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# Actual Usage Conditions and Energy Consumption of Refrigerator-Freezers

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## ABSTRACT

*About 19% of the total electricity production is consumed in the residential sector and this fraction is expected to grow in future. Air conditioners, refrigerators, washing machines and other appliances are significant energy users in this sector. In this paper, the energy consumption and internal cabinet temperatures of 30 domestic refrigerators have been monitored to give an overview of the usage pattern of this appliance in Malaysian households. A questionnaire was designed to get relevant information regarding the usage of this appliance in the actual kitchen environment as well. This information is paramount in shaping or implementing a program that would get more support from users. The statistical analysis such as clustering and segmentation were manipulated and utilized in order to show the influence of the usage conditions on the temperature. The paper also calculated energy, bill savings and associated emission reductions by replacing an old inefficient refrigerator with a new efficient one.*

***Keywords*** - Energy Consumption, Refrigerator-Freezers, Clustering, Segmentation, Usage Behaviors.

## 1. INTRODUCTION

Consumption of energy in the residential sector has increased over time due to improvement of life style, expanding household size, consumer usage pattern and wastage of electricity due to high energy uptake or faulty appliances. Figure 1 shows the percentage of energy consumption by each appliance. It has been observed that refrigerator-freezers consume about 21% of total residential energy consumption. This appliance is one of the major and significant energy users in household environment, as it has to operate 24 hours in a day continuously. Several studies have been carried out in Malaysia regarding the usage behavior of household appliances [1]-[3]. However, there was no study regarding the actual energy consumption of this appliance in Malaysia. In order to fill that gap authors monitored actual energy consumption of this appliance. This information is paramount important for policy implementation such as energy efficiency standard and label, energy modeling, and impact analysis (i.e. benefit of replacing old inefficient appliances with new efficient ones). Authors are members of technical committee on minimum energy performance standard and sub work group for refrigerator-freezers. From the experiences, it has been found that actual data is very much needed for policy measures. Sometimes manufacturers' data is not reliable. Tested data does not reflect usage conditions because it also overestimates or under estimate the actual energy consumption. For example, according to ISO 8187 [4], a refrigerator is tested at 32 $^{o}$C without loading any food and opening the refrigerator door. Higher temperature was selected to compensate door opening and food loading. Meier *et al*., [5] mentioned that actual field energy consumption is less than tested energy consumption. So, the actual energy consumption is desirable as it reflects the actual usage behaviors and conditions.

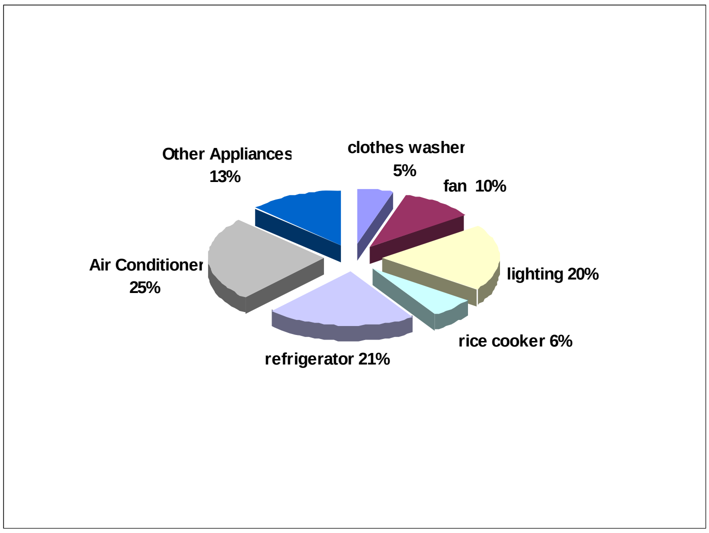


Fig. 1. Household appliances electricity pattern for a single household [3].

As Malaysia is in the process of introducing energy efficiency measures such as standards and labels for household electrical appliances, this study will provide necessary information for establishing those policy measures for refrigerator-freezers. Moreover, this information is important to develop database for domestic appliances to develop residential energy consumption model. Malaysia does not have complete statistical data for all the household appliances. It is very important to have reliable and complete data for policy makers to establish standards and labels. So, the objective of the study is to monitor the energy consumption of this appliance and collecting other relevant information regarding the usage pattern of this appliance.

### 1.1 Structure of the Paper

The information regarding the usage of this appliance in the actual kitchen environment was presented in the abstract. The paper also calculated energy, bill savings and associated emission reductions by replacing old inefficient refrigerator with new efficient one. Aim/purpose or significance of the study with some background information has been presented in introduction.

Section 2 explains questionnaire data collections method, filed and actual energy monitoring approach, internal cabinet temperatures measurement techniques. A mathematical formulation to quantify the impacts has been illustrated in this section as well. Statistical analysis such as cross table, clustering and multidimensional analysis were also carried out in this section.

Section 3 shows the details of monitored yearly energy consumption and cabinet temperatures data, discussions. Questionnaire data in the form of graphs and tables were also presented at the end of this section.

Section 4 shows the multidimensional statistical analysis such as cross table, clustering and segmentation to investigate the interactions among different parameters. Section 5 shows the impact analysis in terms of energy and bill savings and emission reductions associated with energy savings. Section 6 outlines the finding of the research.

## 2. METHODOLOGY

This research has been carried out using two approaches: field energy monitoring and internal cabinet temperature monitoring and questionnaire survey. The approaches are explained in details in sections 2.1 and 2.2. As impact of replacing old inefficient appliances with new efficient ones will be carried out, a mathematical formulation to quantify the impact has been illustrated in this section as well. Statistical analysis such as cross table, clustering and multidimensional was also made in order to clearly define particular parameters or variables of interest. These are elaborated below:

### 2.1 Field Energy and Internal Cabinet Temperatures Monitoring

The objective of this monitoring was to measure actual refrigerator-freezers energy consumption and cabinet internal temperatures. Energy monitoring was carried out by randomly visiting various types of residential dwelling such as double-storey, single storey, condominium, and medium cost apartment at Petaling Jaya, Ampang and Subang Jaya. Petaling Jaya and Subang Jaya are a middle class residential areas situated to the west of Kuala Lumpur. It was established twenty years ago. Although the majority of Subang Jaya residents are Chinese, the areas are generally considered to be multi racial. Ampang on the other hand is situated near the city centre of Kuala Lumpur.

A Phoenix single phase electronic energy meter (model SM68, class 2.0) manufactured by Smart meters technologies (M) Sdn. Bhd. was used to monitor the daily energy consumption in each house. All thirty houses were surveyed sequentially. Meter shows the readings in Wh up to 999.99 and it shows readings in kWh when readings are 1000.00 and above. Temperatures were recorded at three levels (top, middle, and bottom) of refrigerator-freezers compartment using a multi-purpose digital thermocouple. The technical specifications of the thermocouple are shown in table 1. However, only *T* type thermocouple was used in monitoring temperatures at different points of a refrigerator-freezer. A final year student who is working on energy efficiency project conducted data collection as the student has very good understanding about the monitoring approach.

