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Energy and exergy analyses of malt drink production in Nigeria

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ABSTRACT

Energy requirements and exergy inefficiencies for processing of malt drink were estimated for a Nigerian brewery. The process was divided into twenty-one basic unit operations and grouped into four main group operations: silo house, brew house, filter room and packaging house. The energy intensity for processing a batch of 9.8 tonnes brew grains to 562 hl of malt drink was estimated as 261.63 MJ/hl consisting of electrical (41.01%), thermal (58.81%) and manual (0.19%) of the total energy. The most energy intensive group operation was the Packaging House operation, followed by the Brew House operation with energy intensities of 223.19 and 35.94 MJ/hl, respectively. The exergy analysis revealed that the packaging house operation was responsible for most of the inefficiency (92.16%) followed by brew house operation (7.17%) and the silo house and filter room operations with less than 1% of the total exergy lost. The most exergy loss took place in the pasteurizer, which accounted for 59.75% of the overall system inefficiency. Modification in the pasteurizer and use of spent grains as alternate source of energy in the steam boiler were recommended to improve the energy efficiency of the system.

1. Introduction

The Nigerian manufacturing sector is faced with increasingly protracted energy crisis, which has made energy cost a predominant component of the production cost, such that cost of energy accounts for about two-third of the total production cost [1]. This in effect, has led to increase in cost of production and lack of global competitiveness of goods produced in Nigeria. Hence, the Nigerian manufacturers are seeking opportunities to reduce manufacturing costs through the use of cost-effective energy saving technologies and practices that will reduce operating costs while maintaining or increasing product quality and quantity.

The brewery industry is one of the fastest growing sectors of the Nigerian manufacturing industry. It plays a significant role in the national economy by contributing about 28% of the national MVA (Manufactured Value Added). It provides 30,000 direct employment and indirect employment for over 300,000 workers. There are 32 breweries in Nigeria, producing eight brands of malt drinks [2]. Malt drinks production in Nigeria has been a research focus for many years. The nutrients and anti-nutrients components [3] and trace heavy metal composition [4] of some commercial brands of malt drinks produced in the country have been reported. Likewise, the need for potential substitute raw materials for replacement of barley grains to ensure the sustainability and profitability of malt drinks production in Nigeria has been reported by Balami et al. [5]. In recent times, the need for cost-effective energy saving technologies or practices is being recognized by many governments and manufacturing industries, hence forcing them to review their energy policies. This accounts for the extensive energy-related research work that has been done on many industrial systems with the aim of analyzing, improving the design and optimizing the performance of energy systems. Such industrial systems include rice processing [6], sunflower oil expression [7], palm-kernel oil processing [8,9], cashew nut processing [10], poultry processing [11], cassava-based foods [12], organic fertilizer production [13], etc.

The energy analysis is based on the first law of thermodynamics, which expressed the principle of the conservation of energy. However, it provides no information about the irreversibility aspects of thermodynamic processes. Whereas, exergy analysis is a thermodynamic analysis technique based on the combined principles of conservation of mass and energy together with second law of thermodynamics, which provides an alternative and illuminating means of assessing the locations, types and magnitudes of wastes and losses and to identify meaningful efficiencies of the system. Exergy analysis methodologies have been applied to many industrial systems such as: sugarcane bagasse gasification [14], pressurized fluid bed combustion power generation [15], hydrogen production process [16], multi-fueled power plant [17], coal-fired power plant [18], steam heating process [19] and ethylene and propylene production process [20], etc.

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Nomenclature

W_u	useful work
R_s	entropy production
s	specific entropy of process stream (kJ/kg K)
$\dot{I}$	time rate of exergy lost due to irreversibility
$\dot{W}_{CV}$	time rate of exergy transfer by work
I_{ff}	exergy inefficiency of the system
h	specific enthalpy of process stream (kJ/kg)
e	specific flow exergy
c_p	specific heat capacity of the malt drink
T	temperature of process stream
$\dot{Q}_j$	time rate of heat transfer
C_f	calorific value of diesel fuel (J/kg)
E_{CH}	chemical exergy of a production stream
E_F	thermal energy consumed (J)
E_i	energy intensity (MJ/hl)
E_K	kinetic exergy of a production stream
E_m	manual energy (kW h)
E_p	electrical energy consumed (kW h)
E_{PH}	physical exergy of a production stream
E_{PT}	potential exergy of a production stream
E_T	total energy input (MJ)
E_x	total exergy of a production stream
N	number of persons involved in the operation
η	power factor (assumed to be 0.8)
P	rated power of motor (kW)
t	hours of operation (h)
V_p	volume of malt drink produced (hl)
W	quantity of diesel fuel consumed (kg)
x	weight fraction of water in malt drink

Subscripts

1	properties of process stream at inlet
2	properties of process stream outlet
o	properties of process stream evaluated at the reference state ($T_0 = 298.15$ K and $P_0 = 100$ kPa).
j	instantaneous value of properties of the process stream

Although a considerable volume of energy and exergy-related analyses of industrial processes exists in literature, limited work has been reported on energy and exergy analyses of beverage processing operations. Energy analysis for production of beer in some beverage plants in Nigeria has been reported by Akinbami et al. [21] and Okiwelu [2]. Only the work of Waheed et al. [1] reported the energy and exergy analyses of fruit juice processing operations in Nigeria. To the best of the authors' knowledge, no work has been conducted on the energy and exergy analyses of malt drink brewing process in Nigeria. Therefore, the aim of this study is to analyse the energy consumption pattern and exergy inefficiency of malt brewing operations in Nigeria, in view of improving the efficiency of the system, reduce the production costs and hence, increase the profitability of malt drinks production.

2. Materials and methods

2.1. Plant description

Energy and exergy studies of malt drink processing operations were conducted in a brewery located in the southwestern Nigeria. The energy requirement and exergy inefficiency for processing a batch of 9.8 tonnes brew grains consisting of malted barley (65%), sorghum (20%) and maize (15%) into 562 hl of malt drink were estimated. The plant has a design capacity of 1.7 million hl annual production and operates on a 3-shift of 8-working hours per day. The main sources of energy utility for the plant are electrical, thermal and manual. The primary source of electrical energy is either from the national grid or the company's power generating set. Steam generated from a diesel-fueled steam boiler is used for heating purpose, while cooling is effected through a central refrigerating system.

2.2. Process description

The production process was divided into twenty-one defined unit operations, which was then grouped into four main group operations: (1) silo house, (2) brew house, (3) filter room, and (4) packaging house. The process flow chart for production process is shown in Fig. 1.

