Application of energy and exergy analyses for efficient energy utilisation in the Nigerian residential sector

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Abstract: This paper presents energy and exergy analyses as a useful concept in analysing true efficient energy utilisation of the Nigerian residential sector by considering energy and exergy flows in this sector for a period of 15 years from 1991 to 2005. The energy and exergy flows considered include the commercial and the 'non-commercial' energy sources. The most efficiently utilised energy source appears to be the Liquefied Petroleum Gas and the least efficient, kerosene. Electricity utilisation exergy efficiency has been adversely affected by the vapour-compression air-conditioning application apart from low potential thermal energy applications. The overall utilisation energy and exergy efficiencies have been found to be 19.89% and 4.38%, respectively.

Keywords: efficiency; energy and exergy analyses; energy utilisation; residential sector; Nigeria.

Reference to this paper should be made as follows: Badmus, I. and Osunleke, A.S. (2010) 'Application of energy and exergy analyses for efficient energy utilisation in the Nigerian residential sector', *Int. J. Exergy*, Vol. 7, No. 3, pp.352–368.

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1 Introduction

Nigeria is the most populous African country, with a 2006 population estimate of approximately 140 million (NPC, 2007). Although the electric power supply has been quite erratic, in recent times, the domestic sector has accounted for over 50% of the grid electricity consumed in the country while the commercial and industrial sectors have accounted for about 25% each (ECN, 2003). As a matter of fact, the share of the residential sector rose from 37.1% in 1970 to 63.8% in 2005 (NNBS, 2006). In any energy accounting of an African country, especially in the residential sector, one cannot leave out the non-commercial energy sources. The proportion of the population depending on biomass is higher in sub-Saharan Africa than in Asia, extreme poverty and the lack of access to other fuels mean that 80% of the overall African population relies primarily on biomass to meet its residential needs (BP, 2002). In particular, from a survey conducted by Sambo et al. (2006), about 87.5% of households use fossil fuels for lighting in Nigeria.

On the other hand, exergy is the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment (Sciubba and Wall, 2007). It is a useful concept, since it is a link between the physical and engineering world and the surrounding environment, and expresses the true efficiency of engineering systems. This makes it a useful concept in finding improvements. Therefore, it is used in the design of engineering systems as well as in sectoral energy and exergy utilisation (Dincer, 2002).

The scarcity and undesirable side effects of careless utilisation of energy resources on economics and ecology require careful analysis and planning for proper energy consumption. In this regard, exergy analysis appears to be a significant tool in

i addressing the impact of energy-resource utilisation on the environment

ii furthering the goal of more efficient energy-resource utilisation

iii enabling locations, types and true magnitudes of wastes and losses to be determined

iv revealing whether or not, and how much, it is possible to design more efficient energy systems by reducing the inefficiencies in the existing systems v providing a sustainable development as a result of sustainable supply of energy resources

vi distinguishing the high-quality and low-quality energy resources (Dincer et al., 2004a).

In other to thoroughly understand the thermodynamic concepts of energy, an exergetic process optimisation – an optimisation based on exergy analysis – has to be carried out. The exergetic optimisation is based on the concept of optimisation techniques as well as sustainable energy utilisation. Hitherto, the energy utilisation of several systems has been studied using exergy analysis in order to achieve savings, after its pioneering application by Reistad (1975). Thereafter, many authors (Hammond, 2004; Bardouille and Koubsky, 2000; Rosen et al., 2008; Dincer, 2002; Rosen and Dincer, 2001; Gong and Wall, 2001) have written on various topics that are related to exergy analysis ranging from efficiency to sustainable development. A good review work on exergy is in Sciubba and Wall (2007).

Before the advent and popularisation of exergy analysis, the efficiencies of systems and processes were based on 1st law analyses alone. The inadequacy of this approach (Fagbenle, 2002) has led to discarding it and opting for a 2nd law (or exergetic) analysis which looks more realistic. However, despite this popularisation, there has not been a good application of exergy analysis in energy researches in Nigeria. Besides, a sectoral exergy analysis for efficient energy utilisation of Nigeria in this manner has not been found in the open literature. It is hoped that the Nigerian government, in its commitment to solving the energy crisis once-and-for-all, will find this study useful.

2 Analysis and methodology

Energy and exergy analyses would reveal the efficiency of energy utilisation in a particular part of the process considered and also allow comparison of efficiencies and process parameters with currently achievable values.

