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ENERGY ANALYSIS AND ESTIMATION OF CO_2 EMISSION OF SELECTED PLASTIC RECYCLING PLANTS IN NIGERIA

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ABSTRACT

Energy management is a technical and management function which is to monitor, record, analyse, critically examine, alter and control energy flows through systems so that energy is utilized with maximum efficiency. In line with this, a study was conducted in 4 randomly selected plastic recycling plants located in Osun and Oyo States in South West Nigeria. The plants referred to as 1, 2, 3 and 4 in the study were investigated to determine the energy utilization patterns, estimate the CO_2 emission and carry out exergy analysis. The process analysis method of energy accounting was adopted to evaluate the energy requirement for each of the unit operations involved in the selected plants. Investigation revealed that the types of energy used in the recycling plants were electrical, thermal and human labour with percent contribution of 7.14, 92.83 and 0.03% of the total energy in plant 1. The corresponding values in the other plants were 87.81, 0, 11.9%; 22.44, 77.53, 0.03% and 8.12, 91.81, 0.06% respectively. The total energy requirements for the four plants per tons of raw plastic wastes were 16.9, 0.5, 49.3 and 11.5 GJ respectively. The amount of CO_2 emitted in all the four plastic plants, which were mainly from the use of liquid fuels, were 76.8, 77.2, 74.5 and 90.6 tons of CO_2 for 2005, 2006, 2007 and 2008 production years respectively. The exergy analysis revealed that melting operation accounted for the highest exergy (available energy) in all the four selected plants. The results of this study have provided baseline data needed for monitoring energy utilization and policy making decision in the selected plastic recycling plants which could also find useful application in other similar plants in Nigeria.

Keywords: Energy, plastic wastes, carbon dioxide, exergy

NUMENCLATURE

c_p	heat capacity (J/kg K)
C_f	calorific value of fuel (J/kg)
E_m	manual energy (J)
E_p	electrical energy (J)
E_t	thermal energy (J)
E_x	exergy (J)
e_x	specific exergy (J/kg)
h	specific enthalpy (J/kg)
H	enthalpy (J)
I	inefficiency
N	number of persons involved in operation
P	rated equipment power (kW)
p	pressure (kN/m^2)
R_s	production of entropy (J/K hr)
S	entropy (J/K)
s	specific entropy (J/kg K)
t	time (hr)
T	temperature (K)
w	mass flow rates (kg/hr)
W	work per unit time (W)
W_f	Quantity of fuel (l)
x_s	weight fraction (kg/kg)
η	power factor (assumed to be 0.8)

SUBSCRIPTS

f	fuel
i	denotes the number of unit operation
j	denotes type of energy ($j = 1$ represents electrical energy, $j = 2$, manual energy, $j = 3$, thermal energy)
k	section of plant; entrance or exit stream
l	heat exchange surface (l_{in}, input; l_{out}, output)
l_w	liquid water
m	manual energy
o	property of the surroundings
p	constant pressure
p	electrical energy
q	process stream (q_{in}, input; q_{out}, output)
r	useful reversible
seo	sum of energy per unit operation
t	thermal energy
tt	total sum of energy
u	useful

Energy Use in Nigeria

Energy is an essential input to all aspects of human activities. It is indeed the livewire of industries and agricultural production, the fuel for transportation as well as for the generation of electricity in conventional thermal power plants. Rising fuel cost and supply limitations plague every sector of Nigeria's economy. Industries are now, more than before, sensing the need for energy-related research to reduce costs through energy conservation to prevent possible shut downs consequent to reduced availability of energy resources. Nigeria is naturally endowed with abundant energy resources. The industrial sector of Nigeria has contributed greatly to the overall energy consumption in Nigeria, it has been reported that the industrial sector is second to the transport sector in terms of total commercial energy consumption in the country [Akinbami, 2001].

The share of industrial energy use to the total commercial energy consumption annually ranged between 13 and 33.5% in period 1970-1995 and on the average, it accounted for about 20% of total commercial energy use annually over the last three decades [Akinbami, 2001, Adegbulugbe, 1993]. This fraction is expected to increase as industrialization progresses, thereby tending towards the situation in many developed nations which is between 30% and 50% of their energy use annually [Adegbulugbe, 1993].

The major sources of industrial energy in Nigeria are fuel, oil, electricity, natural gas and coal. Coal was the major industrial fuel in the period before the middle of 1960s. This, however, changed as a result of the global shift from coal to crude oil due to the availability and convenience, natural gas became prominent as the leading industrial energy sources with an average of more than 92% per annum of total industrial energy consumption between 1970 and 1995 [Olajide, and Oyelade, 2002]. Consequently most industries in the country now rely mainly on the use of heavy-duty generating plant for the supply of their electrical energy.

CO_2 Emission from fuel consumption

Fuel consumption in industries has been reported [Priambodo and Kumar, 2001] to contribute significantly to global CO_2 emission, with 1990 estimate of 91 EJ of end use energy (including biomass) in the global industrial sector. This resulted in emissions of about 180Gt.C. When electricity consumption in the industries is included, the total primary energy consumed by the global industrial sector rose to 161EJ, increasing the emission to 2.8Gt.C, or about 47% of the global CO_2 emitted of the total GHG emission [IPCC, 2001). CO_2 contributed about 67%, while methane contributed about 18% (GEF, 1995).

The accumulation of carbon dioxide gases (GHG) due to anthropogenic action is seen to be an important reason for recent environmental problems, such as global warming and climate change [IPCC, 2001]. It is noted that liquid and solid fuels accounted for 77.5% of CO_2 emission from global fossil fuel burning in 1996, while the combustion of gaseous fuels accounted for 18.3% of the total emission from fossil fuel. The rest of the CO_2 emission emitted during the year 2001 was due to cement production, while gas flaring accounted for less than 5% [Marland *et al,* 1999)].

Plastic Use and Wastes

The disposal of plastic wastes is of worldwide concern because of its effect on the environment and ecology of the planet. It is observed that we consume bottle water whenever we go to restaurant, move along the road and we dispose this plastic waste without considering environmental factors. Due to increase in consumption of plastic, the disposal of plastic wastes on landfill sites has become increasingly popular close to area of habitation. Plastic industries have now taken this upon themselves to make use of this waste. Plastic materials have different polymers with different chemical structure which makes recycling processes more difficult due to their low density, combustible natures, resistance to biological degradation and degradation take place with ages of 25years. In order to reduce landfill capacity, plastic recycling programme was introduced to bring them back to market or reuse them. Material recycling of plastic wastes involves a number of treatments and operations.

