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Energy, exergy and cost analysis of flour production from wheat in Nigeria: Case study of Nigeria Eagle Flour mills, Ibadan

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Abstract

The significant increase in energy costs has generally contributed to an increase in the cost of production, flour production inclusive. In manufacturing industries, efforts are being made towards the reduction of the cost of energy consumed during production. This study was therefore designed to evaluate the energy requirements, operation costs, exergy losses, and propose methods for optimizing energy use in wheat flour production, using Nigeria Eagle Flour Mill, Ibadan as a case study. Analysis was carried out in three phases, pre-analysis, data collection and detailed analysis phases. A walk-through process analysis method was used for data collection and a model containing the mass, energy, and exergy balance equations were built in Microsoft Excel® 2010 to analyse data collected. Electrical energy was found to be the most used energy in both mills and the milling process was the most energy intensive in flour production, accounting for an average energy intensity of 187.49MJ/ton in Mill A and 280.37MJ/ton in Mill B. Lighting was observed to consume approximately 7% of the electrical energy supplied, prompting a lighting analysis to highlight potential energy savings. The energy cost per ton was found to be the lowest (4404naira/ton) when electrical energy from the gas plant accounted for 77 per-cent of energy input. The mill's overall irreversibility and exergetic efficiency were calculated to be 404.942KW and 15.74 percent, respectively. Only 16% of the total exergy input into the flour mill exited through product streams, 1% through waste streams, and 83% was destroyed due to irreversibilities. The B1/B2 rolling bench destroyed the most exergy, accounting for approximately 8.53 percent of the mill's irreversibility. It was established that the components with the highest waste streams had the highest irreversibilities. Minimizing waste streams would reduce the amount of exergy lost and increase the exergetic efficiency of components. To improve system efficiency, several process optimization and machine modifications were recommended.

Keywords: Exergy; Irreversibility; Efficiency; Flour production

1 Introduction

Flour is a significant component of our daily nutrition, and energy is a key input in wheat flour production. The cost of flour manufacturing is roughly distributed as follows: 81 per cent raw materials, 6.5 per cent electricity, 4 per cent labour, and 8.5 per cent consumables and other expenses, according to the Food and Agriculture Organization of the United Nations (FAO). And the situation is far worse for flour producers in Nigeria. Due to poorly managed and antiquated power facilities, as well as power transmission and distribution issues, Nigeria's electrical supply is severely limited and epileptic. As a result, the majority of companies in the country rely on heavy-duty generating plants to supply their electrical energy [1]. Energy costs more than 35 per cent of the cost of flour production in Nigerian flour mills, and this cost is only going up. Low-profit margins in wheat processing plants have resulted from the significant increase in energy costs, resulting in a continuous rise in product prices. Because of the constant rise in fuel prices, energy efficiency studies are becoming increasingly important. When energy is properly managed, it can save several

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millions of dollars in accumulated energy costs. Several researchers have reported on the energy consumption, potential for energy conservation, and environmental impact of various industrial process operations both within and outside Nigeria based on this fact [2]. The significance of energy in long-term economic development is widely acknowledged.

Climate change and the environmental consequences of energy consumption have become a major international concern. The contribution of the industrial sector to greenhouse gas (GHG) emissions was found to be significant among the various sectors contributing to GHG emissions; thus, reducing GHG emissions from the sector is one of the best ways to address the climate change problem. In this regard, energy efficiency is critical. By improving the efficiency of energy use in the industry, an estimated 10-30% reduction can be achieved at little or no cost [2]. The need to understand the mechanisms that degrade the quality of energy and energy systems is necessitated by increasing energy demands combined with finite energy resources, rising fossil fuel costs, and significant environmental *impacts.* Only a detailed analysis of the entire system will reveal the processes that degrade the quality of energy resources.

1.1 Energy analysis

Energy analysis is nothing more than a tally of the energies that enter and leave a system. It's one of the most comprehensive approaches to boosting energy efficiency and reducing waste. Efficiencies are measured as ratios of energy quantities and are frequently used to evaluate a system's performance. The loss of energy during its use in industrial processes is unavoidable; this is due to designs that do not include energy-saving features like heat recovery. Reduced energy losses will result in a significant increase in inefficiency. Energy analysis provides the data needed to make informed decisions about the most cost-effective energy efficiency measures to implement. Energy efficiency programs provide answers to questions such as the types of energy used in a given industry, how much is used, the cost, where it is used, factors affecting consumption, savings potentials, and economic assessments [2]. The advantages of increased energy efficiency can be divided into three categories: economic, environmental, and social. Although there is a lot of literature on energy audits for many manufacturing processes, this project is a more detailed energy analysis of wheat flour production, providing much richer and actionable data than most energy audits and surveys. The results of energy analysis are useful, but exergy analysis, in addition to energy analysis, can provide more useful results in thermodynamic performance assessments.

1.2 Exergy analysis

The quality of an energy quantity is determined by the exergy associated with it. The first law of thermodynamics, which expresses the principle of energy conservation, is the foundation for energy analysis. It does not, however, provide information on the irreversibility of thermodynamic processes. Exergy analysis, on the other hand, recognizes that, while energy cannot be created or destroyed, it can be degraded in quality, eventually reaching a state of complete equilibrium with the environment and thus becoming useless for performing tasks. Exergy analysis is a thermodynamic analysis technique that uses the combined principles of conservation of mass and energy, as well as the second law of thermodynamics, to assess the exact causes, locations, types, and magnitudes of wastes and losses, as well as to identify inefficiencies in a system. Exergy analysis methodologies have been applied to many industrial systems such as sugarcane bagasse gasification [3], pressurized fluid bed combustion power generation [4], hydrogen production process, multi-fueled power plant [5], steam heating process [6] and ethylene and propylene production process, etc. [7]. Although energy can be converted from one form to another, the second law of thermodynamics states that not all of the converted energy is available for use. The part that is available for use is known as available energy or exergy, while the part that must be rejected to the heat sink according to the second law of thermodynamics is known as non-available energy [8]. As a result, it is self-evident that there will be non-available energy from any energy source, and thus energy utilization cannot be 100 per cent efficient. However, a certain percentage of efficiency is acceptable; however, if the percentage is lower than expected, it is considered energy waste. Exergy analysis is important for assessing and reducing such unnecessary losses. Exergy analysis is a thermodynamic analysis technique that identifies the production process's minimum requirements in terms of exergy destruction. Exergy analysis allows us to pinpoint the exact location, nature, and size of additional inefficiencies in the process that result in exergy being wasted (e.g. waste heat) but which could theoretically be reused due to its exergy content. The waste streams of a food production chain are defined in this paper as raw materials, intermediate products, final products, and waste heat streams that are discarded to the environment without being used (e.g., quality issues, spoilage, mismanagement, etc.). Exergy analysis also allows for the evaluation of entire networks and sequences of processes, from raw materials to final products, to identify points along the chain where significant amounts of exergy are lost. Exergy can be applied at any level and sub-level because it is a universal concept. This qualifies it for the analysis of extremely complex systems such as flour production.

1.3 Cost analysis

A modern economy cannot function without energy. Furthermore, energy use imposes significant financial and environmental costs [9]. The Nigerian manufacturing sector is experiencing an increasingly long-term energy crisis, which has made energy costs a major component of production costs, accounting for roughly two-thirds of total production costs [1]. As a result, the cost of production has risen, and goods produced in Nigeria are no longer globally competitive. As a result, Nigerian manufacturers are looking for ways to cut costs by implementing cost-effective energy-saving technologies and practices that will lower operating costs while maintaining or increasing product quality and quantity [7]. Because the amount of energy used in a flour mill is an important economic consideration, energy management and recovery, where possible, must be used to reduce energy consumption in the production process while increasing profit margins.

1.4 Problem statement

Wheat flour production is an energy-intensive process that necessitates a steady supply of energy. As a result, it is necessary to investigate the pattern of energy consumption and utilization in the wheat flour processing plant, identify the source of energy waste in the plant, and develop appropriate energy-saving methodologies. Energy, Exergy and Cost analysis of flour production from wheat in Nigeria using Nigeria Eagle Flour mills, Ibadan as a case study was therefore studied in this work.

