Disaggregated Electricity Bill Base on Utilization Factor and Time-of-Use (ToU) Tariff

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ABSTRACT

Time of Use tariff is introduced to motivate users to change their electricity usage pattern. Commonly the tariff is high during peak hours and relatively low during off peak hours, to encourage users to reduce consumption during peak hours or shift it to off-peak hours. This tariff scheme provides opportunities for building owners to reduce their electricity bill provided that their electricity usage patterns of various spaces in that building at every hour are known. In practice, the kWh meter installed by the utility can only provide the overall hourly electricity consumption pattern. To know the usage pattern of different spaces or rooms, separate individual meter need to be installed in each space/room, which is costly and impractical. This paper presented the disaggregated electricity bill method based on user utilization factor and time of use (ToU) tariff. It estimates hourly electricity bill of each appliance at each space/room. Utilization factor is used to represent the electricity usage behavior of the occupants. The proposed method is applied on practical load profile data of a university building.

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1. INTRODUCTION

Many countries have introduced Time of Use (ToU) electricity price for commercial buildings. However, many building owner failed to take full advantage of this ToU tariff. The main problem is they unable to identify the right measures that can be made to change their electricity consumption pattern, which rewards them with a reduction in electricity bill. A commercial building consists of a variety of rooms and spaces occupied by multiple users running various jobs. Building’s electricity bill is contributed from electricity usage of these spaces. Under ToU scheme, electricity prices are different for each time block. The electricity bill is different if it is used at different times even though the electricity consumption is the same. To really benefit from the ToU scheme, building owners need to know the hourly contribution of each room or space towards building’s electricity bills, so that the correct strategies can be identified for electricity bill reduction. Since kWh meters are not installed in every rooms/spaces, the electricity bill need to be disaggregated by using load disaggregation methods.

The use of electrical energy for any room or space depends on the electrical equipment contained therein and consumer behavior in the use of electrical appliances. Occupants behaviour is an important factor to be considered for ensuring energy efficiency of a building [1]-[3]. To be more specific, to ensure the successful of either DSM or EE program, the energy usage patterns of major electrical equipment such as air-conditioner and lighting, which depend on occupant’s usage behaviour must be studied and analysed. A number of studies have shown that providing consumers with aggregated real-time power consumption information helps consumer to change their behaviour and save 10-15% on power costs [4]-[6].

Indirect feedback is a system which provides information that has been processed before reaching the energy end user. Indirect feedback programs usually consist of some form of report or statement given to consumer which specifies their energy usage and cost over a set period of time that. Various medium could be used to enhance this feedback such as providing more frequent billing cycles including better detail of historical data, energy use comparison and end use/per appliance energy use data, that has been shown to support in leading energy conversation efforts [5],[7]. On the other hand, direct feedback systems, known as real-time or near-real-time feedback systems, provide consumers with energy information directly usually obtain from a meter either through a software application or separate display monitor. Typically, the real time feedback system include disaggregates consumption information by end use. This type of information comes with additional benefits that inform some better targeted efficiency recommendations to utilities by providing them with highly detail data sets. Disaggregated information providing guidance for energy-saving behaviours as the information are able to aid consumers in identifying which electrical devices in their building are consuming the highest energy. There are several options to practice both feedback systems such as smart meter installation known as intrusive appliance load monitoring and non-intrusive appliance load monitoring method.

Intrusive Load Monitoring (IALM) is known as one of the most accurate and reliable systems to recognize load consumption of an individual appliance. A few smart meter will be installed to recognized consumers' energy consumption in a building where each meter directly interacts with each involve appliances and finally decomposes the total energy consumption [8],[9]. Apparently, this method is not the common preferred option due to the high cost of installation that requires smart meter to be set up on each appliance.

Meanwhile, the study on Non-Intrusive Appliance Load Monitoring (NIALM) is widely evolving which focuses on load signature behaviour to perform load disaggregation. NIALM estimates the number and nature of the individual loads, their individual energy consumption, and other relevant statistics such as time-of-day variations by a sophisticated analysis of the current and voltage waveforms of the total load [10]-[12]. This method is often used to disaggregate overall consumption into individual energy usage of experimented appliances. However, most NIALM approach required high learning such as machine learning, artificial intelligence and quite an advance tool to analyse the load profile. Moreover, the frequency of the data for low sampling installation that require data per second is not really suitable to be applied by common user.