Recycling is the introduction of used plastic products or waste into consumption cycle. During recycling of plastic wastes, the recycled material may be of lower quality than the virgin material. Therefore additives or stabilizers are added to improve the quality of the product. Recycling is also done when the amount of energy consumed in the recycling process is lower than the energy required for the production of new material. Before plastic can be recycled, they have to be sorted out into their different polymers because of their thermal behaviours and polymerization mechanism. Moreover, there are standards for all different type of polymers in which they must conform with. For plastic material to withstand stress and fatigue in services (i.e. to avoid failure), it must undergo some due processes to reduce some defects, which may be introduced during manufacturing processes, in which, chemical and mechanical properties can be altered. Recycling of plastic wastes would help to reduce the increase rate of landfill by proper collection of wastes. If plastic wastes are properly dumped, the effect of contamination would be reduced and prevent food poisoning, in most cases where they are used in food applications.

An overview of the literature reveals that there are no publications concerning the energy usage in plastic recycling industry in Nigeria, whereas literature is replete with information on energy usage in plants processing beverage [Akinbami, 2001], rice [Chang *et al*,1996, Ezeike, 1981], cashew-nut [Jekayinfa and Bamgboye, 2003], tea [Baruah and Bhattacharya, 1996, Megbowon and Adewunmi, 2002, Palaniappan and Subramanian, 1998], sugarbeet [Mrini *et al*, 2002], spinach [Ramadurai, 1994] and poultry [Mahapatra *et al*, 2003, 16], palm-kernel oil industry in Nigeria [Jekayinfa and Bamgboye, 2004, Jekayinfa and Bamgboye, 2006, Jekayinfa and Bamgboye, 2007, Dincer and Cengel, 2001]. This research work was carried out to estimate the carbon dioxide emission and energy use for recycling processes of the four different plastic recycling plants in Osun and Oyo States of Nigeria.

Exergy model equations

Exergy E_x for a closed system may be defined mathematically as

$$E_x = V(p - p_o)\ S(T - T_o) - \sum n_i(\mu_i - \mu_{io}) \qquad 1$$

The exergy of a flow crossing the system boundaries of an open system can be written as

$$E_x = (H - H_o)\ T_o\ (S - S_o) - \sum \mu(n_i - n_o) \qquad 2$$

where

$$H = U = p_o V \qquad 3$$

In the above equations, the extensive quantity, U denotes the internal energy, S the entropy. H the enthalpy, V the volume and n_i the number of mole of substance I, and the intensive quantity T temperature, P the pressure and μ_i the chemical potential of substance i. The subscript "o" denotes the conditions of the reference environment. The third term in equations (1) and (2) takes account of the contribution due to the chemical transformation of the system. The exergy difference ΔE_x between the outgoing and incoming streams for a steady flow process is defined as

$$\Delta E_x = W_u - T_o R_s \qquad 4$$

where W_u is the useful work, R_s the production of entropy and T_o the ambient temperature. The exergy difference ΔE_x is defined in terms of each component exergy $e_{x,q}$

- per unit mass and the mass flow rate w_q
- $$\Delta E_x = \sum_{qout} w_q e_x,_q \sum_{qin} w_q e_x,_q \qquad 5$$
- where each component exergy is defined as
- $$e_{x,q} = h_q - T_o s_q \qquad 6$$
- From Eq (4) it is obvious that the exergy change is a balance of useful work and the entropy production term, which can be regarded as work lost because of irreversibilities. For a reversible process, $R_s = 0$ and thus, the exergy change of a reversible process equal to most the useful work associated with a work-producing process or the least useful work required by
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- **Material and methods**
- **Use of questionnaire**:
- Interview pro-forma was used in the on - the spot assessment of recycling processes to obtain data from four different plastic industries. The plastic industries visited are: Dipson Plastic Limited, Black Horse plastic industry, Altak Industry Limited and Lopin Obelawo Plastic Industry allocated in Osogbo and Ibadan in Osun and Oyo States of Nigeria. The energy analysis was based on process analysis in which the direct energy consumption in every successive production step was estimated and material input to each operation also indicated. The principal operations involved in the production of plastic product are highlighted. The estimation of thermal energy (obtained

work-consuming process. It is evident from the foregoing that the exergy change and the creation of entropy are the energy bounds of the process or set of processes.

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- **Utilities exergy**
- All energy requirements result in the usage of primary utilities such as fuel, cooling water, steam, hot air and electricity. Electrical utilities are however included in the useful work, W_u, term. Process streams consist of raw materials, products, waste and intermediate materials, which are produced as raw materials undergo the corresponding transformation. In order to produce an energy-efficient design, it is often desirable to separate heating and cooling utilities stream from process streams in Eq (7). It follows that:
- $$\Delta E_{x,proc} = W_u + \Delta_{Ex,util} - T_o R_s \qquad 7$$
- Where the change in utility exergy $\Delta E_{x,util,}$ which in this work consists of stream only, can be determined through the following expression:
- $$\Delta E_{x,util} = H_{util,2}\ T_o\ (S_{util,1}\ S_{util,2}) \qquad 8$$
- The enthalpies and the entropies of stream can be obtained from the standard data table. The exergy change of the process stream can be determined using Eq. (4) and (5), which may be evaluated by using the tabulated data for enthalpies and entropies or by using predictive equations to estimate the exergy changes corresponding to the case of constant specific heat capacity and negligible residual exergies over the temperature range being considered [Rotstein, 1986]
- $$e_{x,2} - e_{x,1} = c_p(T_2 - T_1)\left(\frac{1 - T_o}{(T_2 - T_1)ml}\right) \qquad 9$$
- Where $(T_2 - T_1)ml = \dfrac{(T_2 - T_1)}{\ln(T_2/T_1)}$
- The specific heat constant can be determined by using
- $C_p = C_{lm}(0.3823 + 0.6183_{xm})$ where x_m is weight fraction

from the use of fuel), electrical energy (obtained from electricity use from national grid) and manual energy (from human labour) was done [Jekayinfa and Bamgboye, 2004, Dincer and Cengel, 2001].

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- **Energy analysis**
- For consistency, the energy components are calculated on the basis of 1000 kg of plastic and energy component from each source was estimated using the following procedure:

Electrical energy

The electrical energy usage by the equipment was obtained as the product of the rated power of each motor and the number of hours of operation. A motor efficiency of 80 % was assumed to compute the electrical inputs [4].