Table 1. Specifications of Digital Thermocouple

| | | | | |
|---|---|---|---|---|
| Type | K, J, E, T type thermocouple | | | |
| Display | 4 ½ LCD | | | |
| Temperature display | Maximum/Minimum/average readings in $^oC$ and $^oF$ | | | |
| Display channel | 3 channels (T1, T2 and T1-T2) | | | |
| Measurement range | K type | J type | E type | T type |
| | -200~1333 $^oC$ (-328~2431$^oF$) | -200~760 $^oC$ (- 328~1400$^oF$) | -200~703$^oC$ (-328~1297$^oF$) | -200~400$^oC$ (-328~752$^oF$) |
| Accuracy | (0.1%rdg+0.8 $^oC$) (0.1%rdg+1.4$^oF$) | (0.1%rdg+0.8 $^oC$) (0.1%rdg+1.4$^oF$) | (0.1%rdg+0.8 $^oC$) (0.1%rdg+1.4$^oF$) | (0.1%rdg+0.8 $^oC$) (0.1%rdg+1.4$^oF$) |

### 2.2 Data Collection through Questionnaire

As consumers are the final users of this appliance, if their suggestions, needs, perceptions, and opinions are taken into considerations in establishing a program such as standard and label, there are better chances to get success. This information is also important for modeling of residential energy consumption. Keeping that in mind, a questionnaire containing 22 questions was used to gather the most pertinent information regarding the usage behaviors of this appliance in actual usage conditions. The major important information for this questionnaire is listed below:

- Personal profile of respondents
- Specification of the refrigerator-freezers
- Usage pattern of the refrigerator-freezers (i.e. frequency of door opening, location of refrigerator)

- Age of appliances
- Type of refrigerator-freezers
- Ambient temperature

### 2.3 Mathematical Formulation for Impact Analysis

The methodology to quantify the impact of replacing old appliance with new efficient appliance is outlined below based on [6]-[7]: Number of refrigerator-freezers can be estimated by following equation:

$$y_{ref} = 196113 - 1516x + 4469.1x^2, R^2 = 0.992 \quad (1)$$

#### 2.3.1 Shipment

Shipment data is the number of a particular appliance in the predicting year subtracted from the number of appliance in the previous year and adding the number of retired appliances in the current year. Shipments are multiplied by a survival factor to get survivors for a given year.
In the mathematical expression it can be written as:

$$\mathrm{Sh}_i^a = (\mathrm{Na}_i^a - \mathrm{Na}_{i-1}^a) + \mathrm{Na}_{i-L}^a \quad (2)$$

#### 2.3.2 Scaling factor

The scaling factor would linearly scale down the energy savings and incremental cost to zero over the effective lifetime of an appliance. Scaling factors are used for both the AES and the incremental costs in this analysis to simulate the effect of annual efficiency improvements in the absence of policy measures. The scaling factor can be expressed as:

$$SF_i^a = 1 - [YSh_i^a - YSe^a] \frac{AEI_i^a}{TEI_i^a} \quad (3)$$

#### 2.3.3 Shipment survival factor

Shipment survival factor is a function of annual retirement rate. A retirement function (“survival curve”) is used to estimate the retirement rate of an appliance. In this linear function no appliances retire in the first 2/3 of their average life, and all units are retired by 4/3 of their average life. This function is applied to the projected shipments to determine the number of appliances purchased in a given year still existing in 2004, or 2010. Appliance survival curve is shown in figure 2. The function can be calculated by the following equation:

$$\mathrm{SSF}_i^a = 1 - \left[ \frac{(\mathrm{YSe}^a - \mathrm{YSh}_i^a) - \frac{2}{3}\mathrm{L}^a}{(\frac{4}{3} - \frac{2}{3})\mathrm{L}^a} \right] \quad (4)$$

#### 2.3.4 Applicable stock

Appliances those still existing in a given year that was affected by efficiency improvement are termed the “Applicable Stock”. The definition of applicable stock is shipments minus retirements of certain appliance in a particular year. This definition can be expressed in mathematical form as follows:

$$AS_i^a = Sh_i^a \times SSF_i^a \tag{5}$$

### 2.3.5 Initial unit energy saving

The initial unit energy savings is the difference between the annual average energy consumption and average energy consumption by an efficient unit. The actual use for a particular appliance will depend on the capacity of the appliance and the usage pattern. The initial unit energy savings can be calculated as:

$$UES_s^a = EC_a - EC_{eff} \tag{6}$$

### 2.3.6 Annual energy saving (AES)

An annual energy saving is unit energy saving multiplied by the scaling factor. This unit energy saving is then multiplied by the number of devices purchased in that year. In the mathematical expression it can be written as:

$$AES_i^a = \sum_{i=s}^{T} AS_i^a \times UES_s^a \times SF_i^a \tag{7}$$

### 2.3.7 Bill saving

The bill saving is a function of energy savings multiplied by an average energy price and can be expressed in the following equation:

$$BS_i^a = AES_i^a \times Pf \tag{8}$$

### 2.3.8 Emission reduction

It can be assumed that the average electricity emissions factor calculated in this way is an accurate representation of the carbon emissions that would be avoided if electricity demand is reduced. There is currently no simple way to assess marginal carbon emissions factors for electricity, so for simplicity the average emissions factor has been used to calculate carbon savings. It can be stated that only direct emissions from the combustion of fuels has been considered. Emissions associated with the extraction, processing, and transportation of fuels are not included. Emission reduction associated with the energy savings can be expressed by following expression [7]:

$$EM_i = EP_i \begin{pmatrix} PE_i^1 \times Em_p^1 + PE_i^2 \times Em_p^2 + PE_i^3 \times Em_p^3 + \\ ..... + PE_i^n \times Em_p^n \end{pmatrix} \tag{9}$$

where,

$EM_i$ : Total emission reductions for a unit energy savings (ton)

$Em_p^i$ : Fossil fuel emission reductions a unit energy savings of fuel type *n*(ton)

$EP_i$ : Share of energy savings in year *i* (*MWh*)

$PE_i^n$ : Percentage of electricity generation in year *i* of fuel type *n* (%)


Fig. 2. Appliance survival curve [6].

## 3. RESULTS AND DISCUSSIONS

### 3.1 Energy Consumption

Yearly energy consumption with refrigerator-freezers capacity has been shown in table 2. Daily energy consumption was multiplied by 365 to get the yearly energy consumption. From the table 2, it has been observed the maximum and minimum yearly energy consumption is 1177 kWh/yr and 665 kWh/yr, respectively. Table 2 also shows the highest capacity of the refrigerator-freezers is 600 liter and lowest capacity of refrigerator-freezers is 148 liter. Energy consumption as a function of adjusted volume has been plotted in figure 3 to find a relationship between them. A regression line was drawn and found a linear relationship with a regression coefficient of ($R^2$) 0.5063. Average energy consumption was calculated and found to be 871 kWh/yr as well. Table 3 shows the average yearly consumption by a refrigerator-freezer throughout the world. From the Table 3, it has been observed that annual average consumption by a refrigerator-freezer is higher in Canada (919kWh/yr) and Iran (877 kWh/yr) compared to Malaysia (871 kWh/yr). The table also shows that annual average consumption by a refrigerator-freezer is lower in Australia, Jordan, Hong Kong, USA, UK, France, Sweden, Portugal, Mexico, and Sri Lanka [8-14] compared to Malaysia. It can be observed from the figure 3 that energy consumption increases as capacity increases in general. However, some of the appliances are more efficient and consume less energy even though the capacity is higher. On the other hand, some appliances are inefficient and hence consume more energy even though the capacity is smaller. Because of those reasons trend in the figure 3 is scattered. It can be stated that appliances below the regression line consume less energy and appliances above the regression line consume more energy.