2 Literature review

Many researchers have conducted energy analyses on various production processes to evaluate performance and maximize efficiency. And a large number of people have contributed to the creation of this work. Energy analysis in most papers is primarily based on the first law of thermodynamics, which is the law of energy conservation. An energy analysis of a system is a tally of the energies that enter and leave it. Unfortunately, relying solely on energy analysis to describe a system's thermodynamics can be misleading. This is because energy analysis does not accurately identify and assess the thermodynamic losses that occur within a system. Exergy analysis, on the other hand, is a thermodynamic analysis technique that overcomes many of the drawbacks of energy analysis. Exergy analysis is a technique for determining the causes, sources, and magnitudes of process inefficiencies. It is based on the second law of thermodynamics. Although energy cannot be created or destroyed, it can be degraded in quality, eventually reaching a state of incomplete equilibrium with the reference environment, according to exergy analysis [4]. The majority of the research looked at energy analysis without taking into account exergy. Energy analysis is incomplete without exergy analysis. The cost of energy is an important factor influencing energy and exergy analysis. Several industries, particularly energy-intensive industries, use energy cost-production output as a key performance indicator. Only when energy-saving measures have long-term economic benefits are they implemented. Many researchers, on the other hand, do not translate the results of energy or/and exergy analyses into costs. This paper examines the application of energy, exergy, and cost analysis to wheat flour production, as well as literature on these topics.

2.1 Data Collection

The collection of data is the first step in the analysis process. The lack of an effective data management system is one of many challenges that can arise during the course of energy analysis [10]. In general, energy analysis entails examining the energy consumption pattern over time using data that is already available. Analysis can be difficult in many companies because they do not have a structured approach to data management. Meo et al. [10] proposed a structured approach to help with data collection and management. This includes onboard sensors and automated data collection. This would not only reduce the risk of gaps and human error involved with manual data collection but also allow efficient data management for future energy analysis. Because energy analysis is not constrained by strict guidelines, various methods and approaches for data collection and analysis are employed. The primary source of data for analysis of the performance of industrial operations in a study by Aiyedun et al. in [11] to optimize the energy efficiency of a manufacturing industry using Nigeria Eagle Flour Mills as a case study was the individual plant operator, and the study was carried out with data calculated for a period of 5 years (1996–2000). The power rating of the electrical devices and the capacity of each unit of production were collected from the plant's manager and data was collected over a period of two months in the energy analysis for the production of powdered and pelletised organic fertilizer in Nigeria [12]. A walkthrough energy audit provided data for the power rating, operation time of energy-consuming equipment and machinery, and power factor in a study to analyze the energy use and energy-saving opportunities of selected industries in southwest Nigeria. In addition to the audit, plant managers and maintenance engineers were interviewed to gain a better understanding of the manufacturing processes and equipment [13].

Different approaches, on the other hand, have their own set of limitations. Short-term energy audits and surveys have limitations, according to Agha et al. in [14], such as only picking up a small number of improvement opportunities based on a single visit. It was hypothesized that observations based on long-term energy studies would produce a more accurate result.

2.2 Energy analysis

Three types of energy are commonly used in production companies, according to the literature reviewed. Electrical energy (from power generators), thermal energy (from combustible resources), and manual energy are all examples of this (energy from human input). Green et al., (2019) conducted an energy audit to identify areas for energy efficiency improvements and to determine the level of energy consumption of various energy sources. They discovered that three types of energy were used: electrical, thermal (diesel and gas), and manual, with proportions of 14.63 per cent, 85.31 per cent, and 0.05 per cent, respectively, of total energy input. The study also found that thermal (diesel and gas) energy was the most commonly used form of energy, accounting for 73 per cent of total energy input over the study period, followed by electrical energy, which accounted for 25 per cent of total energy input, and manual energy expended in operating machines and lifting loads, which accounted for only 3% of total energy input [15]. According to a study of cashew nut processing mills in Ibadan, Nigeria, thermal energy was used more than the other two sources of energy (electricity and manual labour) [16]. Thermal energy per kilogram (kg) of processed cashew nut ranged from 14.9MJ to 63.62MJ, while electricity consumption ranged from 5.56MJ to 13.48MJ per kg of processed cashew nut, and manual energy ranged from 1.25MJ to 3.08MJ per kg of processed cashew nut, according to them. To determine the energy consumption pattern in an orange juice manufacturing industry in Nigeria, energy, and exergy studies were conducted [1]. Electrical, steam, and manual energy were used in the production of orange juice, accounting for 18.51 per cent, 80.91 per cent, and 0.58 per cent of total energy, respectively. Thermal energy is typically used in greater proportions in production processes that require a large supply of heat, according to several literature. When no heat is required, electrical and manual energy are the primary sources of energy. According to energy analysis of the production of powdered and pelletised organic fertilizer in Nigeria [12], the electrical and manual energy required for powdered fertilizer production was 94.45 per cent and 5.55 per cent of total energy, respectively, with 93.9 per cent and 5.07 per cent for pelletized fertilizer production. Manual energy is usually the least significant energy input because production processes, especially in wheat flour production, require a higher proportion of machine input than human input. According to Adefajo in [17], the types of energy used in the processing of wheat flour were electrical and manual, accounting for 99.87 and 0.13 per cent of total energy, respectively. According to the study, only two processes (truck unloading and packaging) required manual labour, accounting for 0.13 per cent of total energy consumption. According to studies, most businesses in Nigeria rely solely on self-generated electricity due to the national grid's intermittent power supply. Natural gas or diesel is the most common fuel for generators. According to a survey of 210 Nigerian food and beverage companies, 89.7% of respondents used generators as their sole source of power due to power outages or low voltage from the national grid. Only when their generating sets were being serviced did the remaining 10.3 per cent rely on the national grid [18]. Another study found that natural gas was the most commonly used energy source during the study period, accounting for 99.75 per cent of total energy consumption. Due to the high cost of diesel fuel compared to Liquefied Natural Gas (LNG), only a small percentage of diesel fuel was consumed. The percentage of electricity supplied from the national grid varies between 0.04 per cent and 1.78 per cent in all of the industries studied. This low percentage is due to Nigeria's power sector's poor performance [12].

2.3 Key Performance Indicators (KPIS)

Energy productivity/intensity is a key performance indicator used in energy analysis, according to the literature reviewed. Aiyedun et al. in [10] investigated the company's energy consumption, productivity, and efficiency. The study's findings revealed that energy was not being used efficiently in this industry, as energy productivity increased significantly from 0.369 $MJkg^{-1}$ in 1996 to 0.716 $MJkg^{-1}$ in 2000. 0.527 $MJkg^{-1}$ and 1.084 GJm^{-2} are the average energy productivity and intensity of energy, respectively. In another study to analyse the energy consumption pattern of malt brewing operations in Nigeria, because of improving the efficiency of the system. Fadare et al. in [19] showed that 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. An energy analysis conducted on a milling plant concluded that the most energy-intensive operation is the milling unit with an energy intensity of about 0.073MJ/kg (72.20%) of the total energy consumption in that plant, followed by the packaging unit using 0.015MJ/kg (14.39%) of the total [20]. Waheed et al. in [1] established that the manufacturing of orange juice required an average energy intensity of 1.12 MJ/kg in his study to determine the energy consumption pattern of orange processing. The pasteurizer was found to be the most energy-intensive operation, followed by the packaging unit, with energy intensities of 0.932 and 0.119 MJ/kg, respectively. Another important performance indicator in energy analysis is the amount of energy consumed. Energy analysis is used to determine how much energy is consumed by various operations or machines to identify the areas that consume the most energy. Aliu et al. in [21] and [22] established that the roller mill machines in Mill A and B consume the most energy, which is 32,078,200MJ/year and 20,808,191.27MJ/year, respectively, based on the results of an energy audit. This accounts for 91.8 per cent and 62.6 per cent of the energy used in both plants, respectively. Among the process machines used in the flour production process, the purifier machine in Mill A and the blower standby machine in Mill B use the least amount of energy. This accounts for 0.13 and 0.14 per cent of total energy consumption, respectively. It was also discovered that the months of January and May had the highest specific energy consumption (1.046MJ/kg). According to Aiyedun et al. in [11], an average of 47,810.59 GJ of energy was consumed annually during this period, with electricity, lubricants, diesel, and petrol accounting for 44.68 per cent, 0.23 per cent, 42.16 per cent, and 12.93 per cent, respectively. Another key performance indicator that can be used in energy analysis is the energy use ratio. It calculates how much of the energy input was wasted. An energy audit of manufacturing and processing industries in Nigeria was conducted, and the energy used ratios in the two industries surveyed were less than unit during the study period. This demonstrates inefficient energy use, with more energy spent on unit production of the finished product [1].

2.4 Exergy analysis

Exergy analysis has been applied by various authors to several production processes and sectors, including sugar production [23], steam process heating [6], distillation [24], industrial bread production [25], ethanol and biogas polygeneration facilities [26], mixed feed [27] and power plants [4]. Many studies demonstrate the extensive range of applications of exergy analysis for different processes and systems. By reducing the sources of existing inefficiency, exergy analysis aids in the design of more efficient energy systems. Rosen et al. in [4] conducted energy and exergy analyses on a PFBC power plant and discovered that if no exergy was destroyed, the process became completely reversible and the exergy efficiency was 100%. As a result, fuel consumption fell 61.7 per cent, environmental emissions fell 61.7 per cent, and energy efficiency rose to 104.1 per cent.