Mathematically

$$E_p = \eta P t \qquad (2)$$

where

E_p :- Electrical energy consumed in kWh

P :- Rated power of motor in kW

t :- Hours of operation in hr

η :- Power factor (assumed to be 0.8)

Manual energy

This was estimated based on the values recommended by Odigboh [Priambodo, 1998]. According to him, at the maximum continuous energy consumption rate of 0.30 kW and conversion efficiency of 25%, the physical power output of a normal human labourer in tropical climates is approximately 0.075 kW sustained for an 8-10 h workday.

Mathematically,

$$E_m = 0.075 N t \text{ (kWh)} \qquad (3)$$

where

0.075 is the average power of a normal human labour in kW

N :- Number of persons involved in an operation

t :- Useful time spent to accomplish a given task in hours

Thermal energy

The thermal energy derived from the fossil fuel (diesel) which is used to run the internal combustion engine for the generation of electrical power and the quantity of diesel used in the steam boiler was estimated by multiplying the quantity of fuel consumed by the corresponding calorific value of the fuel used [Wangskarn *et al,*].

Mathematically,

$$E_t = C_f W \qquad (4)$$

where

E_t :- Thermal energy consumed (J)

C_f:- Calorific value of fuel used (J/l)

W:- quantity of fuel used (l)

- The computation of energy used was done using spreadsheet program on Microsoft Excel. This eliminates the need for employing expensive simulation software and for labouring over hand calculations. Furthermore, the computational procedure is easy to follow by any plant operators desiring to compute the energy consumption in each processing operation at any accounting period. The equations will provide baseline information needed for carrying out budgeting, forecasting energy requirements and planning expansion in plastic recycling plants. [Johnson, 1999].

- **Methodology**

Before the commencement of the experiments, known quantity of fuel was measured into the empty tank of the captive electricity generator in each plant. The initial reading of the electric power reading meter installed in each section of the plant was taken at this time. After the completion of the processing of 1000 kg of plastic waste, the quantity of the fuel left in the generator's tank and the final reading of the electric meter were taken. The differences in these readings represented the quantity of fuel used (in litres) and the electric power consumed (in kilowatt), respectively. For each of the operations, the number of persons involved was noted and the time taken was also recorded using a stopwatch with all intermittent resting and idle period deducted. From this procedure, it was possible to assign thermal, electrical, both thermal and electrical, or manual energy to each unit operation. Conversion of these raw data to energy equivalents was done using the developed energy equations. For consistency, the energy components were calculated on the basis of 1000 kg of plastic wastes. This approach is similar to that used in previous studies by Ezeike [1981] and Jekayinfa and Bamgboye [2003, 2004, 2006, and 2007].

- **Performance parameters**
- The following energy performance parameters were measured in the course of the study:
- 1. Specific Energy Consumption: which is given by

$$SEC = \frac{\text{total energy (fuel and/electricity) consumption in the factory during a year}}{\text{total production in the factory during the year}} \qquad 16$$

- 2. Energy Intensity: The energy intensity was defined as the energy consumed per unit of plastic waste recycled.

- **Estimation of CO_2 emission**
- The CO_2 emission from each selected plastic recycling plant was estimated using the available data on fuel and electricity consumption. A procedure used in a similar study [ ] was followed. From the energy use data of individual factories (based on the energy audits), the CO_2 emission due to fuel (direct CO_2 emission) and electricity (indirect CO_2 emission) use were calculated based on intergovernmental panel on climate change (IPCC) guideline [IPCC, 2001].
- Fuel consumption refers to the total fuel used in the industrial sector or electricity generation sector. The carbon content of the fossil fuel was given by the CEF. The IPCC has established CEF values which can be used for general cases when data regarding fuel composition in a particular country has not been determined even though these may vary considerably for a given type of fuel. The fraction oxidized is used to take into account the carbon content which is not oxidized. The ratio of 44/12 converts the mass of carbon to that of CO_2 generated. The quantities have been first converted into energy units (TJ). These are standards by IPCC for emission factors: fuel oil (21.1tC/TJ), kerosene (19.6tC/TJ), Diesel (20.2tC/TJ) etc. [SSMIS,1993]
- annual direct CO_2 emission = C_f x

$$FC \times CEF \times fo \times 44/12 \qquad 17$$

annual indirect CO_2 emission

$$= \frac{EC \times CEF_e}{\eta_{TD}} \qquad 18$$

- where,
- CEF = Carbon emission factor (ton of carbon/TJ)
- CEF_e = Carbon dioxide emission factor due to electricity generation (CO_2/MWh_c)
- f_o = Fraction oxidized (%)
- EC = Annual electricity consumption in a factory (MWh_c/year)
- FC = annual fuel consumption in the factory.
- The CO_2 emission factor due to electricity generation, CEF_e (CO_2 /MWh_e) is estimated using (annual fuel consumption in the electricity generation sector in Nigeria by specific technology/process) × CEF × f_o × 44/12), The emission factors depend on the production method (e.g fuel used) and the technology used [Priambodo, 1998].
- The CO_2 emission per unit of electricity generated, CEF_e was then estimated to be 0.93ton of CO_2 /MWh_e and the transmission and distribution efficiency, η_{TD} is 0.79 to estimate the annual indirect CO_2 emission due to electricity consumption.
- The specific CO_2 emission from the factory could then be estimated by
- $$\text{Specific } CO_2 \text{ emission} = \frac{\text{Annual emission (direct and indirect)(ton) from the factory}}{\text{Annual production (ton of product)}} \qquad 19$$
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[Wangskarn, et al]

- **Conversion of Plastic Scrap or Waste**
- Plastic wastes were collected from different locations by cheap labours and then taken to recycling planst to undergo some operational processes of recycling. Although plastic wastes are meant to undergo all processes of recycling but due to variation in their chemical compositions, most plastic industries have different modes of operational procedures through which their wastes are recycled. The Chart in Fig. 1 explains the typical processes plastic wastes undergo before it is finally recycled.

Table 1: Required Parameters for Evaluating Energetic and Technical Data in Operational Units of Plastic Waste Recycling in the Selected Plants Producing 1000kg of Plastic Waste Product.

