Assessment of Household Energy Utilization in Ibadan, Southwestern Nigeria

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Abstract: The critical energy situation in Nigeria suggests the need to study energy and exergy utilization in households, with the aim of pinpointing areas of waste and suggesting alternative measures for effective and efficient utilization of scarce resources. Household energy and exergy consumption trends are thus simulated in this study by considering 125 homes randomly selected in Ibadan, southwestern Nigeria. The energy flow for the first three months of 2009 was evaluated using both primary and secondary data. The results show that average efficiency of household energy and exergy utilization are 62.5 and 21%, respectively. Furthermore, approximately 32% of total exergy losses are caused by refrigerator-freezers, followed by air conditioners (30.0%), lighting from bulbs (16.2%), ironing (5.0%), and fluorescent light (3.7%). Other appliances accounted for less than 2.0%. This study provides fundamental guidelines and baseline data for policymakers in Nigeria on sustainable energy policy measures that would reduce energy losses at the household level. **DOI: 10.1061/(ASCE)EY.1943-7897.0000083.**

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Introduction

The efficiency of household appliance energy utilization of any nation represents the state of its socio-economic development. It is therefore important to ensure that household appliances are as energy efficient as possible. Energy degradation attributable to poor energy utilization is becoming alarming in every sector of society, and for this reason a clear understanding of energy loss is currently an issue of discussion among various researchers from different regions of the world (Rosen 1992; Ozdogan and Arikol 1995; Ertesvag and Mielnik 2000; Xi and Chen 2005; Saidur et al. 2007). Studies have shown that inefficient energy utilization is directly related to escalation in energy cost, in addition to carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions. These are potential environmental pollutants that deplete the ozone layer with the attendant effects on global warming, climate, rain and wind pattern changes, and rising sea levels, changes that could have unpredictable and catastrophic consequences. It is therefore important to investigate how effective and efficient a society manages its energy resources.

Energy is wasted in homes during the process of energy transformation. The question of how, when, and where the energy loss occurs is primarily based on the first law of thermodynamics. The first law concept explains that the energy involved in any transfer must be conserved, i.e., energy is neither created nor destroyed but is transferred from one form to another. This would seem to indicate that energy usage is endless and energy is never lost, irrespective of the process condition. The problem is that this is not the only law that governs energy transfers. Whereas the total amount of energy does not change, the second law of thermodynamics limits the amount of usable energy that can be transferred. One of the consequences of this law is that the total amount of usable energy that comes out of any process will be less than the total amount of energy that went into the process. The difference between the total amount of energy input and usable energy output is expended as waste heat. This is an implication that second law analysis can better and more accurately pinpoint the location of inefficiencies, and therefore can be used to optimize the performance of household appliances (Dincer and Rosen 2007). In addition, second law analysis, which is also referred to as exergy analysis, is strongly related to sustainability and environmental impact. Consequently, application of exergy methods will result in very little energy waste and reduced environmental impact, with improved sustainability.

Exergy analysis has demonstrated technological and educational information for individuals or organizations seeking understanding on techniques and technologies related to residential, transport, commercial and industrial energy efficiency. It provides a linkage between the physical and engineering world and the surrounding environment. It furthermore expresses the true efficiency of engineering systems and sectoral energy analysis of any country. Application of exergy analysis is also useful for promoting awareness of energy degradation in different sectors, regions and countries (Dincer et al. 2004b; Dincer and Rosen 2007). It thus encourages one to undertake a holistic assessment of how energy is degraded in society. A number of applications of energy and exergy analysis to homes or residential sectors have been reported.

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Asada and Takeda (2002) investigated the ceiling radiant cooling system, and determined that cooling with well water is not exergy efficient because of the relatively large electricity consumption by pumps. Rosen et al. (2001) reported that one major weakness in energy account in building is the lack of use of second law analysis. Saidur et al. (2007) applied the exergy concept to the residential sector of Malaysia and identified the major causes of energy losses in home appliances. The concept has also been applied to residential sectors of many countries, such as the U.S. (Reistad 1975), Japan, Finland and Sweden (Wall 1990), Canada (Rosen 1992), Italy (Wall et al. 1994), Turkey (Ozdogan and Arikol 1995), Norway (Ertesvag and Mielnik 2000), Saudi Arabia (Dincer et al. 2004a) and China (Xi and Chen 2005).