2.1 The basic parameters for exergy analysis

This section discusses some basic quantities necessary for the thermodynamic analyses relevant to this section. The forms of exergy for the analysis, like what is known in case of energy, can be expressed as enthalpy, internal exergy, chemical exergy, work, heat, electricity, etc.

2.1.1 Chemical exergy

One of the most common energy carriers is hydrocarbon/fossil/biomass fuels. The specific exergy of this class of thermodynamic systems, the chemical exergy, can be written as

$$\varepsilon_{ff} = \gamma_{ff} H_{ff} \tag{1}$$

where γ_{ff} is the ratio of fuel chemical exergy to the Higher Heating Value, H_{ff} of the fuel. Usually, the specific chemical exergy of a fuel at T_o and P_o as defined in this paper is approximately equal to the Higher Heating Value, H_{ff}. This is because the heating value of a carbon-based fuel is commonly used to describe its work value, exergy (Hermann, 2005). In practice, this is extended to all fuels (Valero, 2006; Baloh, 1982) quoted in Schmidt (2003).

One of the relevant fuels in this study, kerosene, for instance, has a higher heating value of 46117 kJ/kg and a γ_{ff} of 0.99, giving a chemical exergy of 45897 kJ/kg (Rosen and Dincer, 1997). Table 1 shows the exergy factors (energy/exergy) for different energy carriers.

Table 1 Energy carriers and their exergy factors

Energy carriers	*Exergy factors*
Electrical energy	1.0
Oil, petroleum products	0.94
Coal	0.94
Coke	0.95
Fuel-wood (20% humidity)	0.90
Gaseous hydrocarbons	0.96–0.98
Liquid hydrocarbons	~1.0
Wooden pellets	0.8
Mechanical energy	1.0

Sources: Ertesvag (2005), Ertesvag and Mielnik (2000), Johannesson (2001) quoted in Schmidt (2003), Baloh (1982) and Wall et al. (1994)

It is apparent from the foregoing that the heating values of fuels are very important in determining their chemical exergies. Based on this, the fuels in Table 2 and their heating values have been used in this study.

Table 2 Fuels and their heating values

Fuel	*Heating value* (kJ/kg)
LPG	57,431
Kerosene	46,117
Fuel-wood	13,571
Other biomass*	15,070
Charcoal	25,250

*As estimated from Jekayinfa and Scholz (2007).

Sources: Sambo et al. (2006) and Fuwape (2004)

Based on the explanation at the beginning of this section, the energy grade function, γ_{ff}, is assumed to be unity for this study.

2.1.2 The reference environment (dead state)

Exergy is usually evaluated with respect to a reference environment. This makes it vary with varying sinks. For instance, the exergy content of a fuel is lower in the tropical region than in temperate regions. The reference environment is in equilibrium, acts as an infinite system, a sink or source for materials and thermal energy, and experiences only internally reversible processes in which its intensive properties remain constant.

Based on the climatic conditions in Nigeria, a tropical Sub-Saharan West African country, which lies between latitudes 4°N and 13°9’ North of the Equator and longitudes 2°2’ and 14°30’ East, with modifications of the Gaggioli and Petit’s model (Gaggioli and Petit, 1977), which is recommended by Dincer et al. (2004c), this analysis uses T_o = 25°C as the surrounding temperature, P_o = 1 bar as the surrounding pressure as the chemical composition is taken to be air saturated with water vapour, and the following condensed phases are used at 27°C and 1 bar: water (H_2O), gypsum ($CaSO_4 \cdot 2H_2O$) and limestone ($CaCO_3$) (Dincer et al., 2004b).

2.1.3 Energy and exergy efficiencies for principal types of processes

The expressions for energy efficiency (η) and exergy efficiency (ψ) for the main types of processes in this paper are as follows:

$$\eta = \frac{\text{Energy in products}}{\text{Total energy input}} \tag{2}$$

$$\psi = \frac{\text{Exergy in products}}{\text{Total exergy input}}. \tag{3}$$

2.1.3.1 Heating and cooling

Electrical and fossil fuel heating processes are considered to generate product heat, Q_p, at a temperature, T_p, either from electrical energy, W_e, or fuel mass, m_f, relative to an ambient temperature, T_o. The energy and exergy efficiencies for electrical heating are (Dincer et al., 2004a):

$$\eta_{h,e} = \frac{Q_p}{W_e} \tag{4}$$

and

$$\psi_{h,e} = \frac{E^{Q_p}}{E^{W_e}} = \frac{\left(1 - \frac{T_o}{T_p}\right) Q_p}{W_e}. \tag{5}$$