Unit Operation	Required Parameters	Plant			
		1	2	3	4
Sorting (Plastic waste)	Number of persons involved	2	2	2	3
	Time taken (h)	1.30	1.40	6	1
Washing	Number of persons involved	4	2	-	5
	Time taken (h)	2	2.20	-	1
Cutting (with cutlass)	Number of persons involved	3	-	-	4
	Time taken (h)	1	-	-	0.75
Crushing	Electrical power (kW)	15.42	15	200	-
	Time taken (h)	1.20	2.15	8	-
Stabilization/Colouring	Number of persons involved	1	2	1	2
	Time taken (h)	0.083	0.33	0.33	0.6
Melting	Electrical power (kW)	160	-	200	100
	Time taken (h)	1.50	-	8	1
Cooling	Temperature (^{o}c)	60	-	-	27
	Time taken (h)	0.67	-	1	0.75
Packaging	Number of persons involved	3	-	6	2
	Time taken (h)	1.45	-	2	1.3
Rinsing	Electrical power (kW)	-	2.2	-	-
	Time taken (h)	-	2.40	-	-
Drying	Number of persons involved	-	2	-	4
	Time taken (h)	-	2.15	-	3
Palletizing	Electrical power (kW)	-	5.5	-	-
	Time taken (h)	-	3.20	-	-
Grinding	Electrical power (kW)	-	-	80	8.27
	Time taken (h)	-	-	8	1.30

nd energy use data in plastic waste recycling plant 1

i		Operation time (h)	Electrical energy, $E_{p,i}$, (MJ)	Thermal energy, $E_{t,i}$, (MJ)	Manual energy, $E_{m,i}$, (MJ)	Total energy, $E_{seo,i}$, (MJ)	($E_{seo,i} / E_{tt}$) x 100, (%)
1	Sorting	1.29	-	-	0.70	0.70	0.0041
2	Washing	2	-	-	1.79	1.79	0.01
3	Cutting	1.0	-	-	0.66	0.66	0.0039
4	Crushing	1.2	54.51	5913.5	-	5968.01	35.29
5	Additive/Colourant	0.083	-	-	0.02	0.02	0.0001
6	Melting	• 1 .45	1041.95	6557.98	0.54	7599.93	44.94
7	Cooling	0.67	112.17	3225.3	-	3337.47	19.74
8	Packaging	1.45	-	-	1.18	1.18	0.0069
	Total		$E_{p,tt} = 1{,}208.63$	$E_{t,tt} = 15{,}696.78$	$E_{m,tt} = 4.88$	$E_{tt} = 16{,}909.$	100.00
	Percent of Total (%)		7.14	92.83	0.029	100	

$$, \quad E_{t,tt} = \sum_{i=1}^{8} E_{t,i}, \quad E_{m,tt} = \sum_{i=1}^{8} E_{m,i}, \quad E_{seo,i} = \sum_{j=1}^{3} \left(E_{te,i}\right)_j, \quad E_{tt} = \sum_{i=1}^{8} E_{seo,i}$$

nd energy use data in plastic waste recycling plant 2

i		Operation time (h)	Electrical energy, $E_{p,i}$, (MJ)	Thermal energy, $E_{t,i}$, (MJ)	Manual energy, $E_{m,i}$, (MJ)	Total energy, $E_{seo,i}$, (MJ)	($E_{seo,i} / E_{tt}$) x 100, (%)
1	Sorting	1.29	5.43	-	0.73	6.16	1.30
2	Washing	2	291.7	-	1.21	292.91	61.77
3	Crushing	1.2	94.61	-	1.79	96.40	20.33
4	Rinsing	2.1	15.25	-	1.24	16.49	3.48
5	Drying	2.4	9.44	-	0.64	10.08	2.13
6	Additive/Colourant	0.083	-	-	0.15	0.15	0.032
7	Palletizing	• 2. 0	-	-	51.12	51.12	10.78
8	Packaging	1.45	-	-	0.92	0.92	0.20
	Total		$E_{p,tt} = 416.43$	-	$E_{m,tt} = 57.80$	$E_{tt} = 474.23$	100.00
	Percent of Total (%)		87.81	-	12.19	100.00	

$$, \quad E_{t,tt} = \sum_{i=1}^{8} E_{t,i}, \quad E_{m,tt} = \sum_{i=1}^{8} E_{m,i}, \quad E_{seo,i} = \sum_{j=1}^{3} \left(E_{te,i}\right)_j, \quad E_{tt} = \sum_{i=1}^{8} E_{seo,i}$$

nd energy use data in plastic waste recycling plant 3

i		Operation time (h)	Electrical energy, $E_{p,i}$, (MJ)	Thermal energy, $E_{t,i}$, (MJ)	Manual energy, $E_{m,i}$, (MJ)	Total energy, $E_{seo,i}$, (MJ)	$(E_{seo,\,i} / E_{tt})$ x 100, (%)
1	Sorting	1.29	-	-	3.12	3.12	0.006
2	Crushing	1.2	4621	14063	4.3	18688.3	37.87
3	Grinding	2.0	1789	10645	4.2	12438.2	25.21
4	Additive/Colourant	0.083	-	-	0.083	0.083	0.00017
5	Melting	• 1 .45	4550.2	10322.1	0.54	14872.84	30.14
6	Cooling	0.67	112.17	3225.3	-	3337.47	6.76
7	Packaging	1.45	-	-	3.243	3.24	0.0065
	Total		$E_{p,tt} = 11{,}072.37$	$E_{t,tt} = 38{,}255.40$	$E_{m,tt} = 15.49$	$E_{tt} = 49{,}343.2$	100.00
	Percent of Total (%)		22.44	77.53	0.03	100	

$$, \quad E_{t,tt} = \sum_{i=1}^{7} E_{t,i}, \quad E_{m,tt} = \sum_{i=1}^{7} E_{m,i}, \qquad E_{seo,i} = \sum_{j=1}^{7} \left(E_{te,i}\right)_j, \qquad E_{tt} = \sum_{i=1}^{7} E_{seo,i}$$

nd energy use data in plastic waste recycling plant 4

i		Operation time (h)	Electrical energy, $E_{p,i}$, (MJ)	Thermal energy, $E_{t,i}$, (MJ)	Manual energy, $E_{m,i}$, (MJ)	Total energy, $E_{seo,i}$, (MJ)	$(E_{seo,\,i} / E_{tt})$ x 100, (%)
1	Sorting	1.29	-	-	0.853	0.853	0.0074
2	Washing	2	-	-	1.30	1.30	0.01
3	Cutting	1.0	-	-	0.82	0.82	0.007
4	Drying	1.2	-	-	3.24	3.24	0.028
5	Grinding	3.2	31.74	6127.8	1.1	6160.64	53.69
6	Additive/Colourant	0.083	-	-	1.26	1.26	0.011
7	Melting	• 1.4 5	821.8	4407.8	0.54	5230.14	45.58
8	Cooling	0.67	77.72	-	-	77.72	0.68
	Total		$E_{p,tt} = 931.26$	$E_{t,tt} = 10{,}535.60$	$E_{m,tt} = 7.05$	$E_{tt} = 11{,}475.97$	100.00
	Percent of Total (%)		8.12	91.81	0.061	100	

$$, \quad E_{t,tt} = \sum_{i=1}^{8} E_{t,i}, \quad E_{m,tt} = \sum_{i=1}^{8} E_{m,i}, \qquad E_{seo,i} = \sum_{j=1}^{3} \left(E_{te,i}\right)_j, \qquad E_{tt} = \sum_{i=1}^{8} E_{seo,i}$$

nary of the exergy (MJ) results for each unit operations of the 4 of plastic waste recycling plants