Table 2. Refrigerators' Energy Consumption with Type and Capacity

| Refrigerator's no. | Capacity (liter) | Type of refrigerator | Energy consumption (kWh/year) |
|---|---|---|---|
| 1 | 148 | B | 693 |
| 2 | 156 | B | 693 |
| 3 | 175 | A | 665 |
| 4 | 195 | B | 693 |
| 5 | 195 | B | 698 |
| 6 | 195 | A | 884 |
| 7 | 240 | B | 835 |
| 8 | 245 | B | 761 |
| 9 | 253 | B | 712 |
| 10 | 272 | A | 739 |
| 11 | 286 | B | 684 |
| 12 | 329 | C | 865 |
| 13 | 365 | B | 821 |
| 14 | 370 | D | 1177 |
| 15 | 407 | B | 939 |
| 16 | 407 | B | 873 |
| 17 | 407 | A | 986 |
| 18 | 425 | A | 890 |
| 19 | 425 | B | 898 |
| 20 | 447 | C | 890 |
| 21 | 452 | B | 1150 |
| 22 | 465 | B | 912 |
| 23 | 465 | A | 898 |
| 24 | 472 | B | 898 |
| 25 | 472 | A | 912 |
| 26 | 486 | C | 881 |
| 27 | 524 | D | 887 |
| 28 | 525 | B | 1144 |
| 29 | 567 | A | 1158 |
| 30 | 600 | B | 884 |

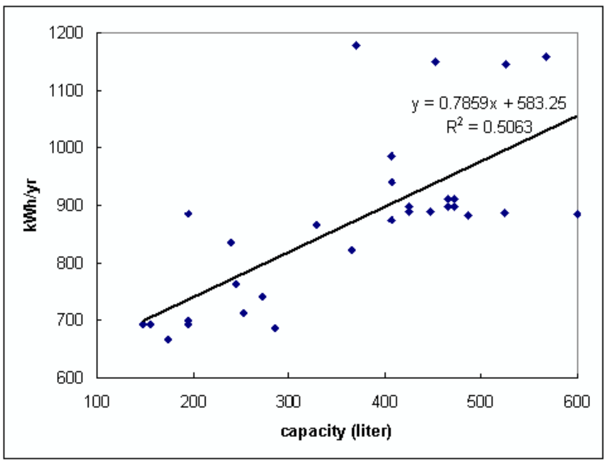


Fig. 3. Energy consumption as a function of refrigerator volume.

Table 3. Refrigerator-Freezers Energy Consumption (kWh/yr) throughout the World

| Australia | Iran | Jordan | Hong Kong | USA | Canada | UK | France | Sweden | Portugal | Mexico | Sri Lanka | Malaysia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 781 | 877 | 523 | 472 | 690 | 919 | 228 | 581 | 763 | 622 | 618 | 468 | 871 |

### 3.2 Internal Cabinet Temperatures

The temperatures recorded for a period of 4 days for three levels (top, middle, and bottom) have been shown in table 4. Table 4 also shows the actual kitchen temperatures. As kitchen temperatures has highest influence on energy consumption as found in literature [15], it has been recorded and presented as well. $T_t$ is the mean temperature recorded at the top of a refrigerator, $T_m$ is the mean temperature recorded at the middle of a refrigerator, $T_b$ is the mean temperature recorded at the bottom of a refrigerator. The tlobal temperature ($T_g$) is the mean of top, middle and bottom levels. Frequencies of global temperature $T_g$ at different ranges are shown in figure 4. It has been observed that $T_{max}$, $T_{average}$, and $T_{min}$ are 5.8 °C, 1.5 °C, and -2.8 °C respectively. It can be stated that the average temperature of the population is between 0.5°C to 2.3°C. However, it can be stated that 16.7% of the populations had temperatures from 4°C to 5.8 °C that is considered a high range of temperatures.

Table 4. Kitchen and Internal Cabinet Mean Temperatures

| Refrigerator no | Mean temperature ($T_T$) top | Mean temperature ($T_m$) middle | Mean temperature ($T_b$) bottom | Global Temperature ($T_g$) | Mean kitchen temperature (°C) |
|---|---|---|---|---|---|
| 1 | -15.1 | 4.4 | 7.0 | -1.2 | 30 |
| 2 | -14.8 | 4.8 | 7.4 | -0.7 | 31 |
| 3 | -17.1 | 4.4 | 14.5 | 0.6 | 31 |
| 4 | -16.8 | 4.7 | 14.5 | 0.8 | 32 |
| 5 | -15.1 | 6.0 | 10.1 | 0.3 | 30 |
| 6 | -14.8 | 6.2 | 10.2 | 0.5 | 30 |
| 7 | -15.2 | 6.1 | 10.1 | 0.3 | 32 |
| 8 | -15.1 | 6.2 | 10.3 | 0.5 | 31 |
| 9 | -17.1 | 6.9 | 12.1 | 0.6 | 31 |
| 10 | -18.1 | 8.9 | 15.1 | 2.2 | 32 |
| 11 | -11.2 | 10.1 | 15.1 | 4.7 | 30 |
| 12 | -18.1 | 4.9 | 12.1 | -0.4 | 31 |
| 13 | -15.2 | 6.0 | 10.2 | 0.4 | 31 |
| 14 | -15.1 | 5.4 | 10.2 | 0.2 | 30 |
| 15 | -12.2 | 5.5 | 13.3 | 2.2 | 31 |
| 16 | -13.7 | 4.8 | 11.5 | 0.9 | 30 |
| 17 | -19 | 2.1 | 9.1 | -2.6 | 30 |
| 18 | -12.4 | 5.4 | 10.1 | 1.0 | 30 |
| 19 | -15.0 | 7.0 | 12.2 | 1.4 | 32 |
| 20 | -15.0 | 8.5 | 16.1 | 3.2 | 31 |
| 21 | -17.0 | 4.6 | 21.1 | 2.2 | 30 |
| 22 | -17.1 | 12.1 | 15.6 | 3.6 | 31 |
| 23 | -6.7 | 4.8 | 9.1 | 2.4 | 30 |
| 24 | -15.2 | 6.0 | 11.4 | 0.8 | 32 |
| 25 | -13.2 | 4.5 | 14.5 | 2.0 | 30 |
| 26 | -13.7 | 4.9 | 15.1 | 2.2 | 30 |
| 27 | -17.1 | 12.1 | 16.5 | 4.3 | 31 |
| 28 | -17.1 | 12.1 | 17.5 | 4.2 | 30 |
| 29 | -18.6 | 8.9 | 22.2 | 4.2 | 31 |
| 30 | -18.1 | 13.5 | 16.9 | 4.1 | 32 |
| Average Mean Temperature | -15.3 | 6.73 | 12.7 | 1.48 | 31 |

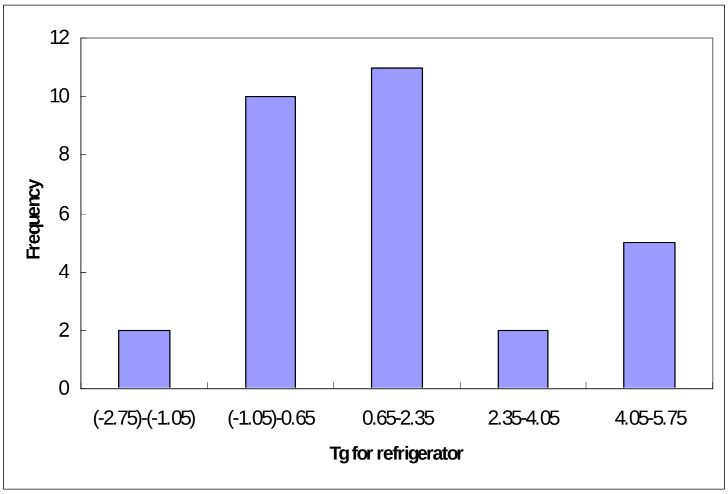


Fig.4. Frequency of global temperatures.

