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Energy, Exergy and Economic Analyses of Energy Sourcing Pattern in a Nigerian Brewery

Wasiu Oyediran Adedeji, Ismaila Badmus*
Department of Mechanical Engineering, Yaba College of Technology, Lagos, Nigeria
Email: diranadedeji@yahoo.com, *ismail.badmus@gmail.com

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ABSTRACT

Energy, exergy, and economic analyses of energy sourcing pattern in a Nigerian brewery have been carried out. The mean annual energy efficiencies have varied from 75.62% in 2004 to 81.71% in 2006, while the mean annual exergy efficiencies have varied from 42.66% in 2004 to 57.10% in 2005. Diesel fuel combustion, whether for local electricity generation via internal combustion engines or for process steam raising in boilers, has adversely affected the efficiencies of energy utilisation in the company. The negative effect of steam raising on efficient energy utilisation is more, although steam raising is unavoidable, due to the nature of the company under investigation. The annual mean energy unit costs have also varied from 27.86 USD per Giga-Joule in 2006 to 32.80 USD per Giga-Joule in 2004, confirming the inverse proportion of energy efficiency and costs. On the other hand, the annual mean exergy unit costs have varied from 40.19 USD per Giga-Joule in 2005 to 58.46 USD per Giga-Joule in 2004. The most efficient year has been 2006 energetically and 2005 exergetically. The difference in the two years lies in the proportions of generator diesel and boiler diesel utilised as the system exergy is most sensitive to boiler diesel use while the system energy is more sensitive to generator diesel utilisation due to their different device efficiencies.

Keywords: Exergy; Energy; Diesel; Electricity; Process Steam Boiler

1. Introduction

Historically, energy has been the pivot of economic development of most countries all over the world and this trend persists. It has brought great economic prosperity to nations and has been the centre for social and overall human development. Unfortunately, due to the way energy is sourced, produced and used historically, two major drawbacks have evolved. Firstly, the overall energy system has been very inefficient; and secondly, major local and global environmental, social and health problems have been associated with the energy system [1]. This throws up the twin challenge of energy conversion efficiency improvement and sustainable environmental management.

Nigeria is endowed with a vast amount of energy resources. According to the OPEC annual statistical bulletin [2], Nigeria proven crude oil reserves and natural gas are 37.2 billion barrels and 5292 trillion standard cubic metres, respectively.

Despite these huge resources which should have translated into cheap, affordable and reliably constant power supply, an estimated 60 million Nigerians now own power generating sets for their electricity, while the same number of people spend a staggering $10 billion to fuel them annually [3] quoted in ECN [4]. According to Oniwon [5], 15% of Nigeria's produced natural gas is still flared while only 12% is utilized locally between Industrial and power sectors.

Nigerian industrialists and other stakeholders have bitterly decried the situation of the Nigerian power sector. For instance, the manufacturers, who operate under different trade associations like the Manufacturers Association of Nigeria (MAN) and Nigeria Association of Small Scale Industries (NASSI), once said that the major problem facing the manufacturing sector was the lack of power, explaining that the volume of diesel consumed daily in Nigeria was currently put at between 12 million and 13 million litres [6] quoted in [4].

Activities in the company revolve round brewing of (non-alcoholic) malts and (alcoholic) lager beer. To carry out this production there are various processes involved and these include: decoration, bottle washing, filling, capping, pasteurization, cooling and so on. All these processes require steam, air, water, electricity, etc. Generators are used as alternative source of electricity when there is power outage from the national grid (the Power Holding Company of Nigeria, PHCN). But due to inefficient and unavailable electricity supply from the Power

*Corresponding author.

Holding Company of Nigeria, as testified to by many stakeholders like Iwayemi [7], most companies largely depend on generators. At this brewery, generators supply power for most of the running hours, while PHCN supply power for the rest. The boiler is used most of time because most of the processes require steam for washing, sterilizing, heating, pasteurizing, etc.

2. Theory

The principle of energy conversation is the first law of thermodynamics, which stipulates that under no circumstance can energy be destroyed. This law states that the amount of heat transferred into a system less the amount of work done by the system must be equal to the corresponding change in the system energy. In effect, heat and work are means by which systems exchange energy with one another. Mathematically,

$$ {}_1Q_2 - {}_1W_2 = E_2 - E_1 \tag{1} $$

Although electrical, mechanical and kinetic energies are all forms of energy which can be transformed into one other nearly completely, this is not so in the case of thermal energy as in case of internal combustion engine where the heat generation occurs in the cylinder but the useful component converted to mechanical use is less than 50%.

The first law of thermodynamics treats all energy forms in the same way. There are, however, certain types of energy that are more valuable than others.

Thus, we define the quality of the energy as the potential to produce useful work.

Exergy is the maximum work potential of a material or of a form of energy in relation to its environment. This work potential can be obtained by reversible processes. However, in reality there are only irreversible processes. Thus, we seek the work potential of a system, relative to the dead state, or reference environment.

The dead state of a system is the state in which it is in equilibrium with the environment. This means same temperature and pressure, no relative motion and same altitude.

For practical reasons a reference environment has been defined for the environment. The reference environment is considered to be so large, that its parameters are not affected by interaction with the system under consideration. In this work, the reference system as stated in Szargut *et al.* [8] and Kotas [9], both quoted in Cornelissen [10], has been used with a reference temperature (T_0) of 298.15 K and a reference pressure (P_0) of 1 atm. There are exergy transfers with work and heat transfers as well as material streams.

2.1. Exergy Transfer with Work Interaction

The exergy transfer with work interaction is associated with work transfer rate or shaft power. Because exergy is defined as the maximum work potential, work is equivalent to exergy in every respect.

2.2. Electrical Energy and Exergy

Electrical energy is not affected by ambient conditions and therefore is equivalent in work. In other words, electrical energy can be treated as totally convertible to work.

2.3. Exergy Transfer with Heat Interaction

The exergy transfer rate $(\dot{E})$ connected with the heat transfer rate $(\dot{Q})$ can be calculated using the following formula:

$$ \dot{E} = \int_A \left(1 - \frac{T_0}{T}\right) \dot{Q} \mathrm{d}A \tag{2} $$

where A is the heat transfer area, T_0 is the temperature of the environment, T is the temperature at which the heat transfer takes places. When there is a uniform temperature distribution, the expression becomes:

$$ \dot{E} = \dot{Q}\left(1 - \frac{T_0}{T}\right) \tag{3} $$

2.4. Exergy Transfer Associated with Material Streams

Chemical Exergy

One of the most common energy carriers is hydrocarbon/fossil/biomass fuels. The specific exergy of this class of thermodynamic systems is the chemical exergy. Chemical exergy is equal to the maximum amount of work obtainable when the substance under consideration is brought from the environmental state, defined by the parameters T_0 and P_0, to the reference state by processes involving heat transfer and exchange of substances only with the environment.