Unit operation	**Exergy (MJ)**				
	Plant 1	**Plant 2**	**Plant 3**	**Plant 4**	**Total**
Sorting	-	5.432	-	-	5.432
Washing	-	291.65	-	-	291.65
Rinsing	-	15.253	-	-	15.253
Drying	-	9.44	-	-	9.44
Cutting	-	-	-	-	-
Grinding	-	-	13072.3	6527.2	19599.5
Crushing	6322.82	94.609	19527.7	-	25945.13
Addition of additives/stabilizers	-	-	-	-	-
Melting/ heating	7993.41	-	15491.68	5494.08	28979.17
Cooling	3530.99	-	-	77.724	3608.714
Packaging	-	-	-	-	-
Total	17847.22	416.384	48091.68	12099.004	78454.3

y use indices as measured in the selected 4 plastic wastes recycling plants

Plant													
1				2				3					
1	Yr2	Yr3	Yr4	Yr1	Yr2	Yr3	Yr4	Yr1	Yr2	Yr3	Yr4	Yr1	Yr2
94	63.91	67.29	657.58	76.24	81.91	84.73	76.90	1224.05	1239.68	1221.63	1234.08	382.94	434.53
.27	8183.10	9114.14	8009.97	-	-	-	-	3522.60	3560.12	3614.97	5030.01	4861.14	5118.1
.9	543.6	572.8	517.4	167.5	173.6	171.43	171.37	110.7	111.9	113.9	112.46	452.2	425.1
455	9394468	10463339	9195708	-	-	-	-	4044064	4087135.3	4150102	5774620	5580746	587575
3.0	12539.5	13202.7	12901.9	1495.8	1607.16	1662.4	1508.9	24016.1	24322.9	23968.7	124213	7513.3	8525.6
.5	252.8	284.8	296.6	7.58	7.86	8.24	7.48	714.6	714.9	707.7	928.3	14.11	17.04
78	17.307	18.29	17.82	8.93	9.26	9.70	8.81	36.75	3674	36.65	51.6	12.36	13.84

Yr2 – 2006 Yr3 – 2007 Yr4 – 2008

mission/unit product of plastic recycling plant in south western Nigeria

Plant 1			Plant 2				Plant 3				Pla	
Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 1	Year 2	Year 3	Year 4	Year 1	Year 2
9394468	10463339	9195708	-	-	-	-	4044064	4087135.3	4150102	5774620	5580746	5875750
12539.5	13202.7	12901.9	1495.8	1607.16	1662.4	1508.9	24016.07	24322.9	23968.7	24213	7513.3	8525.6
17.30	18.29	17.82	8.93	9.26	9.70	8.81	36.75	36.74	36.65	51.6	12.36	13.842

Figure 1

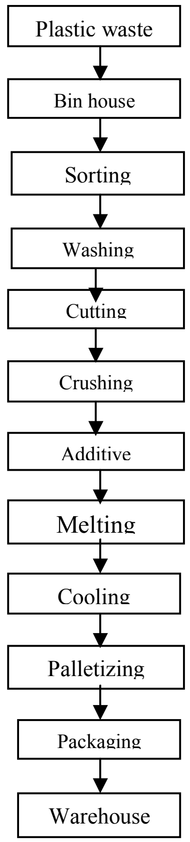


Fig. 1 Process flow diagram of plastic waste recycling at one of the four selected plants