### 3.3 Results and Discussions of Questionnaire Data Collection

Table 5 shows the summary of the questionnaire data for this appliance. Family members have been grouped into 3 categories (i.e. 1 or 2, 3 or 4 and 5 and above). Percentage of each category is shown in figure 5. From the figure 5, it has been observed that the majority of the families are in category 3 (i.e. family members 5 and above). This can be stated that the more the family members there are, the more food is stored and more frequently a refrigerator-freezer door is opened. As a fundamental function of a refrigerator, it has to cool the food items by cooling off the heat from the environment and from the food itself. When the more food items are stored, the refrigerator needs to provide stronger cooling in order to preserve all food items. Stronger cooling requires more energy leading to higher energy consumption.

Refrigerator-freezers are categorized into 4 types. Type A has single door, type B has double door, type C has triple doors and type D has side by side door.

Figure 6 shows that majority of the refrigerator-freezers are type B followed by type A (26.7%). It can be seen from the Figure 6 that there are only 6.7% of D type refrigerator-freezers available in this survey.

Type A, the single door refrigerator-freezers are less used by consumers as they do not provide a better control of temperatures and cannot provide variable temperatures for different food compartments. Moreover, users had to both open fresh food and freezer compartment even though users need to open only one compartment. Besides, single door refrigerator has weaker ability to maintain the temperature of a refrigerator. Type B is still more popular as it has standard quality control in food storage. Type C and D are less preferred as type C is quite expensive and side by side is not convenient for users. This may be due to the too big size and high purchase price.

Figure 7 shows the frequency of door openings. As the control of temperature in the refrigerator space is very important, the exposure of heat in the air will disturb the cooling. Therefore, the opening of doors will contribute to higher energy for cooling purpose. When the refrigerator door is opened, warm ambient air descends into the upper part of the compartment filing the void left by the colder air, which flows out near the bottom of the compartments. During this process, heat is transferred to the cold surfaces inside the compartments. This imposes an additional cooling load on the refrigeration system. As the door of a household refrigerator is opened, the moist and warm ambient air will come into the cabinets. This will cause an increase in thermal load for a refrigerator and the change the freshness of [16]. Masjuki *et al*. [17] investigated the impact of door openings on refrigerator-freezers' energy consumption and reported that energy consumption increases 10 Wh/day for each door opening. Parker and Stedman [18] estimated that each door opening causes 9 Wh increase of energy consumption.

Table 5. Summary of Questionnaire Data Collection

| Serial no. | No. of family members | Age of refrigerator | Refrigerator type | Frequency of door openings (times/day) | Location of refrigerator (near a heat or free from heat source) |
|---|---|---|---|---|---|
| 1 | 5 | 5-10 | B | <10 | Near |
| 2 | 3 | <4 | B | <10 | Free |
| 3 | 7 | 5-10 | A | 10-20 | Free |
| 4 | 6 | 5-10 | B | >20 | Near |
| 5 | 4 | <4 | B | 10-20 | Near |
| 6 | 9 | >11 | A | >20 | Near |
| 7 | 4 | 5-10 | B | 10-20 | Near |
| 8 | 5 | 5-10 | B | 10-20 | Free |
| 9 | 2 | <4 | B | <10 | Free |
| 10 | 8 | >11 | A | 10-20 | Near |
| 11 | 2 | <4 | B | <10 | Near |
| 12 | 5 | 5-10 | C | <10 | Free |
| 13 | 6 | >11 | B | 10-20 | Near |
| 14 | 10 | 5-10 | D | >20 | Near |
| 15 | 3 | <4 | B | <10 | Near |
| 16 | 8 | 5-10 | B | 10-20 | Near |
| 17 | 5 | 5-10 | A | <10 | Free |
| 18 | 4 | >11 | A | <10 | Near |
| 19 | 7 | 5-10 | B | 10-20 | Near |
| 20 | 10 | 5-10 | C | 10-20 | Free |
| 21 | 5 | <4 | B | <10 | Near |
| 22 | 3 | <4 | B | <10 | Free |
| 23 | 4 | 5-10 | A | 10-20 | Near |
| 24 | 6 | 5-10 | B | 10-20 | Near |
| 25 | 2 | <4 | A | <10 | Free |
| 26 | 6 | 5-10 | C | >20 | Free |
| 27 | 10 | <4 | D | 10-20 | Near |
| 28 | 3 | >11 | B | <10 | Free |
| 29 | 5 | 5-10 | A | <10 | Near |
| 30 | 7 | >11 | B | 10-20 | Near |

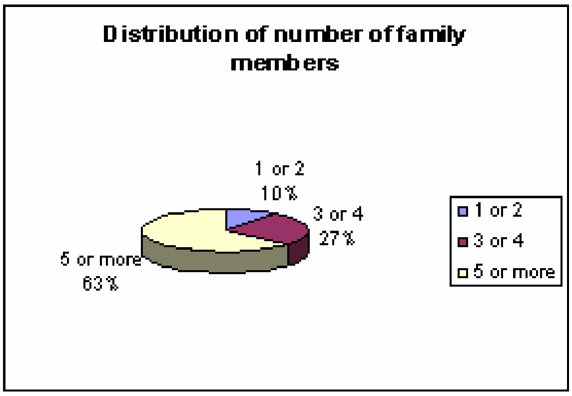


Fig. 5. Distribution of family members.

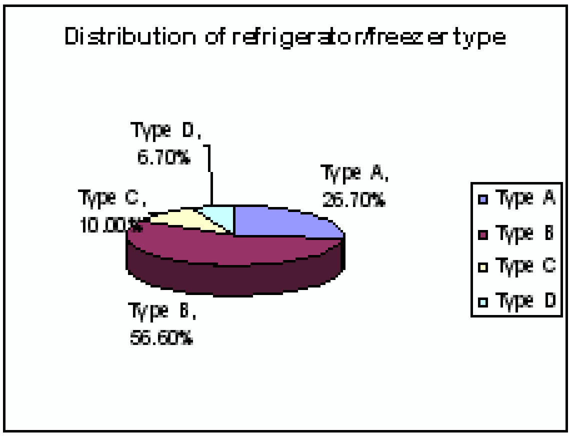


Fig. 6. Type of refrigerators used by consumers.

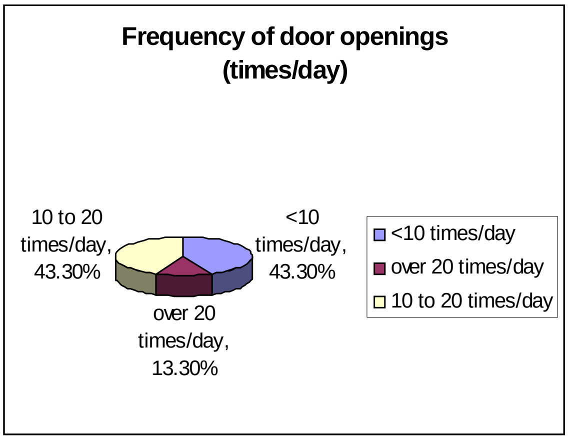


Fig. 7. Frequency of door openings.