In the silo house, the brew grains were received, weighed manually, debagged, sieved and loaded into the silos using Fulsin as preservative. Processing operations began by removing particles like stones, chaff, dust and metal objects from the grains. The grains were weighed in appropriate proportions and milled into grist.

In the brew house, the milled grist was conveyed to the premasher where it was mixed with water at 60 °C and other additives such as activated carbon, calcium chloride ($CaCl_2$) and potassium hydroxide (KOH), α-amylases and proteases enzymes were added and cooked in the mash cooker for about 20–30 min to a temperature of 78 °C. The mash was then pumped into the mash conversion vessel where β-amylases enzyme was added and cooled to a temperature range between 52 °C and 55 °C for 20–30 min and then pumped to the mash filter where hot water at 78 °C was used to sparge it to remove the dissolved sugar. In the wort kettle, additives such as hops, phosphoric acid, sugar and colourant were added and boiled at a temperature of 100 °C for about 90 min before the temperature was reduced drastically to -1.5 °C. The product was then pumped into the settling vessel, where it was kept for about 24 h.

The filter room operations started in the kieselguhr filter unit where the clear wort was filtered, followed by high gravity blending of the filtered wort where the concentration of sugar per unit volume of the wort was reduced by adding de-aerated water, biofoam and ascorbic acid. The bright malt was then passed through the trap filter and CO_2 was added as preservative and pumped into the bright malt tank.

The packaging house operations started in the depalletizer unit where bottles were removed from the crates and both bottles and crates were washed, followed by sorting to remove damaged bottles. The bottles were filled with the bright malt and cocked. This was followed by the pasteurization of the product, which involved gradual heating in seven zones to a peak temperature of 70 °C and gradually cooled. The bottles were labeled and packed into the washed crates, followed by packaging in pallets.

2.3. Data collection

The plant utilized electrical, thermal and manual energy for the production process. The required parameters for evaluating energy consumption and exergy efficiency in each unit operation were

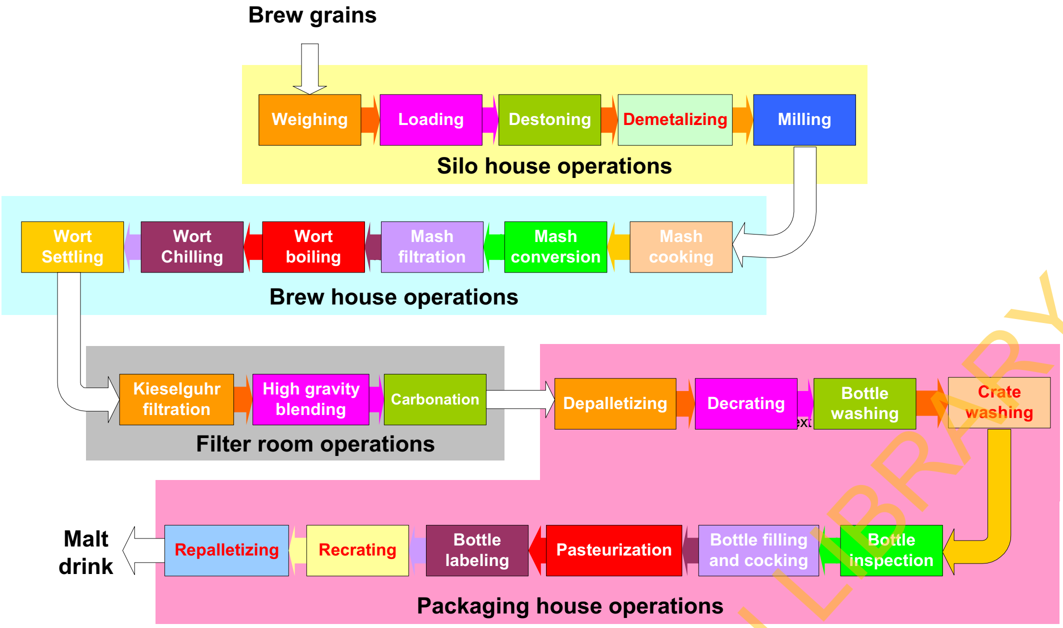

Fig. 1. Process flow chart for processing of malt drink.

measured directly or obtained from the factory's energy department. An inventory of the power rating of electric motors, properties of steam, coolant and product streams, boiler and chiller operating conditions, number of man-power required for manual labour and time taken for each operation were determined. The data were collected from the plant over a period of 2 months. The measuring quantities used in the course of the data acquisition include: (1) a stopwatch for measuring the time spent in each operation, (2) a measuring cylinder for measuring the amount of fuel consumed and (3) a weight balance for measuring the quantity of grains.

2.3.1. Evaluation of electrical energy

The electrical energy input, E_p, in kWh was obtained by multiplying the rated power of the electric motor, P, in kW with the corresponding hours of operation, t. The motor efficiency, η, was assumed to be, 80% [1].

$$E_P = \eta P t \tag{1}$$

2.3.2. Evaluation of thermal energy

Thermal energy input, E_F, was calculated based on quantity of diesel fuel used to generate steam in the boiler. The quantity of diesel fuel, W, in kg used was converted to energy (J) by multiplying the quantity consumed by the corresponding calorific value, C_f, of diesel fuel (J/kg) [1]:

$$E_F = C_f W \tag{2}$$

2.3.3. Evaluation of manual energy

Manual energy, E_m, in kW was estimated based on the value recommended by Odigboh [22]. According to him, at maximum continuous energy consumption rate of 0.30 kW and conversion efficiency of 25%, the physical power output of a normal human labour in tropical climates is approximately 0.075 kW sustained for an 8–10 h workday:

$$E_m = 0.075Nt \quad (\text{kW h}) \tag{3}$$

N is the number of persons involved in the operation and t is the useful time spent to accomplish a given task in hours.

2.3.4. Evaluation of energy intensity

Energy intensity is the amount of energy required per unit output of production. Production volumes in the brewery industry are commonly expressed in hectoliters, gallons or barrels. The energy intensity was evaluated as the ratio of total energy input, E_t, in MJ and the volume of malt drink produced, V_P in hl:

$$E_i = \frac{E_T}{V_P} \tag{4}$$

The required parameters for evaluating energy and exergy in the four group operations are represented in Tables 1–4.

2.4. Exergy change of the process stream

The exergy of process stream (E_x) can be expressed as the sum of the physical (E_{PH}), chemical (E_{CH}), kinetic (E_K) and potential (E_{PT}) exergy. Mathematically [23],

$$E_x = E_{PH} + E_{CH} + E_K + E_{PT} \tag{5}$$

where

$$E_{PH} = (h - h_0) - T_0(s - s_0) \tag{6}$$

In Eq. (6) h is the specific enthalpy (kJ/kg), s is the specific entropy (kJ/kg K), both evaluated at T and P of each process stream;

Table 1
Required parameters for evaluating energy and exergy in the silo house operations.

