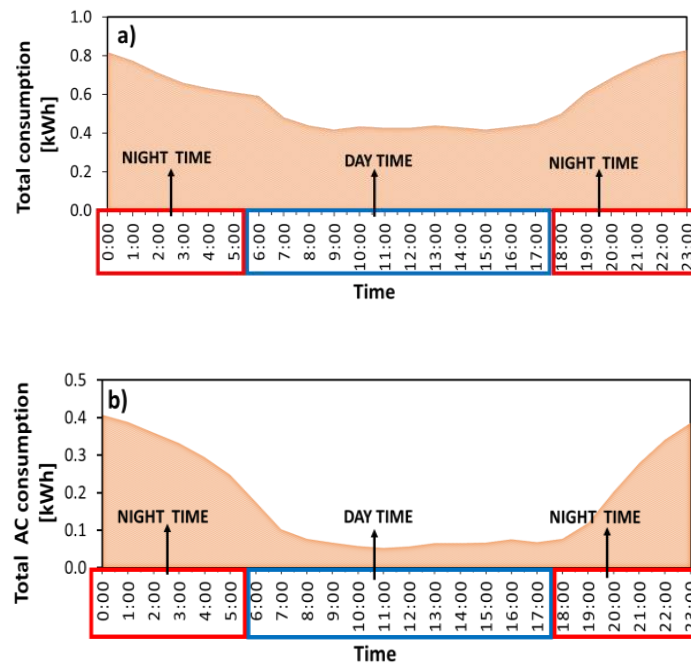


Figure 5. Time slots for, (a) Total daily energy consumption, (b) Total AC energy consumption

3.3. Characteristics of AC load

Figure 6 illustrates the time variations of the combined AC loads for the total dwellings of 1, 5, and 10. The electricity consumption of every minute from randomly selected dwellings was averaged and transformed into the combined AC load by concluding the coefficient of performance (COP) as 3.0, which is the minimum performance standard required in Malaysia [24].

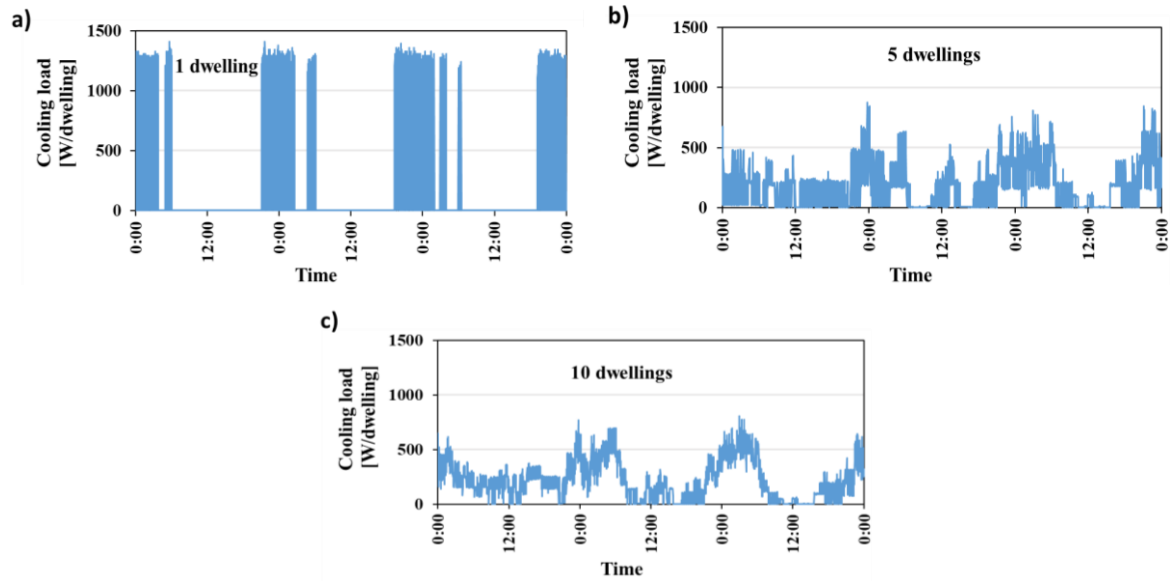


Figure 6. Time variations of the averaged AC loads for the total dwellings of, (a) 1, (b) 5, (c) 10

The monitoring data were collected from three consecutive days, from 13 to 15 March 2016. Only 10 dwellings out of 20 targeted dwellings were used for the calculation as the measurement of electricity consumption was not conducted simultaneously. This finding highlighted that the AC load of one dwelling had a high frequency and strong fluctuations due to the use of the on/off controller when the compressor operated at its maximum speed, and adjusted the indoor temperature to reach the temperature setting. When the total number of dwellings increased to 5 and 10, both short term fluctuations and peak cooling loads reduced, and long-term patterns, such as daily variation, corresponding to the various patterns of AC usage among different dwellings can be seen.