Figure 8 shows the location of refrigerators whether it is near to or free from a source of heat. It is more appropriate to place the refrigerators free from heat source in order to avoid the draw of stronger current for the purpose of cooling the refrigerators. Refrigerator, which is placed near a heat source, will require stronger cooling. As the physical part of the refrigerator is not totally made by insulating material, the temperature surrounding the refrigerator will affect the overall refrigerator system. This factor is also related to the few criteria mentioned above, for example the frequency of door opening.

Meier *et al*. [5] showed that energy consumption increased 120 Wh for each degree increase in temperature. Kao and Kelly [19] conducted the experiment on top mounted freezer unit to investigate the effect of room temperature and reported 120 Wh/day increase in energy consumption for each degree increase in temperature. Grimes et al. [20]found an average rate of 145 Wh/day increase in energy consumption for each degree increase in temperature.

Saidur *et al*., [15] conducted experiments on six refrigerator-freezers to investigate the combined effect of several parameters on refrigerator-freezers energy consumption and reported that room temperature has highest effect on its energy consumption. As heat source will raise the ambient temperature, it will cause a refrigerator to consume more energy as has been found in literature [21].

The setting of the refrigerator thermostat varies according to brands and models. To avoid all source of confusion, the refrigerator thermostat was set as a portion of full scale and the value varied from 0 to 1 (0 = minimum temperature setting, 1 = maximum temperature setting). The distribution of thermostat setting is shown in figure 9.

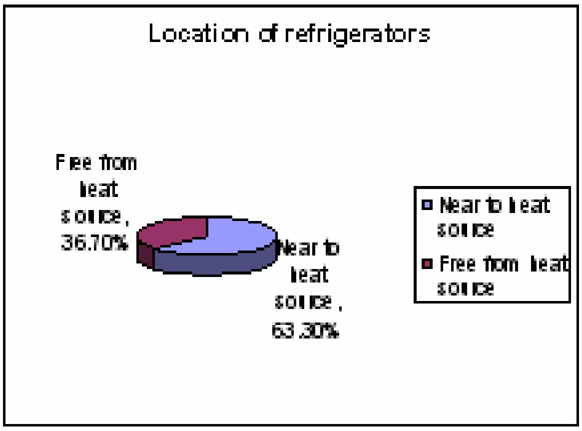


Fig. 8. Location of refrigerators.

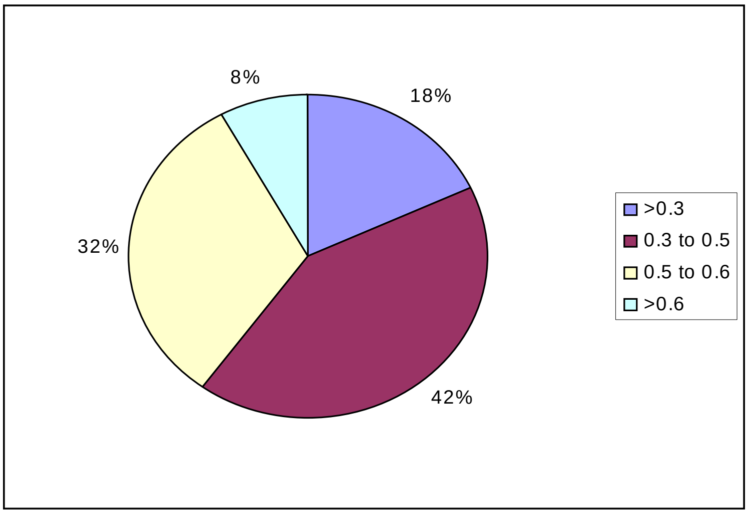


Fig. 9. Distribution of thermostat setting positions.

Just like a house, a refrigerator will use less electricity if its thermostat is re-set to a higher (warmer) temperature. Grimes *et al*; [20] examined the impact of compartment temperature on energy use on 1977 to vintage automatic defrost refrigerator. Authors found that energy consumption rose 26% from the warmest acceptable to the coldest possible settings. Another study of nine large, 1993 to vintage US refrigerators by Parkar and Stedman [18] found 6.5% increase in energy consumption for 1 $^{0}$C reduction in freezer temperature. Meier (1994) stated that lowering the freezer temperature by -15 $^{0}$C causes 133 kWh/yr increases in energy consumption.

Age of the refrigerator as shown in figure 10 determines the physical condition of a refrigerator. This may include the door, gasket, tightness of insulation, effectiveness of the freezer compartment and so on. It has been revealed that most energy wastage was caused by the leakage from a refrigerator. The leakage is most likely happen at the door when the rubber is worn. As the door of the refrigerator is not tightly closed, the temperature of the outer environment will cause the temperature inside the refrigerator to be higher. In this case, in order to maintain the required cabinet temperature, more energy needed to be drawn. It can be stated that there are dusts normally at the back of the wall that covers the area where the refrigerator dissipate heat. A thick layer of dust that is common for old refrigerators will have the refrigerator work harder to maintain desired temperature. The maintaining of the cool environment in a refrigerator is a crucial condition in order for the refrigerator to perform at its best. Whenever there is an unbalance in the temperature, the refrigerator needs energy to balance up.

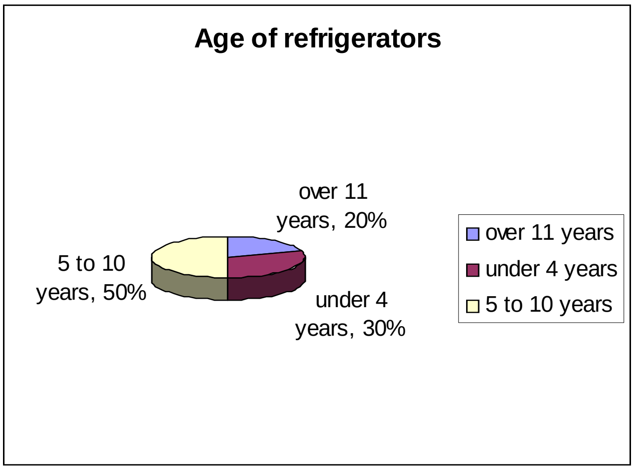


Fig. 10. Age of refrigerator.

## 4. MULTIDIMENSIONAL STATISTICAL ANALYSIS

### 4.1 Two-Dimensional Analysis (Crossed Table)

This was used to investigate the relationship between factors (characteristics of refrigerator, usage conditions and characteristics of participants) and overall temperature ($T_g$). It was found that there is no direct relationship between them, particularly in terms of temperature settings and refrigerator temperatures. Some of the surveyed refrigerator with high temperature settings still has low temperature (< 3 $^{o}$C) while some of them, which have low temperature settings, still have a high temperature (> 8.0$^{o}$C).

### 4.2 Clustering

The clustering makes it possible to consider refrigerators with as many as common characteristics as possible in a same group. Moreover, each group must have different common characteristics compared with the other groups.

