

**Energy, Exergy and Environmental Compatibility
Analyses of LPG and Household Kerosene
Utilisations as Domestic Fuels in Nigeria: 1980 – 2019**

ABSTRACT

Household kerosene and Liquefied Petroleum Gas form the bulk of domestic fuels, especially in Nigerian urban areas. Data on both fuels, from 1980 to 2019, were collected, mainly from Nigerian National Petroleum Corporation sources. Energy, exergy and environmental compatibility analyses were carried out on the utilisation of LPG for cooking, and household kerosene for both cooking and lighting. Kerosene lighting, with 0.05% energy efficiency and 0.045% exergy efficiency, was extremely poor. Cooking, with different mixes of both fuels, yielded energy efficiencies ranging from 35.04% to 44.54%. Corresponding exergy efficiencies were from 7.75% to 9.98%. Associated environmental compatibility factors were from 0.71749 to 0.73945. Overall process energy efficiencies, involving both cooking and lighting, were from 4.05% to 34.19%. Corresponding exergy efficiencies were from 0.93% to 7.61%. Overall environmental compatibility factors ranged from 0.71746 to 0.73259. Energy and exergy efficiencies, as well as environmental compatibility factors, increased directly with increase in LPG utilization in the fuel-mix.

Keywords: Energy, Exergy, Liquefied petroleum gas, Household Kerosene, Lower Heating Value, Environmental Compatibility.

1. INTRODUCTION

Energy is the ultimate measure of the advancement of a nation, as it plays the most vital role in the economic growth, progress and development, as well as poverty eradication and security of any society. A continuous and reliable supply of energy is essential for ensuring sustainable development [1]. Presently, demand for energy is increasing swiftly in all facets of the society. To meet this increasing demand, societies are leaning towards fossil fuels, since they are readily available. Human dwelling constitutes an important part of any society, and documented energy consumption patterns in the domestic sector confirm this [2]. Nigeria is bountifully blessed with energy resources. These include abundant traditional and modern energy resources which provide many households with biomass (mostly firewood, straw) and some other households with transition and modern energy sources (such as household kerosene [HHK], liquefied petroleum gas [LPG] and electricity) for cooking, lighting etc. However, energy generation from fossil fuels has some disadvantages. The

increasing use of fossil fuels has an adverse environmental health risk factor globally (such as acid rain, greenhouse gas emission, global warming among others) and accounts for about 4.3 million premature deaths annually [3], [4], [5], [6]. Cooking is the most energy-intensive activity in Nigerian households [54]. The use of dirty-burning cooking fuels that emit high levels of underburned products is widespread due to lack of energy consumption behaviour data among rural households. There has been a steady transition from biomass to HHK for cooking, and HHK has been reported as the commonest cooking fuel in urban areas. An appropriate design of both wick and pressurised kerosene stoves can be efficient and cook quickly as they are easily controlled, convenient and popular, in comparison with other rural cooking technologies. On the other hand, HHK stoves give unpleasant smell and can be dangerous when handled improperly. They can also be noisy when running [7], [8]. In 2013, the Nigeria demographic study reported that 26% of the populace utilised HHK for food preparation comprising 48% and 9% of urban and rural household respectively [9].

Primarily, this switch was motivated by government subsidisations on HHK and energy sector influences which improved the affordability and accessibility of HHK for quite some time [10]. Nevertheless, in 2016 HHK subsidies were removed. This consequently led to a drastic increment of the pump price of HHK and in-affordability of the product by the poor. Countless independent marketers were unable to continue importation of the product, and most HHK consumers bought the product at approximately four times the government regulated price [11].

LPG is not commonly found in the rural regions, but it is readily accessible and moderately affordable among the middle or high income groups in urban zones in Nigeria. For the purpose of household cooking and lighting, it is cleaner and more efficient than HHK [12]. Besides, it is a sustainable fuel for refrigeration and sterilisation of processes in hospitals, with expected health, social and economic benefits [13], [14]. This study focuses on energy, exergy and environmental compatibility analyses of HHK and LPG consumption patterns in the Nigerian residential sector for forty years: 1980 to 2019. It brings out the trends and shows our energy consumption patterns in the sector have improved over the four decades.