Despite the significance of the exergy concept to the residential sector of various countries, there is a paucity of information concerning the application of exergy analysis to the study of energy degradation in Nigeria, particularly in the residential sector. Hence, this study is aimed at assessing the energy and exergy of 125 households in Ibadan, southwestern Nigeria. Ibadan, the capital city of Oyo State, is a mega city, the second most populous city in sub-Saharan Africa after the city of Cairo. Ibadan is therefore a typical presentation of many cities in Nigeria and Africa at large. The study is expected to give a clear perception of energy consumption patterns and degradation in the residential sector of Nigeria. It is also anticipated that the study will provide policy makers in the country with knowledge on how efficiently the country utilizes its energy resources, which will guide in the formulation of energy policy measures that would reduce energy losses at the household level.

Methodology and Analysis

Nigeria is a developing country, just being awakened to energy issues, and is critically faced with problems such as lack of availability and consistency in energy-related data. These associated problems present a serious limitation on energy-related studies in the country. Hence, researchers in this area of research are obliged to undertake field surveys for collection of primary data, which is time-consuming and costly. In this study, a lack of field data required for detailed energy studies has constrained data collection to a relatively short period of three months and sampling of 125 households in the Ibadan metropolis. The limited duration of sampling and size of the data should not by any means jeopardise accurate trends in the energy and exergy of the system.

Ibadan metropolis has a population of 3.56 million [National Population Commission of Nigeria (NPCN) 2006] with six local government areas (LGAs), of which five were randomly selected. Simple random quota sampling techniques were then used to select 25 households from each LGA. The energy consumption parameters and socio-economic status of the households were taken into cognisance in sampling to reduce error inherent in the sampled population. Energy data was collected using a structured questionnaire. The questionnaire was administered to different households for a period of three months to examine information relating to patterns of energy usage. The information considered includes electricity and fossil fuel sources available to households, supply and demand characteristics of these sources (quantities consumed), and the energy services derive from the fuels and electricity sources that were consumed. Staff of LGAs in charge of district planning, the department of energy, and other energy stakeholders was interviewed to gain insight into past and current trends of energy data. Furthermore, focus group discussions were used to collect data in the study area.

The questionnaire is comprised of two sections. The first deals with information such as demographic description of the neighborhood, type of house, family size, number of rooms, household income level and commercial venture being run in the household. The second section was further divided into eight sub-sections. The first five sub-sections lead with the use of electricity, liquefied petroleum gas (LPG) and kerosene. Attempts were made to induce respondents to reveal the quantity and sources of each of these fuels that the household consumes, the period of its use, the purpose of its use, methods employed in using it and any problems they encounter in using each of these fuel types. The last three sub-sections lead with a survey of other energy sources that generally contribute little to the overall household energy budget.

Determination of Energy Consumption

In the following sections, the methods used to estimate energy utilization are described. Energy-related parameters such as appliance utilization hours, ownership level and power rating were extracted from the questionnaire.

Duration of Appliance Use

To evaluate the total energy consumed by household appliances, the duration of an appliance operation was determined. Hourly usages of each appliance were collected and the average usage duration was calculated.

Appliance Ownership and Power Rating

The number of each appliance in every household is a measure of appliance ownership, whereas the power rating is a measure of the required amount of power that can be used to operate a specific device or appliance. The power rating, in watts, indicates the rate at which the device converts electrical energy into another form of energy, such as light, heat, or motion. Different types of appliances and brands (i.e., two or more refrigerators of differing model or brand) operate on different power ratings. However, appliances of the same type operate in an average range of 120–550 W. This trend can be observed in appliances such as washing machines, air conditioners, and televisions. Therefore, it is essential to determine the power rating of appliances along with the ownership level.

Overall Energy Consumption

The primary sources of energy in the region are fossil fuels and electricity. The primary source of energy for electrical appliances is power from the national grid, whereas non-electrical cooking appliances use energy from fossil fuels. The overall energy consumed from each sources of energy was evaluated as described in the following section.

Electrical Energy Consumption

The electrical energy, A_e, used over a period of time depends on the power rating, number of appliances and duration in hour of the appliances used. This was evaluated using the following formula:

$$A_e = N_a \times P \times t \tag{1}$$

where N_a = number of appliances; P = power rating of the appliances in watts; and t = duration of an appliance usage in hours. The sum of the energy used by all appliances for a year can be calculated using the following equation:

$$A^n = \sum_{i=1} A^n_{ei} \tag{2}$$

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where A^n = energy consumed by all appliances for year n and A_{ei}^n = energy used by an appliance i for year n.

