Fuel-mix and energy utilization analysis of Port Harcourt Refining Company, Nigeria

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Abstract

This study analyses the fuel-mix and energy utilization patterns in Port Harcourt Refining Company from 2000 to 2011. The average fuel mix over the study period is 43% refinery fuel gas, 0% liquefied petroleum gas (LPG), 44% low pour fuel oil (LPFO), 8% Coke, and 5% automotive gas oil (AGO). The present ratio of high-carbon fuel consumption to low-carbon fuel consumption adversely influences the specific fuel consumption by increasing it. Our proposal is that the present AGO and LPFO consumption levels are totally replaced with equivalent amounts of natural gas. This would yield the following fuel mix: 46% refinery fuel gas, 46% natural gas, and 8% coke. This, in effect, would result in a proportion of 92% low-carbon fuels and 8% coke. It would also lead to a specific fuel consumption that is averagely unaffected by high-carbon/low-carbon fuel consumption ratios. Natural gas utilization has its main advantage in its flare/waste and consequent environmental degradation reduction. Finally, the proposed fuel mix would generally lead to a reduction in specific fuel consumption, thus saving energy and reducing costs.

Introduction

The Nigerian economy depends primarily on the oil sector. Moreover, the country holds the largest natural gas reserves in Africa. Natural gas associated with oil production is mostly flared. However, regional pipeline development, liquefied natural gas (LNG) infrastructural expansion, as well as policies to ban gas flaring are expected to accelerate growth in the sector, both for export and domestic electricity generation [1]. Nigeria has four domestic refineries, with a total capacity of 445,000 barrels per day [2]. In 2001, the country had 150,000 km road network, 5,900 km of pipelines for product receipts/transportation, 21 government-owned fuel depots, and numerous marketers’ terminals/depots. All these were in addition to a storage capacity in excess of 7 million barrels, 6 ocean/tanker terminals, 2,000 fuels tank trucks, 5,100 service stations, and 50 inland terminals/depots [3]. For about a decade there was very little change, except the fact that the country reduced its pipeline network to 5,000 km [4].

An assessment of the oil and petrochemical industry in Nigeria would yield a myriad of challenges. Despite the oil fortune, Nigeria is a net importer of refined petroleum products. At the top of the petroleum industry is the Federal Government–owned Nigerian National Petroleum Corporation (NNPC) that operates joint venture agreements with some foreign multinational oil companies in Nigeria to produce the nation’s oil and gas. In contrast, the Venezuelan Petroleum Corporation, which was established about the same time as NNPC as a public corporation, has grown to be the third largest international conglomerate and also a net exporter of refined petroleum products [5]. As observed by Iwayemi [6], despite the fact that Nigeria has domestic refineries owned by the government, with capacity to process nearly 450,000 barrels of oil per day, the country still imports more than 75% of petroleum products requirements for local consumption.

This situation has led to very unstable petroleum product price regimes in the country, forcing poor Nigerians to look for cheaper fuel alternatives to satisfy their
domestic energy needs, with the attendant negative environmental effects [7, 8]. Aigbedion and Iyayi [9] observe that: “The sub-sector has also been constrained by the unenviable state of the nation’s refineries which have been producing at minimal capacities in the past few years, despite huge expenses incurred on the Turn Around Maintenance of the crisis – ridden refineries. This development has led to massive importation of petroleum products to fill demand gaps that exist in domestic consumption.” Importation of refined petroleum products obviously increases their pump prices. For instance, the Petroleum Products Pricing Regulation Agency (PPPRA) pricing templates are a function of the exchange rate of Nigerian Naira to the US Dollar, landing costs, and distribution margins. The landing cost, which accounts for most of the cost, is the cost of imported products delivered into the jetty depots [10].

Virtually every Nigeria life is affected by availability or otherwise of petroleum products, primarily through transportation, but also through household energy use and industrial use, which includes operation of internal combustion engines to generate electricity due to the electrical power crisis in the country. However, before these products can be obtained from crude oil it has to pass through the refining process where it is ‘cracked’ into different useful components such as premium motor spirit (PMS) or gasoline, automotive gas oil (AGO) or diesel oil, dual purpose kerosene (DPK), and others. As there is no other way of obtaining these components from crude oil except through this process, the energy consumed during the process is a critical determinant of the final product price in the energy market.