2. PROPOSED METHOD

This paper proposes an electricity bill disaggregation method for estimating the kWh cost contributed by various appliances to the overall electricity bill of a building. The proposed method considers occupants' electricity usage behaviour, historical electricity consumption data and building specification. Historical electricity consumption was used to study the relationship of user usage pattern and kWh electricity consumption. Meanwhile, power input of each area was evaluated based on building specification that this information will be use to estimate energy consumption afterwards. These factors will determine the utilization factor (A) of an appliance for a particular space/room in the building at hour j (A_{ij}). The utilization factor will then be used to estimate the usage of that appliance at the particular space and hour. It is calculated through the following steps;

Step 1: Determine building's average electricity consumption of each hour

First, the average electricity consumption of each hour is determined from the historical data. If the load profiles have the same pattern for working days and different pattern for weekends, the calculation of hourly average kWh consumption for weekdays and weekends must be done separately. In cases where the load profiles depend on the day of the week, for example, similar profile pattern for Mondays but differ from other days, hourly average kWh consumption for each day needs to be calculated, which will give different utilization factor for each day.

Step 2: Determine the rating of electricity usage for each electrical appliance at each space

Occupants of each space *i* need to provide their energy usage rating of each electrical appliance for each hour j, $usage_{i,j}^{appliance}$. Occupants shall provide the following rating scales;

Table 1. Electricity usage ratings

Rating	Notes
Off (OFF)	completely turned-off during the time interval (0% usage)
Very Low (VL)	Very low usage (approximately 0-20% usage)
Low (L)	Low usage (approximately 20%-40%)
Medium (M)	Medium usage (approximately 40%-60%)
High (H)	High usage (approximately 60%-80%)
Very High (VH)	Very high usage (approximately 80%-100%
On (ON)	appliance is fully turned-on during the time interval (100% usage)

Step 3: Determine the utilization factor for each electrical appliance at each space

The summation of electricity usage of all appliances in all spaces in the building at hour j, must equal to the mean electricity consumption (from historical data) of hour *j* calculated in step 1. The kWh electricity usage of each appliance can be calculated by multiplying the power input of each appliance at hour *j* to the utilization factor, *A* of that appliance at space *i* at hour *j*, $A_{i,j}^{appliance}$

Since the occupants only provide usage rating of the appliances, the utilization factor A is optimized as follows;

Objective function:

$$\max\left\{\sum_{i=1}^{N_s} A_{i,j}^{k}\right\} \tag{1}$$

Subject to:

$$\sum_{all\,k}\ \sum_{i=1}^{N_s} A_{i,j}^{k} P_i^{k} = \mu_j \tag{2}$$

$$A_{i,j}^{k,MIN} < A_{i,j}^{k} \le A_{i,j}^{k,MAX} \tag{3}$$

Where,

$A_{i,j}^{k}$ = utilization factor of appliance *k* at space *i* for hour *j*

P_i^{k} = Power input of appliance *k* at space *i*

N_s = total number of spaces

μ_j = mean electricity consumption at hour *j*

The objective function given in equation 1 optimizes the utilization factor of appliance *k* at space *i* at hour *j*, $A_{i,j}^{k}$. The summation of utilization factors of all appliances at hour *j* is maximized to ensure that all appliances in all spaces will generate utilization factors unless stated OFF by occupants. Equation 2 indicates that the multiplication between utilization factors of *appliance k* at space *i* for hour *j*, $A_{i,j}^{appliance\ k}$and power input of appliance *k* at space *i* must equal to mean electricity consumption at hour *j* calculated in Step 1. Equation 3 states that the optimized utilization factor of appliance *k* at space *i* at hour *j*, $A_{i,j}^{appliance\ k}$must be within the predetermined limit set by occupants. These limits depend on the electricity usage rating given by Table 1 in step 2. Utilization factor limits for equation 3 of each space is based on usage rating specified given in Table 2.