This gives:

$$\psi_{h,e} = \left(1 - \frac{T_o}{T_p}\right) \eta_{h,e} \tag{6}$$

For fuel-heating, whether fossil or biomass,

$$\eta_{h,f} = \frac{Q_p}{m_f H_f} \tag{7}$$

$$\psi_{h,f} = \frac{E^{Q_p}}{m_f \gamma_f H_f}. \tag{8}$$

But $\eta_{ff} \approx 1$. Hence, equation (8) becomes

$$\psi_{h,f} = \left(1 - \frac{T_o}{T_p}\right) \eta_{h,f}. \tag{9}$$

Double subscripts indicate the processes in which the quantity represented by the first subscript is produced by the quantity represented by the second one. For instance, the double subscript '*h*, *e*' means heating with electricity.

2.1.4 Work production

Electric and fossil-fuel work production processes produce shaft work, *W*. The efficiencies for shaft work production from electricity are given by

$$\eta_{m,e} = \frac{W}{W_e} \tag{10}$$

$$\psi_{m,e} = \frac{E^W}{E^E} = \frac{W}{W_e} = \eta_{m,e}. \tag{11}$$

2.2 Data sources

In this section, the methods used to estimate or obtain all the energy and exergy consumptions are described. Data for national energy consumptions have been obtained from UN Statistics Division (2008) Common Database on Nigeria and NBS (2005). The data is of three categories; electricity, biomass and fossil fuels.

2.2.1 Electricity

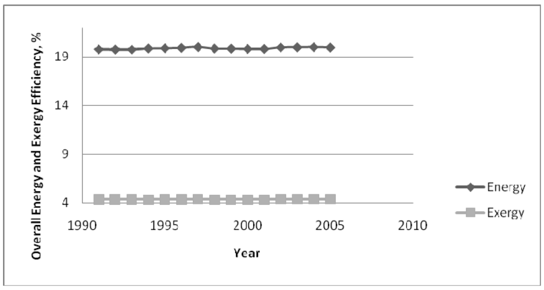
For the various appliances, the following parameters in Table 3 have been used.

Table 3 Energy efficiency, exergy efficiency, product and reference temperatures of different types of electrical appliances

Appliance	η (%)	T_p (K)	T_o (K)	ψ (%)
Fluorescent light	22.5	–	–	17.5
Incandescent bulb	5	–	–	4.5
Air conditioner	55.1	287	308	4.03
Water heater	90	333	300	8.9
Cooking (electric stove)	80	393	300	18.93
Household appliances	11.1	–	–	11.1

Sources: Cremer et al. (2003) quoted in Pachauri and Spreng (2003), Boelman and Asada (2003), Utlu and Hepbasli (2003) http://www.energieinfo.de/eglossar/node204.html quoted in Pachauri and Spreng (2003), Rosen and Dincer (1997) and Dincer et al. (2004c)

Figure 1 Mean energy and exergy utilisation efficiencies from 1991 to 2005



2.2.2 Fossil and bio-fuels

These include LPG, kerosene, coal, wood as well as other biomass and wastes.

For cooking, parameters in Table 4 have been used.

Table 4 Cooking energy and exergy efficiencies of some fossil and biomass fuels

Energy source	η (%)	T_p (K)	T_o (K)	ψ (%)
LPG	61	393	300	14.44
Kerosene	37	393	300	8.76
Coal	26.45*	393	300	6.26
Wood	20*	393	300	4.73
Other biomass and wastes	18.6*	393	300	4.40

*Estimation from Utlu and Hepbasli (2003).

Sources: Siyanbola et al. (2004) and Pachauri and Spreng (2003)

For water heating, Table 5 parameters were used:

Table 5 Water heating energy and exergy efficiencies of some fuels

Energy source	η (%)	T_p (K)	T_o (K)	ψ (%)
LPG	73	333	300	7.23
Kerosene stove	46	333	300	4.56
Wood	25	333	300	2.48

Source: Anozie et al. (2007)

2.2.3 Lighting

It is assumed that 95% of electric lighting uses incandescent bulbs and 5% uses fluorescent tubes. The lighting efficiency of a kerosene lamp is 0.05% (Plas and de Graaf, 1988). This makes its exergetic efficiency 0.045%, using the incandescent lamp analogy.