Fossil Fuel Energy Consumption

The overall energy generated from fossil fuels was obtained by multiplying the total mass or volume of fuel consumed per day, m_f, and their corresponding heating values, C_f.

$$E_F = C_f m_f \quad (3)$$

Energy and Exergy Efficiency Analysis

Appliance energy-exergy efficiency was evaluated based on the methodology described by Utlu and Hepbasli (2003), Dincer et al. (2004a) and Saidur et al. (2007). For mechanical and electrical energy, the exergy content is equal to the energy content, as reported by Dincer and Rosen (2007) and Saidur et al. (2007). Exergy efficiencies for the fuels were written as a function of their corresponding energy efficiencies by assuming the energy grade function to be unity for this study, in accordance with Ertesvag and Mielnik (2000), Ertesvag (2005), Dincer and Rosen (2007) and Saidur et al. (2007). The operating data used for evaluation of appliance energy and exergy efficiency are presented in Table 1.

Energy efficiencies, in addition to process and reference-environmental temperatures, were assumed to be the same as those used by Reistad (1975) and Rosen (1992). However, the exergy efficiency of cooking appliance was calculated using the following known values: energy efficiency $\eta_f = 65\%$, reference temperature $T_0 = 300°K$, and product temperature = 393°K.

Energy efficiency, η, is defined as the following:

$$\eta = \text{energy in products/total energy input} \quad (4)$$

Exergy efficiency, ψ, is defined as the following:

$$\psi = \text{exergy in products/total exergy input} \quad (5)$$

Table 1. Energy and Exergy Efficiency, Product and Reference Temperatures of Different Types of Appliances

Appliance	η_e (%)	T_p (K)	T_o (K)	ψ_e (%)
Fluorescent light	20			18.5
TV	80			80
Fan	80			80
Iron	98	432	300	30
Refrigerator-freezer	60	265	300	7
Electric cooker	80	382	300	17.2
Washing machine	80			80
Bulb	25			25
Hi-fi	70			70
Blender/mixer	80			80
Vacuum cleaner	70			70
Toaster	98	432	300	30
Electric kettle	90	341	300	10.8
Hand phone charger	70			70
Hair dryer	70			70
Air conditioner	60	287	300	4.09
Personal computer	70			70
Microwave oven	70			70
Water heater	90	323	300	2.54
Electric stove	98	324	300	7.3
Electric gate	80			80
Electric water filter	70			70
VCD/VCR/DVD player	70			70
Cooking appliances (LPG)	65	393	300	14.88

Source: Utlu and Hepbasli (2003) and Saidur et al. (2007).

The energy efficiency for electrical heating, $\eta_{h,e}$, is defined in terms of the reference temperature, T_o, product temperature, T_p, product heat, Q_p, and electrical energy, W_e, as given in the following (Dincer and Rosen 2007):

$$\eta_{h,e} = [1 - (T_o/T_p)]Q_p/W_e \quad (6)$$

The exergy efficiency for electrical heating, $\psi_{h,e}$, is calculated from the following:

$$\psi_{h,e} = [1 - (T_o/T_p)]\eta_{h,e} \quad (7)$$

The energy efficiency for fuel heating, $\eta_{h,f}$, is determined from the following expression:

$$\eta_{h,f} = Q_p/m_f C_f \quad (8)$$

The exergy efficiency for fuel heating, $\psi_{h,f}$, is defined as the following:

$$\psi_{h,f} = [1 - (T_o/T_p)]\eta_{h,e} \quad (9)$$

The weighted mean overall energy and exergy efficiency were determined by applying the three steps discussed next.

Step 1

The overall weighted mean for electrical energy efficiency was evaluated by using the weighing factor, which is the ratio of electrical energy input to the total electrical energy input, to all appliances, as provided in the following expression (Saidur et al. 2007):

$$M_{\eta e} = \frac{\sum e_{app(i)}\eta_{app(i)}}{\sum e_{app(i)}} \quad (10)$$

where M_{η_e} = weighted mean electrical energy efficiency; $e_{app(i)}$ = appliance energy consumption; and $\eta_{app(i)}$ = appliance energy efficiency. Similarly, the weighted mean for the electrical exergy efficiency is defined as the following:

$$M_{\psi e} = \frac{\sum e_{app(i)}\psi_{app(i)}}{\sum e_{app(i)}} \quad (11)$$

where $M_{\psi e}$ = weighted mean electrical exergy efficiency and $\psi_{app(i)}$ = appliance exergy efficiency.