There is a widespread acceptance that there is a general decline in the level of technical efficiency at which Nigerian refineries operate. Naturally, inadequate maintenance and technological obsolescence would lead to a general decline in technical efficiency of a system. Perhaps this is why even social scientists such as Bamisaye and Obiyan [11] have also advocated urgent repair of Nigeria’s oil refineries.

The Port Harcourt Refining Company (PHRC) comprises an old plant which was commissioned in 1965 and a newer one which was commissioned 1989. The old plant has an installed capacity of 60,000 barrels per stream day (bpsd), whereas the new plant has a capacity of 150,000 bpsd, giving a combined capacity of 210,000 bpsd and 47% of all NNPC refining capacity.

In particular, there have been several studies on the PHRC. Isah et al. [12] discussed the importance fluidized catalytic cracking (FCC) unit in improving gasoline production rate in the PHRC. Akpabio and Ekott [13] discussed the need for incorporation of delayed coking process units into the Nigerian refineries, including PHRC. Tonnang and Olatunbosun [14] applied a neural network controller in the analysis of a crude distillation unit (CDU), using PHRC as a case study. Akpa and Okoroma [15] carried out a pinch analysis of the heat exchanger network in the CDU of PHRC. Uzukwu and Iyagba [16] also carried out a process analysis of the new Port Harcourt refinery crude charge heater.

Jesuleye et al. [17] analyzed the energy demand of the Port Harcourt refinery, Nigeria, based on information obtained from its annual publications, backed-up by spot interviews. The analytical approach adopted for the study involves the calculation of energy intensities to determine the refinery’s annual energy demand for various energy types from 1989 to 2004. The results showed that the actual energy demand per year for processing crude oil into refined products exceeded, in varying degrees, the stipulated refinery standard of 4 barrels of oil equivalent (BOE) per 100 BOE. It varied from 4.28 to 8.58 BOE per 100 BOE. In terms of energy demand efficiency, this implies very poor performance of the refinery during the 16-year period under investigation. Lack of optimal fuel utilization mix and noncompliance with the turnaround maintenance schedules were attributed to the refinery’s inefficient energy demand pattern.

As observed by Badmus et al. [18] while appraising Jesuleye et al. [17], despite apparent preponderance of literature on general assessments of Nigerian refineries in the open literature, only this recent one by Jesuleye et al. [17] appears to be an in-depth energy analysis of only one of the refineries. However, although Jesuleye et al. [17] observed that “the refinery energy demand mix (by type of fuel use) did not follow the most technically efficient path”, they have not stated this “most technically efficient path” explicitly. This is why the work embarked upon in this study is important.

Methodology

Data collection

The study employs a quantitative method of analysis through intensive data gathering, collation, and processing. In particular, data collection has been done for a period spanning 2000 to 2011. Two separate field visits were paid to the PHRC, Port Harcourt, for the purpose of primary data gathering and secondary data authentication. The required secondary data were obtained from annual reports of the government-owned refineries and various publications of relevant institutions such as NNPC, US Energy Information Administration and Organisation of Petroleum Exporting Countries (OPEC), Austria. In particular, NNPC Annual Statistical Bulletin editions for the respective years and the PHRC library...
have been consulted extensively for secondary data. The aggregated data on overall annual fuel types and utilization, total quantity of crude oil processed, and refinery capacity utilization in the refinery have been obtained for a period of 12 years. Interviews with some of the PHRC technical staff were also used to elicit information concerning data authentication. An energy analysis (based on first law of thermodynamics) of the data collected has been done and the results are presented. In addition to this, the mass conservation law has also been applied in conjunction with this energy conservation law.

**Theoretical background**

In applying mass conservation law, the total mass of crude oil processed must be equal to the total mass of various products.

\[
\sum m_{in} = \sum m_{out}
\] (1)

In practice, as refinery fuels are derived from the crude oil itself,

\[
\text{Mass of crude oil processed} = \text{Total mass of various finished products} + \text{Total mass of refinery fuels} + \text{Total mass of losses}
\] (2)

From the first law of thermodynamics,

\[
\sum \dot{E}_{in} + \dot{Q}_{cv} = \sum \dot{E}_{out} + \dot{W}_{cv}
\] (3)

As a combustion process involves no work interaction, the relevant steady flow energy equation is as follows:

\[
Q = H_{products} - H_{reactants} = \Delta H.
\] (4)

\(\Delta H\) is called enthalpy of combustion.