Unit operation	Required parameters	Value
Weighing	No of persons involved	12
	Time taken for weighing (h)	1.3
Loading	Electrical power rating (kW)	18.5
	Time taken for loading (h)	1.3
Destoning	Electrical power rating (kW)	13.5
	Time taken for destoning (h)	1.8
Demetalizing	Electrical power rating (kW)	0.6
	Time taken for demetalizing (h)	1.8
Milling	Electrical power rating (kW)	80.5
	Time taken for milling (h)	1.9

Table 2
Required parameters for evaluating energy and exergy in the brew house operations.

Unit operation	Required parameters	Value
Mash cooking	No of persons involved in dozing	1
	Time taken for dozing (h)	0.3
	Electrical power rating of conveyor (kW)	8
	Electrical power rating of water pump (kW)	11
	Electrical power rating of mixer (kW)	10
	Flow rate of water (kg/h)	40,000
	Time taken to pump water (h)	0.53
	Time taken to convey grist (h)	1.3
	Time taken for mash mixing and cooking (h)	1
	Weight fraction of water in mash	0.7
	Mash inlet temperature (K)	333
	Mash outlet temperature (K)	351
	Steam inlet temperature (K)	453
	Steam outlet temperature (K)	453
	Water inlet temperature (K)	298
	Water outlet temperature (K)	333.2
Mash conversion	No of persons involved in dozing	1
	Time taken for dozing (h)	0.3
	Electrical power rating of mash pump (kW)	22
	Electrical power rating of mash converter (kW)	10
	Flow rate of mash (hl/h)	350
	Time taken to pump mash (h)	0.88
	Time taken for mash conversion (h)	3
	Weight fraction of water in mash	0.7
	Mash inlet temperature	351
	Mash outlet temperature	351
Mash filtration	Power rating of mash pump (kW)	15
	Power rating of water pump (kW)	15
	Power rating of mash filter (kW)	140
	Flow rate of water and mash (hl/h)	350
	Time taken to pump mash (h)	0.88
	Time taken for mash filtration (h)	1.2
	Time taken to pump sparging water (h)	0.29
	Weight fraction of water	0.85
Wort boiling	Electrical power rating of wort pump (kW)	37.3
	No of persons involved in dozing	1
	Time taken for dozing (h)	0.3
	Electrical power rating of mixer (kW)	10
	Flow rate of wort (hl/h)	1001
	Time taken to pump wort (h)	0.4
	Time taken for boiling (h)	1.5
	Wort inlet temperature (K)	351
	Wort outlet temperature (K)	373
	Weight fraction of water in wort	0.85
Wort chilling	Electrical power rating of chiller compressor (kW)	22
	Time taken for chilling (h)	1.11
	Wort inlet temperature (K)	373
	Wort outlet temperature (K)	271.7
	Weight fraction of water in wort	0.85
Settling vessel	Electrical power rating of pump (kW)	22
	Time taken to pump into vessel (h)	1.16
	Time taken for settling (h)	24
	Wort inlet temperature (K)	271.7
	Wort outlet temperature	271.7
	Weight fraction of water in bright malt	0.87

Table 3
Required parameters for evaluating energy and exergy in the filter room operations.

Unit operation	Required parameters	Value
Kieselguhr filtration	Electrical power rating of filter (kW)	127
	Flow rate of wort (hl/h)	250
	Time taken for filtration (h)	1.6
	Wort inlet temperature(K)	271.7
	Wort outlet temperature (K)	298
	Weight fraction of water in wort	0.9
High gravity blending	Electrical power rating of pump (kW)	33
	Flow rate of de-aerated liquor (hl/h)	101
	Time taken to pump (h)	1.6
	No of persons involved	1
	Bright malt inlet temperature(K)	298
	Bright malt outlet temperature (K)	298
	Weight fraction of water in bright malt	0.9
Carbonation	Electrical power rating of carbonator (kW)	12
	Time taken for carbonation (h)	2.25
	Bright malt inlet temperature(K)	298
	Bright malt outlet temperature (K)	298
	Weight fraction of water in bright malt	0.9

h_0 and s_0 are, respectively, the specific enthalpy and specific entropy evaluated at the reference state ($T_0 = 298.15$ K and $P_0 = 100$ kPa).

For a typical control volume with steady flow and accumulation of exergy occurring in the system, the exergy balance of the system can be represented as [24]:

$$\sum_j \left(1-\frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W}_{\mathrm{cv}} + \sum_i \dot{m}_i e_i - \sum_0 \dot{m}_i e_i - \dot{I}_{\mathrm{cv}} = 0 \tag{7}$$

The term $\dot{Q}$ represents the time rate of heat transfer across the boundary, T_j is the instantaneous temperature of the boundary, $\dot{W}_{\mathrm{CV}}$ is the time rate of exergy transfer by work, $\dot{I}$ is the time rate of exergy lost due to irreversibility within the system, the term $\dot{m}_i e_i$ accounts for the time rate of exergy transfer accompanying mass flow and flow work, while subscripts i and o represents the inlet and outlet, respectively.

The specific flow exergy (e) of the system can be expressed as:

$$e = h - h_0 - T_0(s - s_0) + \frac{V^2}{2} + gz \tag{8}$$

Neglecting the kinetic and potential energy, the net change of exergy of the system can be expressed as:

$$e_2 - e_1 = h_2 - h_1 - T_0(s_2 - s_1) \tag{9}$$

The net exergy changes of the process stream in and out of each unit operation in the malt drink production system were evaluated using the predictive model proposed by [1,25]:

$$e_2 - e_1 = c_p(T_2 - T_1)\left[1 - \frac{T_0}{(T_2 - T_1)ml}\right] \tag{10}$$

where

$$\left(T_2 - T_1\right)ml = \frac{T_2 - T_1}{\ln(T_2/T_1)} \tag{11}$$

The specific heat capacity of the malt drink can be determined using the expression [1]

$$c_p = 4.1868(0.3823 + 0.6183x) \tag{12}$$

where x is the weight fraction of water in the malt.

2.5. Exergy efficiency and useful work of the system

The exergy efficiency can be evaluated with the expression

$$\psi = 1 - I_{\mathrm{ff}} \tag{13}$$

$$I_{\mathrm{ff}} = \frac{I}{\sum I_{\mathrm{all}}} \tag{14}$$

where I_{ff} is the inefficiency of the system and is defined as the ratio of the irreversibility in each unit operation to the irreversibility in the overall operations.

Table 4
Required parameters for evaluating energy and exergy in the packaging house operations.