For many fuels the chemical structure is unknown. To overcome this problem the chemical exergy for these fuels can be estimated on the basis of the higher heating value (HHV). The relationship between the HHV and the chemical exergy is:

$$ b_{\mathrm{ch}} = \varphi \cdot \mathrm{HHV} \tag{4} $$

φ, the fuel chemical exergy factor can be calculated with formulae based on the atomic composition. For diesel [11], φ is 1.07 and for natural gas, it can be approximated as 0.94 [12] quoted in Hepbasli [13].

2.5. Energy and Exergy Efficiencies of the Processes

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

$$\eta = \frac{\text{Energy in products}}{\text{Total energy input}} \quad (5)$$

$$\psi = \frac{\text{Exergy in products}}{\text{Total exergy input}} \quad (6)$$

The particular efficiencies are as follows:
Boiler energy efficiency:

$$\eta_b = \frac{Q_{o,b}}{Q_{i,b}} \quad (7)$$

Boiler exergy efficiency:

$$\psi_b = \frac{X_b}{\varphi Q_{i,b}} \quad (8)$$

Generator energy efficiency:

$$\eta_g = \frac{W_{e,g}}{Q_g} \quad (9)$$

Generator exergy efficiency:

$$\psi_g = \frac{X_{e,g}}{\varphi Q_g} \quad (10)$$

Electrical energy efficiency:

$$\eta_e = \frac{W_{e,m} + \eta_g Q_g}{W_{e,m} + Q_g} \quad (11)$$

Electrical exergy efficiency:

$$\psi_e = \frac{W_{e,m} + \psi_g \varphi Q_g}{W_{e,m} + \varphi Q_g} \quad (12)$$

Total energy efficiency:

$$\eta_{total} = \frac{W_{e,m} + \eta_g Q_g + \eta_b Q_{i,b}}{W_{e,m} + Q_g + Q_{i,b}} \quad (13)$$

Total exergy efficiency:

$$\psi_{total} = \frac{W_{e,m} + \psi_g \varphi Q_g + \psi_b \varphi Q_{i,b}}{W_{e,m} + \varphi Q_g + \varphi Q_{i,b}} \quad (14)$$

In all cases,

Q = fuel mass × fuel heating value (15)

2.6. Economic Analysis

2.6.1. Mains Electricity Tariff

Mains electricity tariff for the industrial sector from 1st Feb. 2002 to 30th June 2009, for power consumption above 20MVA is N8.50 per kWh [14]. This is equivalent to a unit cost, $C_{n,m},\left(= C_{x,m} = C_m\right)$ of $15.74 per GJ of mains electricity, at N150 per US dollar.

2.6.2. Diesel Generator Output Electricity Unit Costs

Energy unit cost, $C_{n,g}$, is given by:

$$C_{n,g} = \frac{c_f}{\eta_g HV} \quad (16)$$

Exergy unit cost, $C_{X,g}$, is given by:

$$C_{X,g} = \frac{c_f}{\varphi_g \psi_g HV} \quad (17)$$

2.6.3. Boiler Steam Generation Unit Costs

Boiler energy unit cost, $C_{n,b}$, is given by:

$$C_{n,b} = \frac{c_f}{\eta_b HV} \quad (18)$$

Boiler exergy unit cost, $C_{X,b}$, is given by:

$$C_{X,b} = \frac{c_f}{\varphi_b \psi_b HV} \quad (19)$$

Since, in our case, both the boiler and the generator use the same fuel, $\varphi_b = \varphi_g = \varphi$

2.6.4. Mean Output Electricity Unit Costs

Mean electrical energy unit cost

$$\bar{C}_{n,e} = \frac{C_m \times W_{e,m} + C_{n,g} \times Q_g}{W_{e,m} + \eta_g Q_g} \quad (20)$$

Mean electrical exergy unit cost

$$\bar{C}_{X,e} = \frac{C_m \times W_{e,m} + C_{X,g} \times \varphi Q_g}{W_{e,m} + \psi_g \varphi Q_g} \quad (21)$$

2.6.5. Overall Mean Unit Costs

Overall mean energy unit cost

$$\bar{C}_n = \frac{C_m \times W_{e,m} + C_{n,g} \times Q_g + C_{n,b} \times Q_{i,b}}{W_{e,m} + \eta_g Q_g + \eta_b Q_{i,b}} \quad (22)$$

Overall mean exergy unit cost

$$\bar{C}_X = \frac{C_m \times W_{e,m} + C_{X,g} \times \varphi Q_g + C_{X,b} \times \varphi Q_{i,b}}{W_{e,m} + \psi_g \varphi Q_g + \psi_b \varphi Q_{i,b}} \quad (23)$$

3. Methodology

Due to difficulties in accessing the production process lines details; this work concentrates on the assessment of the company energy sourcing efficiencies rather than the end uses. Electricity has been sourced from both the national grid and diesel fuelled generators. Steam has been raised using diesel fuel alone to fire the boilers. Are there better options on ground for the company? This is the focus of this work.

To examine the energy utilization efficiency of the company, a five-year data (2004-2008) was collected from the company utilities section. The data collected covers the following areas:

i) Mains Electricity bill (PHCN)—kWh/$ values

ii) Energy value computed from volumes of fuel consumed for firing the boilers and running electrical generators on monthly basis (GJ).

Energy consumption in the factory affects the period costing and pricing directly. Considering energy value of diesel oil, one litre is equivalent to 39 MJ [15], using the higher heating value. The diesel engine power plant energy efficiency and exergy efficiency are taken to be 47% and 43.8% respectively [16]. Also, we are taking boiler energy efficiency to be 72.46% and its exergy efficiency to be 24.89% [17].

4. Results

The results in **Tables 1-5** were obtained for the years 2004-2008 respectively from available data.