Step 2

The overall weighted mean for fossil fuel energy efficiency was evaluated with the following definition of the weighted mean for electrical energy efficiency:

$$M_{\eta f} = \frac{\sum C_{app(i)}\eta_{app(i)}}{\sum C_{app(i)}} \quad (12)$$

where M_{η_f} = weighted mean fossil fuel energy efficiency; $C_{app(i)}$ = cooking appliance energy consumption; and $\eta_{app(i)}$ = appliance energy efficiency. The weighted mean for fossil fuel exergy efficiency is defined similarly as the following:

$$M_{\psi f} = \frac{\sum C_{app(i)}\psi_{app(i)}}{\sum C_{app(i)}} \quad (13)$$

where M_{ψ_f} = weighted mean fossil fuel exergy efficiency and $\psi_{app(i)}$ = appliance exergy efficiency.

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Step 3

The overall weighted means of energy and exergy efficiencies for electrical and fossil fuel processes were subsequently evaluated. The weighting factor is defined as the ratio of either the total electrical or fossil fuel energy input to the total energy input. The weighting factor for electrical energy was thus determined using the following expression:

$$Wm_e = \frac{\sum E}{\sum E + \sum F} \quad (14)$$

where Wm_e = overall weighting factor for electrical energy; $\sum E$ = overall electrical energy consumption; and $\sum F$ = overall fossil fuel energy consumption. The weighting factor for fossil fuel was similarly evaluated using the following expression:

$$Wm_f = \frac{\sum F}{\sum F + \sum E} \quad (15)$$

where Wm_f = overall weighting factor for electrical energy. The overall weighted energy efficiency is thus given as the following:

$$O_{\eta e} = (M_{\eta e} \times Wm_e) + (M_{\eta f} \times Wm_f) \quad (16)$$

where O_{η_e} = overall energy efficiency. The overall weighted exergy efficiency is given similarly by the following:

$$O_{\psi e} = (M_{\psi e} \times Wm_e) + (M_{\psi f} \times Wm_f) \quad (17)$$

where O_{ψ_e} = overall exergy efficiency.

Results and Discussion

Energy and Exergy Utilization

The sources of energy used in the households were identified as electrical and fossil fuel. The electrical energy used over the period of three months (January—March, 2009) is summarized in Table 2. The fossil fuels used were liquified petroleum gas (LPG) and kerosene, with respective heating values of 57,431 and 46,117 kJ/kg and respective utilization efficiencies of 65 and 37%. The energy and exergy used by the appliances were evaluated and appliances susceptible to losses were identified.

Figs. 1 and 2 illustrate the energy and exergy flow pattern with respect to energy and exergy inputs, in addition to products and losses, for the month of January 2009. Electrical energy is primarily used for purposes such as space cooling, recreation, cleaning, grinding, and so on, whereas fossil fuels are commonly used for cooking purposes. For every month considered (January, February and March), electrical energy consumed accounted for 59.0, 56.5, and 59.0% of total household energy consumption, respectively, whereas that of fossil fuels was estimated to be 41, 43.5, and 41%, respectively.

The weighted mean for electrical energy and exergy were obtained by using Eqs. (10) and (11), respectively. The calculated values for both energy and exergy efficiencies were the same for each month, with respective values of 60.49 and 29.74%. Similarly, Eqs. (12) and (13) were used to evaluate the weighted mean for fossil fuel energy and exergy. The calculated values for both energy and exergy efficiencies were the same for each month, with respective values of 65.00 and 14.88%. The overall weighted means were obtained for energy and exergy efficiencies, for electrical and fossil fuel processes, in which the weighing factors are the ratio of energy input into an appliance to the total energy input into all appliances. The overall weighted mean exergy efficiency for the three months was lower: 21% for every month than the corresponding energy efficiencies of 62, 63, and 62% for January, February and March, respectively. The disparity observed between the energy and exergy efficiencies is approximately 41.5% on average for the three months investigated in this study.