3.4. Correlation of AC consumption with outdoor temperature

The strength of the relationship between two variables can be evaluated using correlation coefficients equation such as the Pearson correlation coefficient (or Pearson’s *r*) as shown in (3).

$$r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{[n \sum x^2 - (\sum x)^2][n \sum y^2 - (\sum y)^2]}} \tag{3}$$

where *n* is number of pairs of scores, $\sum xy$ is the sum of the products of paired scores, $\sum x$ is the sum of *x* scores, $\sum y$ is sum of *y* scores, $\sum x^2$ is the sum of squared *x* scores and $\sum y^2$ is the sum of squared *y* scores. The values can range between -1 to +1 at which means the greater the absolute value of the correlation coefficient, the stronger the relationship. In this research, this correlation coefficient is used by SPSS to measure the relationship between the total daily AC consumption and the mean daily outdoor temperature.

From the calculation of the correlation coefficient, all 20 dwellings with their corresponding correlation coefficient were shown in Table 1. The highest correlation coefficient is 0.52 (ID4) and the lowest is -0.10 (ID9). The AC electricity usage in most of the targeted dwellings is positively correlated with outdoor temperature, for which the correlation coefficient ranged from -0.1 to 0.5. Yoshino *et al.*, [25] also revealed a strong correlation between the cooling energy consumption and the outdoor temperature.

Table 1. Correlation coefficient of each dwelling

ID	Correlation coefficient	ID	Correlation coefficient
1	0.32	11	0.44
2	0.29	12	0.23
3	0.28	13	0.24
4	0.52	14	0.33
5	0.21	15	0.38
6	0.20	16	0.42
7	0.39	17	0.25
8	0.14	18	0.27
9	-0.10	19	0.33
10	0.08	20	0.48

3.5. Time of AC electricity usage increase with outdoor temperature

The variation of electricity consumption with time is shown in Figure 7. Three targeted dwellings with the highest and lowest correlation coefficients as displayed in Figures 7(a)-(b), respectively, were selected for comparison. Figure 8(a) shows that the daily AC electricity consumption changes linearly with the usage time. This is because when the outdoor temperature is higher, the AC is used for a longer duration. The plot for ID20 is nonlinear because the residents tend to turn the AC on for a short time only. Nevertheless, in Figure 7(b), the graph is more scattered and does not show the same pattern as in Figure 7(a). As a result, the effect of high outdoor temperatures can lead to an increase in the AC usage time.

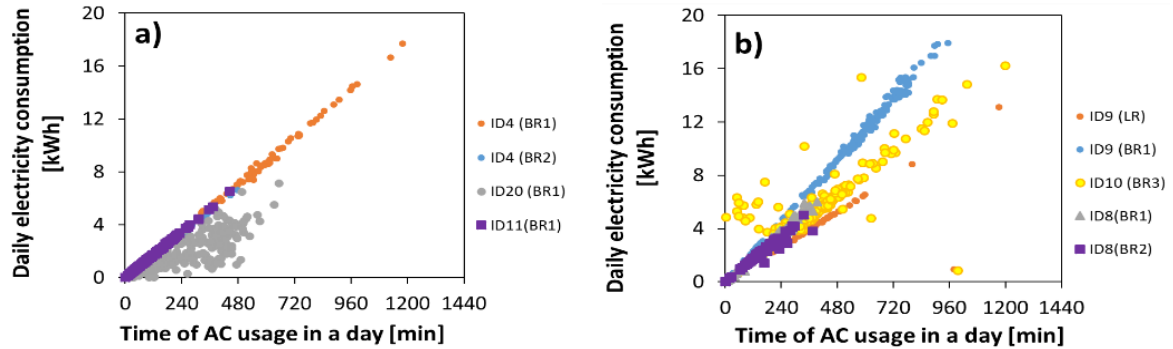


Figure 7. Change of AC consumption with the usage time, (a) Data of dwellings with 3 highest correlations, (b) Data of dwellings with 3 lowest correlations

3.6. Pattern of AC consumption based on outdoor temperature

The pattern of AC consumption based on outdoor temperature is shown in Figures 8. As mentioned before, the measurement was not conducted simultaneously, so the clustering process had to be split into two groups, Group 1 (ID1-ID10) and Group 2 (ID11-ID20). According to Yusof *et al.*, [26], at a lower outdoor temperature, less work from the compressor of AC is produced as it uses less energy to maintain the temperature setup on the AC. However, the result by clustering process showed the uncommon behavior at which the energy was not corresponding with outdoor temperature. For Group 1, the uncommon behaviour is from cluster 5. Cluster 5 has high hourly AC usage ranging from 0.8 to 1.6 kWh when low outdoor temperatures ranging from 25 to 31°C. This might be due to their AC performance. Higher differences between the indoor and outdoor temperatures can also be one of the reasons for this situation. The same situation is observed through cluster 4 in Group 2. Cluster 4 has a high hourly AC consumption ranging from 0.8 to 1.5 kWh when low outdoor temperatures range from 23 to 28°C.