2. METHODOLOGY

Data on LPG and Household Kerosene (HHK) consumed in Nigeria, from 1980 to 2019, were collected from different sources [26]-[43]. They are presented as Table 2 in this paper. Practically, LPG is assumed to be used entirely for cooking as less than 1% of it is used for lighting [15]. Proportions of HHK utilised for cooking and lighting are presented in Table 3. Energy values E , of mass m , of either LPG or HHK, of a Lower Heating Value, LHV, is given by equation (1).

$$E = mLHV \quad (1)$$

The corresponding exergy value, E_x , is determined from equation (2):

$$E_x = \phi mLHV \quad (2)$$

According to [15], LHV of LPG and HHK are given, respectively, as follows:

$$(LHV)_{LPG} = 45.3 \text{ MJ/kg}$$

$$(LHV)_{HHK} = 43.1 \text{ MJ/kg}$$

In equation (2), ϕ is the fuel exergy factor [16]. Different fuels have different ϕ values, and a value of 1.056 is used for LPG [17] while 1.07 is used for HHK [16, quoted in 18] in this paper.

Based on [15], LPG stove cooking efficiency is taken as 45% and HHK stove cooking efficiency as 35%. In a similar vein, according to [19], quoted in [20], the lighting efficiency of a kerosene lamp is 0.05% and its exergetic efficiency is 0.045%. Since efficiency is ratio of output to input, the energy efficiency η is, simply:

$$\eta = \frac{Q}{mLHV} \quad (3)$$

This gives:

$$Q = \eta mLHV \quad (4)$$

Where,

Q = cooking thermal energy output,

LHV = Lower Heating Value of cooking fuel

m = mass of the fuel respectively

When using two fuels, (as in HHK and LPG), the efficiency is calculated using equation (5)

$$\eta = \frac{\eta_1 m_1 (LHV)_1 + \eta_2 m_2 (LHV)_2}{m_1 (LHV)_1 + m_2 (LHV)_2} \quad (5)$$

Exergy efficiency, ψ , for cooking was determined using equation (6) [21], quoted in [20]:

$$\psi = \frac{Q \{1 - (T_0/T)\}}{\phi mLHV} = \{1 - (T_0/T)\} \frac{\eta}{\phi} \quad (6)$$

T = the cooking temperature.

T_0 = the reference temperature.

In this paper, T is $393K$ and T_0 is $300K$. From equation (6), we have:

$$Q \{1 - (T_0/T)\} = \psi \phi mLHV \quad (7)$$

And, from equations (3) and (6), we obtain:

$$\psi = \frac{\{1 - (T_0/T)\}}{\phi} \eta \quad (8)$$

A similar argument to the one in equation (5) above gives the exergy efficiency, ψ , in the case of two or more fuels.

Environmental Compatibility, (ξ), of an energy source, a measure of its sustainability, is defined [22] as follows:

$$\xi = \frac{\text{Exergy in}}{(\text{Exergy in}) + (\text{Emission Abatement Exergy})} \quad (9)$$

Besides, according to [23], in [24], based on the data on CO_2 recovery via ethanolamine absorption and stripping, and subsequent compression to 80 atm for storage underground, it can be calculated that $5.862MJ$ exergy (of abatement) is required per kg CO_2 produced from non-renewable energy sources. Hence, to calculate the CO_2 abatement exergy of a fuel, we multiply exergy value of the fuel consumed by the Effective CO_2 Emission Factor (in Table 1) to obtain the mass of CO_2 produced, and then multiply by $5.862MJ$ (abatement exergy required per kg of CO_2).

Table 1. Fuel Emission Factors

Fuel Name	Default Carbon Content (kg/GJ of fuel)	Effective CO_2 Emission Factor (kg/GJ of fuel)

	A	$A \times (44/12)$
Kerosene (HHK)	19.6	71.9
LPG	17.2	63.1

Source: [25]

3. RESULTS AND DISCUSSION

3.1 RESULTS

Table 2. Annual Liquefied Petroleum Gas and Household Kerosene Consumption

UNDER PEER REVIEW

Sources: [26]-[43]