**Heating value**

In practice, the parameter used to determine the energy content of a fuel is its heating value, defined as the amount of heat released when a fuel is burned completely in a steady flow process and the products are returned to the thermodynamic state of the reactants. The heating value is thus equal to the absolute value of the enthalpy of combustion of the fuel:

\[
\text{Heating value (HV)} = |\Delta H|
\] (5)

The heating value depends on the phase of the H₂O that must necessarily accompany the products of combustion of a hydrocarbon fuel, as the hydrogen component is oxidized to H₂O.

**Higher heating value**

The heating value is called the higher heating value (HHV) when the H₂O in the products is in the liquid form.

**Lower heating value**

This is the heating value when the H₂O in the combustion products is in the vapor form. Hence, HHV and lower heating value (LHV) are related thus:

\[
\text{HHV} = \text{LHV} + (m_{h_{fg}})H_{2O} \text{kJ/kg}
\] (6)

\(m\) = mass of H₂O products per unit mass of fuel; \(h_{fg}\) = specific enthalpy of vaporization of H₂O at the specified temperature.

In applying the first law of thermodynamics in this study, LHV of fuels have been used to determine the fuels' energy content. This is because this is the heating value used in practice in situations where the flue gases cannot be safely cooled below temperature values that enable utilization of enthalpy of steam condensation or cooling below dew points. Situations like these arise where it is feared that cooling below dew points will cause corrosive acid formation that can attack the system. Tables 1 and 2 show the LHVs used in this study.

**Mean LHV**

When a fuel is a mixture of different components with distinct LHVs, the mean LHV can be derived.

Total energy consumed based on LHV of the fuels is given by:

**Table 1. Lower heating values of nigerian refinery finished fuel products [19, 20].**

| S/N | Fuel          | LHV (MJ/kg) |
|-----|---------------|-------------|
| 1   | AGO*          | 42.7        |
| 2   | DPK           | 43.1        |
| 3   | FO (fuel oil)*| 40.19       |
| 4   | LPG (liquefied petroleum gas)* | 45.3 |
| 5   | PMS           | 44.0        |

*These are also used as refinery fuels.
AGO, automotive gas oil; DPK, dual purpose kerosene; PMS, premium motor spirit.

**Table 2. Lower heating values of other refinery fuels [19, 21].**

| S/N | Fuel                    | LHV (MJ/kg) |
|-----|-------------------------|-------------|
| 1   | Coke (Petroleum coke)   | 31.00       |
| 2   | Natural gas             | 44.95       |

LHV, lower heating value.
\[
\sum E_i = \sum m_i \text{LHV}_i
\]

Mean LHV is given by:
\[
\text{LHV} = \frac{\sum m_i \text{LHV}_i}{\sum m_i}.
\]

**Equivalent fuel mass**

It may be necessary to obtain the equivalent mass of a particular fuel that will provide the same quantity of thermal energy as the fuel mixture, as in the case of fuel substitution. For instance, in this study, a case is made for natural gas as a fuel substitute. In this case, mass of natural gas, \( m_{NG} \), for the same energy value as in equation (5) is given by:
\[
m_{NG} = \frac{\sum m_i \text{LHV}_i}{\text{LHV}_{NG}}.
\]

**Capacity utilization**

This is one other parameter that is used to assess the performance of systems like the refineries. For the refineries,

\[
\text{Capacity utilization} = \left( \frac{\text{crude oil quantity actually processed annually}}{\text{annual quantity designed to be processed}} \right) \times 100\% \tag{10}
\]

**Specific fuel consumption**

The specific fuel consumption as used in this work is ratio of fuel utilized per unit mass of crude oil processed, expressed as a percentage.

**Results**

Using equation (8), the mean LHV for PHRC fuel gas is 51.91 MJ/kg. It should be noted that the fuel gas is free from hydrogen sulfide, which when combusted, is environmentally deleterious.