5. Discussion of Results

Generally, the electrical energy and exergy efficiencies are very numerically close. This is because electrical energy and exergy values are thermodynamically equal. The small disparities that exist between the energy and exergy efficiency values in our case is due to the relatively low electrical energy generation efficiency of diesel powered internal combustion engines (47% for energy and 43.8% for exergy). Secondly, the total energy and exergy efficiencies are further brought down in value by the relatively low thermal efficiencies of the process steam boilers. The boiler energy efficiency (72.46%) and exergy efficiency (24.89%) have led to very wide gaps between the total energy efficiencies and total exergy efficiencies.

Considering the year 2004 (**Figure 1(a)**), all efficiencies except for total exergy one, record their lowest values in the month of January. This is due to the fact that the electricity supply is dominated by low efficiency diesel engine generated electric power for the month but the low percentage of boiler fuel in the overall fuel mix (**Figure 1(b)**) has led to the improvement of the overall exergy efficiency. February has high electrical energy and exergy efficiencies because the generator diesel portion of the total energy supply mix is only about 3.6%. In May, we have low overall energy efficiency since practically all the three energy supply types have equal quantities (**Figure 1(b)**). The month of June has the highest electrical energy and exergy efficiencies (97.06% and 96.68% respectively) for the year because its diesel generator supply (2.7%) is the least after the month of December (2.5%) but its boiler fuel supply (52%) is almost half of that of December (95.7%).

Table 1. Energy consumption pattern for the year 2004.

Month	Mains Electricity (GJ)	Generator Diesel Energy Value (GJ)	Generator Diesel Exergy Input (GJ)	Generator Elect. Energy Output (GJ)	Generator Elect. Exergy Output (GJ)	Total Elect. Energy Output (GJ)	Total Elect. Exergy Output (GJ)	Boiler Diesel Energy Value (GJ)	Boiler Diesel Exergy Input (GJ)	Boiler Energy Produced (GJ)	Boiler Exergy Produced (GJ)	Total Energy Produced (GJ)	Total Exergy Produced (GJ)
Jan.	255.4	682.4	730.168	320.728	319.8136	576.128	575.2136	546.9	585.183	396.2837	145.652	972.4117	720.8656
Feb.	447	39.2	41.944	18.424	18.37147	465.424	465.3715	614.7	657.729	445.4116	163.7087	910.8356	629.0802
Mar.	445.3	329	352.03	154.63	154.1891	599.93	599.4891	852.1	911.747	617.4317	226.9338	1217.362	826.423
April	748.9	214.8	229.836	100.956	100.6682	849.856	849.5682	771.9	825.933	559.3187	205.5747	1409.175	1055.143
May	1077.7	1008.7	1079.309	474.089	472.7373	1551.789	1550.437	1006.4	1076.848	729.2374	268.0275	2281.026	1818.465
June	897	52.7	56.389	24.769	24.69838	921.769	921.6984	1028.9	1100.923	745.5409	274.0197	1667.31	1195.718
July	900.4	195.8	209.506	92.026	91.76363	992.426	992.1636	1306.6	1398.062	946.7624	347.9776	1939.188	1340.141
Aug.	924.3	130.2	139.314	61.194	61.01953	985.494	985.3195	1612.6	1725.482	1168.49	429.4725	2153.984	1414.792
Sept.	1013.7	158.3	169.381	74.401	74.18888	1088.101	1087.889	1581.9	1692.633	1146.245	421.2964	2234.346	1509.185
Oct.	797.1	482.4	516.168	226.728	226.0816	1023.828	1023.182	2258.6	2416.702	1636.582	601.5171	2660.41	1624.699
Nov.	833.1	770	823.9	361.9	360.8682	1195	1193.968	1142.7	1222.689	828.0004	304.3273	2023	1498.295
Dec.	250.39	356	380.92	167.32	166.843	417.71	417.233	13.467	14409.69	9758.188	3586.572	10175.9	4003.805
Total	8.590	4.420	4728.865	2077.165	2071.243	10667.46	10661.53	26.190	28023.62	18977.49	6975.079	29644.95	17636.61
Mean	715.8575	368.2917	394.0721	173.0971	172.604	888.9546	888.4611	2182.525	2335.302	1581.458	581.257	2470.412	1469.718

Table 2. Energy consumption pattern for the year 2005.

Month	Mains Electricity (GJ)	Generator Diesel Energy Value (GJ)	Generator Diesel Exergy Input (GJ)	Generator Elect. Energy Output (GJ)	Generator Elect. Exergy Output (GJ)	Total Elect. Energy Output (GJ)	Total Elect. Exergy Output (GJ)	Boiler Diesel Energy Value (GJ)	Boiler Diesel Exergy Input (GJ)	Boiler Energy Produced (GJ)	Boiler Exergy Produced (GJ)	Total Energy Produced (GJ)	Total Exergy Produced (GJ)
Jan.	592.9	335.2	358.664	157.544	157.0948	750.444	749.9948	669.2	716.044	484.9023	178.2234	1235.346	928.2182
Feb.	575.2	225.4	241.178	105.938	105.636	681.138	680.836	928.1	993.067	672.5013	247.1744	1353.639	928.0103
Mar.	1068.1	208.9	223.523	98.183	97.90307	1166.283	1166.003	1054.9	1128.743	764.3805	280.9441	1930.664	1446.947
April	774.5	184.5	197.415	86.715	86.46777	861.215	860.9678	805.6	861.992	583.7378	214.5498	1444.953	1075.518
May	773.4	484.4	518.308	227.668	227.0189	1001.068	1000.419	1391.3	1488.691	1008.136	370.5352	2009.204	1370.954
June	688	117.8	126.046	55.366	55.20815	743.366	743.2081	92.3	98.761	66.88058	24.58161	810.2466	767.7898
July	773.4	117.8	126.046	55.366	55.20815	828.766	828.6081	923.3	987.931	669.0232	245.896	1497.789	1074.504
Aug.	643.18	87.6	93.732	41.172	41.05462	684.352	684.2346	1066.1	1140.727	772.4961	283.927	1456.848	968.1616
Sept.	914.8	169.3	181.151	79.571	79.34414	994.371	994.1441	39.6	42.372	28.69416	10.54639	1023.065	1004.691
Oct.	723.2	1274.8	1364.036	599.156	597.4478	1322.356	1320.648	1206.9	1291.383	874.5197	321.4252	2196.876	1642.073
Nov.	1032	1223.8	1309.466	575.186	573.5461	1607.186	1605.546	949.6	1016.072	688.0802	252.9003	2295.266	1858.446
Dec.	859.8	135	144.45	63.45	63.2691	923.25	923.0691	711.4	761.198	515.4804	189.4622	1438.73	1112.531
Total	9.418	4.565	4.884	2145.315	2139.199	11563.8	11557.68	9.838	10526.98	7128.832	2620.166	18692.63	14177.84
Mean	784.8733	380.375	407.001	178.7763	178.2664	963.6496	963.1397	819.8583	877.2484	594.0693	218.3471	1557.719	1181.487

Table 3. Energy consumption pattern for the year 2006.