2.3 Energy consumption pattern

According to a survey carried out by Sambo et al. (2006), the data in Table 6 can be deduced:

Table 6 Nigeria energy consumption pattern

Energy type	*Energy end use*	*Percentage consumption*
Electricity	Cooking	23.47
	Water heating	14.62
	Lighting	32.21
	Air-conditioning	12.81
	Household appliances	16.89
	Total	100
Kerosene	Cooking	36.41
	Water heating	8.23
	Lighting	55.36
	Total	100
LPG	Cooking	86.39
	Water heating	13.61
	Total	100
Fuel-wood	Cooking	74.31
	Water heating	25.69
	Total	100
Charcoal	Cooking	100
Other biomass and wastes	Cooking	100

3 Results and discussions

The overall energy used can be broken down into three major sources: electrical, fossil fuels and bio-fuels. The energy use over the period 1991–2005 is summarised in Table 7. For each year, the mean energy and exergy efficiencies are calculated for each source of residential energy consumption, using the conversion efficiencies of the sub-sectors (air-conditioning, cooking, water heating and household appliances). Weighted mean energy and exergy efficiencies are then calculated using a seven-step procedure as outlined in Dincer et al. (2004d) with some subtle modifications. The result is shown in Figure 1.

Table 7 Summary of residential energy consumption pattern over the period 1991–2005 in PetaJoules

Year	*Area of application*	*Electricity*	*LPG*	*Kerosene*	*Wood*	*Charcoal*	*Other Biomass*
1991	A/C	2.287482	–	–	–	–	–
	Lighting	5.75174	–	33.49312	–	–	–
	Cooking	4.1910379	2.761601	22.02826	463.3006	17.86816	1234
	Heating	2.6106934	0.435066	4.979197	160.1694	–	–
	Appliances	3.016047	–	–	–	–	–
	Total	*17.857*	*3.196667*	*60.50057*	*623.47*	*17.86816*	*1234*

Table 7 Summary of residential energy consumption pattern over the period 1991–2005 in PetaJoules (continued)

Year	*Area of application*	*Electricity*	*LPG*	*Kerosene*	*Wood*	*Charcoal*	*Other Biomass*
1992	A/C	2.620926	–	–	–	–	–
	Lighting	6.590166	–	41.15687	–	–	–
	Cooking	4.801962	2.426503	27.06867	475.5023	18.33756	1277
	Heating	2.991252	0.382275	6.118516	164.3877	–	–
	Appliances	3.455694	–	–	–	–	–
	Total	*20.46*	*2.808778*	*74.34406*	*639.89*	*18.33756*	*1277*
1993	A/C	2.656666	–	–	–	–	–
	Lighting	6.680032	–	36.45186	–	–	–
	Cooking	4.8674433	1.799126	23.97421	487.8674	18.80696	1311
	Heating	3.0320418	0.283437	5.419053	168.6626	–	–
	Appliances	3.502817	–	–	–	–	–
	Total	*20.739*	*2.082563*	*65.84511*	*656.53*	*18.80696*	*1311*
1994	A/C	2.898647	–	–	–	–	–
	Lighting	7.288479	–	28.87631	–	–	–
	Cooking	5.3107916	1.022558	18.9918	624.8133	19.089	1361
	Heating	3.3082136	0.161095	4.292847	216.0067	–	–
	Appliances	3.821869	–	–	–	–	–
	Total	*22.628*	*1.183653*	*52.16096*	*840.82*	*19.089*	*1361*
1995	A/C	3.143318	–	–	–	–	–
	Lighting	7.90369	–	17.53219	–	–	–
	Cooking	5.7590686	0.565101	11.53084	641.8972	19.66975	1400
	Heating	3.5874556	0.089027	2.606393	221.9128	–	–
	Appliances	4.144468	–	–	–	–	–
	Total	*24.538*	*0.654128*	*31.66942*	*863.81*	*19.66975*	*1400*
1996	A/C	3.289224	–	–	–	–	–
	Lighting	8.270562	–	23.39108	–	–	–
	Cooking	6.0263919	2.642749	15.3842	661.7974	20.27575	1443.4
	Heating	3.7539774	0.416342	3.477395	228.7926	–	–
	Appliances	4.336845	–	–	–	–	–
	Total	*25.677*	*3.059091*	*42.25268*	*890.59*	*20.27575*	*1443.4*
1997	A/C	3.471894	–	–	–	–	–
	Lighting	8.729876	–	37.10058	–	–	–
	Cooking	6.3610741	7.811974	24.40087	682.307	20.907	1488.145
	Heating	3.9624586	1.230709	5.515495	235.883	–	–
	Appliances	4.577697	–	–	–	–	–
	Total	*27.103*	*9.042683*	*67.01695*	*918.19*	*20.907*	*1488.145*