Unit operation	Required parameters	Value
Depalletizing	Electrical power rating (kW)	54
	No of persons involved in depalletizing (h)	3
	Time taken for depalletizing (h)	21.29
Decrating	Electrical power rating (kW)	46
	No of persons involved	3
	Time taken for decrating (h)	21.29
Bottle washing	Electrical power rating (kW)	227.5
	No of persons involved in washing	5
	Time taken to wash bottles	21.29
	Steam inlet temperature (K)	453
	Steam outlet temperature (K)	453
	Steam flow rate required	
Crate washing	Electrical power rating (kW)	64
	No of persons involved in washing	9
	Time taken for wash crates (h)	21.29
	Steam inlet temperature (K)	453
	Steam outlet temperature (K)	453
	Steam flow rate required	
Bottle inspection	Electrical power rating (kW)	44
	No of persons involved in inspection	6
	Time taken for bottle inspection (h)	21.29
Bottle filling and cocking	Electrical power rating (kW)	70
	No of persons involved in filling and cocking	10
	Time taken for filling & cocking (h)	21.29
Pasteurization	Power rating of pasteurizer (kW)	310
	Time taken for pasteurization (h)	21.29
	No of persons involved in pasteurizing	5
	Malt inlet temperature(K)	298
	Malt outlet temperature (K)	343
	Weight fraction of water in bright malt	0.9
	Steam inlet temperature (K)	453
Bottle labeling	Power rating of bottle labeler (kW)	38
	Time taken to label bottles (h)	21.29
	No of persons involved	3
	Malt inlet temperature(K)	343
	Malt outlet temperature (K)	298
	Weight fraction of water in malt	0.9
Recrating	Electrical power rating (kW)	46
	No of persons involved	3
	Time taken to decrating (h)	21.29
Repalletizing	Power rating of repalletizing (kW)	48
	Time taken for repalletizing (h)	21.29

The useful work input into the system can be expressed as [1,25]:

$$W_u = (e_2 - e_1) - T_0 R_s \tag{15}$$

where W_u is the useful work, R_s the production of entropy and T_0 the ambient temperature. The exergy difference $e_2 - e_1$ is defined in terms of each component exergy e_x per unit mass and the mass flow rate $\dot{m}$. From Eq. (13), 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.

3. Results and discussion

3.1. Energy expenditure of the system

A total of 72 h was required to process a batch of 9.8 tonnes brew grains to 562 hectoliters of malt drink. For this case, there was a total outage of electricity supply from national grid, hence the power generating set was used for the entire production process.

The average rate of diesel consumption by the power generating set and the boiler was 98 and 87 l/h, respectively. A total of 2968.96 and 2523 l of diesel was consumed by the generator and the boiler, respectively, for the entire production.

The energy consumption pattern for each unit operation in silo house operations is shown in Table 5. The total energy consumption in silo house operations was estimated as 587.06 MJ with electrical (99.28%) and manual (0.72%) of the total energy input. The average energy intensity for the silo house operations was estimated to be 1.04 MJ/hl. The milling operation consumed the highest energy with 440.50 MJ (75.03%), followed by the destoning process with 69.26 MJ (11.92%), while the weighing operation accounted for the least energy with 4.21 MJ (0.72%). Fig. 2 shows the energy and material balance diagram of the process stream in silo house operations based on the symbols suggested by Singh [26].

The total energy consumption for the brew house operations was estimated as 20,197.36 MJ, as shown in Table 6, from which the proportion of electrical and thermal energy was 4.86% and 95.14%, respectively. The average energy intensity for the brew house operations was estimated as 35.62 MJ/hl. Mash conversion process was the most energy intensive operation where 9,449.76 MJ of energy was consumed corresponding to 48.27% of the total energy input, followed by the mash cooking process with 9683.15 MJ (47.94%), while the least energy consuming process was the wort cooling with 70.33 MJ (0.35%). The material balance diagram for the brew house operation is shown in Fig. 3.

The energy consumption pattern for each unit operation of the filter house operations is shown in Table 7. The total energy consumption for the filter house operations was estimated as 815.13 MJ, which was largely from the electrical energy and constitutes 99.99% of the total energy input. The average energy intensity for the filter house operations was estimated as 1.44 MJ/hl. The energy and material balance diagram of the operations is shown in Fig. 4. Kieselghur filtration operation was the most energy intensive process with 585.32 MJ (71.80%), followed by the high gravity blending process with 152.14 MJ (18.66%), while the least was the carbonation process with 77.76 MJ (9.54%).

The energy consumption pattern for each unit process in the packaging house operations is shown in Table 8. The total energy consumption was estimated as 125,435.44 MJ from which the proportion of the electrical energy was 46.17%, thermal 53.62% and

Table 5
Energy consumption pattern for the silo house operation.

Unit operation	Electrical energy (MJ)	Thermal energy (MJ)	Manual energy (MJ)	Total energy (MJ)	Total (%)
Weighing	–	–	4.21	4.21	0.72
Loading	69.26	–	–	69.26	11.80
Destoning	69.98	–	–	69.98	11.92
Metal removal	3.11	–	–	3.11	0.53
Milling	440.50	–	–	440.50	75.03
Total	582.85		4.21	587.06	100.00
Total (%)	99.28	0.00	0.72	100.00	