The results obtained in this study follow similar trends as other studies reported in the literature. By comparison, exergy efficiencies for the residential sector were reported to be approximately 14% for the U.S. in 1970, 3% for Japan in 1985, 15% for Canada in 1986, 2% for Italy in 1990, 9% for Saudi Arabia in 1990–2001, 13% for Sweden in 1994, 12% for Norway in 1995, 23% for Brazil in 2001, and 22% for Turkey in 2004–2005 (Reistad 1975; Rosen 1992; Wall et al. 1994; Dincer et al. 2004a; Wall 1990; Ertesvag and Mielnik 2000; Ozdogan and Arikol 1995).

Table 2. Energy Pattern Consumption for the Month of January

Appliance	Ownership level	Duration (h)	Average power (W)	Energy consumed (MJ)	Energy products (MJ)	Exergy products (MJ)	Energy loss (MJ)	Exergy loss (MJ)
Florescent light	300	240.87	40	10.41	2.08	1.93	8.32	8.48
TV	188	188.48	80	10.21	8.16	8.16	2.04	2.04
Fan	189	277.76	130	24.57	19.65	19.65	4.91	4.91
Iron	103	37.2	1,200	16.55	16.22	4.97	0.33	11.59
Refrigerator-freezer	195	558	196	76.78	46.07	5.37	30.71	71.40
Electric cooker	78	31	1,000	8.70	6.96	1.50	1.74	7.21
Washing machine	42	49.29	450	3.35	2.68	2.68	0.67	0.67
Bulb	871	264.43	60	49.75	12.44	12.44	37.31	37.31
Hi-fi	89	251.41	25	2.01	1.41	1.41	0.60	0.60
Blender	51	125.24	350	8.05	6.44	6.44	1.61	1.61
Vaccum cleaner	26	77.19	1,200	8.57	6.07	6.07	2.60	2.60
Toaster	75	10.23	700	1.93	1.89	0.58	0.04	1.35
Electric kettle	89	17.05	1,750	9.56	8.60	1.03	0.96	8.53
Hand phone charger	331	68.82	45	3.69	2.58	2.58	1.11	1.11
Hair dryer	14	3.41	1,100	0.19	0.13	0.13	0.06	0.06
Air conditioner	69	193.13	1,500	71.96	43.18	2.94	28.78	69.02
Personal computer	68	72.23	65	1.15	0.80	0.80	0.34	0.34
Microwave oven	12	12.71	700	0.38	0.27	0.27	0.12	0.12
Water heater	33	13.33	1,000	1.58	1.43	0.04	0.16	1.54
Electric filter	11	6.82	100	0.03	0.02	0.02	0.01	0.10
VCD/VCR/DVD player	95	168.64	25	1.44	1.01	1.01	0.43	5.09

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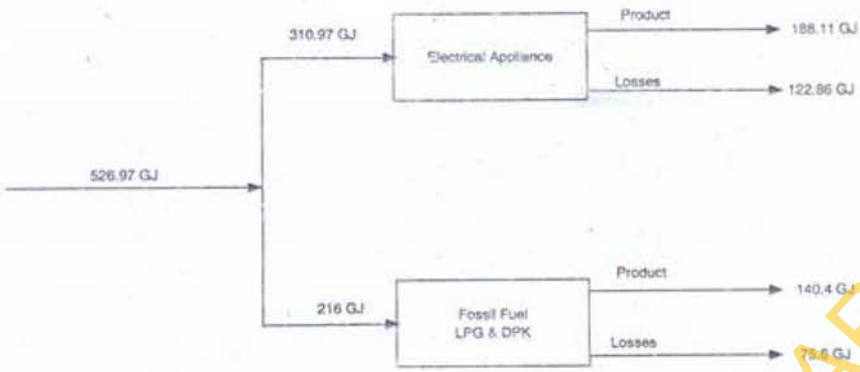