The term cluster analysis encompasses a number of different methods for grouping objects of similar kind into respective categories. Cluster analysis is an exploratory data analysis tool which aims at sorting different objects into groups in a way that the degree of association between two objects is maximal if they belong to the same group and minimal otherwise. Given the above, cluster analysis can be used to discover structures in data without providing an explanation/interpretation [22].

Clustering analysis is based on the simple concept of partitioning data observations (consumers, brands etc.) into group based on their proximity (closeness) to each other. Basic criterion used for Clustering analysis is distance; data observations close together should fall into the same cluster while observations far apart should be in different cluster groups [22].

Clustering is dealt with in almost every aspect of daily life. For example, a group of diners sharing the same table in a restaurant may be regarded as a cluster of people. In food stores items of similar nature, such as different types of meat or vegetables are displayed in the same or nearby locations. There are a countless number of examples in which clustering plays an important role. For instance, biologists have to organize the different species of animals before a meaningful description of the differences between animals is possible [22].

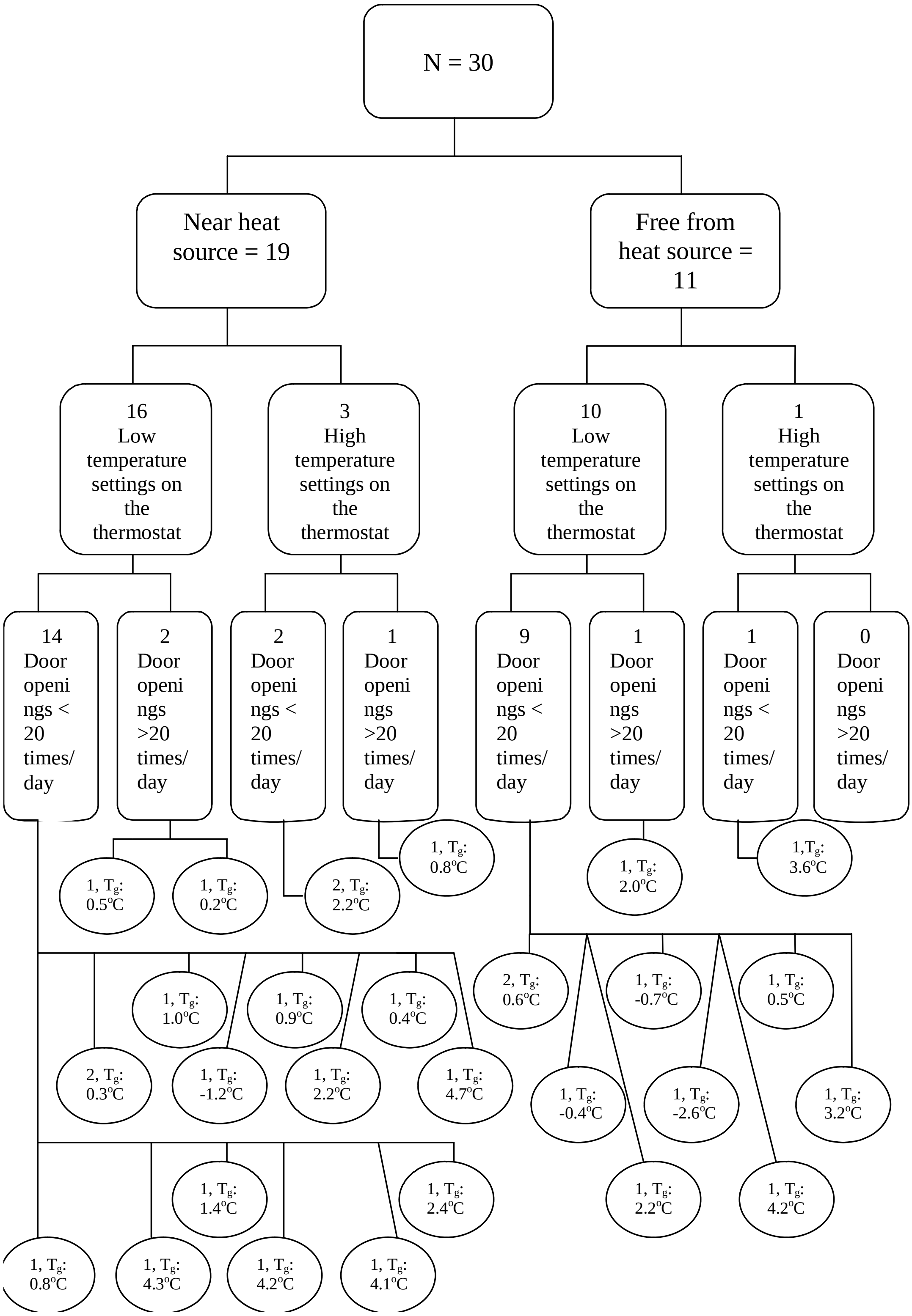


Fig. 11. Clustering diagram.

In this study three factors that may have a major influence on temperature are: heat source (HS), temperature setting (TS), and frequency of door openings (FDO).

Thirty refrigerators surveyed shows different characteristics in their usage behaviors as well as energy consumption. In order to verify the relationship between factors and the overall temperature, the 30 refrigerators have been classified into a few groups. The refrigerators in the same group share common characteristics.

The number of refrigerators has been divided into 2 major groups which are the near to heat source and free to heat source. From here, they have been divided into smaller clusters. Under each group, refrigerators have been differentiated based on high temperature settings or low temperature settings. Finally, they have been grouped according to the frequency of door opening more than 20 times a day or less than 20 times a day. The clustering diagram is shown in figure 11.

As can be seen from figure 11, majority of the refrigerators has low temperature settings. This followed by the statistics shown that most refrigerators have frequency of door opening less than 10 times a day. It can be concluded that the popular behaviors of the consumers are low temperature settings and frequency of door opening of less than 10 times a day. However it was found that there is no direct relationship between the temperature settings and the refrigerator temperatures. For example, there are refrigerators with high global temperature under the low temperature settings category and vice versa.

### 4.3 Segmentation

Segmentation refers to the process of partitioning a population into sub-groups. Segmentation analysis is typically used to identify population sub-groups that exhibit certain common characteristics and can be expected to behave similarly with respect to an issue of interest [22].

The study employed a technique known as segmentation analysis that groups the internal refrigerators temperature according to the frequency of door opening and heat source (i.e. how these parameters influence refrigerators internal temperature).

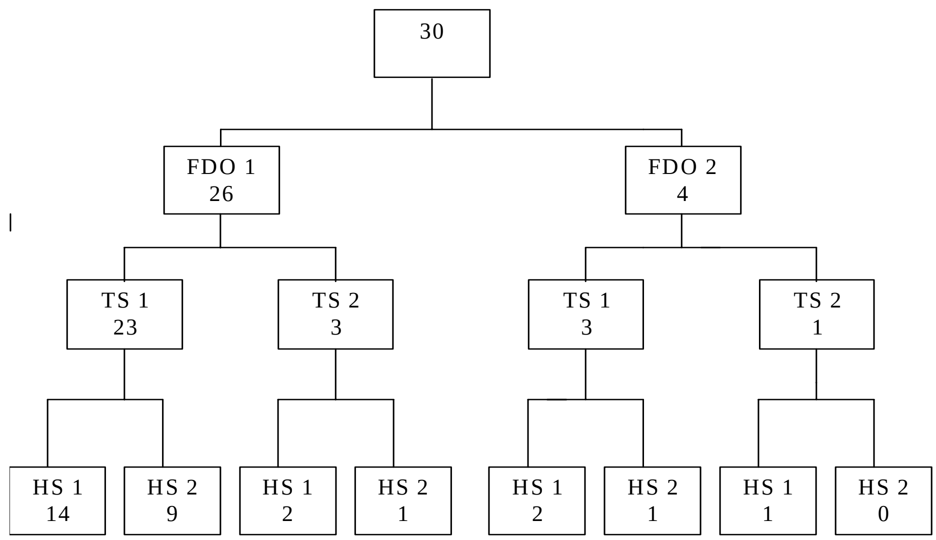


Fig. 12. Segmentation analysis.