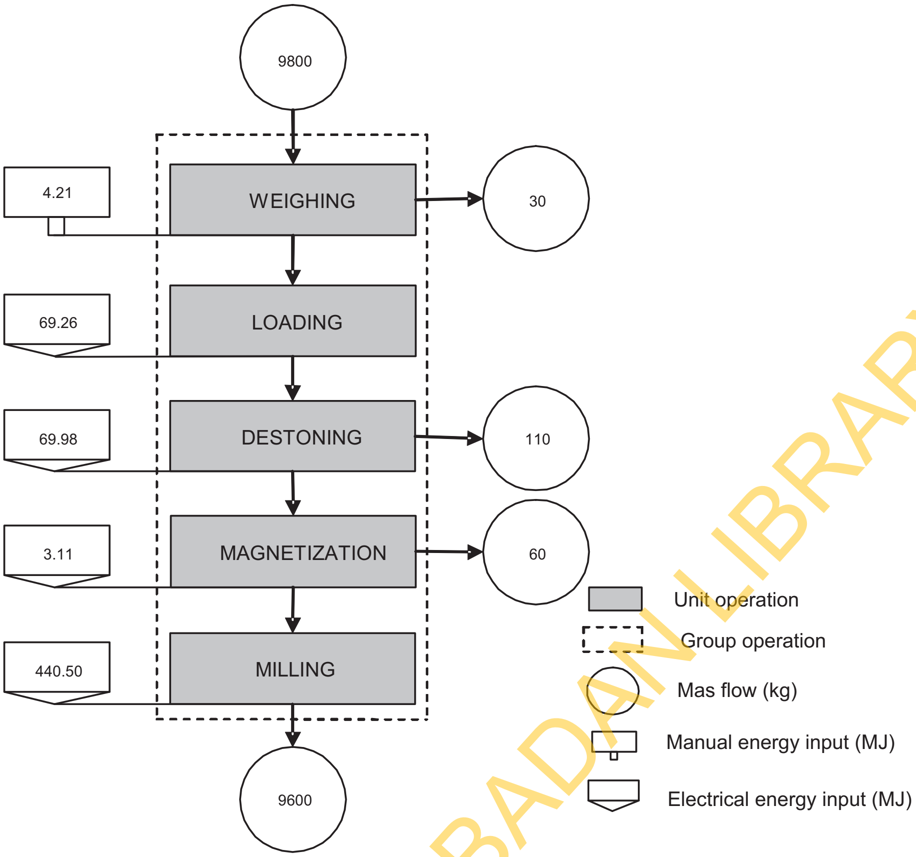

Fig. 2. Energy and material balance diagram of the silo house operations.

manual 0.22%. The average energy intensity for the packaging house operations was estimated as 221.23 MJ/hl. The energy and material balance diagram is shown in Fig. 5. Pasteurization operation was the most energy intensive process with 57,466.782 MJ (45.81%), followed by the bottle washing process with 28,389.32 MJ (22.63%), while the least was the bottle inspection process with 2548.41 MJ (2.03%).

The overview of the entire energy consumption pattern for malt drink production for the four group operations is summarized in Table 9. The total energy requirement to produce 562 hl of malt drink was estimated as 147,034.99 MJ with electrical (41.01%), thermal (58.81%) and manual (0.19%) of the total energy, while the average energy intensity of the process was 259.32 MJ/hl. It can be seen from the table that the most energy intensive group operation was the packaging house, which accounted for around 85.31% of the total energy input, followed by the brew house with 13.74%. The silo house consumed the least energy, which was about 0.40% of the total energy input of process. The energy consumption trend by each unit operation depends among other things on the type of operation, the size and age of the equipment and the extent to which available plant capacity was used. The mean values of errors between the measured value and true value for total energy consumption and energy intensity were 0.125 and 0.023, respectively. The standard deviation of the differences and the worst-case error for the two indices were, respectively, 0.152 and 0.06. Energy and mass material balance diagram for the entire production process is shown in Fig. 6.

The average energy intensity of 259.32 MJ/hl value obtained in this study, compared favourably with energy intensities for beer production with 250.20 MJ/hl for large breweries (greater than 500,000 hl annual production) and lower than 428.40 MJ/hl for small breweries (less than 20,000 hl) in Germany and 306.68 MJ/hl for breweries in the US [27]. The variation in intensities is partly influenced by the type of products being produced, size of the brewery, climatic condition of the location, the type of technology and equipment used [27]. The energy intensity of beer production

Table 6
Energy consumption pattern of the brew house operation.

Unit operation	Electrical energy (MJ)	Thermal energy (MJ)	Manual energy (MJ)	Total	Total (%)
Mash cooking	75.54	9607.53	0.08	9683.15	47.94
Mash conversion	142.15	9607.53	0.08	9449.76	48.27
Mash filtration	534.38	–	–	534.38	2.65
Wort boiling	86.17	–	0.08	86.25	0.43
Wort cooling	70.33	–	–	70.33	0.35
Wort settling	73.49	–	–	73.49	0.36
Total	982.06	19,215.06	0.24	20,197.36	100.00
Total (%)	4.94	95.14	0.00	100.00	

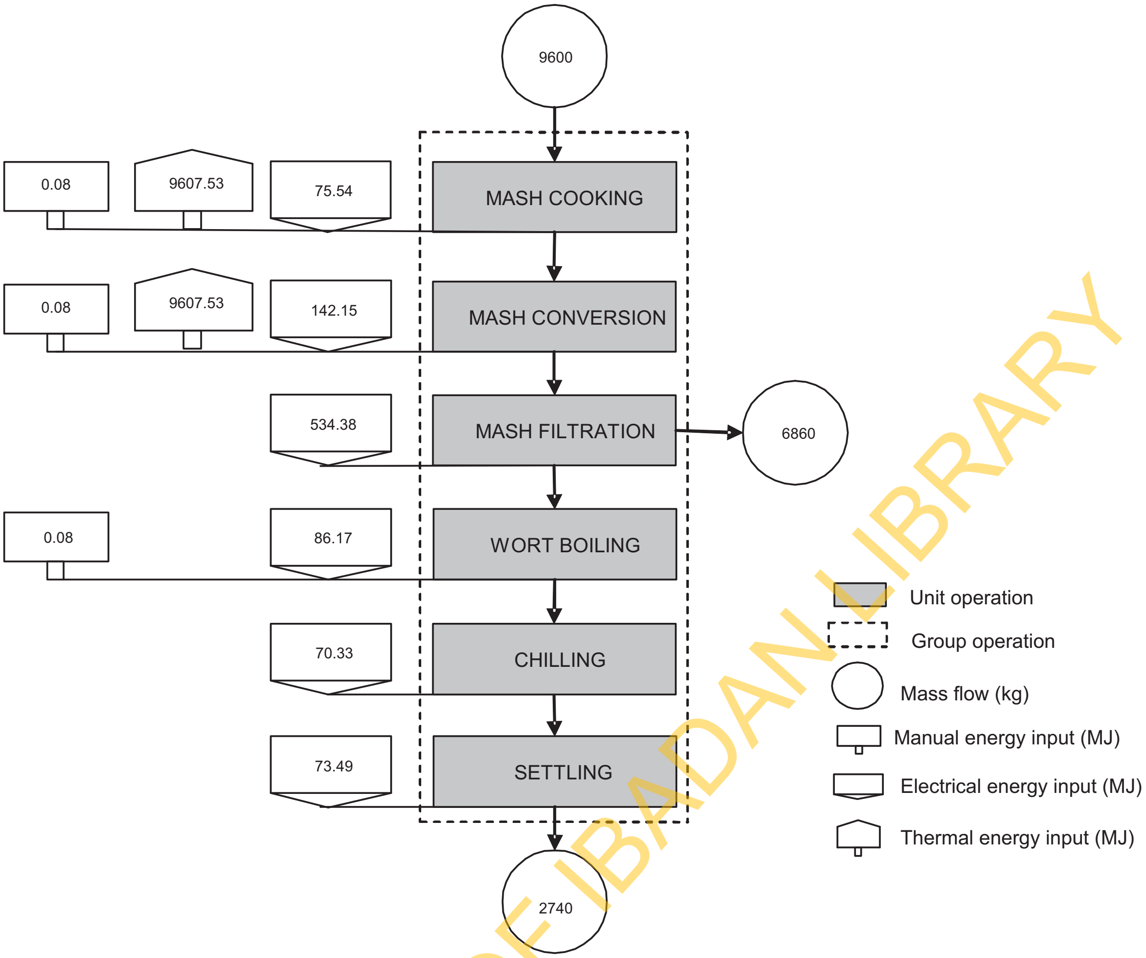

Fig. 3. Energy and material balance diagram of the brew house operations.