Table 2. Example of utilization factor representation

Usage Rating	$A_{i,j}^{k,MIN}$	$A_{i,j}^{k,MAX}$
OFF	0	0
VL	0	0.2
L	0.2	0.4
M	0.4	0.6
H	0.6	0.8
VH	0.8	1.0
ON	1.0	1.0

Step 4: Electricity bill disaggregation

The proposed utilization factor will be used to disaggregate the electricity bill of a building at space *i* and hour *j* into individual appliances as given in the following equation 4 and 5;

$$E_{i,j}^{k} = \frac{A_{i,j}^{k} P_{i}^{k}}{\sum_{all\,k} \sum_{i=1}^{N_s} A_{i,j}^{k} P_{i}^{k}} \times E_{j}^{total} \tag{4}$$

$$kWhCost_{i,j}^{k} = E_{i,j}^{k} \times ToU_{j} \tag{5}$$

Where;

$E_{i,j}^{k}$ = kWh electricity consumption of appliance *k* at space *i* at hour *j*

E_{j}^{total} = kWh electricity consumption of the building at hour *j*

ToU_{j} = Time of Use tariff at hour *j*

$kWhCost_{i,j}^{k}$ = kWh electricity bill of appliance *k* at space *i* at hour *j*

3. RESULTS AND ANALYSIS

3.1. Test system

The proposed method is tested against practical data to test its feasibility. In this study, the load profile data of building P19a, Faculty of Electrical Engineering, Universiti Teknologi Malaysia was used. The building is an academic building; consists of 13 laboratories mostly occupied by technicians and students. There are 123 lecturers' rooms, 10 tutorial rooms and two prayer rooms. Several working spaces are categorized as offices, and there are five meeting rooms. Normally, the load energy consumption of the building is high during weekdays and very low on weekends and holidays since there is no significant usage on those days. During weekdays, the building is usually occupied between 7 a.m. and 7 p.m. Figures 1 shows the load profile data used in the analysis. The experimental analysis presented in this paper focuses on estimating the electricity bill contributed by two main electrical equipment of different spaces which are lighting and air-conditioning system. Other electrical equipment was neglected due to their very low power rating and their presence in total energy consumption is too small compared to lighting and air-conditioning system. The data was collected by using Kyoritsu Kew Power Quality Analyzer installed at two main incoming cables of the building to record power and energy consumption. Usage ratings defined by occupants of the building for air-conditioning and lighting system is given in Table 3. The power input for lighting and air-conditioning system was obtained through walk-through audit and building specification data as illustrates in Table 4 meanwhile ToU price in Malaysia is present in Table 5.

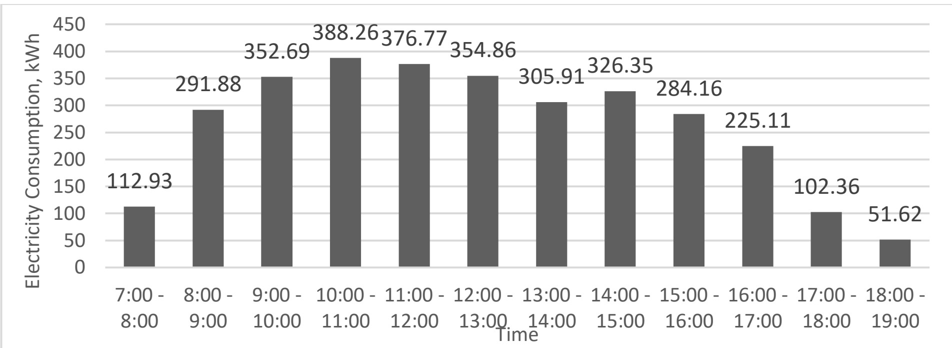

Figure 1. Building's load profile on Wednesday (18/2/15)

Table 3. Usage ratings defined by occupants of the building for air-conditioning and lighting system

Area/Time	7:00 - 8:00	8:00 - 9:00	9:00 - 10:00	10:00 - 11:00	11:00 - 12:00	12:00 - 13:00	13:00 - 14:00	14:00 - 15:00	15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00
Lab	VL	H	VH	VH	VH	VH	VH	VH	H	M	L	L
Lecturer's Room	L	M	M	H	H	M	M	H	M	M	L	VL
Tutorial Room	VL	M	VH	VH	VH	VH	VH	VH	VH	H	VL	VL
Office	M	ON	ON	ON	ON	ON	ON	ON	ON	ON	M	L
Meeting Room	VL	L	H	H	H	H	M	H	H	M	L	VL
Prayer Room	VL	VL	VL	VL	VL	L	VH	H	H	VH	L	VL

Table 4. Total power input of lighting and air-conditioning system of respective area

Type of Room	Total Power Input of lighting system (kW)	Total Power Input of air-conditioning system (kW)
Laboratory	25.200	190.238
Lecturer's Room	28.800	188.081
Tutorial Room	10.800	89.171
Office	8.280	64.950
Meeting Room	3.512	37.752
Prayer Room	1.368	7.557

Table 5. ToU Prices in Malaysia

Country	Time of Use Electricity Details	
	Period	Price
Malaysia (ToU)* [1,10]	peak	RM 0.365/kWh
	off-peak	RM 0.365/kWh
Malaysia (EToU)* [1,10]	peak	RM 0.584/kWh
	mid-peak	RM 0.357/kWh
	off-peak	RM 0.281/kWh
*Commercial customers at medium voltage (tariff C1)		

It was assumed that the state of lighting and air-conditioning systems were simultaneously turned-on when an occupant enters the room which yielded equivalent data input for both appliances on similar hour.