Figure 2

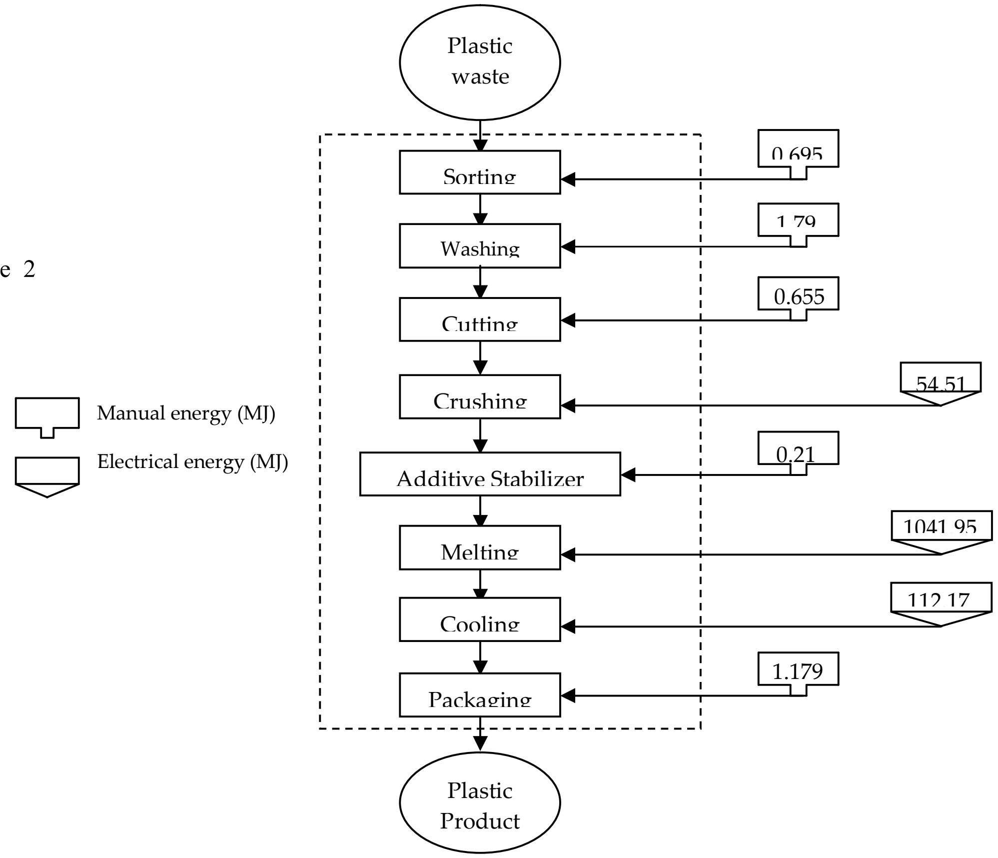


Fig. 2 Energy flow diagram in plastic waste recycling plant 1

Figure 3

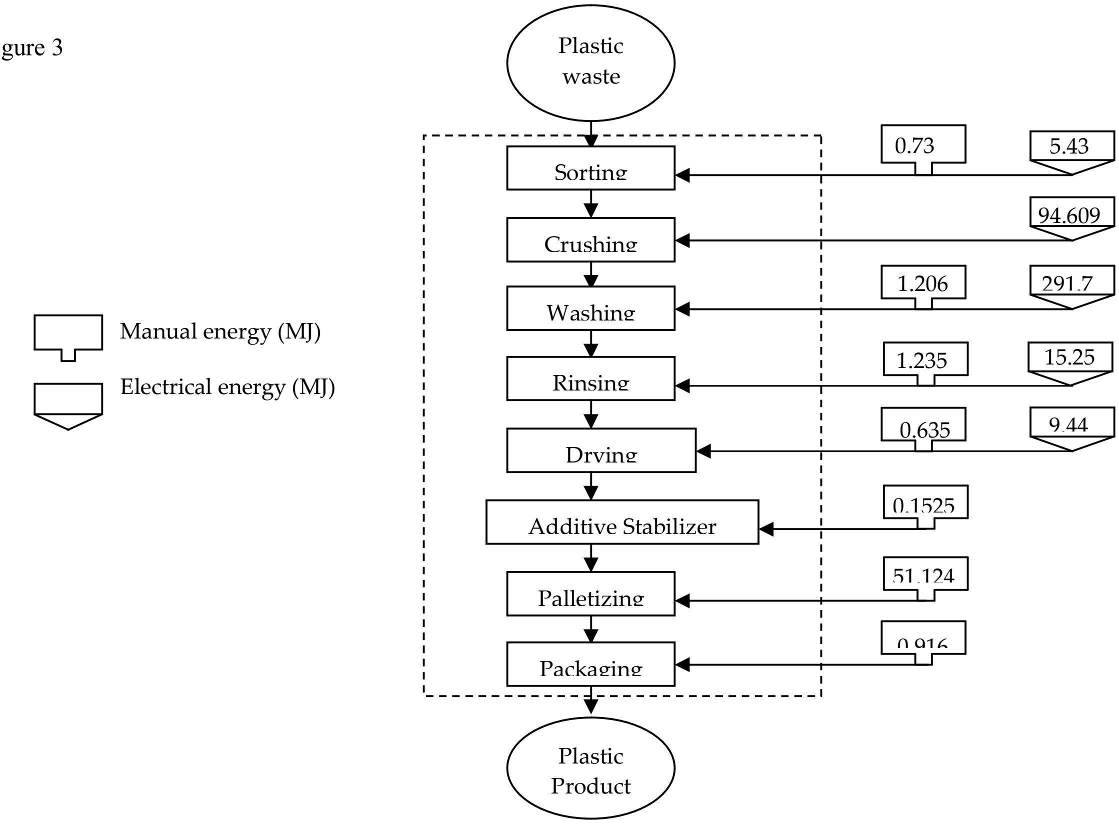


Figure 4

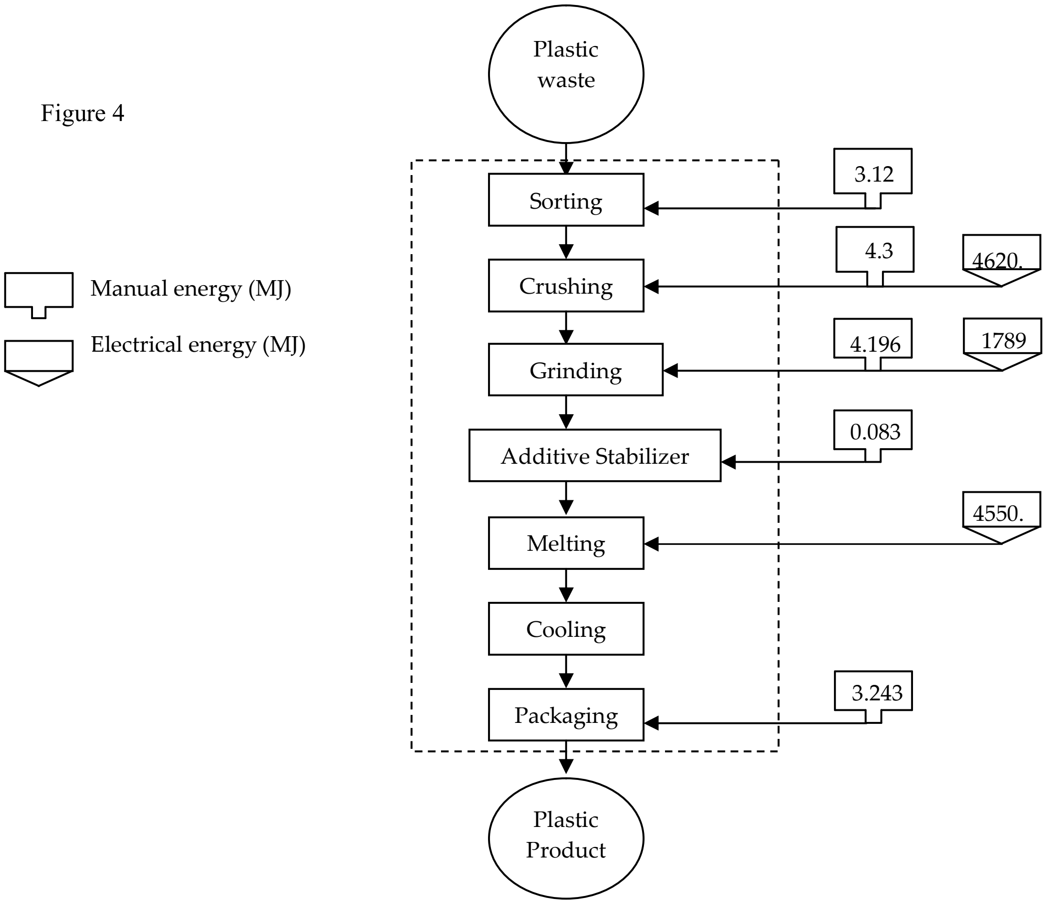
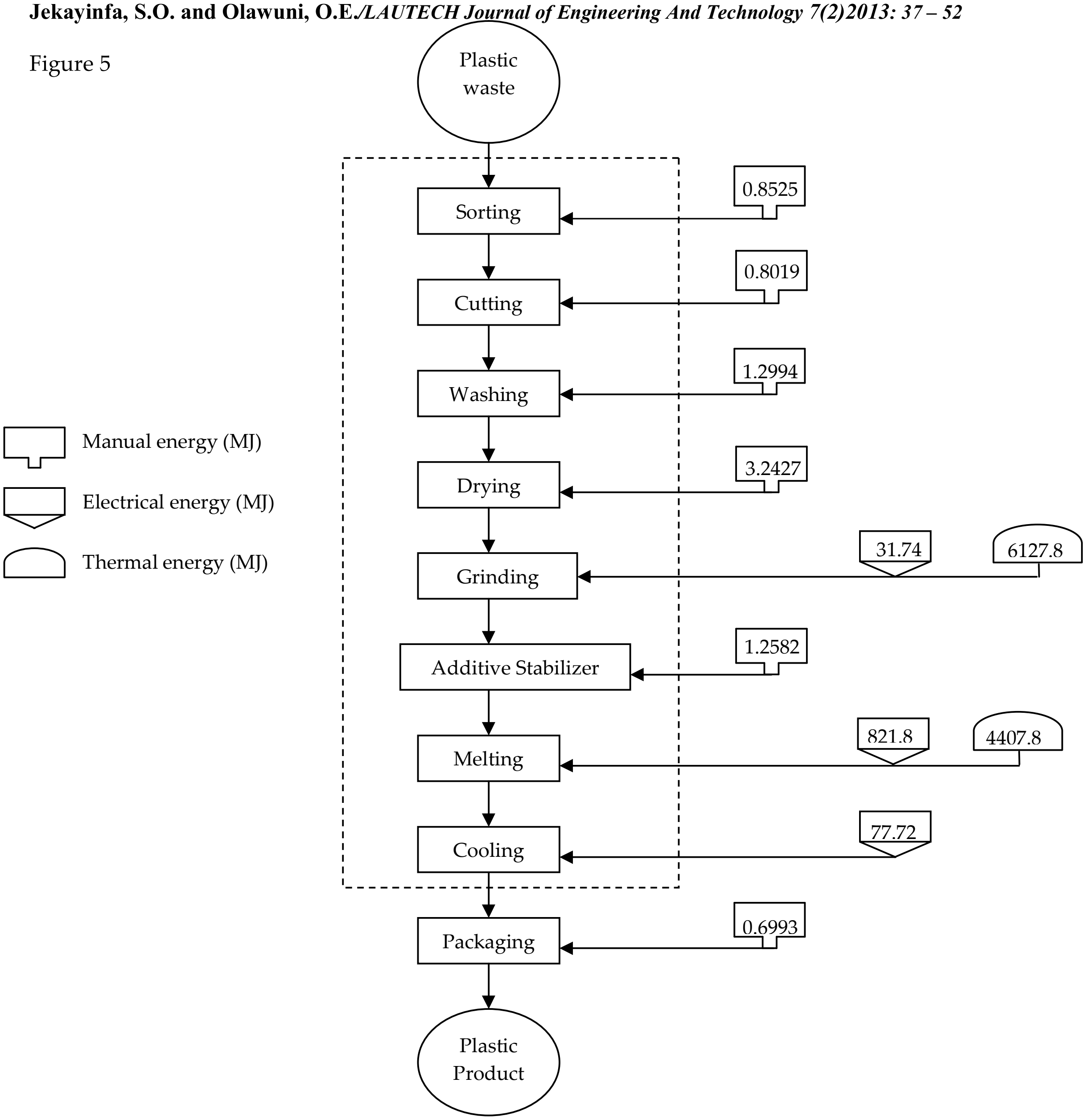


Figure 5



FIGURES CAPTIONS

Figure Number	Figure Title
1	Process flow diagram of plastic waste recycling at one of the four selected plants
2	Energy flow diagram in plastic waste recycling plant 1
3	Energy flow diagram in plastic waste recycling plant 2
4	Energy flow diagram in plastic waste recycling plant 3
5	Energy flow diagram in plastic waste recycling plant 4

Results and discussion

Energy Requirement for plastic waste recycling processing operation

Table 1 presents the type of parameters measured for the energy evaluation of each unit operation in all the four selected plastic waste recycling plants. Average energy input at different stages of production of plastic waste recycling are presented in Table 2 and Fig 2. It was observed from Table 2 and Fig 2 that in plant 1, thermal energy is mostly used, followed by electrical and manual energy. This shows that most of the machinery of this plant depend on fuel for operations. About 92.83% of the average total energy in this plant was obtained from thermal source, followed by 7.14% and 0.026% obtained from electrical and manual sources respectively. This evidently shows that most of the tedious operations involved in plastic recycling processing are actually carried out mechanically with over 80% of