Table 3. Annual Quantities of HHK Consumption for Cooking and Lighting Purposes

Year	LPG (Metric Tonnes)	HHK (Metric Tonnes)	Year	LPG (Metric Tonnes)	HHK (Metric Tonnes)
1980	39,050	1,201,830	2000	2,580	1,194,920
1981	48,040	1,385,290	2001	13,600	1,644,263
1982	51,140	1,485,890	2002	22,696	1,541,711
1983	52,990	1,845,760	2003	50,000	1,105,189
1984	64,100	1,749,590	2004	3,459	674,464
1985	65,350	1,735,710	2005	7,783	1,119,329
1986	73,250	1,923,020	2006	12,904	746,671
1987	102,280	2,068,480	2007	5,000	431,289
1988	106,420	2,157,900	2008	7,019	789,275
1989	104,280	2,392,800	2009	18,095	1,530,370
1990	106,000	2,273,370	2010	26,000	538,850
1991	98,260	2,273,990	2011	130,000	725,970
1992	209,350	1,866,790	2012	145,000	508,551
1993	119,600	2,256,950	2013	110,000	2,146,877
1994	592,650	1,627,340	2014	350,000	2,382,652
1995	81,220	1,445,540	2015	250,000	1,381,527
1996	89,680	1,633,720	2016	500,000	766,966
1997	93,410	1,640,540	2017	600,000	761,179
1998	66,050	1,266,370	2018	300,054	499,607
1999	37,610	1,217,380	2019	411,157	217,794

Year	Cooking HHK (Metric Tonnes)	Lighting HHK (Metric Tonnes)	Year	Cooking HHK (Metric Tonnes)	Lighting HHK (Metric Tonnes)
1980	938810.230	263019.770	2000	721828.241	473091.759
1981	1115045.357	270244.643	2001	1177797.362	466465.851
1982	1208527.324	277362.676	2002	1063333.755	478377.403
1983	1561278.395	284481.605	2003	614519.109	490670.347
1984	1457822.460	291767.540	2004	171072.135	503391.970
1985	1436369.535	299340.465	2005	562458.343	556870.933
1986	1615785.700	307234.300	2006	133816.858	612854.288
1987	1753072.383	315407.617	2007	17556.686	413732.383
1988	1834084.051	323815.949	2008	364432.247	424842.278
1989	2060412.668	332387.332	2009	1094062.361	436307.451
1990	1932297.846	341072.154	2010	90729.933	448120.239
1991	1896133.465	377856.535	2011	396899.964	329069.862
1992	1479284.376	387505.624	2012	239019.055	702429.738
1993	1859621.327	397328.673	2013	1799695.548	347181.761
1994	1219979.733	407360.267	2014	2088769.977	293882.268
1995	1027909.482	417630.518	2015	1144118.649	237408.646
1996	1205564.570	428155.430	2016	541296.057	225670.176
1997	1201594.993	438945.007	2017	548535.450	212643.576

Sources: [44], [45]-[49], [50], [51], [52], [53]

