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 utilisation 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 [3-6]. Cooking is the most energy-intensive activity in Nigerian households [7]. Use of dirty-burning cooking fuels, that emit high levels of pollutants, is due to lack of adequate awareness of the hazards as well as energy poverty 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 [8,9]. 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 [10].

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 [11]. 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 [12].

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 [13]. Besides, it is a sustainable fuel for refrigeration and sterilisation of processes in hospitals, with expected health, social and economic benefits [14,15]. 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 [16]-[33]. 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 [34]. 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).

$$ E = mLHV $$

(1)

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

$$ E_x = \varphi mLHV $$

(2)

According to [34], LHV of LPG and HHK are given, respectively, as follows:
Table 1. Fuel emission factors

| Fuel Name     | Default Carbon Content | Effective CO\textsubscript{2} Emission Factor |
|---------------|------------------------|---------------------------------------------|
| Kerosene (HHK)| 19.6                   | 71.9                                        |
| LPG           | 17.2                   | 63.1                                        |

Source: [35]

\[(LHV)_{LPG} = 45.3\text{MJ/kg}\]
\[(LHV)_{HHK} = 43.1\text{MJ/kg}\]

In equation (2), \(\phi\) is the fuel exergy factor [36]. Different fuels have different \(\phi\) values, and a value of 1.056 is used for LPG [37] while 1.07 is used for HHK [36, quoted in 38] in this paper.

Based on [34], LPG stove cooking efficiency is taken as 45% and HHK stove cooking efficiency as 35%. In a similar vein, according to [39], quoted in [40], 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 \(\eta\) is, simply:

\[\eta = \frac{Q}{mLHV}\]  \hspace{1cm} (3)

This gives:

\[Q = \eta mLHV\]  \hspace{1cm} (4)

Where,

\[Q = \text{cooking thermal energy output},\]
\[LHV = \text{Lower Heating Value of cooking fuel}\]
\[m = \text{mass of the fuel respectively}\]

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

\[\eta = \frac{\eta_1 m_1 (LHV)_1 + \eta_2 m_2 (LHV)_2}{m_1 (LHV)_1 + m_2 (LHV)_2}\]  \hspace{1cm} (5)

Exergy efficiency, \(\psi\), for cooking was determined using equation (6) [41], quoted in [40]:

\[\psi = \frac{Q\{1 - (T_0/T)\}}{\phi mLHV} = \left\{1 - \left(\frac{T_0}{T}\right)\right\} \frac{\eta}{\phi}\]  \hspace{1cm} (6)

\[T = \text{the cooking temperature}\].

\[T_0 = \text{the reference temperature}\].

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

\[Q\{1 - (T_0/T)\} = \psi \phi mLHV\]  \hspace{1cm} (7)

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

\[\psi = \frac{\{1 - (T_0/T)\}}{\phi} \frac{\eta}{\eta}\]  \hspace{1cm} (8)

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

Environmental Compatibility, \(\xi\), of an energy source, a measure of its sustainability, is defined [42] as follows:

\[\xi = \frac{\text{Exergy in Exergy in Emission Abatement Exergy}}{(\text{Exergy in}) + (\text{Emission Abatement Exergy})}\]  \hspace{1cm} (9)

Besides, according to [42], in [43], based on the data on CO\textsubscript{2} recovery via ethanolamine absorption and stripping, and subsequent compression to 80 atm for storage underground, it can be calculated that 5.862\text{MJ} exergy (of abatement) is required per kg CO\textsubscript{2} produced from non-renewable energy sources. Hence, to calculate the CO\textsubscript{2} abatement exergy of a fuel, we multiply exergy value of the fuel consumed by the Effective CO\textsubscript{2} Emission Factor (in Table 1) to obtain the mass of CO\textsubscript{2} produced, and then multiply by 5.862\text{MJ} (abatement exergy required per kg of CO\textsubscript{2}).

3. RESULTS AND DISCUSSION

3.1 Results

Annual LPG and HHK utilization values are depicted in Table 2. Since HHK served the dual purposes of both lighting and cooking, its values...
utilized for the two different purposes are shown in Table 3 on annual basis.

**Table 2. Annual liquefied petroleum gas and household kerosene consumption**

| 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              | 2,273,340           | 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             |

**Sources:** [16]-[33]

**Table 3. Annual quantities of HHK consumption for cooking and lighting purposes**

| 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 | 171027.135                 | 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                | 332837.332                 | 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 | 179695.548                 | 347181.761                 |
| 1994 | 1219979.733                | 407360.267                 | 2014 | 2088769.977                | 293882.268                 |
| 1995 | 1027909.462                | 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]

3.2 Discussion of Results

3.2.1 Energy analysis

There are two types of efficiency in Fig. 1: process energy efficiency and fuel utilization efficiency. The processes are cooking and lighting while the fuels are HHK and LPG. Process-wise, cooking is more energy efficient than lighting. Fuel-wise, LPG is more energy efficient than HHK. 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 as indicated in Fig. 1. 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% (in 2007) to 34.19% (in the year 2017). HHK (cooking and lighting) processes are the least efficient, ranging from 3.40% (in 2019) to 30.69% (in the year 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

Fig. 2 is about exergy analysis. When Fig. 1 is compared with Fig. 2, it is clearly seen that 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. The differences are because exergy analysis generally accounts for irreversibilities in energy conversion systems, while ordinary energy
analysis does not. This is the main reason why exergy analysis is more realistic than ordinary energy analysis. This fact is shown in Table 4. Throughout the period, LPG exergy efficiency 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. This underscores the importance of the need to increase the LPG proportion in the cooking fuel-mix.

![Fig. 5. Effects of LPG percentage in cooking on environmental compatibilities](image1)

![Fig. 6. Effects of LPG percentage in cooking on overall cooking efficiencies](image2)
Environmental compatibilities of LPG and HHK had (expected constant) values of 0.7406 and 0.7174 respectively. As expected and shown in Fig. 3, lighting process had the same value with that of HHK, the sole lighting fuel considered in this study. Also, as depicted in Fig. 3, LPG is more environmentally compatible than HHK. This is because the carbon content of a particular quantity of LPG is lower than that of a similar quantity of HHK. 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.

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. There is need to increase LPG proportion in the cooking fuel-mix because of these advantages.
Use of HHK for lighting purposes should also be discouraged. Besides, considering the trend of LPG utilization in Fig. 7, it has an upward trend during periods of relative political stabilities in Nigeria. Hence, it can also be concluded that political stability is contributive to good energy policies of a country.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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