2.5 Cost analysis

Although there is a large body of literature on the energy and exergy analysis of many manufacturing processes, only a few studies assess the economic impact and cost implications of energy inefficiencies. According to Olaoye et al. in [18], optimizing the milling process and making efficient use of fuel, electricity, and manual energies would reduce economic loss and flour costs. Furthermore, the average energy intensity required for wheat flour production would be reduced to a bare minimum. A study was conducted to audit the energy consumption rate of Crown Flour Mill's Mills A and B in Apapa [20]. The researchers calculated the cash equivalent of diesel fuel consumed by analyzing the diesel fuel consumption rate. When compared to a report on the manufacturing industry prepared by the United States Census Bureau in 2005, the total energy cost per tonne of wheat milled was found to be N5260. According to the report, the total energy cost per tonne of wheat milled was approximately $4 to $7 (N1600 to N2800) [28]. This demonstrates the significance of efficient energy use, particularly in Nigeria. In a study to assess the energy efficiency of a manufacturing industry [10], the average cost of energy input per unit kg was determined to be 28 kobo/kg. The cost of electrical energy based on the national grid was calculated as the product of energy consumption per unit operation and unit cost of energy in a study on the energy and cost analysis of wet and dry cement production [29] While the electrical energy cost for the gas-powered plant was calculated as the product of the power plant's gas consumption in standard cubic feet (SCF) and the unit cost of gas (Naira per standard cubic feet). The minimum wage per month paid by the Federal Government was used to compute the unit cost of manual energy.

2.6 Energy-Saving Solutions

Researchers have proposed several energy-saving measures. One of the most important measures for increasing energy efficiency is regular maintenance. According to Aiyedun et al. in [10], effective maintenance not only improves the efficiency of equipment and systems but also extends their life span [10]. During an energy audit of a flour mill plant, analysis of energy consumption data revealed that a large quantity of energy-consuming equipment, such as electric motors used to power the majority of the machines in the flour Mill Manufacturing Plant, were operating at less than their installed capacity. This was primarily because the majority of the electric motors were old and had been rewound twice or more [20]. It was suggested that the plant develop an overall motor inventory and replacement plan to save a significant amount of electrical energy. Aderemi et al. in [17] conducted a study on the pattern of electrical energy consumption from 210 selected micro and small-scale food and beverage companies in Nigeria (2009). Energy loss as a result of worn-out or slack/misaligned belts that require timely replacement or tensioning, training and retraining of staff, and power factor of electrical equipment, among other things, were identified as direct and indirect sources of electrical energy waste and inefficient energy utilization in the industry. Three of the eleven strategies were successful in reducing the companies' electricity bill by 3% for the same amount of production. These include: turning off most lighting during the day; replacing/tensioning worn-out/slack belts or chains immediately; and disconnecting all faulty equipment [17]. Another area where energy consumption can be reduced is lighting. Olayinka et al. in [8] proposed measures to reduce energy consumption by lighting in their study. For example, using light reflection to improve workplace brightness, providing electronic control for lighting control during the day, and replacing low-efficiency lighting with energy-saving types. In addition, power sources, which are typically overlooked in most studies when suggesting energy-saving measures, were taken into account. To reduce energy waste, measures such as replacing diesel generators with gas generators and using a generator with a smaller capacity for load shedding were proposed. The cause of irreversibility was identified as unrestrained steam expansion in low-efficiency prime mover turbines in a study by [22]. It was proposed that replacing turbines with an electric shredder, knife, and dewatering mill drivers would reduce irreversibility. Although much of the literature reviewed contributed significantly to this work, some gaps are addressed in this project. Due to inefficiencies and transmission losses, energy generated is usually greater than the energy consumed, and many studies fail to account for this difference or propose solutions to reduce these losses. During an energy audit of a flour mill plant [20], it was discovered that the calculated amount of diesel fuel energy consumption for Mill A and B is approximately 18441262.78kWh/year and 29467997.22kWh/year, for a total of 47909260kWh/year. However, when compared to the calculated energy requirement from the process machine capacities of 4769636.47kWh/year and 9338765.07kWh/year for Mill A and B, a total of 14108401.54kWh/year for the period under study, it was determined that there was overconsumption of energy. This project accounts for the difference between energy generated and energy consumed and also suggests ways to reduce losses. Many studies fail to include lighting as a source of energy waste. According to a study conducted by Olayinka et al.in [8], industrial lighting consumes approximately 20% of electrical energy and 7% of total energy. This project calculates the amount of energy used by lighting and suggests ways to reduce the amount of energy wasted by lighting. The most energy-intensive operating unit in the production system was identified while working on energy analysis for the production of powdered and pelletized organic fertilizer in Nigeria [7] and process and machine design modifications were proposed to optimize the unit's energy consumption, but no implementation method was provided. (Olaoye et al. in [18] also did not specify the methods to be used to improve the system's efficiency/optimize the manufacturing process. Many studies fail to identify the source and magnitude of inefficiencies because exergy analysis is not performed. To account for inefficiencies, this project conducts a comprehensive exergy analysis of wheat flour production. The study aimed to identify energy inefficiencies in unit operations as a step towards system optimization in the energy analysis for the production of powdered and pelletized organic fertilizer in Nigeria [7]. Exergy analysis was not performed, so inefficiencies were not identified because energy analysis can only calculate the quantity of energy, not the quality. The energy consumption pattern of wet and dry cement processing was analyzed in a study on the energy and cost analysis of cement production using the wet and dry processes in Nigeria [29], but the inefficiencies and sources of energy waste were not identified. Exergy analyses of both production processes would reveal the sources of energy waste and their magnitude. Due to a lack of implementation method and knowledge of the measures, most audits and studies propose very limited solutions, and actual implementation of energy efficiency measures usually ends up as only theoretical calculations. This project includes theoretical calculations as well as recommendations for energy efficiency improvements.

3 Methodology

Efficient energy use in flour production industries has promising economic and environmental benefits, necessitating research into energy consumption patterns and identifying the sources and magnitude of inefficiencies in the manufacturing process. The efficiency of energy used in the Nigeria Eagle Flour Mill was examined in this study, and all areas and sizes of energy waste were identified. Because energy analysis is based on numerical data, a quantitative research approach was used for this study. Energy, exergy, and cost analysis are carried out in three stages in this study: pre-analysis, data collection, and detailed analysis.

3.1 Pre-analysis phase

The pre-analysis phase was the first stage of this research project's development. During this phase, a thorough literature study and research was conducted, and the approach to be employed was determined. Meetings and discussions on the project's goals and objectives were held with plant management. An initial investigation of flour production techniques and equipment, as well as energy generation facilities, was conducted. All data recording devices were identified after watching the production conditions. This was done to determine whether or not metering devices would be required before data collection. Pre-existing energy-saving methods were also discovered.

3.2 Plant Description

The selected plant of study, Nigeria Eagle Flour Mills, is located in Southwest Nigeria. The factory produces flour, semolina, and bran. Eagle flour mills are designed to process 5000 tonnes of wheat per day. Electrical and manual energy are the two types of energy employed. Workers work eight-hour shifts per day, with two 12-hour stints for factory workers. Electricity from the national grid and self-generated electricity are the primary sources of electrical energy. Diesel and gas plants are the sources of self-generated electricity. The generated electricity is distributed in a 60:40 split to Nigeria Eagle Flour Mills and Premier Feeds. Electricity supplied to Nigeria Eagle Flour Mills is mainly consumed by lighting, and the two mills (Mill A and B).

3.3 Process Description

Depending on the type of flour required for the final product, each mill varies slightly. The Nigeria Eagle Flour mill, on the other hand, follows the steps outlined below in roughly the same order.

3.3.1 Product Control

Trucks deliver wheat to the mill. Samples of wheat are taken before it is unloaded to ensure that it passes inspection. To achieve the desired end product, different types of wheat (hard, soft, and durum) are blended.

3.3.2 Magnetic Separator

The wheat is then passed through a magnet, which removes any iron or steel particles. The wheat is separated by a separator that determines the kernel size even more precisely. Anything longer, shorter, more round, more angular, or has a different shape is rejected.

3.3.3 Conditioning the Wheat

The wheat is now ready for conditioning before milling. Tempering is the term for this process. To toughen the bran and mellow the inner endosperm, moisture is added in precise amounts. Depending on the type of wheat - soft, durum, or hard-tempered wheat is stored in bins for 18 to 24 hours.