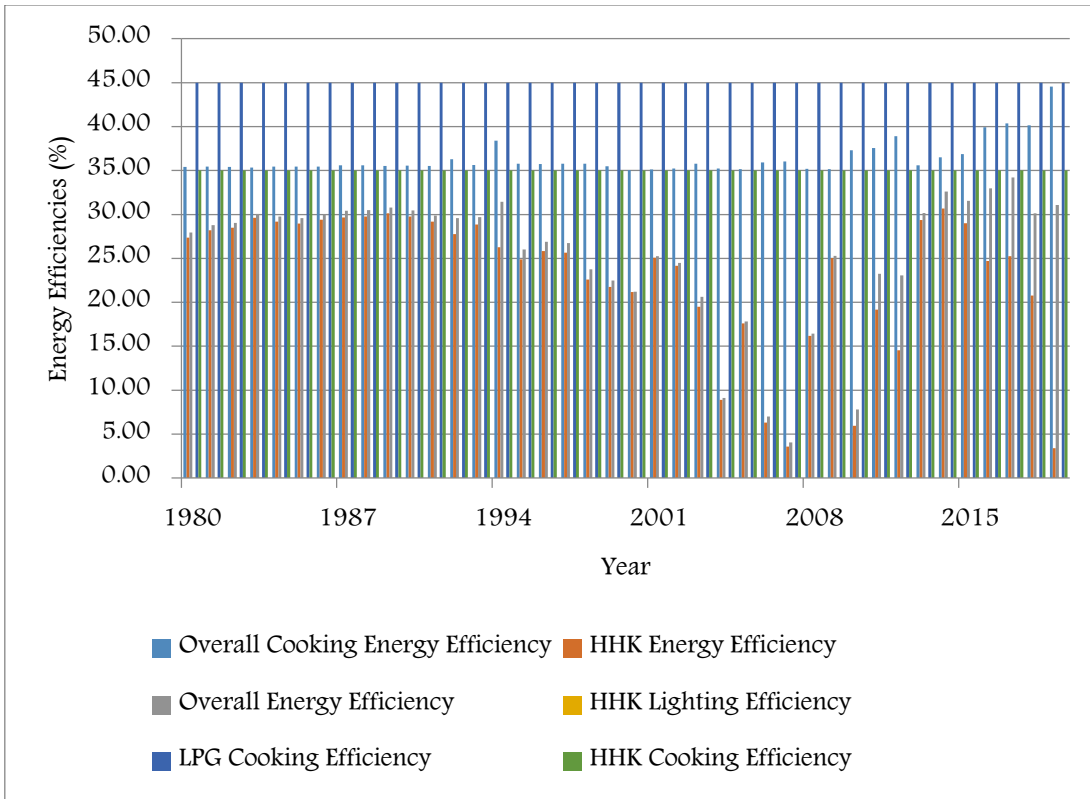


Fig. 1. Graphical Energy Analysis

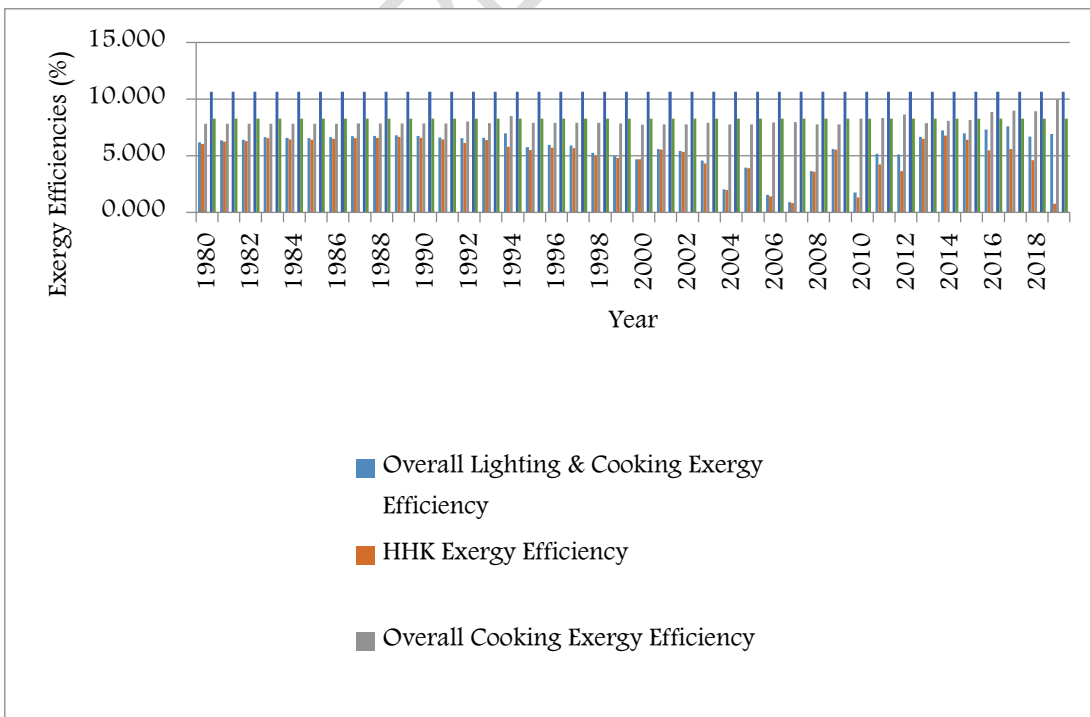


Fig. 2. Graphical Exergy Analysis

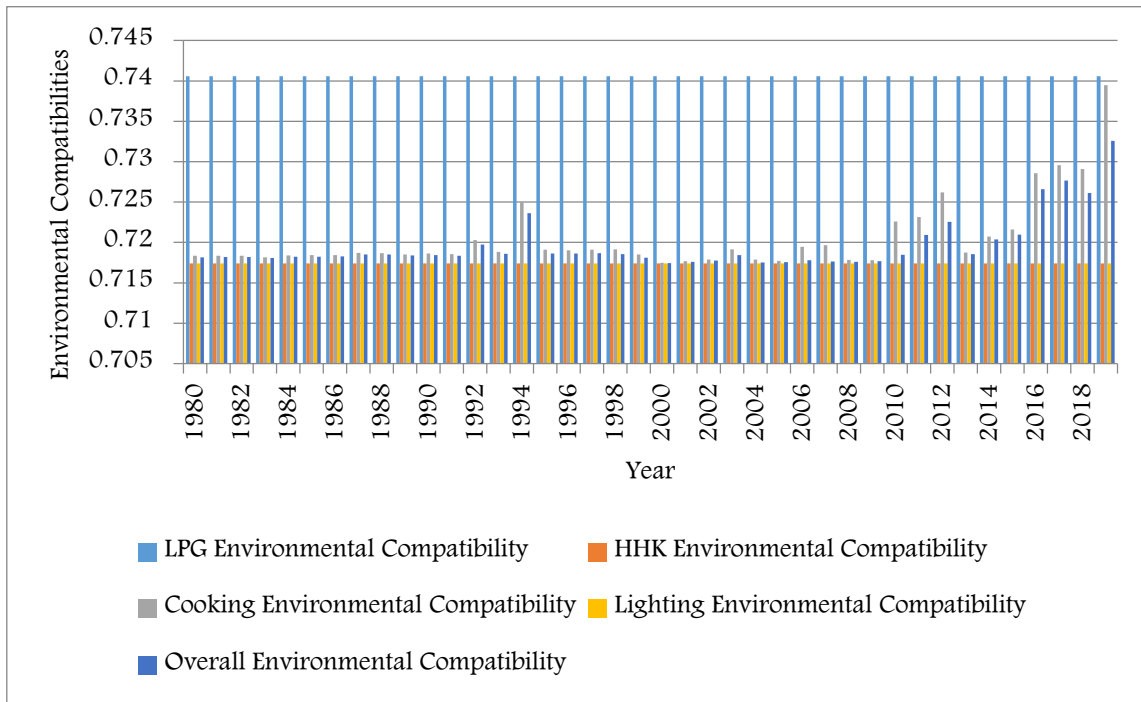


Fig. 3. Environmental Compatibilities

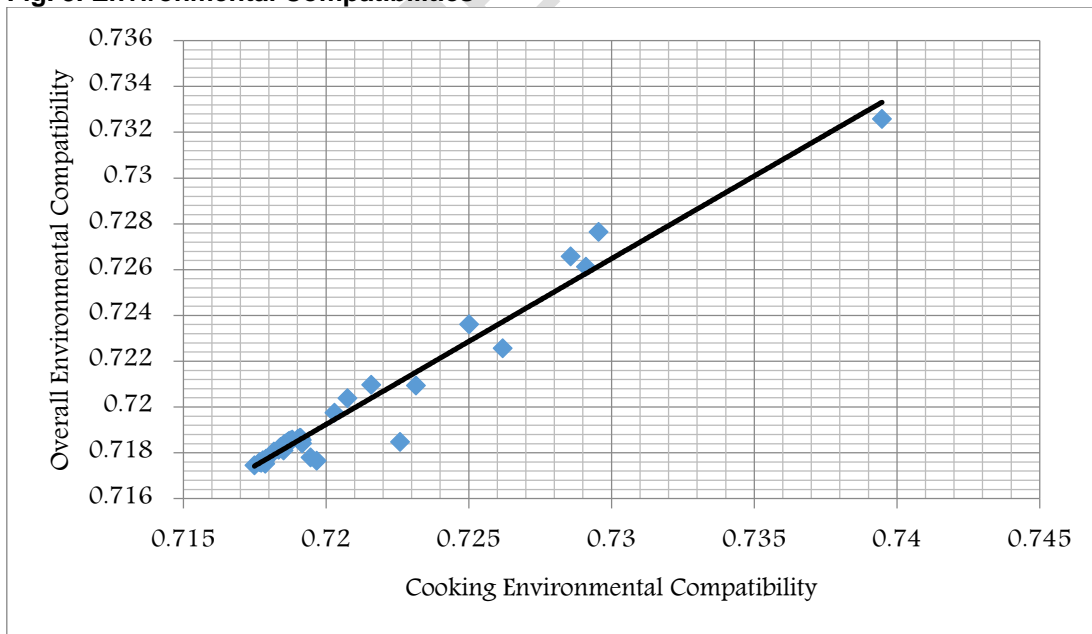


Fig. 4. Relationship between Cooking and Overall Environmental Compatibilities

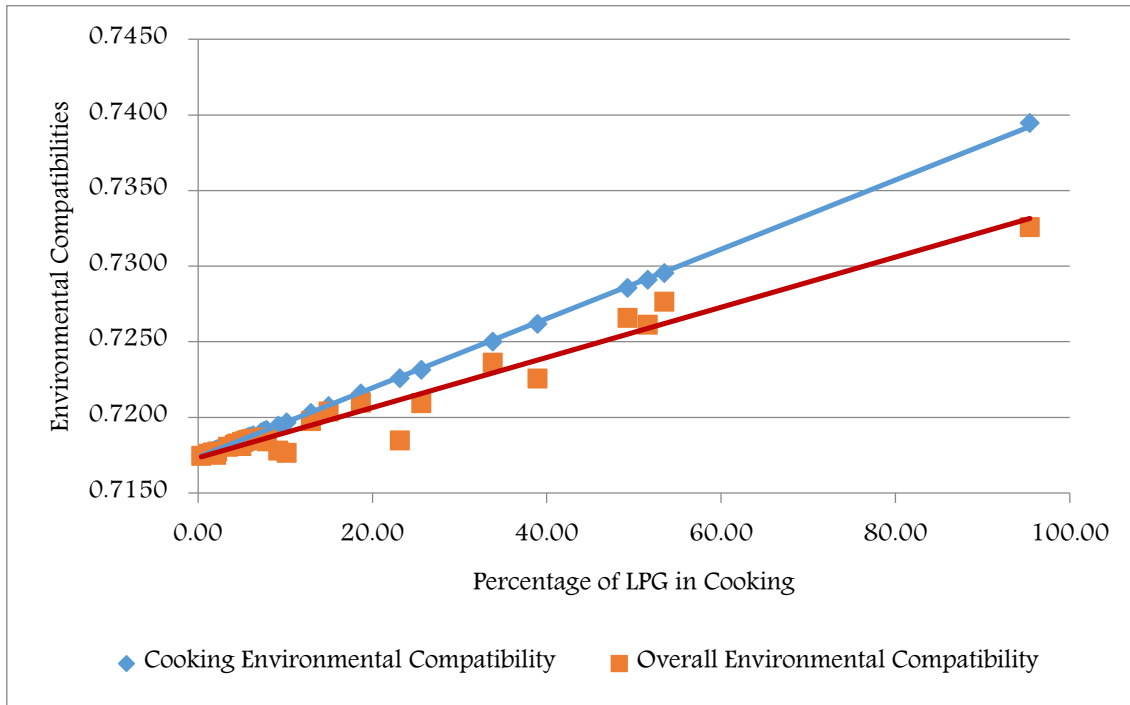


Fig. 5. Effects of LPG Percentage in Cooking on Environmental Compatibilities

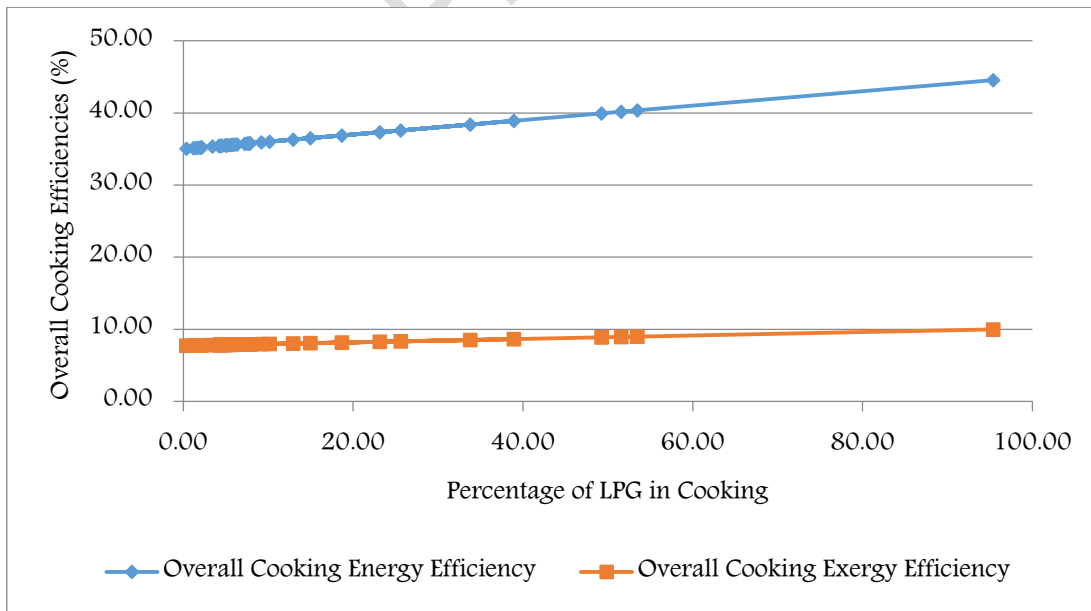


Fig. 6. Effects of LPG Percentage in Cooking on Overall Cooking Efficiencies

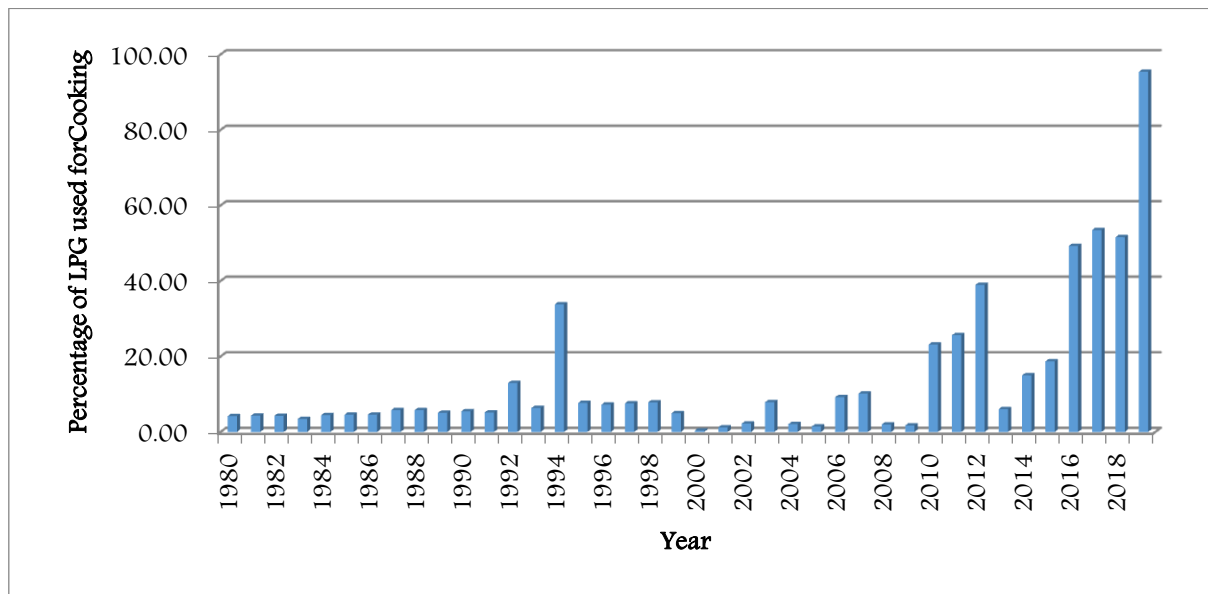


Fig. 7. A Four-Decade Annual Utilisation Trend of LPG for Cooking in Nigeria

3.2 DISCUSSION OF RESULTS

3.2.1 Energy Analysis

As stated earlier, HHK and LPG energy utilisation efficiencies were 35% and 45% respectively throughout the period. HHK lighting efficiency was also 0.05% throughout. Apart from these, cooking (HHK and LPG) energy efficiencies ranged from 35.04% in the year 2000 to 44.54% in 2019. This was followed by the overall (cooking and lighting) energy efficiencies (HHK