Fig. 1. Energy flow diagram for the month of January

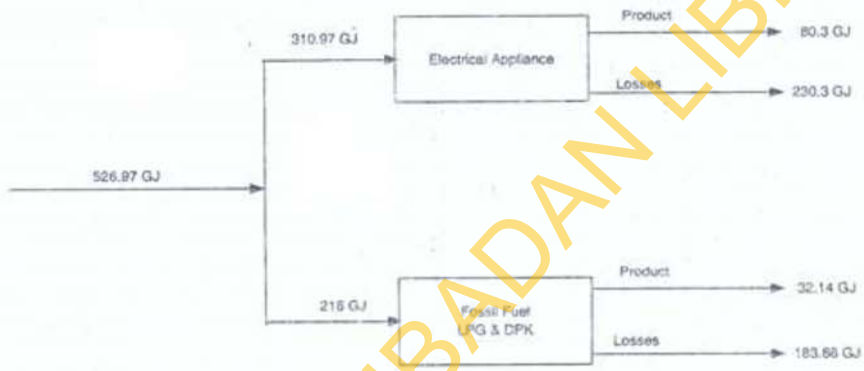

Fig. 2. Exergy flow diagram for the month of January

Energy and Exergy Losses

The energy and exergy losses for each of the appliances for the month of January are shown in Figs. 1 and 2. The high disparity observed between energy and exergy losses underscores the inadequacy of the first law concept for energy analysis. The electrical and fossil energy losses for the month of January were 122.86 and 75.60 GJ, respectively, whereas losses from the exergy standpoint were 230.00 and 183.86 GJ, respectively. The refrigerator-freezer was the major exergy-consuming household appliance, accounting for approximately 32% of total exergy loss. The refrigerator-freezer is usually a continuous working device, and its poor performances can be traced to energy degradation for the transformation of energy from electrical to thermal energy. The air conditioner was the second major exergy consuming device, accounting for 30% of total exergy loss. The compressor of the air conditioner consumes a large amount of electrical power, which contributes to its large exergy loss. Furthermore, bulb lighting (incandescent), iron, and fluorescent light accounted for 16.2, 5.0, and 3.7%, respectively, of total exergy loss. All other appliances accounted for less than 2.0%. The results show that there were large differences between the energy and exergy inputs, in addition to energy and exergy of products, indicating inefficiencies in the appliances. These losses also revealed that there is potential for improvement in the systems.

There are various approaches that could enhance efficient use of energy in homes. For example, public enlightenment to change consumers' behavior and usage pattern, in addition to proper insulation of homes, can result in reduced cooling load in buildings to achieve and maintain a comfortable temperature. Furthermore, energy-efficient technological appliances—such as those using a compact fluorescent lamp (CFL) bulb—require less energy and also reduce exergy loss attributable to lower heat generation, relative to traditional incandescent light bulbs for the same level of illumination. The major source of exergy loss in incandescent lamps is from the additional cooling load imposed on the space, as it converts electrical energy into heat much more than a CFL bulb. Installation of these energy-efficient appliances is cost-effective, despite their higher initial cost, with payback periods as low as a few months. Furthermore, implementation of energy policies which support provision of funds, low-interest loans, subsidies, and so on would promote the use of such appliances and discourage influx of less efficient appliances into the country. Policymakers should consider such energy proposals. This is important because no matter what goals are set for energy utilization within a region, such goals must be ranked alongside technological, economic, social and environmental requirements to attain sustainable development.

Conclusions

Analyses of energy and exergy utilization in the residential sector—consisting of 125 households in Ibadan, Nigeria, based on actual data collected for a period of three months—have been presented. The study provides a clearer insight and quantitative grasp of inefficiencies in addition to the relative magnitudes of energy utilization performance of household appliances. The primary conclusions derived from the present study may be summarized as follows:

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- The analysis clarified that there were large disparities between the energy and exergy efficiencies of each appliance studied. This was primarily because of low exergy efficient appliances used in each household. It also showed the unreliability of energy analysis, which is based on the first law of thermodynamics, in identifying the true magnitude and direction of losses. The disparities in energy and exergy utilized indicated the availability of energy losses and also revealed possible improvement in the systems.
- The overall weighted mean energy efficiencies for each month were 62, 63 and 62%, respectively, whereas overall exergy efficiencies for the months of January, February and March remained at the same value of 21%. Variations in energy and exergy efficiencies clearly indicate that a conscious and planned effort is needed to improve exergy utilization in the household.
- Electrical energy was primarily used for purposes such as space cooling, recreation, cleaning, grinding, and so on, and fossil fuel was commonly used for cooking purposes. Among the appliances studied, refrigerator-freezers and air conditioners exhibited the highest exergy loss of 32 and 30% of total losses, respectively, whereas electric water filters exhibited the lowest exergy loss of 0.004%. The disparities in the energy losses can be traced to inefficiencies of the appliances used.
- Improvements in energy efficiency of household appliances can be achieved by adopting more efficient technologies and public enlightenment that could change consumers' behavior and usage patterns. Furthermore, implementation of energy policies must be reaffirmed. This is because no matter what goals are set for energy use within a region, they must be ranked alongside technological, economic, social and environmental requirements to attain sustainable development.

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