3.3.4 Scourer

With intense scouring action, the scourer removes outer husks, crease dirt (dirt contained in the crease of the wheat berry), and any smaller impurities. All of the loosened material is pulled away by air currents.

3.3.5 Grinding the Wheat

The wheat kernels are gradually reduced in size during this modern milling process. The goal is to create coarse endosperm particles. Sieves and purifiers are used to grade the particles and separate them from the bran.

3.3.6 Rollers

The break rolls are fed wheat from the clean wheat tank (corrugated rollers made from chilled cast iron). The rolls are paired and rotate inward at different speeds against each other. The separation of bran, endosperm, and germ begins with just one pass through the first break rolls.

3.3.7 Sifters

The broken wheat particles are sifted through a series of bolting cloths or screens to separate the larger from the smaller particles in massive, rotating, box-like sifters. There could be as many as 78 frames inside the sifter, each with a nylon or stainless steel screen and square openings that get smaller and smaller as they go down.

3.3.8 Purifiers

In a purifier, a controlled flow of air separates and grades coarser fractions by size and quality while a bolting cloth separates and grades bran particles.

3.3.9 Enrichment

A device measures out specified amounts of enrichment as the flour stream passes through conveyors. Finally, the flour millstream is pumped into startup bins via pneumatic tubes.

3.3.10 Packaging

Screw conveyors transport flour from various startup bins to bucket elevators. Screw conveyors blend excess enrichment that may be present due to production downtime or measurement errors by mixing flour from different startup bins. Bucket elevators transport flour to bulk storage silos. Flour is conveyed to the turbo sifter from silos. Before packing, the turbo sifter is used for secondary sifting of flour. The flour is then transported to the flour tanks, where it will be packed. Flour is transferred from the flour tank to the flour scale, then to the carousel (with three to five sprouts), and bagged in 50kg bags.

3.3.11 Truck Unloading

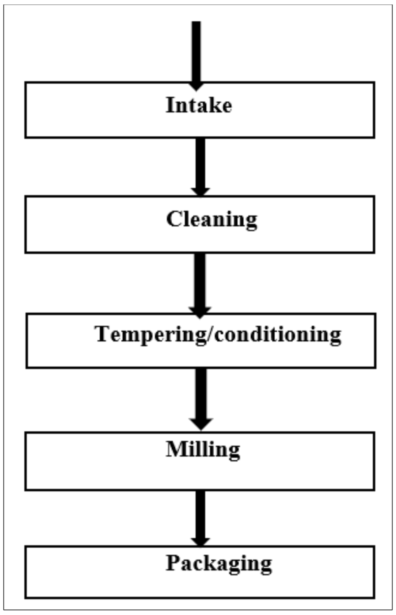

Figure 1 Process diagram of flour production from wheat

3.4 Data Collection Phase

This study is based on energy consumption data gathered during a five-month period (April – August). Data was gathered by observation, direct measurement, and existing production and technical department records. Measuring devices used include: stopwatches and meters. Although the majority of the data obtained is based on reliable daily demand meter readings, there is a possibility of minor discrepancies due to the risk of gaps and human error in manual data gathering. To avoid errors, all data collected was double validated.

3.5 Data Collected For Energy Analysis

Table 1 Monthly Run Time of Processes in Mill A

S/N	Process	April	May	June	July	August
1	Cleaning	618.29	610.63	548.14	615.9	651.2
2	Milling	618.29	610.63	548.14	615.9	651.2
3	Packing	605	540	547.7	583.5	532.5

Table 2 Monthly Run Time of Processes in Mill B

S/N	Process	April	May	June	July	August
1	Cleaning	620.58	645.15	608.99	568.55	609.44
2	Milling	620.58	645.15	608.99	568.55	609.44
3	Packing	609.5	538.95	577.75	540.25	550.6

All light fittings were identified and collated.

The primary data was gathered from all major units of electricity consumption. An inventory of machines and electrical motors, along with their respective power ratings, was compiled for Mill A's three main sections - cleaning, milling, and packing. An inventory of machines and electrical motors, along with their respective power ratings, was compiled for Mill B's three main sections: cleaning, milling, and packing. During the study period, the production process in both mills was monitored to determine how long it takes to complete each unit operation for one production cycle (from intake to warehouse).

Table 3 Light Fittings

	No of Fittings	Rating (W)	Length	Total (W)
Flourescent Total	208	36	4ft	7488
Halogen Security Bulbs	5	250	-	1250
Flourescent Total	65	18	2ft	1170
LED (4ft)	250	72	4ft x 2	18000

The type and amount of fossil fuels (diesel and natural gas) used were documented.

Table 4 Gas Consumed During Study Period

Gas Consumed (Sm3)	April	May	June	July	August
Lighting	30699.7	37324.3	5087.1	0.0	0.0
Mill A	35557.1	101429.7	408.6	0.0	0.0
Mill B	168035.2	211721.7	731.4	0.0	0.0
PFM	0.0	42854.1	12352.3	0.0	0.0

Table 5 Diesel Consumed

Diesel Consumed (Litres)					
	April	May	June	July	August
Lighting	20633	10399	9784	20682	9524
Mill A	130053	71142	165726	167043	193960
Mill B	38358	22237	135361	95531	67100
PFM	105343	52393	93019	94803	121231

The availability of electricity from the national grid was recorded

Table 6 Electricity Supplied From National Grid (IBEDC)

	April	May	June	July	August
Lighting (Kwh)	6300	900	113000	77700	118900
Mill A (Kwh)	0	0	8310	20	0
Mill B (Kwh)	9807	1610	285891	360709	525120
PFM (Kwh)	0	0	11	49	77

The plant's output was monitored and recorded during the study period.

Table 7 Production Data

(in MT)	April	May	June	July	August
MILL A	6688.59	7669.05	8628.53	9420.88	9508.83
MILL B	6721.73	8487.45	8667.09	9062.05	8802.79
TOTAL	13410.32	16156.5	17295.62	18482.93	18311.62

The number of employees involved in unit operations, as well as their working hours, was recorded.

3.6 Data Collected For Exergy Analysis

The exergy analysis was evaluated for the milling operation in Mill A, which is a major energy consumption unit in the plant.

3.6.1 Procedure for data collection

All input and output streams (matter stream, work, and heat), for milling equipment considered, were identified.

The thermodynamic properties for each stream were determined. The temperature for all matter streams was obtained from the evaluation of samples using an infrared temperature scanner. The moisture and protein fractions were obtained by evaluating samples from each of the streams, through a Near-infrared Analyzer (NIR). The mass flow rates for all streams were obtained from meters for different machines' output scales. The work values were obtained from the measurement of the electrical power consumed in each of the machines in the plant.

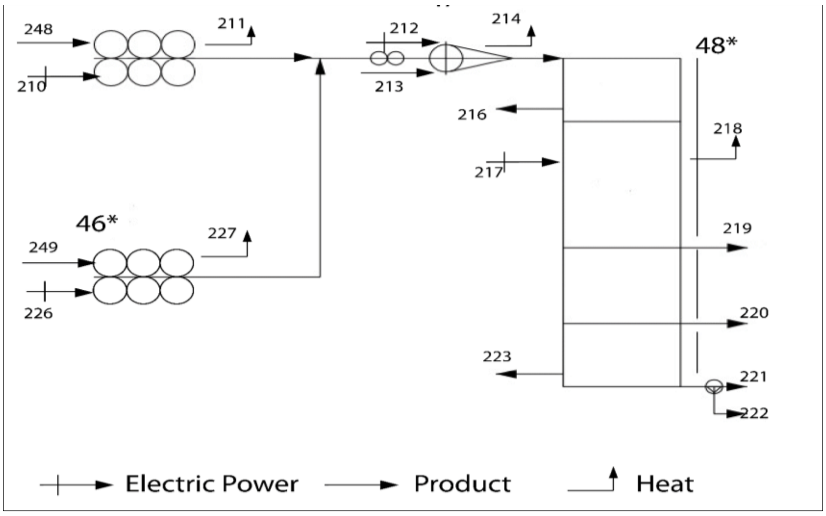

Figure 2 The schematic diagram of input and output streams of machines in Mill A

3.7 Detailed Energy Analysis Phase

The following procedures were used to properly analyze the operation data collected. The energy use in unit operations was assessed to investigate the pattern of energy distribution and consumption. The percentage breakdown of total energy consumption was examined to determine the dominant energy consumption unit. Data collected were subjected to energy model equations.

For the study period, tables, charts, and figures displaying energy consumption for various units were generated.