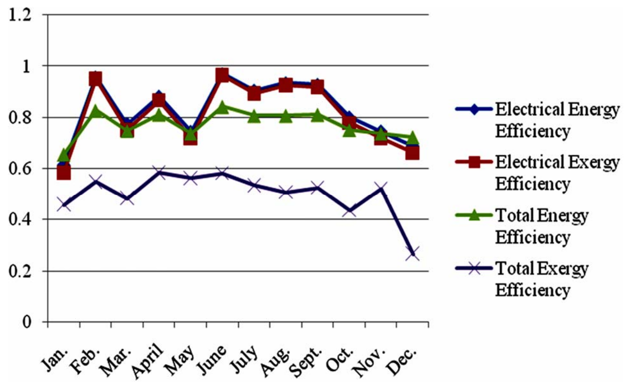
Month	Mains Electricity (GJ)	Generator Diesel Energy Value (GJ)	Generator Diesel Exergy Input (GJ)	Generator Elect. Energy Output (GJ)	Generator Elect. Exergy Output (GJ)	Total Elect. Energy Output (GJ)	Total Elect. Exergy Output (GJ)	Boiler Diesel Energy Value (GJ)	Boiler Diesel Exergy Input (GJ)	Boiler Energy Produced (GJ)	Boiler Exergy Produced (GJ)	Total Energy Produced (GJ)	Total Exergy Produced (GJ)
Jan.	866.7	94.2	100.794	44.274	44.14777	910.974	910.8478	634.4	678.808	459.6862	168.9553	1370.66	1079.803
Feb.	611.8	237	253.59	111.39	111.0724	723.19	722.8724	1317.1	1409.297	954.3707	350.774	1677.561	1073.646
Mar.	783.2	348.3	372.681	163.701	163.2343	946.901	946.4343	1083.8	1159.666	785.3215	288.6409	1732.222	1235.075
April	782.5	276.2	295.534	129.814	129.4439	912.314	911.9439	1335.1	1428.557	967.4135	355.5678	1879.727	1267.512
May	973	176.1	188.427	82.767	82.53103	1055.767	1055.531	1370.1	1466.007	992.7745	364.8891	2048.541	1420.42
June	970.1	182.4	195.168	85.728	85.48358	1055.828	1055.584	927.1	991.997	671.7767	246.9081	1727.605	1302.492
July	862.4	174.3	186.501	81.921	81.68744	944.321	944.0874	1250.9	1338.463	906.4021	333.1434	1850.723	1277.231
Aug.	1159.4	13.3	14.231	6.251	6.233178	1165.651	1165.633	1496.1	1600.827	1084.074	398.4458	2249.725	1564.079
Sept.	1159.4	29.5	31.565	13.865	13.82547	1173.265	1173.225	1643	1758.01	1190.518	437.5687	2363.783	1610.794
Oct.	1169.1	13.1	14.017	6.157	6.139446	1175.257	1175.239	1122.3	1200.861	813.2186	298.8943	1988.476	1474.134
Nov.	929.5	249.5	266.965	117.265	116.9307	1046.765	1046.431	1905.3	2038.671	1380.58	507.4252	2427.345	1553.856
Dec.	1205.9	74.3	79.501	34.921	34.82144	1240.821	1240.721	1600.1	1712.107	1159.432	426.1434	2400.253	1666.865
Total	11473	1868.2	1998.974	878.054	875.5506	12351.054	12348.55	15685.3	16783.27	11365.57	4177.356	23716.62	16525.91
Mean	956.0833	155.6833	166.5812	73.17115	72.96257	1029.25445	1029.046	1307.108	1398.606	947.1307	348.113	1976.385	1377.159

Table 4. Energy consumption pattern for the year 2007.

Month	Mains Electricity (GJ)	Generator Diesel Energy Value (GJ)	Generator Diesel Exergy Input (GJ)	Generator Elect. Energy Output (GJ)	Generator Elect. Exergy Output (GJ)	Total Elect. Energy Output (GJ)	Total Elect. Exergy Output (GJ)	Boiler Diesel Energy Value (GJ)	Boiler Diesel Exergy Input (GJ)	Boiler Energy Produced (GJ)	Boiler Exergy Produced (GJ)	Total Energy Produced (GJ)	Total Exergy Produced (GJ)
Jan.	983.2	14	14.98	6.58	6.56124	989.78	989.7612	1608.6	1721.202	1165.592	428.4072	2155.372	1418.168
Feb.	1260.7	238.7	255.409	112.189	111.8691	1372.889	1372.569	1220.1	1305.507	884.0845	324.9407	2256.973	1697.51
Mar.	1034.5	153.9	164.673	72.333	72.12677	1106.833	1106.627	1808.2	1934.774	1310.222	481.5652	2417.055	1588.192
April	950	154	164.78	72.38	72.17364	1022.38	1022.174	1338.3	1431.981	969.7322	356.4201	1992.112	1378.594
May	1058.8	176.1	188.427	82.767	82.53103	1141.567	1141.331	1190	1273.3	862.274	316.9244	2003.841	1458.255
June	828.4	302.7	323.889	142.269	141.8634	970.669	970.2634	1493.3	1597.831	1082.045	397.7001	2052.714	1367.964
July	1070.8	186.2	199.234	87.514	87.26449	1158.314	1158.064	1824.7	1952.429	1322.178	485.9596	2480.492	1644.024
Aug.	1274.2	33.7	36.059	15.839	15.79384	1290.039	1289.994	1671.2	1788.184	1210.952	445.079	2500.991	1735.073
Sept.	1161.8	73.2	78.324	34.404	34.30591	1196.204	1196.106	12043.7	12886.76	8726.865	3207.514	9923.069	4403.62
Oct.	1248.2	61.6	65.912	28.952	28.86946	1277.152	1277.069	1957.3	2094.311	1418.26	521.274	2695.412	1798.343
Nov.	904.5	700.7	749.749	329.329	328.3901	1233.829	1232.89	1863.7	1994.159	1350.437	496.3462	2584.266	1729.236
Dec.	960.4	249.5	266.965	117.265	116.9307	1077.665	1077.331	1925.7	2060.499	1395.362	512.8582	2473.027	1590.189
Total	12.736	2.344	2508.401	1101.821	1098.68	13837.321	13834.18	29.945	32040.94	21698	7974.989	35535.32	21809.17
Mean	1061.292	195.3583	209.0334	91.8184	91.55662	1153.1101	1152.848	2495.4	2670.078	1808.167	664.5824	2961.277	1817.431

Table 5. Energy consumption pattern for the year 2008.