3.2. Results

Based on the studied test system, the data information obtained was analysed. The proposed method was tested against practical data and energy consumption of respective appliance was disaggregated according to the classified area. The result was presented in term of electricity bill of corresponding spaces by referring to the Tou prices in Table 5. The electricity bill contributed by air-conditioning and lighting is illustrated in Figure 2 and Figure 3 respectively from the overall load profile on 18 February 2015 for respective utility system. Figure 2 represents the air-conditioning system electricity bill showing a diversity in percentage of usage according to the area categories. Laboratories are constantly occupied between 7 a.m. and 7 p.m by students and technicians to run their research every weekday. This spaces consumed the highest energy consumption from total load profile due to the huge number of spaces occupied inside the building, thus result in highest electricity bill compare to other type of area. Meanwhile, lecturer's room contribute the second highest from overall electricity bill. Next, office areas utilized air-conditioning system constantly as these areas is constantly occupied by staff to carry out their daily task. On the other hand, tutorial room areas consumed energy starting from 8 a.m. to 5 p.m. to accommodate lecture sessions except for lunch break hour. Electricity bill of other areas are distributed in uniform from the total load profile. Similarly, as seen in Figure 3, the pattern of electricity bill for lighting system is identical to lighting system as they share the same utilization factor. Each area proportion is very much similar to air-conditioning system area disaggregation except for the amount of air-conditioning energy consumption which is marginally higher.