3.7.1 Energy Model Equations [1-28]

Evaluation of electrical energy

The amount of electrical energy used in Ep in kWh was calculated by multiplying the rated motor power by the operational time and the expected motor efficiency of 80%. Mathematically:

$$EP=\eta Pt \text{ .... } (1)$$

Where:
Ep is the electrical energy in kWh
P denotes the motor power in kW.
t denotes the operational time in hours
η denotes the motor efficiency (assumed to be 0.8)

Evaluation of manual energy

According to Odigboh in [30], the physical power production of regular human labor in tropical climes is roughly 0.075kW sustained over an 8-10-hour workday at a maximum continuous energy consumption rate of 0.30 kW and a conversion efficiency of 25%. Therefore, the manual energy input would be determined as:

$$Em = 0.075Nmtm \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where
E_m is the manual energy input by a worker in kWh
N_m is the number of workers
t_m is the time used by workers

Total energy input

For each unit operation, the total energy input is given as:

$$Et = Ep + Em \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where:
E_t is the total energy input
E_p is electrical energy input (kWh)
E_m is manual energy input (kWh)

Energy consumption

This is the total energy utilized by the plant's motors and generators. It is calculated using the following formula: Energy Consumption = Units Wattage x Number of Hours Used.

$$EC = Pt \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where:
E_C denotes the energy consumption (J)
P denotes the power ratings for each unit (kW)
t denotes the operational time (h)

Percentage energy consumption

This is the energy consumption in percentage. It is calculated using:

$$Energy = \frac{EnergyType}{TotalEnergy} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Energy intensity

It assesses how much a unit of energy contributes to the economy. It is used to determine how efficiently a plant uses its input energy. This value is computed as follows:

$$EI = \frac{Totalenergyinput}{Totalweightoftheproduct} \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where:
E_I denotes the energy intensity (MJ/ton)

Energy Use Ratio

The energy use ratio is the ratio of total energy input to the total energy content of the finished product [12]. It is computed as:

$$ER=\frac{E0}{Et} \quad .... (7)$$

Where:
ER denotes the energy use ratio
Et denotes the total energy input (MJ)
E0 denotes the total energy output (MJ)

Total energy content (energy output) of the finished product

This is the energy output in a finished product of wheat flour. This is calculated using the model equation:

$$E0= MFP\times ECP \quad .... (8)$$

Where:
E_0 is the energy output of the finished product (J)
M_{FP} is the energy content of a unit mass of the product (J)
E_{CP} is the mass of the finished product (kg)

3.8 Detailed Exergy Analysis Phase

Exergy analysis is for calculating the proportion of exergy destruction which is useful for identifying the magnitude and the exact source of thermodynamic inefficiencies in a system. In a general steady-state, steady-flow process, the balance equations are applied to find the work and heat interactions, the exergy, the rate of exergy decrease, the rate of exergy destruction, and exergy efficiencies. The balance equations used are as proposed by Ghannadzadeh et al. in [31]

The mass balance in rate form is given below as:

$$\sum \dot{m}_{\boldsymbol{i,in}} = \sum \dot{m}_{\boldsymbol{i,out}} .... (9)$$

Where $\dot{m}_{\boldsymbol{i}}$ **i**s the mass flow rate of the stream *i* (kg/s), and the subscript *in* stands for inlet and *out* for outlet.

The general energy balance in rate form is expressed as:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} .... (10)$$

$$\dot{W} + \sum \dot{m}_{\boldsymbol{in}} \boldsymbol{h_{in}} = \dot{Q} + \sum \dot{m}_{\boldsymbol{out}} \boldsymbol{h_{out}} \quad .... (11)$$

Where $\dot{E}$ is the rate of energy transfer (kW), and the subscript stands for inlet and *out* for outlet.

The general exergy balance can be expressed in rate form as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \sum \dot{E}x_{destroyed} = 0 .... (12)$$

The exergy of a stream consists of physical, chemical, and mixing exergies and can be calculated as follows:

$$Ex_i = Ex_{i,physical} + Ex_{i,chemical} + Ex_{i,mix} \quad .... (13)$$

The physical exergy, which is the only relevant form of exergy considered in this study is the maximum work obtainable by taking the mass stream at thermal and mechanical equilibrium with the environment [32]. Chemical exergy is the maximum work obtained when taking a stream to an equilibrium position with the environment, in terms of chemical composition. Mixing exergy is relevant to two or more material streams mixing.

The relevant form of exergy considered in this study is the physical exergy which can be expressed as:

$$Ex_{i,physical} = Ex_{i,thermal} + Ex_{i,pressure} + Ex_{i,electrical} \text{ .... (14)}$$

Thermal exergy is the only form of physical exergy relevant to this study and it can be expressed as:

$$Ex_{i,thermal} = \dot{m}_i c_{p,i}\left[(T_i - T_0) - T_0 \ln\left(\frac{T_i}{T_0}\right)\right] \text{ .... (15)}$$

3.8.1 Procedure for exergy analysis

- The ambient temperature and pressure were set as 25°C and 101.3 kPa. The boundary temperature T_j was assumed to be 30^{0}C. And production capacity was assumed as 500,000kg/day. The process was defined as a steady-state flow process. Since the density of the material throughout the process did not undergo significant variations, it was assumed constant. Also, it was assumed that processes carried out by the system are not reactive, so the chemical exergy was not considered.
- With the thermodynamic data determined, the specific heat for all matter streams was calculated as proposed by Engineering, (2007):

$$c_{p,i} = 1.056 + 0.0058T_i + 3.71W_{m,i} - 2.34{W_{m,i}}^2 + 0.62W_{p,i} \text{ .... (16)}$$

This equation was used as opposed to the equation proposed by Leitfahigkeit, (1970) that specific heat can be calculated as shown below because wheat flour has relatively low moisture and protein content.

$$c_{p,i} = 1.23 + 0.0023T_i + 0.018W_{m,i} + 0.00048{W_{m,i}}^2 \text{ .... (17)}$$

Where $c_{p,i}$ is the specific heat capacity (J/g°C), T_i is the temperature, $W_{m,i}$ is the moisture content, $W_{p,i}$ is the protein content of the matter stream.

- The enthalpy for each matter stream was calculated as shown below:

$$h_i = c_{p,i}T_i \qquad \text{........................ (18)}$$

Where h_i is the enthalpy of the individual matter stream (KJ/kg).

- The specific exergy of each matter stream was calculated as expressed below:

$$\Psi_i = (hi - h0) - T0(si - s0) \qquad \text{........................ (19)}$$

$$\Psi_i = c_{p,i}\left[(T_i - T_0) - T_0 \ln\left(\frac{T_i}{T_0}\right)\right] \qquad \text{........................ (20)}$$

Where Ψ_i is specific exergy of each matter stream, s is the specific entropy (kJ/kgK), T is the temperature and the subscript "*0*" and "*i*" represents the reference and state of matter stream respectively.

The exergy of each matter stream in rate form was calculated as shown below:

$$\dot{Ex}_{M,i} = \dot{m}_i \Psi_i = \dot{m}_i (hi - h0) - T0(si - s0) \qquad \text{........................ (21)}$$

$$\dot{Ex}_{M,i} = \dot{m}_i c_{p,i}\left[(T_i - T_0) - T_0 \ln\left(\frac{T_i}{T_0}\right)\right] \qquad \text{........................ (22)}$$

- The work rate values for each machine considered were obtained from the measurement of the electrical power consumed in each of the machines in the plant as shown below:

$$\dot{W} = \eta P \text{ .... (23) 22}$$

Where η is efficiency of motor and P is the power rating of motor.

The heat rate values for each of the machines considered were obtained as expressed below:

$$\dot{Q} = \dot{W} - \sum \dot{m}_{out} h_{out} + \sum \dot{m}_{in} h_{in} \qquad \text{........................ (24)}$$

- The rate of exergy destroyed (or irreversibility) was calculated as expressed below:

$$\dot{E}x_{destroyed} = \sum \dot{m}_{in} \Psi_{in} - \sum \dot{m}_{out} \Psi_{out} - \sum \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j + \dot{W} \qquad \text{........................ (25)}$$

  - The exergetic efficiency was calculated as expressed as proposed by Ghannadzadeh et al., (2012):

$$\eta II = \frac{\sum \dot{E}x\,out - \dot{E}x\,out^{waste}}{\sum \dot{E}x\,in} \qquad \text{........................ (26)}$$

Where ηII is the second law efficiency, $\sum \dot{E}x\,out$ is the total exergy output (KW), and $\sum \dot{E}x\,in$ is the total exergy input (KW), $\dot{E}x\,out^{waste}$ is the exergy loss due to heat (KW).