Table 7 Summary of residential energy consumption pattern over the period 1991–2005 in PetaJoules (continued)

Year	*Area of application*	*Electricity*	*LPG*	*Kerosene*	*Wood*	*Charcoal*	*Other Biomass*
1998	A/C	2.874948	–	–	–	–	–
	Lighting	7.22889	–	28.18709	–	–	–
	Cooking	5.2673721	1.836883	18.53851	700.5129	21.4625	1527.849
	Heating	3.2811666	0.289385	4.190385	242.1771	–	–
	Appliances	3.790623	–	–	–	–	–
	Total	*22.443*	*2.126268*	*50.91598*	*942.69*	*21.4625*	*1527.849*
1999	A/C	2.929135	–	–	–	–	–
	Lighting	7.365139	–	37.26066	–	–	–
	Cooking	5.3666502	2.14886	24.50615	700.5798	21.4625	1528.002
	Heating	3.3430092	0.338534	5.539292	242.2002	–	–
	Appliances	3.862067	–	–	–	–	–
	Total	*22.866*	*2.487394*	*67.3061*	*942.78*	*21.4625*	*1528.002*
2000	A/C	2.971151	–	–	–	–	–
	Lighting	7.470787	–	38.50146	–	–	–
	Cooking	5.4436318	0.685079	25.32222	717.3962	21.9675	1564.674
	Heating	3.3909628	0.107928	5.723754	248.0138	–	–
	Appliances	3.917467	–	–	–	–	–
	Total	*23.194*	*0.793007*	*69.54743*	*965.41*	*21.9675*	*1564.674*
2001	A/C	3.121669	–	–	–	–	–
	Lighting	7.849255	–	44.53595	–	–	–
	Cooking	5.7194043	0.685297	29.29107	733.9004	22.4725	1600.662
	Heating	3.5627478	0.107963	6.62086	253.7196	–	–
	Appliances	4.115924	–	–	–	–	–
	Total	*24.369*	*0.79326*	*80.44788*	*987.62*	*22.4725*	*1600.662*
2002	A/C	5.283356	–	–	–	–	–
	Lighting	13.28469	–	40.02812	–	–	–
	Cooking	9.6799668	1.146396	26.3263	751.8686	23.028	1639.851
	Heating	6.0298728	0.180605	5.950713	259.9314	–	–
	Appliances	6.966112	–	–	–	–	–
	Total	*41.244*	*1.327001*	*72.30514*	*1011.8*	*23.028*	*1639.851*
2003	A/C	5.305005	–	–	–	–	–
	Lighting	13.33913	–	28.69448	–	–	–
	Cooking	9.7196311	1.073264	18.87222	770.3272	23.5835	1680.124
	Heating	6.0545806	0.169083	4.265816	266.3128	–	–
	Appliances	6.994656	–	–	–	–	–
	Total	*41.413*	*1.242347*	*51.83251*	*1036.64*	*23.5835*	*1680.124*

Table 7 Summary of residential energy consumption pattern over the period 1991–2005 in PetaJoules (continued)

Year	*Area of application*	*Electricity*	*LPG*	*Kerosene*	*Wood*	*Charcoal*	*Other Biomass*
2004	A/C	5.368543	–	–	–	–	–
	Lighting	13.49889	–	23.17384	–	–	–
	Cooking	9.8360423	1.409855	15.24132	787.2773	24.11375	1717.087
	Heating	6.1270958	0.22211	3.4451	272.1727	–	–
	Appliances	7.07843	–	–	–	–	–
	Total	*41.909*	*1.631965*	*41.86026*	*1059.45*	*24.11375*	*1717.087*
2005	A/C	5.435795	–	–	–	–	–
	Lighting	13.66799	–	35.45523	–	–	–
	Cooking	9.9592598	0.689495	23.31873	804.599	24.26778	1754.863
	Heating	6.2038508	0.108624	5.270891	278.161	–	–
	Appliances	7.167103	–	–	–	–	–
	Total	*42.434*	*0.798119*	*64.04485*	*1082.76*	*24.26778*	*1754.863*

Firstly, weighted mean efficiencies are obtained for the electrical energy and exergy efficiencies for the sub-sectoral devices listed in Table 3, where the weighting factor is the ratio of the electrical energy input to the device to the total electrical input to all the devices in a particular year.