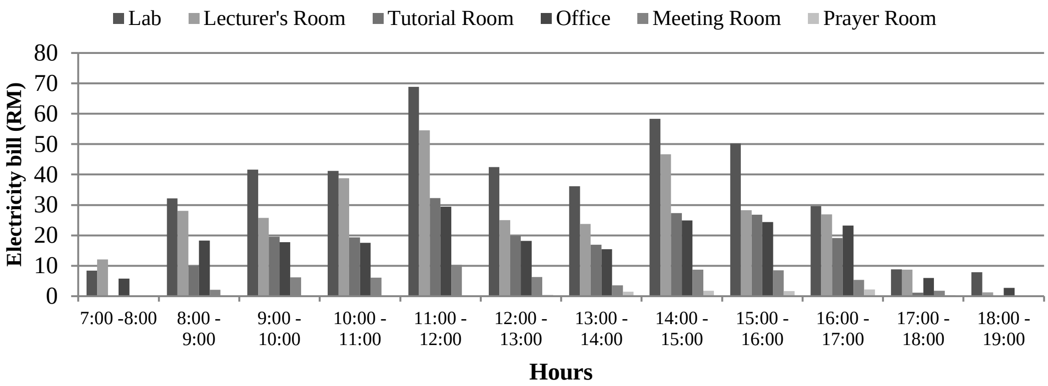

Figure 2. Electricity bill of air-conditioning system at different spaces

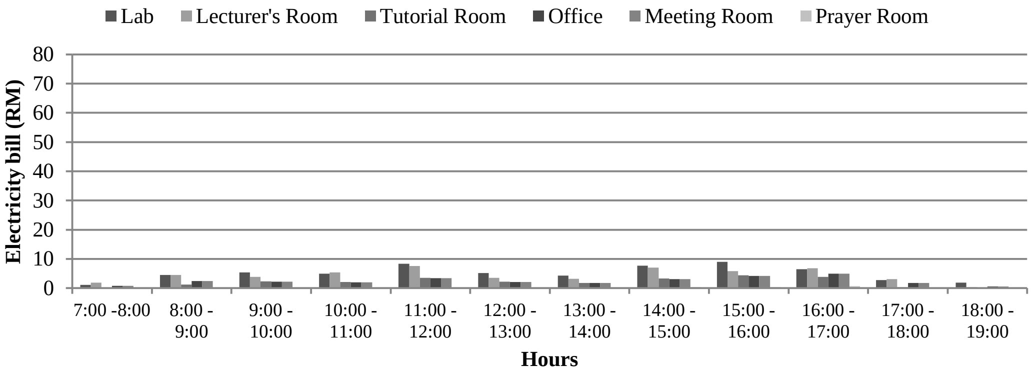

Figure 3. Electricity bill of lighting system at different spaces

Based on Figure 2 and 3, it can be seen that different spaces consume certain amount of energy and electricity bill according to particular area is different. Thus, by disaggregating electricity bill through various type of spaces inside an academic building, consumer will be more aware on their daily energy utilization that lead to high electricity bills. As can be seen through Figure 2 and 3, laboratories area spends almost RM70 for an hour between 11 a.m. and 12 p.m. and contribute as the highest consumer in overall electricity bill. Laboratories continuously contribute in high electricity bill for the remaining hours around 12 p.m. until 4 p.m. Lecturer's room electricity consumption at certain hour also produce a huge amount of electricity bill especially between 11 a.m. to 12 p.m. and 2 p.m. until 3 p.m. It is due to ToU prices during peak period is high and activities inside laboratories requires high energy demand for that time being. Therefore, this study provides useful information for occupants, so that they are able to control their energy usage during particular time at corresponding areas to avoid high electricity charges. The accuracy of the development method for disaggregating air-conditioning system and lighting system is about 98% and 64% respectively, however it much depends on the utilization factor given by user. Based on the results, it shows that air-conditioning system is the main utility system that lead to rise in electricity bill. Consequently, a few methods can be applied to reduce electricity bill such as reduction of air-conditioning utilization during peak period and self-awareness to turn off air-conditioning system for unoccupied area.

4. CONCLUSION

This paper proposed electricity bill disaggregation method to break electricity bill of a building into hourly electricity cost for each equipment for each space in the building. Utilization factor is introduced to represent the consumer usage behaviour as one of the input for the proposed method. The method was tested against practical data of the experimented building. The proposed method can be used to estimate the contribution of various equipment towards the overall electricity bill of the building. This study was beneficial in terms of informing occupants on the detailed energy consumption and electricity bill of major appliance involved in their buildings. Consequently, occupants can nurture self-awareness on their daily usage level that which affects the variation of energy consumption as well as electricity bills.

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REFERENCES

[1] D. Lindelöf and N. Morel, "A field investigation of the intermediate light switching by users," *Energy and Buildings*, vol. 38, pp. 790-801, 2006.
[2] O. T. Masoso and L. J. Grobler, "The dark side of occupants' behaviour on building energy use," *Energy and Buildings*, vol. 42, pp. 173-177, 2010.
[3] R. V. Andersen, *et al.*, "Survey of occupant behaviour and control of indoor environment in Danish dwellings," *Energy and Buildings*, vol. 41, pp. 11-16, 2009.
[4] D. H. D. Parker, *et al.*, "How much energy are we using? potential of residential energy demand feedback devices," presented at the *Proceedings of the 2006 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficiency Economy, Asilomar, CA*, 2006.
[5] S. Darby, "The effectiveness of feedback on energy consumption: a review for DEFRA of the literature on metering, billing and direct displays," 2006.
[6] C. Fischer, "Feedback on household electricity consumption: a tool for saving energy?," *Energy Efficiency*, vol. 1, pp. 79-104, 2008.
[7] "Residential Electricity Use Feedback: A Research Synthesis and Economic Framework," Power Delivery & Utilization - Distribution & Utilization, 2009.
[8] M. Weiss, *et al.*, "Leveraging smart meter data to recognize home appliances," in *2012 IEEE International Conference on Pervasive Computing and Communications*, pp. 190-197, 2012.
[9] S. Y. Son, "Home Electricity Consumption Monitoring Enhancement Using Smart Device Status Information," *International Journal of Smart Home*, vol/issue: 9(10), pp. 189-196, 2015.
[10] A. S. Ardeleanu and C. Donciu, "Nonintrusive load detection algorithm based on variations in power consumption," in *2012 International Conference and Exposition on Electrical and Power Engineering*, pp. 309-313, 2012.
[11] G. Elafoudi, *et al.*, "Power disaggregation of domestic smart meter readings using dynamic time warping," in *2014 6th International Symposium on Communications, Control and Signal Processing (ISCCSP)*, pp. 36-39, 2014.
[12] K. Matsui, *et al.*, "Disaggregation of Electric Appliance's Consumption Using Collected Data by Smart Metering System," *Energy Procedia*, vol. 75, pp. 2940-2945, 2015.

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