- The improvement potential was calculated using the equation below:

$$\dot{IP} = (1 - \eta)\left(\sum \dot{E}x\,in - \sum \dot{E}x\,out\right) \qquad \text{........................ (27)}$$

The relative irreversibility was computed as expressed below:

$$RI_i = \frac{\dot{E}x_{D,i}}{\dot{E}x_{D,tot}} \times 100 \qquad \text{........................ (28)}$$

Where $\dot{E}x_{D,i}$ is the rate of exergy destruction for each machine and $\dot{E}x_{D,tot}$ is the total rate of exergy destroyed.

A model containing the mass, energy, and exergy balance was built in Microsoft Excel® 2010.

Tables, charts, and figures showing the magnitude and sources of exergy destroyed and irreversibility was generated.

4 Results and discussion

4.1 Energy analysis

The major sources of energy required in the plant are electrical and manual energy, and flour production requires three processes: cleaning, milling, and packing. These procedures are carried out in continuous and repetitive cycles, and the energy inputs into each operation have been taken into account. The amount of electrical and manual energy utilized was calculated, as well as the overall energy demand for each unit of operation. The entire energy usage for Mills A and B from April to August is shown in figure 3 and 4. Electrical energy was the most commonly utilized type of energy in both mills, with percentages ranging from 99.77 percent to 99.79 percent in Mill A and 99.83 percent to 99.85 percent in Mill B. Manual energy input was minimal in comparison to electrical energy consumed, ranging from 0.20 percent to 0.23 percent of total energy consumed in Mill A and 0.15 percent to 0.17 percent of total energy consumed in Mill B. In Mill A, the percentage of energy consumed in the cleaning section ranged from 12.3 percent to 12.4 percent, with an average of 8.8 percent. The milling process utilized the most energy, accounting for 80.3 percent to 81.4 percent of total energy consumed in Mill A and 84.4 percent to 85.2 percent of total energy consumed in Mill B. The packing section consumed the least energy, accounting for 6.2 percent to 7.5 percent of total energy consumed in Mill A and 5.9 percent to 6.9 percent of the total energy consumed in Mill B. As seen in figure 3, within the study period, the highest energy consumption in Mill A, 2,030,631.8 MJ was recorded in August and the highest energy consumption in Mill B, 2,863,631.6 MJ was recorded in May.

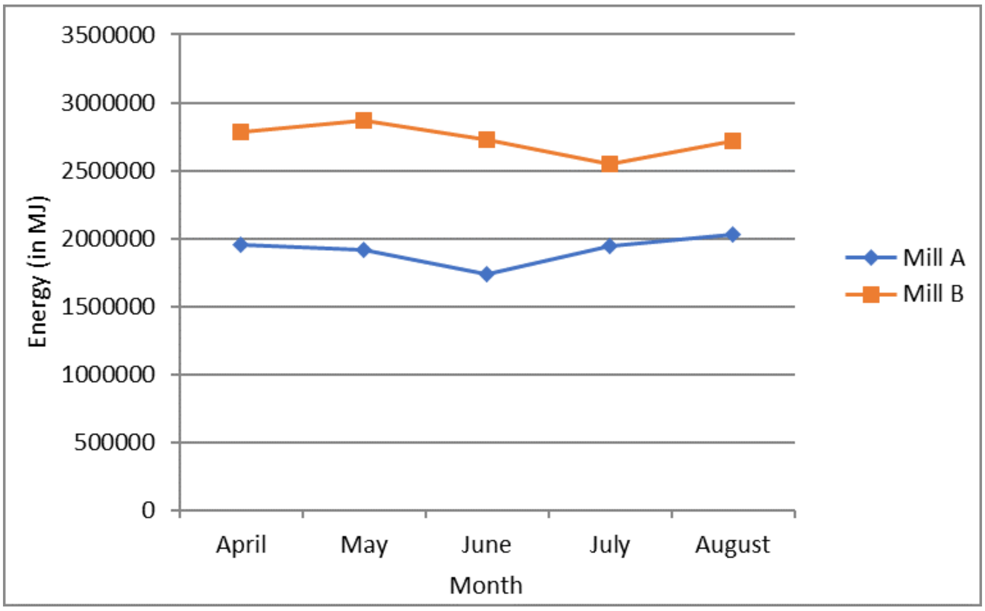

Figure 3 Energy consumption in Mill A and B

According to figure 3 and 4 below, energy consumed by Mill B is significantly larger than the energy consumed by Mill A throughout the study period. Mill B uses more energy since the manufacturing process is manual, as opposed to Mill A, where operations are entirely automated. Furthermore, because manufacturing is not automated, Mill B employs more machines for flour production than Mill A. Consequently, more energy is consumed.

4.1.1 Energy Intensity

The energy intensities of Mills A and B are depicted in Figure 1. During the research period, Mill B has the highest energy intensity for all processes. This is due to Mill B having more and older machinery, making it less energy efficient than Mill A.

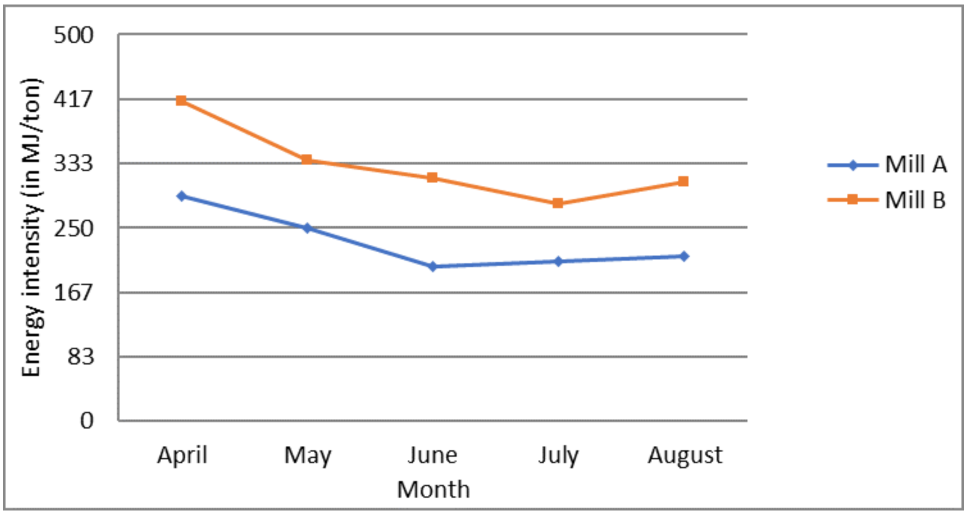

Figure 4 Energy Intensity of Mill A and B

During the study time, it can be shown that the milling operation consumes the most energy, followed by the cleaning and packing processes for both mills. The energy intensity used in Mill A ranged from 292MJ/ton in April to 214MJ/ton in August, with 201MJ/ton in June being the lowest figure reported throughout the research period and 292MJ/ton being the highest. Mill B's energy intensity ranged from 414MJ/ton in April to 309MJ/ton in August, with 281MJ/ton having the lowest energy intensity over the study period and 414MJ/ton having the highest. The observed increase in energy intensity in both mills is the result of energy-saving measures used by the plant.