Secondly, the same procedure is followed for fossil fuels, namely, LPG, kerosene and charcoal (3 steps).

Thirdly, the same procedure is followed for biomass fuels as fuel-wood, other biomass and wastes (2 steps).

That is,

$$\eta_i = \frac{\sum_{r=1}^{n} \eta_r E_{i,r}}{\sum_{r=1}^{n} E_{i,r}}. \tag{12}$$

Here,

η_i: Mean weighted efficiency for the energy source, 'i'

η_r: Sub-sectoral Device 'r' energy conversion efficiency

$E_{i,r}$: Energy input per year from the source 'i' to sub-sectoral device 'r'.

Lastly, the overall energy efficiency for the year is evaluated as

$$\frac{\sum_{i=1}^{n} \eta_i W_i}{\sum_{i=1}^{n} W_i} = \frac{\eta_e W_e + \eta_f W_f + \eta_b W_b}{W_e + W_f + W_b}. \tag{13}$$

Here, W_i = the total energy supplied per year to all the devices from all the sources.

The same procedure is used to evaluate exergy efficiency, ψ as shown in Table 8.

Table 8 Mean energy and exergy utilisation efficiencies of the residential sector in Nigeria (%)

Year	*Electricity*		*LPG*		*Kerosene*		*Wood*		*Charcoal*		*Other Bio-fuels*		*Overall*	
	X1	*X2*	*X1*	*X2*	*X1*	*X2*	*X1*	*X2*	*X1*	*X2*	*X1*	*X2*	*X1*	*X2*
1991	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.78	4.38
1992	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.77	4.38
1993	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.76	4.38
1994	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.88	4.36
1995	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.90	4.37
1996	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.94	4.38
1997	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	20.02	4.39
1998	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.87	4.36
1999	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.86	4.36
2000	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.83	4.35
2001	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.83	4.35
2002	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.98	4.39
2003	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.99	4.39
2004	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	20.01	4.40
2005	42.76	9.79	62.63	13.46	17.29	3.59	21.28	4.15	26.45	6.26	18.6	4.40	19.97	4.39

From the results above, the overall energy efficiency for the 15 years is 19.89, while the overall exergy efficiency is 4.38. These are quite low compared with most of the countries in Table 9. The energy efficiency is lower than any of those in the table, while the exergy efficiency is only higher than those of Italy and Japan.

Table 9 Overall energy and exergy efficiencies of the residential sectors of some countries

Country	*Year*	*Overall energy efficiency*	*Overall exergy efficiency*	*Information source*
Brazil	2001	35	23	Ertesvag (2001)
Canada	1986	50	15	Ertesvag (2001)
China	2005	–	10	Chen and Chen (2006)
Italy	1990	–	2	Ertesvag (2001)
Japan	1985	–	3	Ertesvag (2001)
Malaysia	1997–2004	69.44	28.49	Saidur et al. (2007)
Norway	2000	–	12	Ertesvag and Mielnik (2000)
Saudi Arabia	2004	76	9	Dincer et al. (2004d)
Sweden	1994	–	13	Ertesvag (2001)
Turkey	2004–2005	80.98	22.17	Utlu and Hepbasli (2005, 2006)
USA	1970	50	14	Ertesvag (2001)

4 Conclusions

The overall energy and exergy efficiencies of the residential sector in Nigeria for a period of 15 years (1991–2005) have been obtained using energy and exergy analyses techniques. Conclusions have been drawn at first based on specific energy sources utility and then overall for all the processes.

Liquefied petroleum gas

In this study, LPG is only used for cooking and water heating. It ranks the best utilised of the energy sources that were studied, with overall energy efficiency of 62.63% and overall exergy efficiency of 13.46%. While it may be difficult to exclude LPG from cooking energy sources, it is necessary to consider solar heating application for water heating, for the fact that Nigeria is a tropical country with long sunshine hours and relatively high clearness indices. This will boost the exergy efficiency under this section and also make the fossil fuel more available for local consumers as well as for other applications, since little of it will now be used for water heating.