energy consumption attributed to either the use of electrical or internal combustion engine for operating processing machines. Considering the unit operations during plastic waste recycling for this plant, it was observed that not all the unit operations required manual energy in different quantity. The average energy used in melting (heating) was about 7.6GJ, which was the highest accounting for about 45% of the total energy consumption. This was followed by crushing (6GJ, 35%), cooling (0.34MJ, 20%), other results include sorting (0.7MJ, 0.004%), washing (1.8MJ, 0.01%), cutting (0.66MJ, 0.004%), packaging (1.18MJ, 0.007%) and addition of additives/stabilizers (0.0207MJ, 0.0001%). The entire total energy requirement for processing 1000kg of plastic waste is 17 GJ.

The average energy input at different stages of plastic waste recycling in plant 2 is presented in Table 3 and Fig 3. It was observed that there was no adequate data provided for estimation of thermal energy but electrical energy consumption amounted to about 88% and manual energy 12%. For the different processing operations, the average energy for washing (291.7 MJ) was the highest, accounting for 62% of the total energy consumptions. This was followed by crushing (94.4 MJ, 20.3%), palletizing (51.12 MJ, 10.8%), rinsing (16.49 MJ, 3.5%), drying (10.1MJ, 2.13%), sorting (6.16 MJ, 1.3%), packaging (0.92 MJ, 0.19%) and addition of additives/stabilizers (0.15 MJ, 0.03%). In all, the total energy requirement for processing 1000kg of plastic waste is 474 MJ.