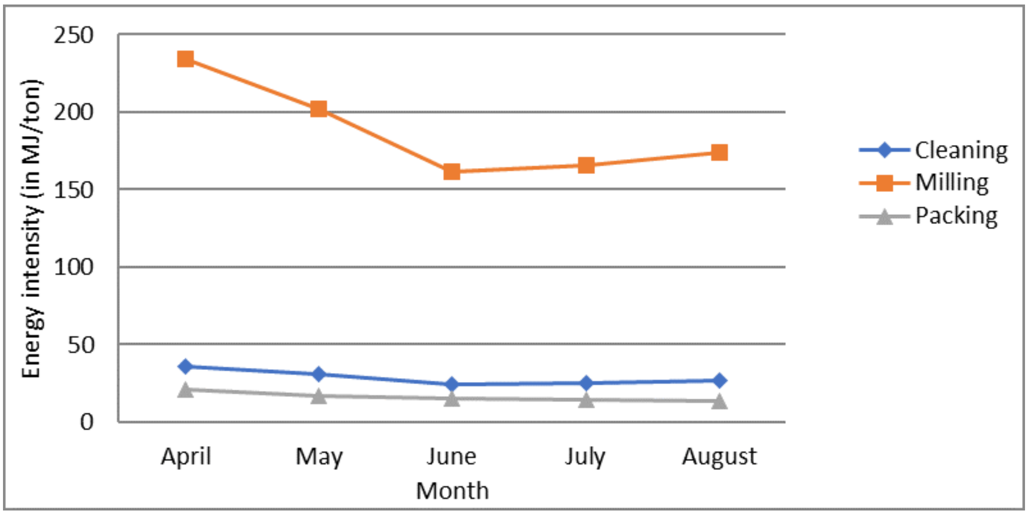

Figure 5 Energy Intensity for Mill A

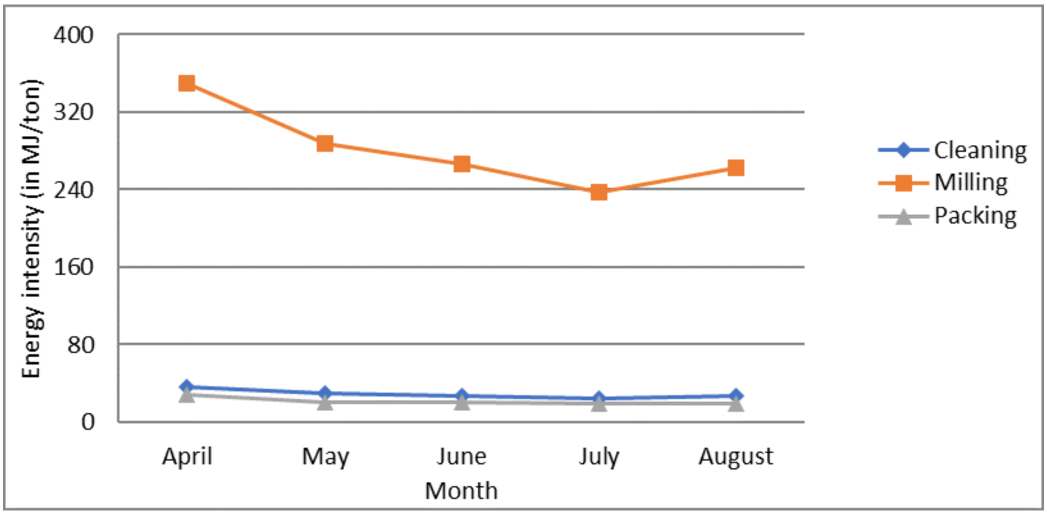

Figure 6 Energy Intensity for Mill B

4.1.2 Electrical energy sources and consumption

The power supplied by the national grid, the diesel generators, and the gas plant is the primary source of electrical energy in the plant. Tables 8, 9 and 10 show the total electricity generated in the facility, and it can be seen that electricity was supplied at a 54:46 ratio to Nigeria Eagle Flour Mills and Premier Feeds Mills.

Table 8 Breakdown of Electricity Generated From Gas Plant

	April	May	June	July	August
NEFM Lighting	52650	64098	6858	0	0
PFM Lighting	44850	54602	5842	0	0
Mill A (Kwh)	112927	322570	1020	0	0
Mill B (Kwh)	533668	673324	1826	0	0
PFM (Kwh)	0	136286	30838	0	0
Total	744095	1250880	46384	0	0

Table 9 Breakdown of Electricity Generated From Diesel Generators

	April	May	June	July	August
NEFM Lighting	38201	18348	19010	42095	17590
PFM Lighting	32541	15629	16193	35859	14984
Mill A (Kwh)	445899	232447	596296	629607	663371
Mill B (Kwh)	131514	72656	487040	360069	229491
PFM (Kwh)	361180	171186	334690	357324	414628
Total	1009335	510266	1453229	1424954	1340064

Table 10 Breakdown of Electricity Generated From National Grid

	April	May	June	July	August
NEFM Lighting	3402	486	61020	41958	64206
PFM Lighting	2898	414	51980	35742	54694
Mill A (Kwh)	0	0	8310	20	0
Mill B (Kwh)	9807	1610	285891	360709	525120
PFM (Kwh)	0	0	11	49	77

Figure 7 summarizes the electrical energy delivered to Nigeria Eagle Flour Mills over the research period. Lighting consumed approximately 5% to 7% of the electrical energy supplied; Mill A consumed 40% to 44% of the electrical energy supplied, and Mill B consumed 50% to 54% of the electrical energy supplied.

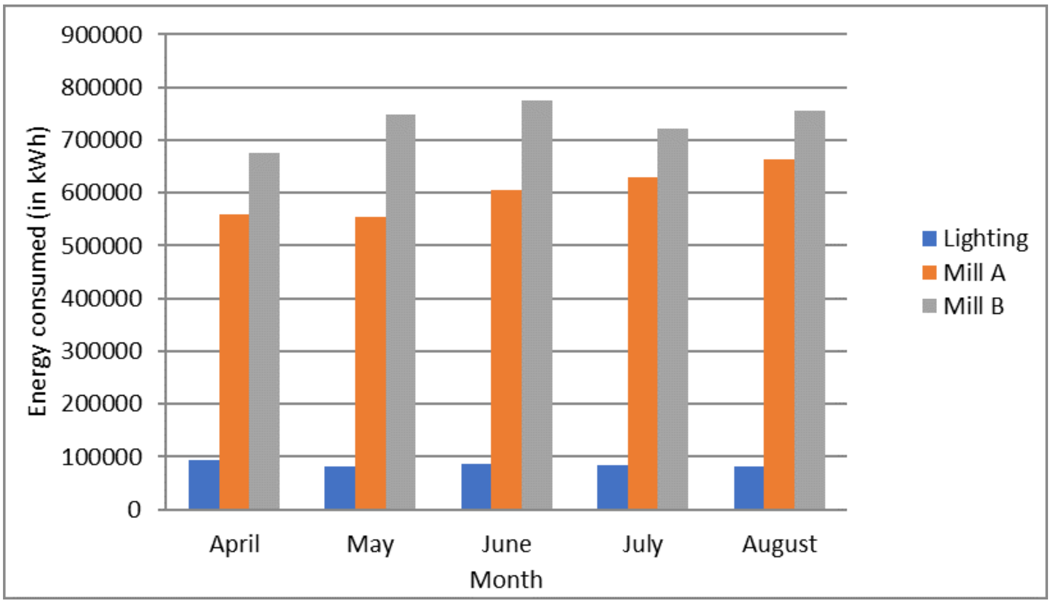

Figure 7 Electrical energy consumed by Lighting, Mill A and Mill B

Table 11 and Figure 8 summarize the total energy consumption in the plant during the study period. Diesel fuel consumed the most energy in June, July, and August, accounting for 75 percent, 72 percent, and 61 percent of total energy intake, respectively. Natural liquefied gas was the most utilized energy source in April and May, accounting for 53 percent and 71 percent of total energy input in the plant, respectively.

Table 11 Total Electrical Energy Consumption

(In kWh)	April	May	June	July	August
Diesel	615614	323451	1102346	1031771	910452
Gas	699245.0	1059992.0	9704.0	0.0	0.0
IBEDC	13209	2096	355221	402687	589326
Total	1328067.7	1385538.58	1467270.62	1434458.16	1499777.96

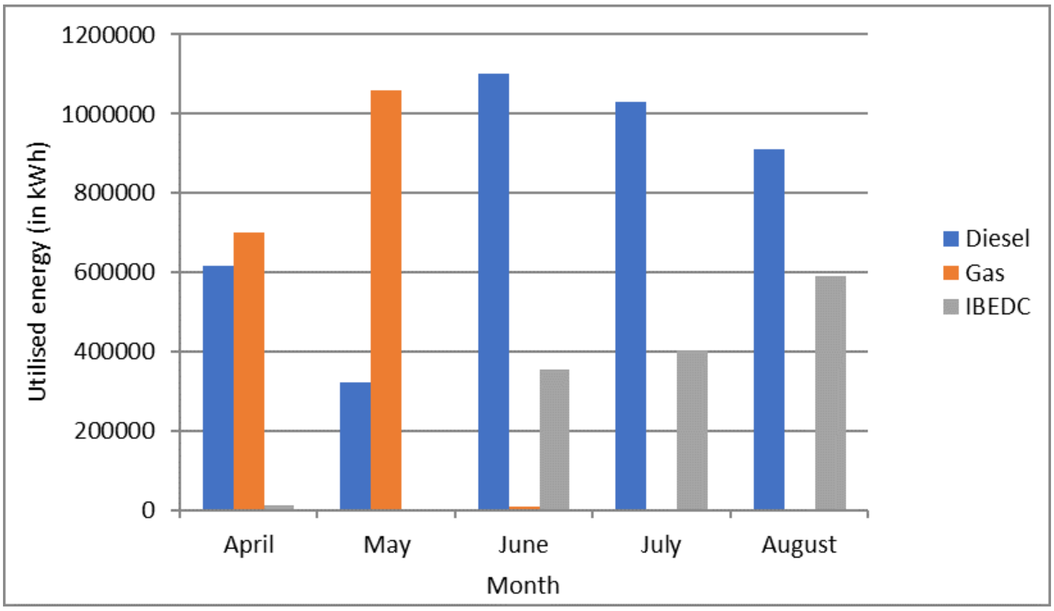

Figure 8 Total Electrical Energy Consumption

The percentage of electricity supplied by the national grid ranged from 0% to 41%. The low proportion recorded is attributable to Nigeria's power sector's poor and unstable performance. The low use of liquefied gas in June, July, and August is owing to protracted maintenance on the gas plant, which forced the company to rely on diesel generators and public power supply.