Electricity

This energy source has been found to be the most widely used one in Nigeria during the period under study. This is despite the electrical power supply crisis in the country. It has been applied in air-conditioning, lighting, cooking, water heating and in powering other household appliances like the television. Its overall energy and exergy efficiencies are 42.76% and 9.79% respectively, ranking second best utilised energy source after LPG. Its dismally poor exergy performance has been largely due to its application in vapour compression refrigerated air-conditioning, lighting with incandescent bulbs, cooking and water heating. These can be replaced with vapour absorption air-conditioning, lighting with fluorescent lamps, cooking with LPG and solar heating, for improved performances. Besides, fairly used electrical appliances importation to the country should be discouraged as these are usually of poor energy utilisation efficiencies.

Charcoal

In this study, charcoal has been found to be used for cooking only, ranking overall third best used energy source. However, when comparing cooking efficiencies only, it ranks fourth, with LPG and kerosene being better cooking fuels after electricity. This suggests kerosene for cooking in areas with low or no accessibility to LPG, while clean coal utilisation technology is popularised for power generation. Improved coal stoves design can also assist in improving the utilisation efficiency for cooking.

Other bio-fuels

Various local agricultural wastes, as studied by Jekayinfa and Scholz (2007) have been lumped together and their heating values estimated according to their relative proportions. Presently, they are used for cooking alone. Overall, it has the fourth best exergy efficiency and fifth (second to the last) best energy efficiency. When assessed among the fuels that are used for cooking in this study, it has the lowest cooking efficiencies. This is not surprising, since these wastes are often used in open fires or local tripods, where most of the heat obtained through combustion of the wastes is transferred away from where it is needed for cooking. Each of the agricultural wastes needs further processing before it can be more efficiently utilised as an energy source.

Fuel-wood

Fuel-wood has also been used for both cooking and water heating. It ranks fourth in overall energy efficiency and fifth in overall exergy efficiency. Using wood as fuel is environmentally threatening as it leads to deforestation. Considering cooking and water heating processes separately, its efficiencies are lower than the corresponding ones for kerosene. However, since it is just a bio-fuel, its CO_2 contribution may not be given as serious a consideration as that of fossil fuels. More importantly, wood exergy should be utilised elsewhere other than as fuels. While on its way to being phased out as a conventional cooking fuel, improved woodstoves are necessary to improve the cooking efficiencies.

Kerosene

Kerosene has the poorest overall energy and exergy efficiencies of the six energy sources in this study. It is used for cooking, water heating and, due to low access to electricity even in the urban areas, for lighting. While it ranks as the second best fossil fuel energy source for cooking and water heating after LPG, its performance in lighting is woeful. In fact, its ranking as the utilised energy source in this study has been due to its use for lighting. The efficiencies in cooking and water heating can be improved by using improved design kerosene stoves for cooking and also using solar thermal collectors for water heating. Lighting with kerosene lanterns should be highly discouraged.

Finally, both the best and the worst performing energy sources in this study are fossil fuels, namely, LPG and kerosene, respectively. These overall values are 19.89 and 4.38, respectively. The most efficiently utilised energy source is LPG, while the least efficiently used one is kerosene. A closer look reveals that the major factor responsible for the grossly poor utilisation efficiency of kerosene in the residential sector is its use for lighting purposes. Besides, the utilisation efficiencies of electricity could be improved by avoiding its use to provide low potential thermal energy for cooking and water heating. Being a tropical country, energy utilisation efficiency could also be improved by considering a replacement of vapour-compression air-conditioning with vapour-absorption systems.

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Nomenclature

m	Mass
Q	Heat
T	Temperature
H	Heating value
P	Pressure
E	Exergy
W	Energy
Greek symbols	
η	Energy efficiency (%)
ψ	Exergy efficiency (%)

γ	Exergy factor
ε	Chemical exergy
Superscripts	
Q_p	Product heat
W_c	Shaft work
Subscripts	
e	Electrical
f	Fuel
h	Heating
m	Mechanical
o	Ambient
p	Product
Abbreviations	
A/C	Air-conditioning
BP	British Petroleum
ECN	Energy Commission of Nigeria
LPG	Liquefied Petroleum Gas
NBS	National Bureau for Statistics
NPC	National Population Commission
UN	United Nations
*X*1	Energy analysis
*X*2	Exergy analysis