and LPG), ranging from 4.05% (2007) to 34.19% (2017). HHK (cooking and lighting) processes are the least efficient, ranging from 3.40% (2019) to 30.69% (2014). Overall cooking energy efficiencies appear to be largely influenced by the percentage LPG utilised in cooking. This is because, as indicated in Table 4, year 2000 (with 35.04% efficiency, the lowest) recorded the least LPG percentage utilisation of 0.37%, while 2019 (with 44.54% efficiency, the highest) recorded the highest percentage of 95.39%. This is expected, as LPG has a higher LHV (45.3 MJ/kg) and a higher utilisation efficiency (45%) than HHK (43.1 MJ/kg; 35%). However, (cooking and lighting) processes utilising HHK only were apparently influenced by the percentage of HHK utilised for lighting. Their highest energy efficiency (30.69%) was recorded when HHK utilisation for lighting was lowest (12.33%) in 2014, and the lowest energy efficiency (of 3.40%) when HHK percentage utilisation for lighting was highest (90.41%) in 2019. This is expected, as no LPG was involved, and lighting with HHK was the most energy inefficient process (utilisation efficiency = 0.05%) considered.

For overall (cooking and lighting using both HHK and LPG) process efficiencies, there is interplay between positive effects of LPG utilised and negative effects of percentage HHK utilised for cooking and, especially, lighting. Low percentage LPG utilisation in cooking (10.16%) along with very high percentage utilisation of HHK in lighting (89.91%) in 2007 led to the lowest overall energy utilisation efficiency of 4.05%. Similarly, above average LPG utilisation in cooking (53.48%) coupled with low percentage utilisation of HHK in lighting

(27.94%) in 2017 led to the highest overall energy utilisation efficiency of 34.19%. In general, overall cooking energy efficiency increases directly as LPG percentage in cooking, as shown in Fig. 6.

3.2.2 Exergy Analysis

Exergy efficiencies are generally lower than their corresponding energy values due to the Carnot factor in cooking processes and extremely low exergy efficiency (0.045%) of HHK lighting. This fact is shown in Table 4. Throughout the period, LPG exergy was 10.649% while HHK exergy efficiency was 8.282%. Lighting exergy was also 0.045% efficient. However, overall cooking exergy efficiency increases directly as LPG percentage in cooking as well, as shown in Fig. 6.