The Average energy inputs at different stages of operation of plastic waste recycling processes in plant 3 are presented in Table 4 and Figure 4. It was observed that in this plant, thermal energy is mostly used, followed by electrical and manual energy. This shows that this plant depend majorly on fuel for operation. Over 92% of the average total energy in plastic recycling plant 3 was obtained from thermal source, followed by 7.9% and 0.01% obtained from electrical and manual energy respectively. This shows that more than 90% of energy consumption is attributed to the use of electric motor. The average energy use for crushing (18.69 GJ) was the highest, accounting for 38% of total energy consumption. This was followed by melting (14.87 GJ, 30.14%); grinding (12.44. GJ, 25.21%); packaging (3.24 MJ, 0.007%); sorting (3.12 MJ, 0.006%) and additives/stabilizers (0.083 MJ, 0.0002%). The total energy requirement for processing 1000kg of plastic waste product in plant 3 was about 140 GJ.

Table 5 and Fig 5 show the average energy inputs at different stages of plastic waste recycling in plant 4. It was observed that in all stages of operation in this plant, thermal energy is the major energy that was used, followed by electrical energy and manual energy in that order. This shows that from all indication, majority of the plants depend on fuel for operation. 91.8% of the total energy in plant 4 was obtained from thermal source, followed by 8.12% and 0.06% obtained from electrical and manual energy sources respectively.

Considering the unit operations during operation of this plant in Fig. 5, it was observed that the average energy use for grinding (6.2 GJ) was the highest which accounted for 53.7% of the total energy consumption. This was followed by melting (5.23 GJ, 45.58%), cooling (77.72 MJ, 0.68%), drying (3.24MJ, 0.03%), washing (1.3 MJ, 0.0113%), addition of additives/stabilizers (1.258MJ, 0.01%), sorting (0.8525MJ, 0.007%), cutting (0.82 MJ, 0.007%) and packaging (0.699MJ, 0.0061%). The overall total energy requirement for recycling 1000kg of plastic waste in plant 4 is 11.47 GJ.

Estimation of exergy

Exergy analysis has been applied to the overall production of plastic waste recycling by the evaluation of the unit processes involved in production. Table 6 shows the exergy used in recycling of 1000kg of plastic waste in each of the selected plants. The exergy content can be calculated for mechanical and electrical energy since the exergy content is equal to the energy content. The exergy of chemical fuels was found from expressions and data given by Kotas (1995). These exergy factors used in this study are based on the lower heating values, which are the quantities used in energy statistics. In the studies of Wall, (Wall, 1986, 1987, 1990 and 1997), the fuel exergy was set equal to the lower heating values. It should be noted that exergy for unit operations that were achieved by human labour is neglected The exergy used by chemical fuels and electrical for crushing, melting and cooling is 6.32 , 7.99 and 3.53 GJ respectively while the overall total exergy used is 17.85 GJ.

For plant 2, the exergy content was also calculated for mechanical and electrical energy, the exergy content equal to the energy content, while the exergy of chemical fuels was found by using the energy factor of fuel. It was observed that unit operation that was achieved by manual is neglected, the exergy used by chemical fuels and electrical: sorting (5.43 MJ), crushing (94.61 MJ), washing (291.65 MJ), rinsing (15.25 MJ), drying (9.44 MJ) and the overall total exergy used is (416.38 MJ). For plant 3, it was observed that unit operation that was achieved by manual energy was neglected, the exergy used by chemical fuels and electrical: crushing (19.53 GJ), grinding (13.07 GJ) melting (15491.68), and the overall total exergy used is

(48.09GJ). Also for plant 4, the exergy used for grinding was 6.53 GJ. Other exergy results in plant 4 are: melting/ heating (5.49 GJ), cooling (77.724 MJ) and the total exergy was (12.09 GJ).

Table 6 summarizes the exergy content of the all the four (4nos) of the plants investigated, the plants have different unit of operation based on the type of plastics waste they produce. Some of the unit operations carried out manually is done mechanically in other plants. There is no exergy change in the sorting, cutting, grinding and packaging operation because these operations take place without any appreciable change in temperature between the inlet and the outlet of the processes. The total exergy used by 1st plant, Black Horse is (17.85 GJ), 2nd plant, Altak industry, (416.38 MJ), 3rd plant, Lopin industry (48.09GJ), and 4th plant, Dipson plastic (78.45 GJ). However, the result obtained from plant 2 was so low because of the inadequate information for fuel estimation.

CO_2 emission

Tables 7 and 8 present the estimated direct, indirect and specific CO_2 emissions of each audited plastic recycling plant that has been done using the annual energy (fuel and electricity) consumption data. Estimates of specific CO_2 emissions for each plant have been obtained for four different years. The 3rd plant (Lopin industry) emitted the highest specific CO_2 during the four audited years: (36.75, 36.74, 36.65 and 51.6 ton / ton of product). The highest direct specific emission of CO_2 (based only on fuel) is from Plant 1 (Black Horse), while the 3rd Plant contributes the highest CO_2 emission from electricity consumption.

The average specific CO_2 emissions of the plastic recycling operations for each plant, based on the energy audit data, ranked in descending order of magnitude for the 1st and 3rd plants, while in ascending order of magnitude for the 2nd plants. It was estimated by using the average specific CO_2 emissions from various plants. The highest average CO_2 emissions/unit product of plastic recycling was found in the 3rd plant followed by the 1st plant. The share of the CO_2 /unit product due to electricity consumption is less than that of due to fuel consumption, indicating that the CO_2 mitigation potential in this sector should focus on the fuel combustion equipment and processes, while electricity management needs to be given priority.

CONCLUSIONS

A study was conducted to assess the energy utilization pattern in four selected plastic recycling plants located in Osun and Oyo States of Nigeria. The data collected on energy usage in these plants were subsequently used to estimate the CO_2 emission and conduct simple exergy analysis. From the results of the study, the following conclusions can be drawn:

1. The common types of energy used in the selected plants are electrical, thermal and manual with proportions of 7.14, 92.83 and 0.03% of the total energy consumed in Plant 1. The corresponding values in plants 2, 3 and 4 are 87.81, 0, 12.19%; 7.95, 92.04, 0.01% and 8.1, 91.8, 0.1% respectively.
2. An average 16.9, 0.48, 140 and 11.5 GJ of energy from the three identified sources was used in plants 1, 2, 3 and 4 respectively.
3. CO_2 emissions from the plants were mainly from the use of liquid fuels. The four plants together emitted about 76.8, 77.2, 74.5 and 90.6 tons of CO_2 in 2005, 2006, 2007 and 2008 respectively.
4. The exergy analysis revealed that melting operation accounted for the highest exergy (available energy) in all the four selected plants.

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