Month	Mains Electricity (GJ)	Generator Diesel Energy Value (GJ)	Generator Diesel Exergy Input (GJ)	Generator Elect. Energy Output (GJ)	Generator Elect. Exergy Output (GJ)	Total Elect. Energy Output (GJ)	Total Elect. Exergy Output (GJ)	Boiler Diesel Energy Value (GJ)	Boiler Diesel Exergy Input (GJ)	Boiler Energy Produced (GJ)	Boiler Exergy Produced (GJ)	Total Energy Produced (GJ)	Total Exergy Produced (GJ)
Jan.	321.7	509.4	545.058	239.418	238.7354	561.118	560.4354	1324.3	1417.001	959.58778	352.69155	1520.7058	913.12695
Feb.	92.3	29	31.03	13.63	13.59114	105.93	105.89114	870.5	931.435	630.7643	231.83417	736.6943	337.72531
Mar.	2	1.1	1.177	0.517	0.515526	2.517	2.515526	2055	2198.85	1489.053	547.29377	1491.57	549.80929
April	1234.4	81.6	87.312	38.352	38.242656	1272.752	1272.6427	2005.2	2145.564	1452.9679	534.03088	2725.7199	1806.6735
May	1122.6	174.1	186.287	81.827	81.593706	1204.427	1204.1937	1040	1112.8	753.584	276.97592	1958.011	1481.1696
June	635	1784.5	1909.415	838.715	836.32377	1473.715	1471.3238	1654.4	1770.208	1198.7782	440.60477	2672.4932	1911.9285
July	926.9	115.5	123.585	54.285	54.13023	981.185	981.03023	2403.9	2572.173	1741.8659	640.21386	2723.0509	1621.2441
Aug.	900.3	51	54.57	23.97	23.90166	924.27	924.20166	1973.1	2111.217	1429.7083	525.48191	2353.9783	1449.6836
Sept.	874.3	77	82.39	36.19	36.08682	910.49	910.38682	2124	2272.68	1539.0504	565.67005	2449.5404	1476.0569
Oct.	787	24.8	26.536	11.656	11.622768	798.656	798.62277	1692.3	1810.761	1226.2406	450.69841	2024.8966	1249.3212
Nov.	716.4	184.5	197.415	86.715	86.46777	803.115	802.86777	1983.8	2122.666	1437.4615	528.33157	2240.5765	1331.1993
Dec.	710.3	136.7	146.269	64.249	64.065822	774.549	774.36582	1789.3	1914.551	1296.5268	476.53174	2071.0758	1250.8976
Total	8323.2	3169.2	3391.044	1489.524	1485.2773	9812.724	9808.4773	20915.8	22379.906	15155.589	5570.3586	24968.313	15378.836
Mean	693.6	264.1	282.587	124.127	123.77311	817.727	817.37311	1742.983	1864.9921	1262.9657	464.19654	2080.6927	1281.5696



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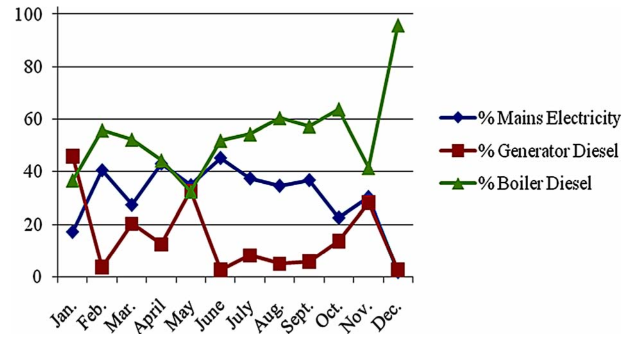

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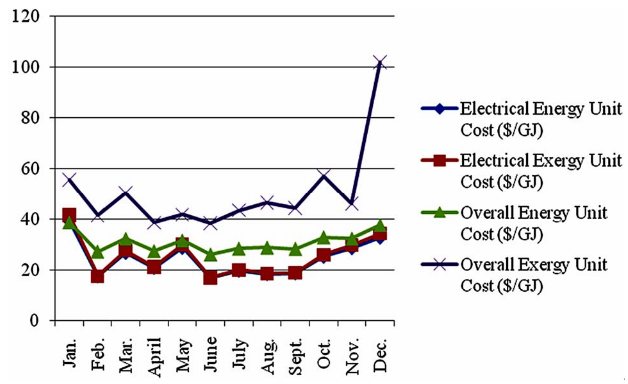


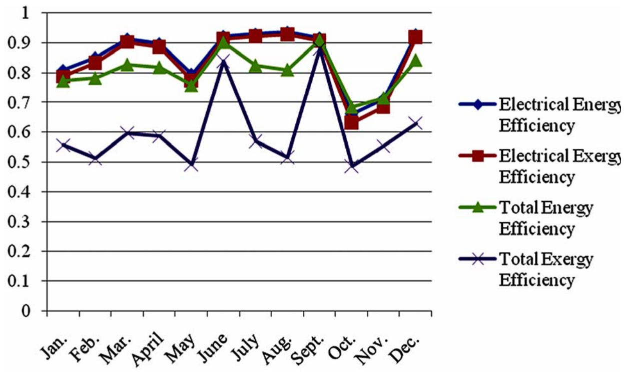
(c)

Figure 1. (a) Energy and exergy efficiencies for the year 2004; (b) Energy supply mix for the year 2004; (c) Energy and exergy unit costs for the year 2004.