is expected to be higher than that of malt drink since fermentation process is not involved in malt drink production. Also, due to economics of scale, large breweries are expected to use less energy intensity compared to small breweries. Breweries located in the temperate region require less refrigeration and more heating compared to that in the tropical region, while modern technology and equipment are designed to be more energy efficient compared to obsolete ones.

3.2. *Exergy expenditure of the system*

The exergy analysis of the system gave insight to the inefficiencies and the opportunities for exergy loss minimization of each unit operations in the four defined group operations. Conceptually, the exergy calculation of the system was divided into process stream exergy and utility exergy. Tables 10–13 show the exergy change in process stream, useful work, steam exergy (utilities), entropy generated and the inefficiency associated with each unit operation for the defined four group operations. The change in the malt exergy was only associated with operations where there was change in the inlet and outlet temperatures of the malt. This can be seen to occur only in the brew and packaging house operations. In the brew house operations, the exergy change was attributed to all the unit operations except for settling unit where the inlet temperature and outlet temperature were maintained constant. For the packaging house operations, exergy change occurred only in the pasteurizer, bottle washing and crate washing unit. Consequently, no exergy change was attributed to each of the unit operations in the silo house and filter room operations because these operations take place without any appreciable change in temperature between the inlet and the outlet of the processes. The negative value of exergy change during mash filtration and wort cooling in the brew house operation was due to the drop in temperature of the malt during the process.

Table 7
Energy consumption pattern for the filter room operations.

Operation	Electrical energy (MJ)	Thermal energy (MJ)	Manual energy (MJ)	Total	Total (%)
Kieselghur filtration	585.23	–	–	585.32	71.80
High gravity blending	152.06	–	0.08	152.14	18.66
Carbonation	77.76	–	–	77.76	9.54
Total	815.05	–	0.08	815.13	100.00
Total (%)	99.99	0.00	0.01	100.00	

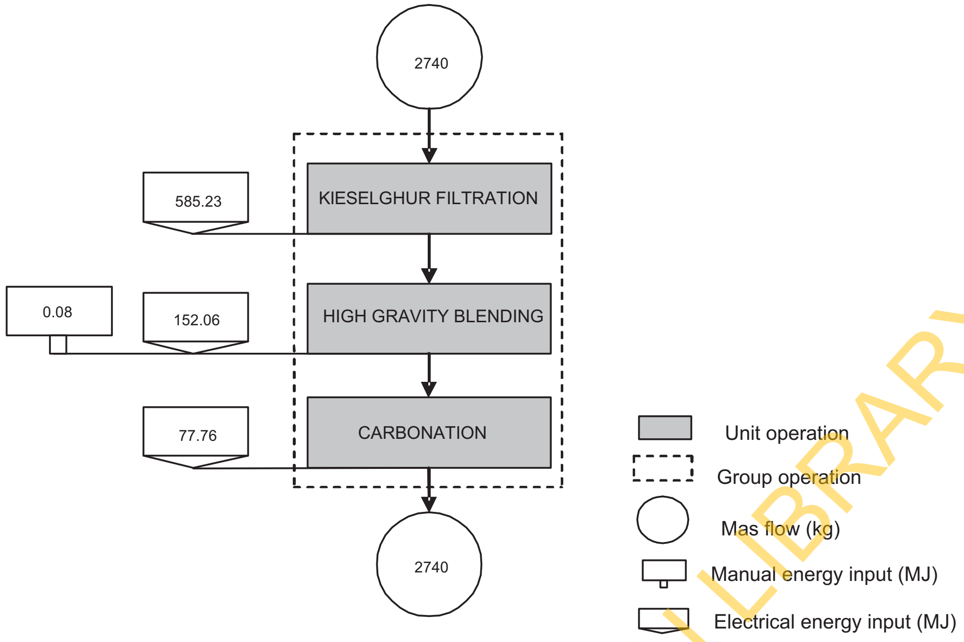

Fig. 4. Energy and material balance diagram of filter room operations.

Of the four group operations, the highest entropy was generated in the packaging house followed by brew house with respective values of 196,234.47 MJ and 15,048.59 MJ. The corresponding overall inefficiency of the packaging and brew house operation were 92.17% and 7.17%, respectively, while the sum total of the inefficiencies in the silo and filter house was about 0.66%. The highest entropy production in brew house operation was generated in the mash conversion process followed by wort boiling, mash filtration, pre-mash and mash cooking, wort cooling and settling unit, with corresponding overall inefficiencies of 2.41, 2.16, 1.30, 0.72, 0.54 and 0.04%, respectively. The losses in the brew house operations were due to irreversibilities within the system as a result of high temperature difference between the inlet and the outlet stream of both the malt stream and heating and cooling utilities. The result also revealed that the heating and the cooling processes were inefficient. This is always the case for exergy calculations and is due to the fact that the exergy value of heat is often much lower than its energy value, particularly at temperatures close to reference temperature [1]. For the packaging house operation, the highest entropy (125,317.11 MJ) was generated in the pasteurizer, which accounted for 59.75% of the overall inefficiency of the system. Bottle washing and crate washing processes had respective values of 30,228.09 MJand 19,497.22 MJ entropy productions with corresponding inefficiencies of 15.40 and 9.94% of the inefficiency of the group operations, while the remaining seven unit operations (depalletizing, decrating, bottle inspection, bottle filling and cocking, bottle labeling, recrating and repalletizing) were responsible for about 10.82% of the inefficiency of the group operation. Although comparison of result of this work is not possible because of lack of report on similar processes, but the present result can be further illustrated by comparing the pasteurizer overall inefficiency found by Waheed et al. [1] as 90%, and that reported by Rotstein [25] as 68% with the overall pasteurizer inefficiency presented in this study which is 59.75%. The inefficiency in the pasteurizer was due to large temperature difference between the inlet and outlet streams (malt stream and utilities stream). The exergy losses in the malt stream accounted for 1029.83 MJ while the exergy loss in heating stream accounted for 68,880.17 MJ. The exergy loss can be reduced by increasing the capacity of the pasteurizer unit which will result in the reduction of the load on the boiler following a similar suggestion made by Dalsgard [28]. This will enable a longer production time and thus reduce avoidable energy wastage and the corresponding exergy destruction that will occur by plant start-up, shutdown, cleaning and sterilization. If this suggestion is taken, it may help

Table 8
Energy consumption pattern for the packaging house operations.