3.2.3 Environmental Compatibility

Environmental compatibilities of LPG and HHK had (expected constant) values of 0.7406 and 0.7174 respectively. As expected, lighting process had the same value with that of HHK, the sole lighting fuel considered in this study. Besides, as shown in Fig. 4, overall environmental compatibility varies directly as cooking environmental compatibility, with the corresponding minimum and maximum values recorded in the years 2000 and 2019, respectively, as shown in Table 4. It is also noteworthy that the two years (of 2000 and 2019) recorded the lowest and highest LPG utilisations of 0.37% and 95.39% respectively, during the period of this study, as shown in Table 4. This indicates that the environmental compatibility depends on the fuel-mix of a process, irrespective of the efficiencies of the process. Indeed, Fig. 5 indicates a linear direct variation between percentage of LPG in cooking and the two environmental compatibilities. Therefore, to improve the environmental compatibilities, LPG percentage should be increased till LPG eventually replaces HHK in cooking.

Table 4. Years with Critical Parameters (%)

Year	LPG	HHK Lighting	η_{cooking}	η_{HHK}	η_{overall}	ψ_{cooking}	ψ_{HHK}	ψ_{overall}	ξ_{cooking}	ξ_{overall}
2000	0.37	39.59	35.04			7.749			0.717492	0.717459
2007	10.16	89.91			4.05			0.925		
2014	14.97	12.33		30.69			6.791			
2017	53.48	27.94			34.19			7.612		
2019	95.39	90.41	44.54	3.40		9.975	0.783		0.739474	0.732588

4. CONCLUSION

Energy, exergy and environmental compatibility analyses of HHK and LPG utilisation as domestic fuels in Nigeria over four decades have been carried out. HHK use for lighting purposes is grossly inefficient. HHK use as a cooking fuel is less efficient than LPG for the same purpose. LPG is more energy efficient, more exergy efficient and more environmentally compatible. Despite all the advantages of LPG utilisation for cooking as enumerated above, it was not so-selected consistently for use during the period of this study, except somewhat during the last decade, as graphically depicted in Fig. 7.

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