The same line of argument applies to all the other years. For instance, for the year 2005, the months of June and September record high efficiencies (**Figure 2(a)**) and favourable energy mixes (**Figure 2(b)**) respectively. Similarly, the months of February, May, August and October have low efficiencies and unfavourable energy mixes respectively.

The year 2006 is with moderate efficiencies (**Figure 3(a)**) because although the boiler fuel consumption is generally high throughout the year, the electrical energy consumption from the mains is also generally high (**Figure 3(b)**). The year 2007 is similar to 2006 except for the month of September which has generally low electricity consumption (about 9.4% of total energy supply), with higher percentage share (8.75%) from the mains but very high boiler fuel consumption (90.7% of total energy supply), leading to the lowest total energy and exergy efficiencies for the year, despite high electrical energy and exergy efficiencies of 96.86% and 96.45%, respectively.

In the year 2008, the generator diesel consumption is generally low, except for the months of January (23.63%) and June (43.8%). However, the fact that June records



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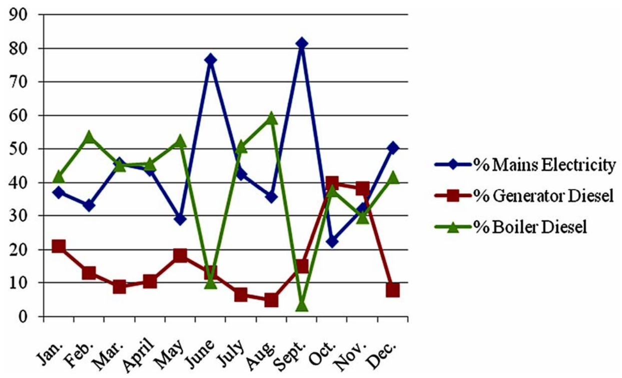

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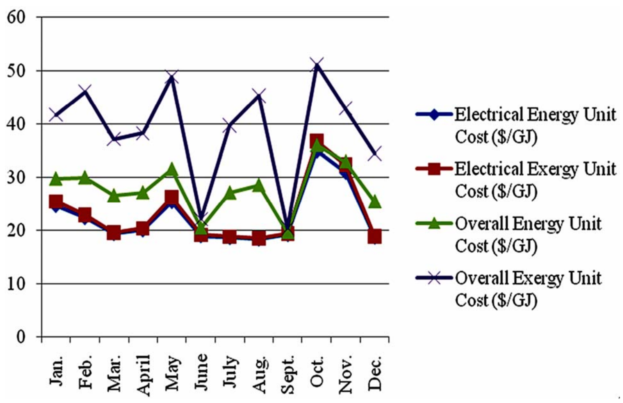

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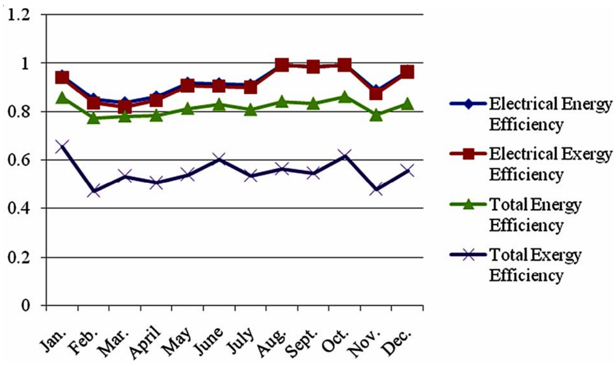
Figure 2. (a) Energy and exergy efficiencies for the year 2005; (b) Energy supply mix for the year 2005; (c) Energy and exergy unit costs for the year 2005.



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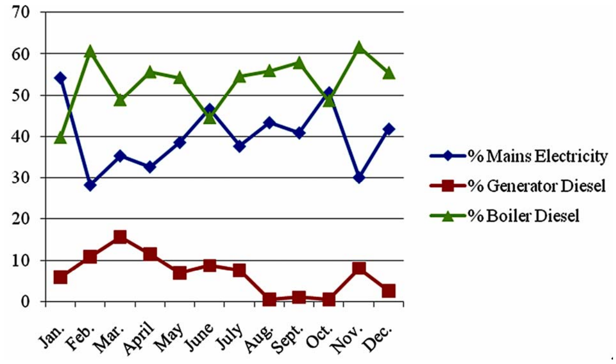

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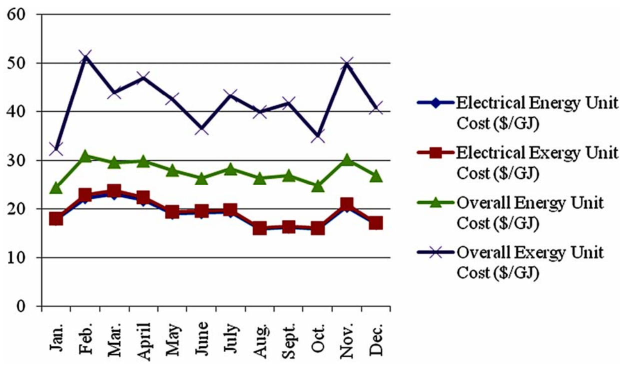

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Figure 3. (a) Energy and exergy efficiencies for the year 2006; (b) Energy supply mix for the year 2006; (c) Energy and exergy unit costs for the year 2006.

the lowest boiler fuel consumption for the year has positively influenced the exergy efficiency for the month to make it fall within the average value. January boiler fuel consumption is very high (61.44%). This, coupled with low mains electricity, has resulted in low efficiencies. March has the lowest total exergy efficiency for the year due to the domination of its energy supply by boiler fuel (99.85%).

Finally, the years 2005 and 2006 are the most energy efficient years with exergy efficiencies of 57.1% and 54.6% respectively. The year 2006 has higher energy efficiency and lower exergy efficiency than the year 2005 despite practically equal percentages of mains electricity supply (39.54% for 2005 and 39.53% for 2006) due to the fact that 2006 has relatively low percentage of generator fuel consumption but high percentage of boiler fuel consumption while 2005 has relatively high percentage of generator fuel consumption and low percentage of boiler fuel consumption. This observation reinforces the fact that high generator fuel consumption largely affects the total energy efficiency adversely while high boiler fuel consumption negatively affects the total exergy efficiency.