**Discussion and Conclusion**

**Discussion of results**

Table 3 gives the details of annualized fuel consumption in PHRC over the study period.

**Capacity utilization and fuel consumption**

As seen in Table 3, there has been gross capacity under-utilization in the PHRC within the period under consideration. The capacity utilization has ranged from 8.82% in 2009 to 60.73% in 2001. The specific fuel consumption as shown in Figure 1A is almost inversely proportional to the capacity utilization at low capacities and practically constant at high capacities. It ranges from 4.47% in 2006 to 10.57% in 2010. The specific fuel consumptions corresponding to the lowest and highest values of capacity utilization of 8.82% and 60.73% are 9.34% and 5.53%, respectively. This implies that the highest specific fuel consumptions are the values for the years 2009 and 2010. However, it should be observed that the ratios of high-carbon fuel to low-carbon fuel in 2009 and 2010 are 2.53 and 4.28, respectively (Table 3). Hence, the adverse effects of high-carbon fuel to low-carbon fuel ratios has aggravated the effect of low capacity utilization to make the specific fuel consumption for 9.17% capacity utilization higher than that for 8.82% capacity utilization. At

| Year | AGO | Coke | Refinery fuel gas | LPFO | Total fuel consumed | Total quantity of crude processed | Specific fuel consumption (%) | Refinery capacity utilization (%) |
|------|-----|------|-------------------|------|--------------------|---------------------------------|------------------------------|---------------------------------|
| 2000 | 26,056 | 4934 | 98,183 | 69,512 | 198,685 | 3,214,333 | 6.18 | 30.95 |
| 2001 | 9736 | 53,229 | 175,839 | 108,818 | 347,622 | 6,290,480 | 5.53 | 60.73 |
| 2002 | 49,619 | 82,710 | 178,895 | 75,357 | 386,581 | 5,403,324 | 7.15 | 52.17 |
| 2003 | 20,213 | 27,395 | 103,007 | 94,300 | 244,915 | 3,980,603 | 6.15 | 41.88 |
| 2004 | 0 | 0 | 111,387 | 113,253 | 224,640 | 3,223,894 | 6.97 | 31.04 |
| 2005 | 0 | 17,790 | 141,864 | 130,194 | 289,848 | 4,368,783 | 6.63 | 42.18 |
| 2006 | 0 | 0 | 89,901 | 142,736 | 232,637 | 5,206,407 | 4.47 | 50.26 |
| 2007 | 0 | 0 | 66,532 | 84,407 | 150,939 | 2,590,779 | 5.83 | 42.47 |
| 2008 | 5208 | 0 | 38,797 | 64,787 | 103,792 | 1,886,074 | 5.77 | 17.84 |
| 2009 | 0 | 4435 | 24,124 | 56,480 | 85,039 | 910,751 | 9.34 | 8.82 |
| 2010 | 9320 | 0 | 19,000 | 72,063 | 100,383 | 950,134 | 10.57 | 9.17 |
| 2011 | 11,750 | 0 | 38,890 | 82,952 | 133,592 | 1,580,767 | 8.45 | 15.26 |

AGO, automotive gas oil; LPFO, low pour fuel oil.
Sources: NNPC [22–33].
high capacities, however, the specific fuel consumptions are nearly constant (Fig. 1A), but above the design value of 4% as observed by Jesuleye et al. [17]. Here also, the effects of relative proportions of high-carbon and low-carbon fuels on the specific fuel consumption values are not apparent.

Although the “degree of complexity” as a parameter of refinery classification as used by Ocic [34] is not clear, only the years 2009 (9.34%), 2010 (10.57%), and 2011 (8.45%) fall outside the benchmark range (4–8%) for refinery specific fuel consumption specified by him. However, according to Oniwon [35], the international benchmark for capacity utilization is 90%, whereas the international benchmark for fuel consumption as far back as 2008 was 6%. Around the same period of this analysis (1998–2008), Brazilian refineries had an average specific fuel consumption of 6% and a capacity utilization of at least 82% while U.S. refineries had a minimum capacity utilization of 79% around the same period [36].