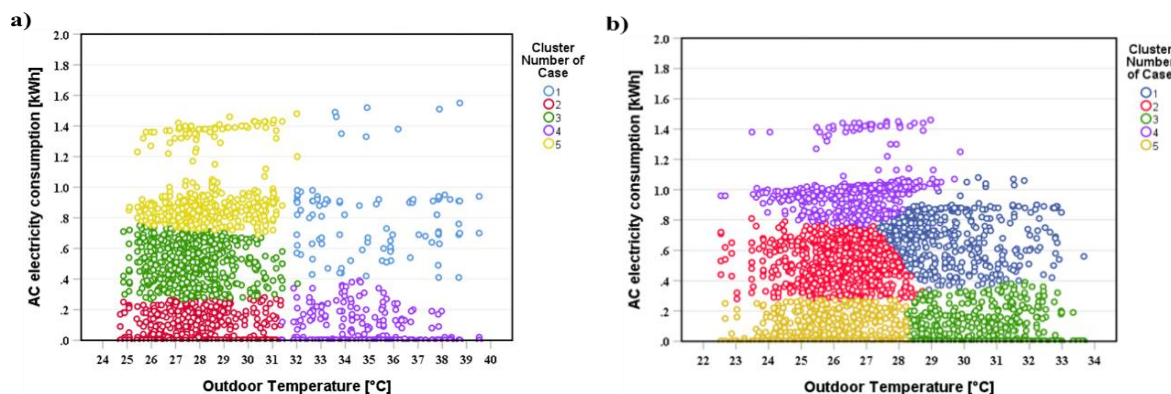


Figure 8. AC consumption pattern based on outdoor temperature for, (a) Group 1, (b) Group 2

As shown in Figure 9(a), the ID9 dwelling is the major contributor to cluster 5 with 48%. Based on the interview with the occupants of the ID9 dwelling, the set point of their AC is 17°C. Also, in Figure 9(b), it can be seen that ID12 dwelling is the most dominant (95%) in cluster 4. The ID12 dwelling has a low set point of temperature which is 16°C. These unveil the uncommon behavior of AC consumption based on the outdoor condition.

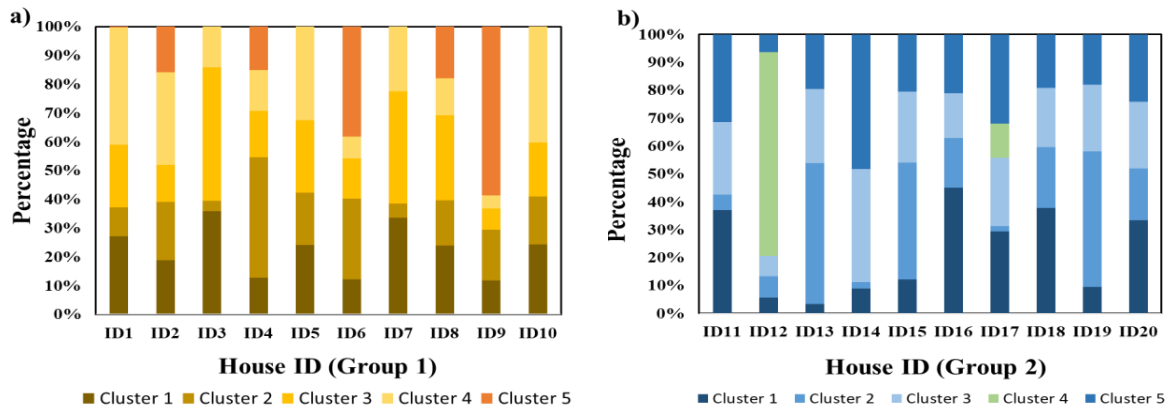


Figure 9. Percentage of cluster group in each dwelling for, (a) Group 1 and, (b) Group 2

4. CONCLUSION

The field measurement of 20 targeted dwellings in Kuala Lumpur and Selangor were conducted in order to investigate the occupants' energy consumption behaviour especially on the AC usage. The main outcomes are as followed; 10 selected dwellings obtained the ratio of daily AC usage of 0.9 and 5 dwellings operated the AC for five to six hours per day; From the total energy consumption, the AC usage accounted for 41% at night time and only 17% during day time. This indicated that most of the residents use the AC at night rather than at day time; Time variation of the combined AC load with the total number of 1 dwelling shows a higher frequency rather than the total number of 10 due to the use of the on/off controller when the compressor operated at its maximum speed, and adjusted the indoor temperature to reach the temperature setting; The relationship between daily total AC consumption and daily mean outdoor temperature shows that 60% from 20 targeted dwellings has a positive correlation of 0.3 to 0.5; The linear correlation between the AC usage time and the daily AC energy consumption proved the dependency of AC electricity consumption on the usage time; Clustering process revealed uncommon behaviour of ID9 and ID12 dwelling whereby high AC energy consumption was recorded at low outdoor temperature. The results obtained are useful for residential energy simulations in forecasting realistic AC loads, particularly in hot and humid climate such as in Malaysia.

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