For the economic analysis, comparisons of **Figures 1(a)** and **(c)**, **Figures 2(a)** and **(c)**, **Figures 3(a)** and **(c)**, **Figures 4(a)** and **(c)**, **Figures 5(a)** and **(c)** as well as **Figures 6(a)** and **(c)** show that graphical representations of energy and exergy efficiencies are practically mirror inverses of those of the energy unit costs. Months and years of minimum efficiencies correspond to months and years of maximum energy unit costs and vice versa. These comparisons inform us that where we have efficient energy utilisation the costs are reduced, resulting in corresponding economic gains and vice versa. Comparing **Figure 6(a)** with **Figure 7**, one discovers that with total switching to the mains supply for electricity sourcing, the mean annual electrical energy and exergy efficiencies both become 100%; the mean annual total energy efficiencies vary from 79.26% to 85.93% while the mean annual total exergy efficiencies now vary from 42.51% to 60.36%. This means that the optimised generator diesel/boiler diesel is zero (zero generator diesel) for electricity. Before the switching, the corresponding values were 82% - 92.58%; 80.05% - 91.66%; 75.62% - 81.71% and 42.66% - 57.1%, respectively. These imply at least 7% savings in electricity and at least about 3% savings in overall energy. Hence, as a first step, the company still needs to consider this power source switching. This suggests that the major energy challenge facing the brewery is in its boiler energy utilization.

6. Conclusions and Recommendations

6.1. Conclusions

Energy, exergy, and economic analyses of energy sourcing pattern in a Nigerian brewery have been carried out. The brewery has relied on electricity from both the national grid and diesel-powered electrical generators. It also utilises diesel fuel oil for process steam boiler firing. The mean annual energy efficiencies have varied from 75.62% in 2004 to 81.71% in 2006, while the mean annual exergy efficiencies have varied from 42.66% in 2004 to 57.10% in 2005. Diesel fuel combustion, whether for local electricity generation via internal combustion engines or for process steam raising in boilers, has adversely affected the efficiencies of energy utilization in the company. The negative effect of steam raising

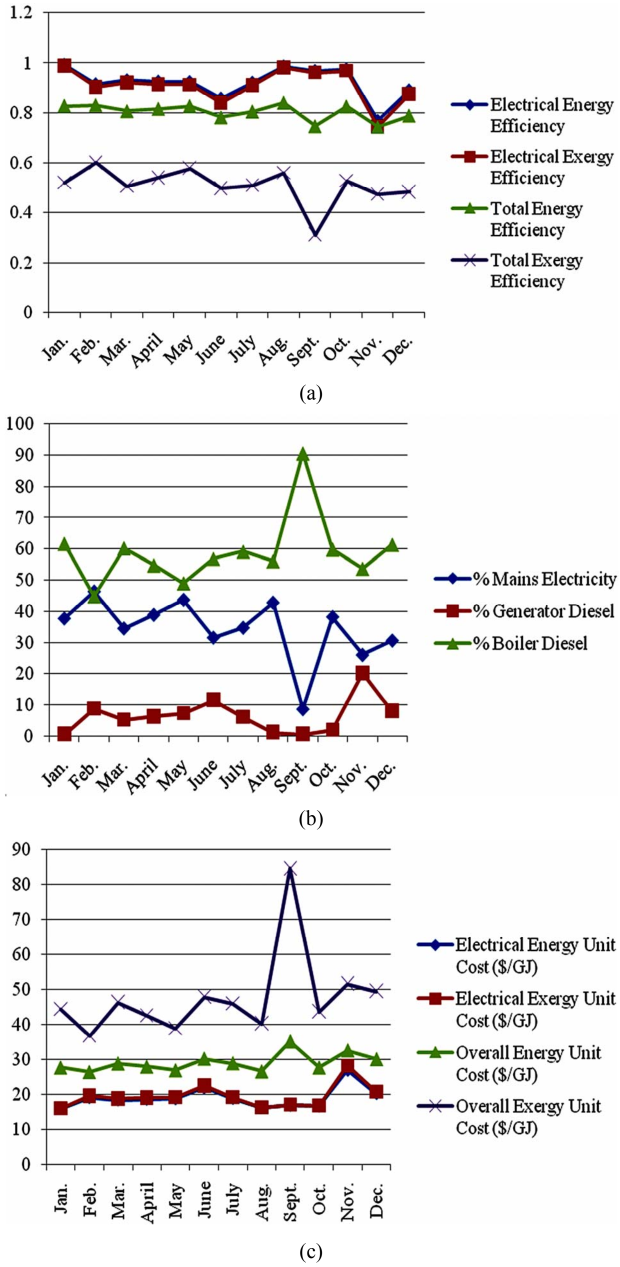


Figure 4. (a) Energy and exergy efficiencies for the year 2007; (b) Energy supply mix for the year 2007; (c) Energy and exergy unit costs for the year 2007.

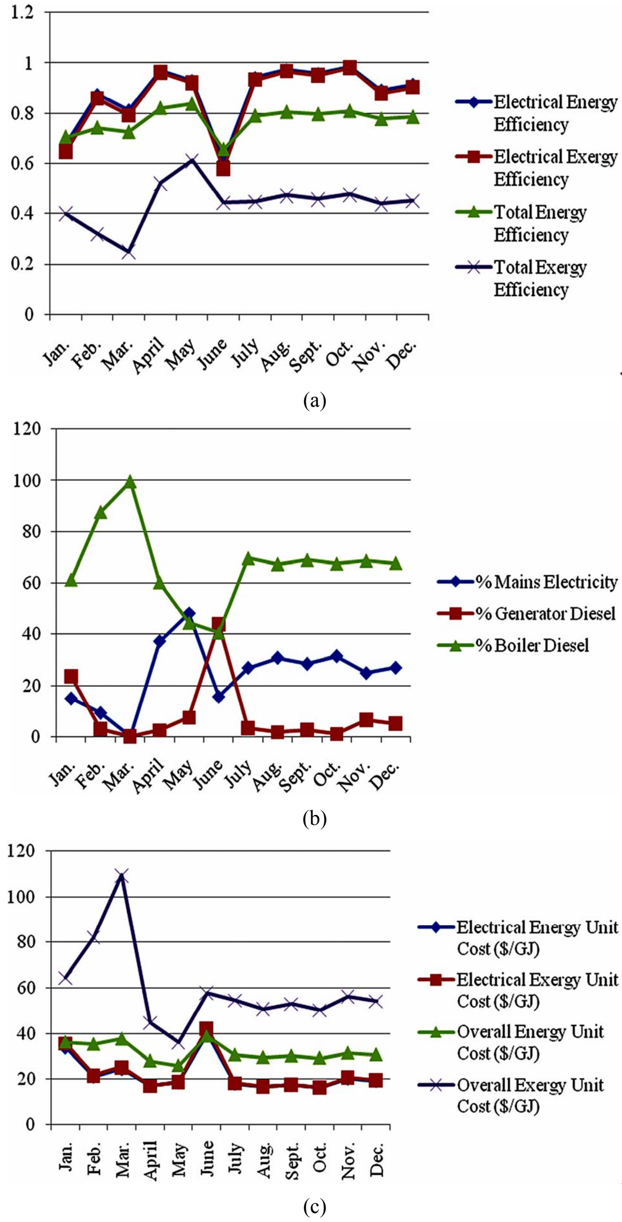
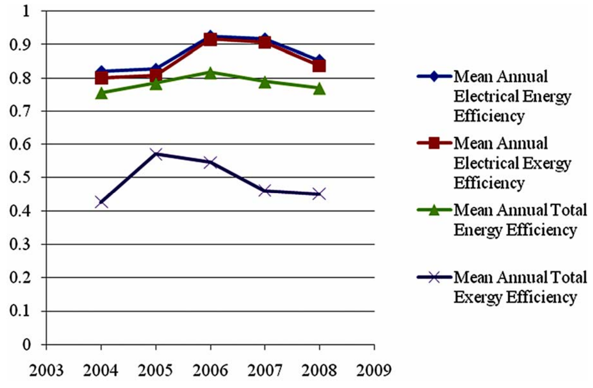