Besides, energy is totally internally sourced in Nigerian refineries. There is no externally purchased steam or electricity. In the particular case of PHRC, the fuel consumption is thus utilized to:

(a) electricity for general use through steam turbine generators (STGs) and gas turbine generators (GTGs)
(b) raise steam for general plant use
(c) fire heaters for process heat generation

Of the three uses enumerated above, only (b) and (c) may stop entirely when the plants are shut down. For as long as the refinery still opens for business, whether the plants are running or not, electricity would still be utilized. However, process steam and fuel consumption may go down depending on the level of activities in the plant. As processed/refined crude is the only commodity for which the refinery exists, it is customary to “bill” the refined and/or processed crude for all the energy consumed. This explains why the specific energy consumption goes up when the capacity is underutilized.

**Fuel-mix trend and its effect on overall fuel energy consumption trend**

Apparently, the main fuel utilized in process units fired heaters is largely the refinery fuel gas. This is because the refinery fuel gas consumed is directly proportional to the...
consumed fuel is fuel oil (44%), closely followed by refinery fuel gas (43%). Although liquefied petroleum gas (LPG) has not been used at all, the least utilized fuel has been AGO (5%). An 8% coke utilization suggests that the FCC unit where the fuel is usually combusted has not been in operation for some years. This can be seen vividly in Table 3 where years 2004, 2006–2008, as well as 2010 and 2011 record zero coke consumption values. Hence, leaving aside the peculiar case of coke, high-carbon fuel consumption in the refinery has still been higher (49%) than that of low-carbon fuel (43%), especially when compared with what is obtainable in the same industry in other countries.

In 2008, Brazilian refineries (Fig. 2B) consumed coke: 31%, natural gas: 15%, refinery fuel gas: 36%, and high pour fuel oil: 18%. This means that, aside from coke, high-carbon fuels were only 18% while low-carbon fuels were 51%. Besides, the FCC unit has been quite operational, with 31% petroleum coke consumed. In 2008, US refineries consumed 30% natural gas, 49% refinery gas, and 21% coke (Fig. 2C). This implies, 79% low-carbon fuel consumption and no high-carbon fuel consumption aside from that of petroleum coke.

However, one positive aspect of the PHRC fuel mix is that it uses refinery fuel gas as its process fuel, with the major combustible components being ethane (35%), methane (29%), and hydrogen (12%) as detailed in Table 4. The fuel gas is also free from hydrogen sulfide (H₂S), which is environmentally unfriendly. All these have culminated in a good average LHV of 51.91 MJ/kg.

**Fuel substitution option**

As a result of the observation in the section Fuel-mix Trend and its Effect on Overall Fuel Energy Consumption Trend above, substituting low-carbon fuels for high-carbon fuels looks promising. The options are LPG and/or natu-

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**Table 4.** PHRC fuel gas properties [16, 38–40].

| Fuel component | LHV (MJ/kg) | Gravimetric contribution (kg) |
|----------------|-------------|------------------------------|
| H₂             | 120.21      | 1.267                        |
| CH₄            | 50.03       | 2.9856                       |
| C₂H₆           | 47.51       | 3.675                        |
| C₃H₆           | 45.661      | 0.7812                       |
| C₃H₈           | 46.33       | 0.0704                       |
| C₄H₁₀          | 45.72       | 0.3422                       |
| C₅H₁₂          | 45.173      | 0.028                        |
| C₆H₁₄          | 44.945      | 0.108                        |
| N₂             | 44.1401     | 0.0774                       |
|                | –           | 1.0752                       |

LVH, lower heating value.
LPG is a product of the crude oil refining process and thus only available in small quantities. Furthermore, its carbon content is more than that of natural gas, although they have comparable LHV. On the other hand, natural gas is a direct by-product of crude oil exploration and the quantity that is flared annually (after utilizing a part) is enormous, when compared with the quantity required for refinery fuel.