The refrigerators were divided into subgroups using explanatory variables such as frequency of door opening (FDO). The frequency of door openings (FDO) was the best criterion enabling division of the 30 refrigerators into 2 subgroups. Subdivision was then continued successively to the greatest possible extent. At the bottom level, the overall temperature and the number of samples are reported.

It has been observed that the global temperatures of the group of refrigerators that has the frequency of door openings for more than 20 times are in the range of 0.2 to 2 °C. The highest global temperature, 4.7°C is found under the frequency of door openings less than 20 times a day, low temperature settings and near to heat source group. The lowest global temperature, -2.6°C has been found under the door openings of less than 20 times a day, low temperature settings and free from heat source group. Figure 12 shows the segmentation diagram. Table 6 shows the characteristics of refrigerators.

Table 6. Representation of Characteristics

| Characteristics | Terms |
|---|---|
| Frequency of door openings of less than 20 times a day | FDO 1 |
| Frequency of door openings of more than 20 times a day | FDO 2 |
| Low temperature settings | TS 1 |
| High temperature settings | TS 2 |
| Near to heat source | HS 1 |
| Free from heat source | HS 2 |

## 5. IMPACT ANALYSIS

Malaysia does not have complete data for household appliances. So, authors had to rely on some other sources to get some data for the projection of energy for this appliance in Malaysia. Keeping that in mind some of the assumptions and data have been taken from [6]. In this paper, authors mentioned that the energy efficiency of appliances tends to improve gradually (for example 1.5 % annual efficiency improvements) over time due to technological advances even in the absence of any policy enforcement. This is the natural progress in the energy efficiency in the absence of any policy measures around the world. It can be assumed that the average life of an appliance throughout the world is same. Using input data from table 7 and the methodology described by Mahlia *et al.*, [7], and Koomey *et al.*, [6], ownership level has been obtained for the year 2005 to 2016 and presented in table 8. Actual average monitored energy consumption (i.e. 871 kWh/yr) has been taken from filed monitoring of 30 refrigerators. Average energy consumption (i.e.702 kWh/yr) by a new efficient appliance has been taken from energy commission of Malaysia. Initial energy savings (169 kWh/yr) was obtained by deducting average energy consumption by a new efficient appliance from actual average monitored energy consumption (i.e. 871-702 = 169 kWh). Using the same methodology, energy consumption for old efficient and new efficient refrigerator-freezers has been estimated for the year 2005 to 2016 and then energy and bill savings has been estimated and presented in table 8. Associated emission reductions along with the energy savings has been calculated using the data in tables 9 and 10 and presented in table 11. A sample calculation is shown in appendix A.

Table 7. Input Data for Projected Estimation

| Description | Values |
|---|---|
| Actual monitored average energy consumption | 871 kWh/yr |
| Average energy consumption by an efficient appliance | 702 kWh/yr |
| Initial unit energy savings | 169 kWh/yr |
| Annual efficiency improvement | 1.5% |
| Total efficiency improvement | 20% |
| Average appliance life span | 12 years |
| Current electricity price | RM 0.235/kWh |

Table. 8 Summary of Impact Analysis

| Year | Refrigerator | sh | SF | UES (kWh) | SSF | AS | AES (MWh) | BS (Million) |
|---|---|---|---|---|---|---|---|---|
| 2005 | 5617 687 | 2632 657 | 1.00 | 169 | 1 | 2632 657 | 444 919 | 105 |
| 2006 | 5933 476 | 2841 188 | 0.92 | 156 | 1 | 2841 188 | 409 063 | 96 |
| 2007 | 6258 204 | 3058 659 | 0.85 | 143 | 1 | 3058 659 | 369 963 | 87 |
| 2008 | 6591 870 | 328 5067 | 0.77 | 130 | 0.99 | 3252 216 | 325 027 | 76 |
| 2009 | 6934 475 | 3520 414 | 0.69 | 117 | 0.99 | 3485 210 | 282 051 | 66 |
| 2010 | 7286 017 | 3764 697 | 0.62 | 104 | 0.98 | 3689 403 | 235 827 | 55 |

Table 9. % of Fuel Mix in Electricity Generation in Malaysia

| Year | Coal (%) | Petroleum (%) | Gas (%) | Hydro (%) |
|---|---|---|---|---|
| 2005 | 15.5 | 3.25 | 58.75 | 22.5 |
| 2006 | 15.84 | 2.96 | 56.8 | 24.4 |
| 2007 | 16.26 | 2.69 | 54.95 | 26.1 |
| 2008 | 16.76 | 2.44 | 53.2 | 27.6 |
| 2009 | 17.34 | 2.21 | 51.55 | 28.9 |
| 2010 | 18 | 2 | 50 | 30 |
| 2011 | 18.74 | 1.81 | 48.55 | 30.9 |
| 2012 | 19.56 | 1.64 | 47.2 | 31.6 |
| 2013 | 20.46 | 1.49 | 45.95 | 32.1 |
| 2014 | 21.44 | 1.36 | 44.8 | 32.4 |
| 2015 | 22.5 | 1.25 | 43.75 | 32.5 |
| 2016 | 23.64 | 1.16 | 42.8 | 32.4 |

Table 10. Emission Factor for Per Unit Electricity Generation in Malaysia

| Fuels | Emission factor (kg/kWh) | | | |
|---|---|---|---|---|
| | $CO_2$ | $SO_2$ | $NO_x$ | CO |
| Coal | 1.18 | 0.0139 | 0.0052 | 0.0002 |
| Petroleum | 0.85 | 0.0164 | 0.0025 | 0.0002 |
| Gas | 0.53 | 0.0005 | 0.0009 | 0.0005 |
| Hydro | 0 | 0 | 0 | 0 |
| Others | 0 | 0 | 0 | 0 |

Table 11. Emission Reductions Associated with Energy Savings

| Year | $CO_2$ (ton) | $SO_2$ (ton) | $NO_X$ (ton) | CO (ton) |
|---|---|---|---|---|
| 2005 | 232 203 | 995 | 418 | 147 |
| 2006 | 209 895 | 932 | 388 | 132 |
| 2007 | 187 189 | 863 | 356 | 116 |
| 2008 | 162 666 | 779 | 319 | 99 |
| 2009 | 140 070 | 697 | 283 | 84 |
| 2010 | 116 593 | 604 | 243 | 68 |
| 2011 | 93 176 | 502 | 201 | 54 |
| 2012 | 70 754 | 396 | 157 | 40 |
| 2013 | 50 795 | 295 | 117 | 28 |
| 2014 | 33 221 | 200 | 79 | 18 |
| 2015 | 18 370 | 115 | 45 | 10 |
| 2016 | 7 626 | 49 | 19 | 4 |

Ownership level for the year 1990 to 2000 has been obtained from the report collected from statistical department of Malaysia [23]. Using the polynomial curve fitting, ownership level has been predicted for the year 2001 to 2016. However, prediction data for the year 2005 to 2016 has been shown in table 8 as prediction of energy, bill savings, emission reduction has been carried out for those years.