Figure 5. (a) Energy and exergy efficiencies for the year 2008; (b) Energy supply mix for the year 2008; (c) Energy and exergy unit costs for the year 2008.

on efficient energy utilisation is more, although steam raising is unavoidable, due to the nature of the company under investigation. The annual mean energy unit costs have also varied from 27.86 USD per Giga-Joule in 2006 to 32.80 USD per Giga-Joule in 2004, confirming the inverse proportion of energy efficiency and costs. On the other hand, the annual mean exergy unit costs have varied from 40.19 USD per Giga-Joule in 2005 to 58.46 USD per Giga-Joule in 2004. This also implies that year 2004 has been the worst year from all (energy, exergy and economic) points of view. The most efficient year has been 2006 energetically and 2005 exergetically. The difference in the two years lies in the proportions of generator diesel and boiler diesel utilised as the system exergy is more sensitive to boiler diesel use while the system energy is more sensitive to generator diesel utilisation due to their different device efficiencies.

6.2. Recommendations

Based on the findings in this paper, it is necessary to avoid electricity generation from diesel powered generators as much as possible. Secondly, steam generation is an unavoidable but very expensive process. Hence, spe-



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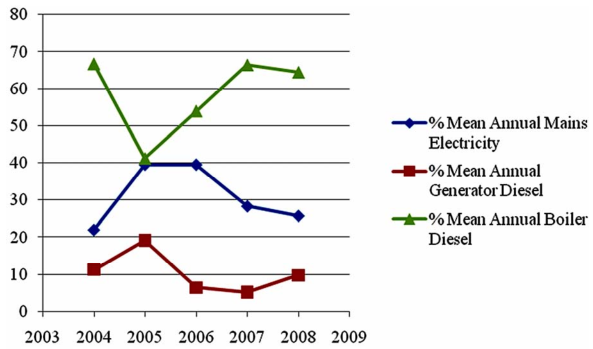

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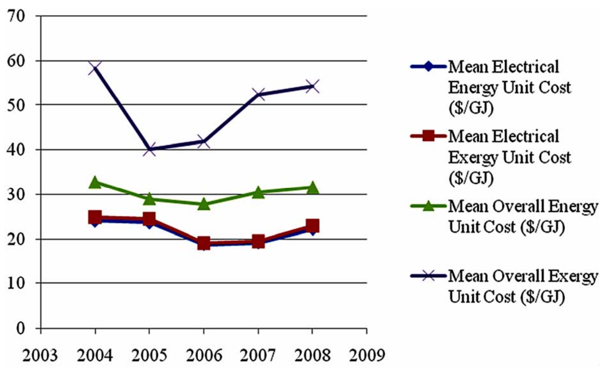

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Figure 6. (a) Mean annual efficiencies; (b) Mean annual energy supply mixes for the years 2004-2008; (c) Annual mean energy unit costs.

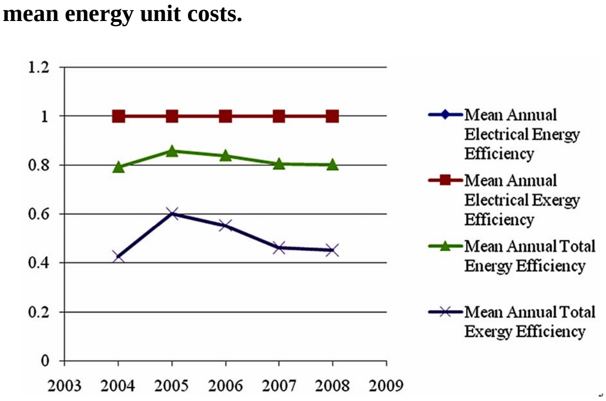

Figure 7. Mean annual efficiencies with zero generator diesel.

cial attention should be paid to process steam management to avoid unnecessary leakages and/or wastages. Lastly, in lieu of stable power supply from the national grid, a big company like this brewery should be able to consider a technically trusted energy conservation technique like cogeneration, since it needs both electrical power and process steam dearly.

For the boiler, the brewery may have to consider bigger size boilers. This is because authors like Pulkrabek [18] quoted in [16] have observed that general trend is that the greater is the plant size, the smaller is the specific fuel consumption. One reason for this is less heat loss due to the higher volume to surface area ratio of the combustion chamber

Secondly, a boiler fuel-switch from diesel to natural gas may be worthwhile, considering the fact that natural gas is a low-carbon fuel with a lower minimum allowable stack temperature than that of diesel oil [19] and Nigeria has the gas abundantly. A lower stack temperature would improve the boiler efficiency, reducing the company energy costs and bring down thermal pollution level, while the low carbon content would reduce CO_2, a green house gas, emission.

Finally, 2% - 8% boiler energy can be saved [17] by enhancing heat transfer rate of flue gases using nanofluids.

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