It is observed in Table 5 that during the years when FCC unit was operational and coke was utilized, change in mean LHV (between the proposed one and the present one) varied from 1.223 MJ/kg in 2002 to 3.256 MJ/kg in 2009. In contrast, whenever coke was not utilized, the change in LHV varied from 2.594 MJ/kg in 2004 to 3.742 MJ/kg in 2010. This implies that the degree of FCC capacity utilization also affects the specific fuel consumption. Hence, there are larger mean LHV gains with natural gas fuel substitution when FCC is not operational and consequently more significant reductions in the specific fuel consumptions. This is not surprising as coke, which is the FCC fuel, is a high-carbon fuel. However, as the LHV still responds favorably to substitution of high-carbon fuels with natural gas, even when the FCC is in operation, it follows that the fuel substitution is still a way out of the present high specific fuel consumption in the refinery.

| Year | Coke consumption (tons) | Present mean LHV (MJ/kg) | Proposed mean LHV (MJ/kg) |
|------|-------------------------|--------------------------|---------------------------|
| 2000 | 4934                    | 46.083                   | 48.184                    |
| 2001 | 53,229                  | 44.781                   | 46.384                    |
| 2002 | 82,710                  | 43.970                   | 45.193                    |
| 2003 | 27,395                  | 44.298                   | 46.381                    |
| 2004 | 0                       | 46.001                   | 48.596                    |
| 2005 | 17,790                  | 45.362                   | 47.628                    |
| 2006 | 0                       | 44.719                   | 47.827                    |
| 2007 | 0                       | 45.356                   | 48.211                    |
| 2008 | 0                       | 44.490                   | 47.606                    |
| 2009 | 4435                    | 43.035                   | 46.291                    |
| 2010 | 0                       | 42.641                   | 46.383                    |
| 2011 | 0                       | 43.823                   | 47.129                    |

LVH, lower heating value.

Table 5. Impact of coke consumption on the refinery fuel mean lower heating values.

Figure 3. (A) Effect of proportions of high-carbon fuels to low-carbon fuels on specific fuel consumption over the Years. (B) New average fuel mix when AGO and low pour fuel oil (LPFO) are replaced with natural gas.
It should also be noted that natural gas as fuel has an additional advantage of lowest carbon content (being mainly CH₄), giving rise to very low CO₂ emissions. Presently, natural gas is not in use as a refinery fuel in PHRC. In principle, when natural gas is used as refinery fuel, all other refinery fuels above (apart from coke which is utilized in the FCC unit) can be added to the product streams. This replacement of fuel oil with natural gas has been done successfully in the Iranian refining industry [41]. Besides, the volume of flared natural gas is correspondingly reduced and, being a low-carbon fuel, atmospheric carbon emission is also reduced. Thus, there is

Figure 4. New effect of high-carbon fuel/low-carbon fuel ratio on specific fuel consumption.

Figure 5. Effect of natural gas/refinery gas ratio on specific fuel consumption.

Figure 6. Comparison between the present and proposed specific fuel consumptions.
more fuel availability for both domestic and industrial use; there are both financial gains and environmental protection as a result of gas flare reduction.

One additional point worthy of consideration is the fact that the present ratio of high-carbon fuel consumption to low-carbon fuel consumption influences the specific fuel consumption negatively. The specific fuel consumption is directly proportional to the ratio (Fig. 3A). Our proposal is that the present AGO and low pour fuel oil consumption levels are totally replaced with natural gas equivalently. This would yield the following fuel mix: 46% refinery fuel gas, 46% natural gas, and 8% coke. This, in effect, means low-carbon fuels of 92% and coke of 8%. It would also lead to a specific fuel consumption that is averagely unaffected by high-carbon/low-carbon fuel consumption ratios (Fig. 4). However, due to the relatively high LHV nature of PHRC refinery fuel gas (51.91 MJ/kg), compared with that of natural gas (44.95 MJ/kg), the specific fuel consumption is still going to be mildly sensitive to the natural gas/refinery fuel gas ratio, signifying that refinery fuel gas may be more preferred in this case (Fig. 5). Nevertheless, natural gas utilization still has its main advantage in its flare/waste, and consequent environmental degradation reduction.

Finally, Figure 6 indicates that the proposed fuel mix would generally lead to lower specific fuel consumption values, thus saving energy and reducing costs.

Conclusion

A fuel-mix analysis of energy utilization in PHRC has been carried out for the period 2000–2011. The analysis has unraveled capacity underutilization and fuel mixes that can still be improved upon for environmental sustainability and higher utilization efficiency as the major challenges. Substituting high-carbon fuels with low-carbon fuels is the main proposal of this study. Capacity utilization also has to be improved upon in order to curb the present energy waste in the refinery.

Conflict of Interest

None declared.

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