## 6. CONCLUSION

Following conclusions could be drawn from this study:

- From table 8, it has been calculated that a cumulative savings of RM619Million would possible.
- From table 8, it can be seen that a cumulative (i.e. from year 2005 to 2016) energy savings of 2632,343MWh would be possible if new efficient refrigerator are used instead of older one.
- Global environment is an important issue now a day. The concern now is to use clean energy system for the benefit of global community. For example, environmental impact on the potential reduction of greenhouse gases such as carbon dioxide, sulfur dioxide, nitrogen oxide and carbon monoxide are major environmental concern. From the table 11, it has been found that 1322,558 tons of $CO_2$, 6427 tons of $SO_2$, 2625 tons $NO_x$ and 798 tons of CO expected to reduce from the year 2005 to 2016.
- This study shows that the combination of the usage conditions (temperature setting, frequency of door openings and heat source) seems to have a major impact on the refrigerator temperature.
- A survey was conducted to investigate the usage behavior of this appliance in order to get a clearer overview of usage pattern of refrigerators in Malaysian households. From the survey it has been found that there are many factors that influence the energy and temperature performance of a refrigerator. Consumers will enjoy tremendous benefit (as shown in tables 8 and 11) in terms of energy savings and emission reductions if they use this appliance correctly and select energy efficient products.
- As Malaysia is in the process of establishing energy efficiency measures, the information that has been obtained in this paper certainly will help in shaping an effective policy measure. To develop an energy efficiency standard, a baseline energy consumption pattern must be established using

energy consumption data such as laboratory testing or actual monitoring or manufacturer's catalogue data. Once a baseline standard is established, efficiency target (for example 5% or 10% energy savings target) can be proposed as a standard. On the other hand to develop an energy guide label for any appliance, consumers inputs (particularly their usage behavior, opinions/views and so on) are crucial as they are the final users of the appliance. If their needs and perceptions (For example the way they use it, how many times refrigerator door is opened, internal thermostat setting positions, location of refrigerator and other features as collected through the survey in this study) are taken into consideration, there are better chances to get a successful program. Moreover, Energy efficiency index (EEI), energy efficiency factor (EEF) are normally used to grade or rate an appliance (such as start rating or A, B, C letter grading). These rating criteria also depend on appliance energy consumption and appliance capacity (appliance volume or capacity). So, it can be stated that this information might be used to establish energy policy measures.

- The data presented in this paper can be used for energy modeling along policy making. It can be used to compare data with other countries as well.
- Finally, as a limitation of the study it could be stated that a larger sample may help to develop a more reliable statistical analysis and an accurate estimation of the residential energy consumption for this appliance

## 7. NOMENCLATURE

| | | |
|---|---|---|
| $AS_i^a$ | : | Applicable stock of in year i of an appliance a |
| $UES_s^a$ | : | Unit Energy savings (kWh) in year i for an appliance a |
| $EC_a$ | : | Average Energy consumption |
| $EC_{eff}$ | : | Average energy consumption by an efficient appliance |
| $BS_i^a$ | : | Bill savings in year i for an appliance a |
| $L^a$ | : | Life span of an appliance a |
| $AEI^a$ | : | Annual efficiency improvement of an appliance a |
| $Na_i^a$ | : | Number of appliance a year i |
| $Na_{i-1}^a$ | : | Number of appliance a year i-1 |
| $Na_{i-L}^a$ | : | Number of appliance a year i-L |
| $S_i^a$ | : | Energy saving in year i for appliance a |
| $SF_i^a$ | : | Scaling factor in year i for appliance a |
| $Sh_i^a$ | : | Shipments in year i for an appliance a |
| $SSF_i^a$ | : | Shipment survival factor in year i for appliance a |
| $\mathrm{YSh}_i^a$ | : | Year i of shipment of appliance a |
| $YSe^a$ | : | Year saving calculation for an appliance a |
| $Em_p^n$ | : | Emission p for fuel type n for a unit electricity generation |
| $P_f$ | : | Fuel price |

## 8. APPENDIX

### Appendix A

### A Sample Calculation

Prediction of ownership, energy savings, bill savings and emission reductions has been calculated using the input data given in table 7 and equations (1)-(9) and presented in table 8. A sample calculation has been shown for the year 2005 as below:

Number of refrigerator-freezers has been predicted using equation (1) and shown here for the year 2005.

$$y_{ref,2005} = 196113 - 1516 \times 35 + 4469.1 \times 35^2$$
$$= 5617687$$

It has to be noted that value of $x$ has been taken as 35 (i.e. 2005-1970 = 35) in the year 2005 as prediction equation has been developed using the historical data from the year 1970.

Using equation (2), shipment has been calculated as below:

$$sh_{2005} = 5617687 - 5310835 + 2325805$$
$$= 2632657$$

where value 2325805 (i.e. number of refrigerator-freezers in the year 1992) is the number of retired appliance in the year 2005 as the life of appliances for the year 1992 is going to expire in 2005.

Scaling Factor (SF) has been calculated using equation (3) and input data in table 4 and shown as below:

$$SF_{2005} = 1 - \left(2005 - 2005\right) \times \frac{0.015}{0.20} = 1.00$$

Using the figure 2, shipment Survival Factor (SSF) has been obtained = 1 for the year 2005.

Applicable Stock (AS) is shown as below using equation (5):

$$AS_{2005} = 2632657 \times 1 = 2632657$$

Using equation (6), initial unit energy savings can be obtained as:

$$UES_s^a = EC_a - EC_{eff} = 871 - 702 = 169kWh$$

Using equation (7), annual energy savings can be obtained as below:

$$AES_i^a = AS_i^a \times UES_i^a \times SF_i^a = 2632657 \times$$
$$169 \times 1.00 = 444919MWh$$

Bill savings has been obtained using equation (8) and shown as below:

$$BS_{2005} = 444919 \times 0.235/1000$$
$$= \text{RM105 Million}$$

Emission reductions has been obtained using equation (9) and shown as below:

Share of annual energy savings by not burning coal, petrol, gas and hydro can be obtained using data from table 9.

$$AES_{coal} = 444919 \times 15.5 / 100 = 68962 MWh$$

$$AES_{petrol} = 444919 \times 3.25 / 100 = 14460 MWh$$

$$AES_{gas} = 444919 \times 58.75 / 100 = 261390 MWh$$

Now $CO_2$, $SO_2$, $NO_x$ and CO reductions can be obtained using equation (9) and emission factor from table 10 as below:

$$E_{CO_2} = 68962 \times 1.18 + 14460 \times 0.85 + 261390 \times 0.53$$

$$= 232203 ton$$

$$E_{SO_2} = 68962 \times 0.0139 + 14460 \times 0.00164 + 261390 \times 0.00005$$

$$= 995 ton$$

$$E_{NO_x} = 68962 \times 0.0052 + 14460 \times 0.0025 + 261390 \times 0.00009$$

$$= 418 ton$$

$$E_{CO} = 68962 \times 0.0002 + 14460 \times 0.0002 + 261390 \times 0.00005$$

$$= 147 ton$$

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