Unit operation	Electrical energy (MJ)	Thermal energy (MJ)	Manual energy (MJ)	Total	Total (%)
Depalletizing	3311.03	–	17.24	3,328.27	2.65
Decrating	2820.50	–	17.24	2,837.74	2.26
Bottle washing	13,949.21	14,411.38	28.73	28,389.32	22.63
Crate washing	3924.18	14,411.38	51.73	18,387.29	14.66
Bottle inspection	2513.92	–	34.49	2548.41	2.03
Bottle filling & cocking	4292.06	–	57.49	4349.55	3.47
Pasteurization	19,007.71	38,430.34	28.73	57,466.78	45.81
Bottle labeling	2329.98	–	17.24	2347.22	1.87
Recrating	2820.49	–	17.24	2837.73	2.26
Repalletizing	2943.13	–	–	2943.13	2.35
Total	57,912.21	67,253.1	270.13	125,435.44	100.00
Total (%)	46.17	53.62	0.22	100.00	

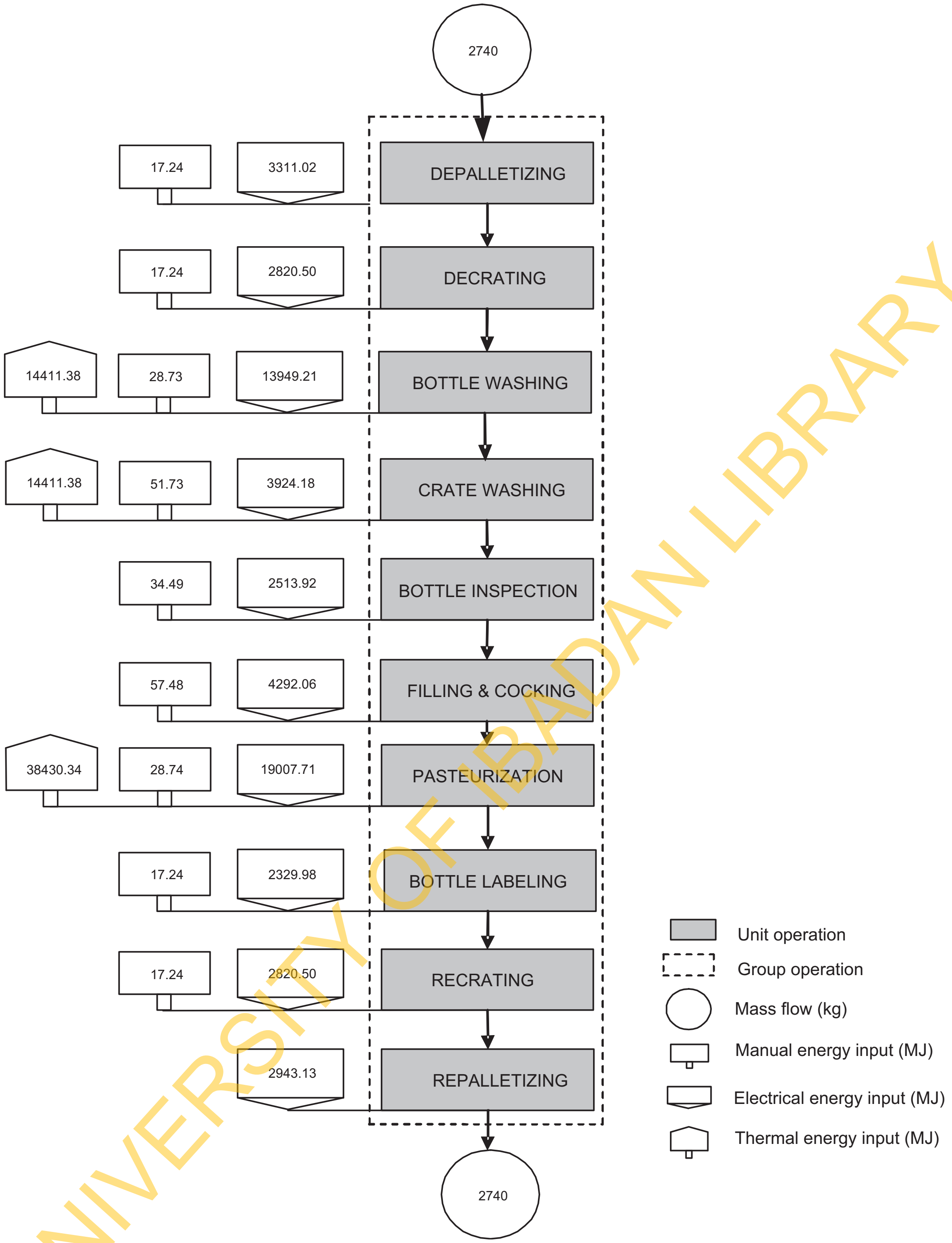

Fig. 5. Energy and material balance diagram of the packaging house operations.

Table 9
Overall energy consumption pattern for the malt drink processing.

Group operation	Electrical energy (MJ)	Thermal energy (MJ)	Manual energy (MJ)	Total	Total (%)
Silo house	582.85	–	4.21	587.06	0.40
Brew house	982.06	19,215.06	0.24	20,197.36	13.74
Filter room	815.05	–	0.08	815.13	0.55
Packaging house	57,912.21	67,253.10	270.13	125,435.44	85.31
Total	60,292.17	86,468.16	274.66	147,034.99	100.00
Total (%)	41.01	58.81	0.19	100.00	

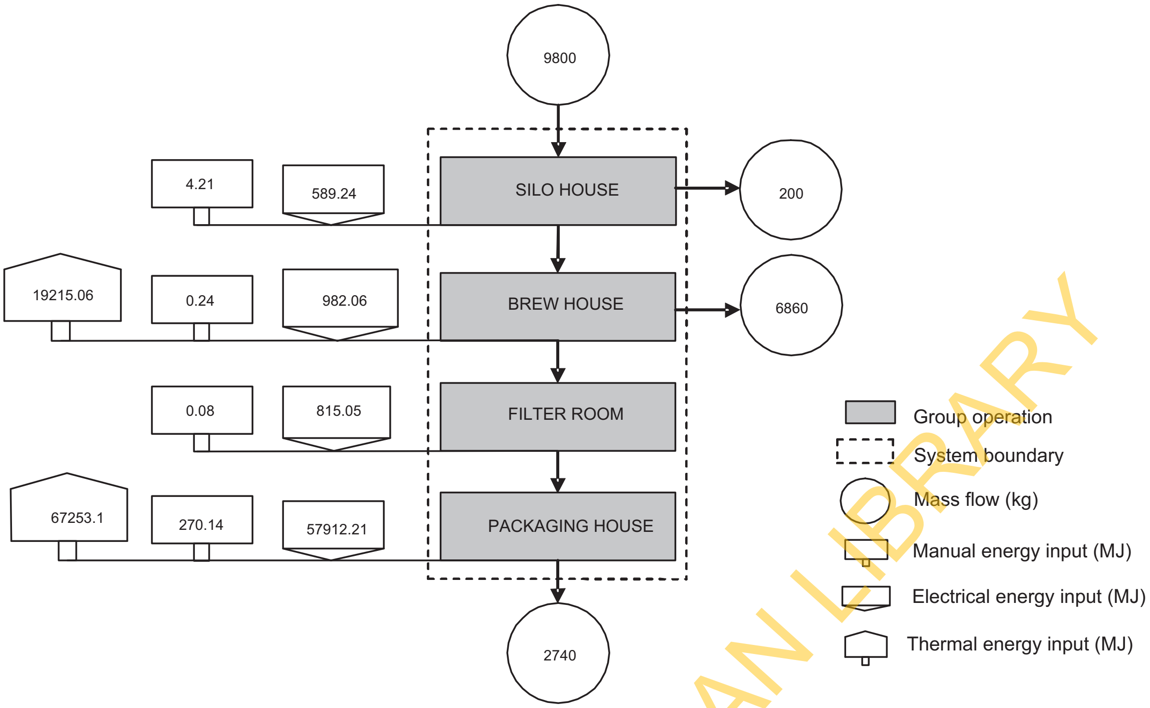

Fig. 6. Energy and material balance diagram for the overall production of malt drink.

Table 10
Exergy balance in the silo house operations.

Unit operation	Change in exergy of the brew (MJ)	Useful work (MJ)	Change in utilities exergy (MJ)	Entropy Production (MJ)	Group operation inefficiency (%)	Overall system inefficiency (%)
Weighing pit	–	4.21	–	4.21	0.72	0.00
Loading	–	69.26	–	69.26	11.80	0.03
Destoning	–	69.98	–	69.98	11.92	0.03
Metal removal	–	3.11	–	3.11	0.53	0.00
Milling	–	440.5	–	440.5	75.03	0.21
Total	–	587.6	–	587.6	100	0.27

Table 11
Exergy balance in the brew house operations.

Unit operation	Change in exergy of the brew (MJ)	Useful work (MJ)	Change in utilities exergy (MJ)	Entropy production (MJ)	Group operation inefficiency (%)	Overall system inefficiency (%)
Pre-mash & mash cooking	13.14	75.62	1453.73	1516.21	10.08	0.72
Mash conversion (cool & boil)	104.17	142.23	5024.97	5063.03	33.64	2.41
Mash filtration	−42.13	534.38	2157.42	2733.93	18.17	1.30
Wort boiling	141.02	86.25	4578.22	4523.46	30.06	2.16
Wort cooling	−115.35	70.33	952.79	1138.48	7.57	0.54
Settling	–	73.49	–	73.49	0.49	0.04
Total	100.85	982.3	14,167.14	15,048.59	100.00	7.17

Table 12
Exergy balance in the filter house operations.

Unit operation	Change in exergy of the brew (MJ)	Useful work (MJ)	Change in utilities exergy (MJ)	Entropy production (MJ)	Group operation inefficiency (%)	Overall system inefficiency (%)
Kieselghur filtration	–	585.32	–	585.32	71.80	0.28
High gravity blending	–	152.14	–	152.14	18.66	0.07
Carbonation	–	77.76	–	77.76	9.54	0.04
Total	–	815.22	–	815.22	100	0.39

the company to reduce its high expenditure on energy and thus improve the profit margin. Another way to reduce the high exergy destruction in the pasteurizer is by the introduction of the heat integration between the pasteurizer and other units in the packaging group operation. Heat integration for minimum utilities consumption corresponds to minimum production of entropy as well as to minimum ideal work given away by the process utilities streams [25].

Table 13
Exergy balance in the packaging house operations.

Unit operation	Change in exergy of the brew (MJ)	Useful work (MJ)	Change in utilities exergy (MJ)	Entropy production (MJ)	Group operation inefficiency (%)	Overall system inefficiency (%)
Depalletizing	–	3328.27	–	3328.27	1.70	1.59
Decrating	–	2837.74	–	2837.74	1.45	1.35
Bottle washing	–	28,389.32	1838.77	30,228.09	15.40	13.54
Crate washing	–	18,387.29	1109.93	19,497.22	9.94	8.77
Bottle inspection	–	2548.41	–	2548.41	1.30	1.22
Bottle filling and cocking	–	4349.55	–	4349.55	2.22	2.07
Pasteurization	1029.84	57,466.78	68880.17	125,317.11	63.86	59.75
Bottle labeling	–	2347.22	–	2347.22	1.20	1.12
Recrating	–	2837.73	–	2837.73	1.45	1.35
Repalletizing	–	2943.13	–	2943.13	1.50	1.40
Total	1029.84	125,435.44	71,828.87	196,234.47	100	92.16

4. Conclusions

The energy and exergy consumption patterns for production of one batch of 562 hl of malt drink were estimated for a Nigerian brewery. Twenty-one defined basic unit operations were identified, which was classified into four main group operations: silo house, brew house, filter room and packaging house. The energy audit revealed that the types of energy input for the production were electrical (41.01%), thermal (58.81%) and manual (0.19%) of the total energy. The average energy intensity of the process was estimated as 261.63 MJ/hl. The packaging house group operation accounted for most of the energy consumption (above 85%) of the total energy input, followed by the brew house with 13.74%. The pasteurization process was the most energy intensive process with 57,466.782 MJ accounting for 45.81% of the energy input of packaging house operations. The company depended mainly on the use diesel fuel to power the steam boiler and the company's power generating set for supply of electrical power, which is not cost effective. The exergy loss in the group operations were: silo house (0.27%), brew house (7.17%), filter room (0.39%) and packaging house (92.16%). The pasteurization process alone accounted for over 50% inefficiency of the overall system. Exergy losses in the system can be reduced by increasing the capacity of the pasteurizer unit which will in turn reduce the load on the boiler. Process heat integration between the pasteurizer and other units in the packaging group operation can also help to improve the energy efficiency of the system.

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