4.1.3 Energy Losses via Power Transmission

Table 12 Quantity of Electrical Energy Generated By Diesel, Gas, and IBEDC

(in kwh)	April	May	June	July	August
Diesel	1085711	556137	1554648	1512264	1397759
Gas	793100	1369700	52200	0	0
IBEDC	16538	2707	412857	508767	662498
Total	1895349	1928544	2019705	2021031	2060257

Table 12 displays the quantity of electrical energy generated by diesel, gas, and IBEDC, whereas Table 13 displays the percentage energy loss. Energy losses during transmission and distribution account for the apparent disparity between energy generated and energy consumed. These can be ascribed to a variety of issues, including distribution line resistance, insufficient size of distribution line conductors, and poor power factor of the distribution system, transformer losses, load factor effect, and transmission line overloading.

Table 13 Percentage Energy Loss

(In %)	April	May	June	July	August
Diesel	7%	8%	7%	6%	4%
Gas	6%	9%	11%	-	-
IBEDC	3%	7%	1%	14%	3%

4.1.4 Energy use ratio

Table 14 displays the energy use ratio in the plant throughout the investigation. The energy use ratio is less than one, indicating inefficient energy utilization. It is implied that the unit generation of flour consumes more energy.

Table 14 Energy Use Ratio

	April	May	June	July	August
Energy use ratio	0.0251	0.0218	0.0215	0.0197	0.0208

Wheat flour has an energy content of 1418KJ per 100g. As a result, the energy content of one kilogram of wheat flour is 14.18MJ.

Table 15 Production Data

	April	May	June	July	August
Production Data (in tonnes)	13410.32	16156.5	17295.6	18482.9	18311.6

Table 15 displays the amount of wheat flour produced (in tonnes) over the study period. 1 ton of wheat flour is equal to 1000kg of wheat flour.

4.1.5 Lighting Analysis

Table 16 Energy Consumed By Lighting

	April	May	June	July	August
Lighting (MJ)	339309.648	298553.688	312795.432	302591.376	294465.456

Table 17 Light Fittings

	No of Fittings	Rating (W)	Length	Total (W)
Flourescent Total	208	36	4ft	7488
LED Replacement	208	20	4ft	4160
			Savings	3328
Halogen Security Bulbs	5	250		1250
LED Replacement	5	150		750
			Savings	500

Flourescent Total	65	18	2ft	1170
LED Replacement	65	10	2ft	650
			Savings	520
LED (4ft)	250	72	4ft x 2	18000
LED (4ft)	250	40	4ft x 2	10000
			Savings	8000
			Total Savings	12348

During energy analysis lighting was observed to have consumed approximately 5% to 7% of the electrical energy supplied during the study period. The range of energy consumed by lighting during the study period is presented in table 16.

A closer analysis of the lighting used in the plant was performed to figure out areas where energy can be saved. The types, number, and power wattage of light fittings in the plant were identified as presented in table 17. The power wattage of LED bulbs that were to be used as the effective replacement was computed as shown in table 17. The total energy savings upon the replacement of bulbs was about 44% of the initial energy consumed

4.2 Cost analysis

4.2.1 Cash equivalent of energy consumption

The cash equivalent of liquefied natural gas use is shown in Table 18. During the operational duration of the gas plant, liquefied natural gas was supplied at a set fee of 126.98naira per sm3. The cost of gas per kWh is calculated to be 38.09naira/kWh using a conversion unit of 0.3sm3/kWh. When compared to other electrical energy sources, this is the most cost-effective rate.

Table 18 Cost of Gas Consumed

(in Naira)	April	May	June	July	August
NEFM Lighting	2,104,978.33	2,559,210.46	348,803.70	-	-
Mill A	4,514,888.66	12,879,099.47	51,878.06	-	-
Mill B	21,336,364.19	26,883,488.14	92,871.91	-	-

Throughout the study period, diesel was supplied at a set rate of 290 naira per liter. The cost of diesel per kWh is calculated to be 87naira/kWh using a conversion unit of 0.3litre/kWh. When compared to other sources of electrical energy, this rate is the least cost-effective. The cash equivalent of diesel use is shown in table 19.

Table 19 Cost of Diesel Consumed

(in Naira)	April	May	June	July	August
NEFM Lighting	3,231,114.78	1,628,472.94	1,532,147.15	3,238,844.13	1,491,487.01
Mill A	37,715,319.48	20,631,257.67	48,060,572.37	48,442,598.50	56,248,520.82
Mill B	11,123,802.76	6,448,715.87	39,254,700.96	27,704,072.54	19,458,989.45

Additionally, the power supply from the national grid was at a fixed charge of 60 naira per kWh. Table 20 shows the cash equivalent.

Table 20 Cost of Power Supplied from IBEDC

(in Naira)	April	May	June	July	August
NEFM Lighting	204,120.00	29,160.00	3,661,200.00	2,517,480.00	3,852,360.00
Mill A	-	-	498,600.00	1,200.00	-
Mill B	588,420.00	96,600.00	17,153,460.00	21,642,540.00	31,507,200.00

4.2.2 Energy cost per tonnage

The energy cost per tonne is the monetary value of the energy required to create one ton of flour. The energy cost per tonne for all electrical energy sources is given in Table 21 for the study period and shown in Figure 9. The energy cost per ton of electricity generated by diesel generators ranged from 1777 naira/ton to 5137 naira/ton, depending significantly on the amount of diesel utilized. The least energy cost for electrical energy supplied by a gas plant was 29 naira/ton and the maximum was 2619 naira/ton, depending on the amount of gas consumed. The energy cost of IBEDC supplied electrical energy ranged from a minimum of 8 naira/ton to a maximum of 1931 naira, depending on the quantity of electrical energy supplied.

Table 21 Energy Cost per Tonnage

	April	May	June	July	August
Diesel	3,883	1,777	5,137	4,295	4,216
Gas	2,085	2,619	29	-	-
IBEDC	59	8	1,232	1,307	1,931

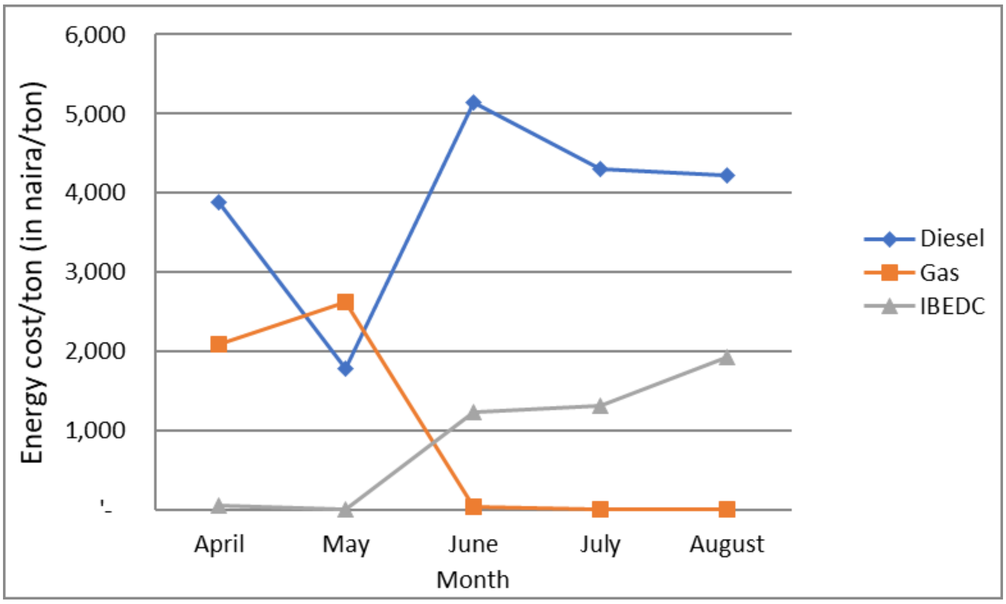

Figure 9 Energy cost per tonnage

Figure 10 depicts a comparison of total energy utilized by all sources as well as total energy cost per tonnage. The energy cost/ton was 4404 naira per ton when electrical energy from the gas plant accounted for 77 percent of energy input. This demonstrates that electricity generated by a gas plant is the least expensive source of electrical energy input.

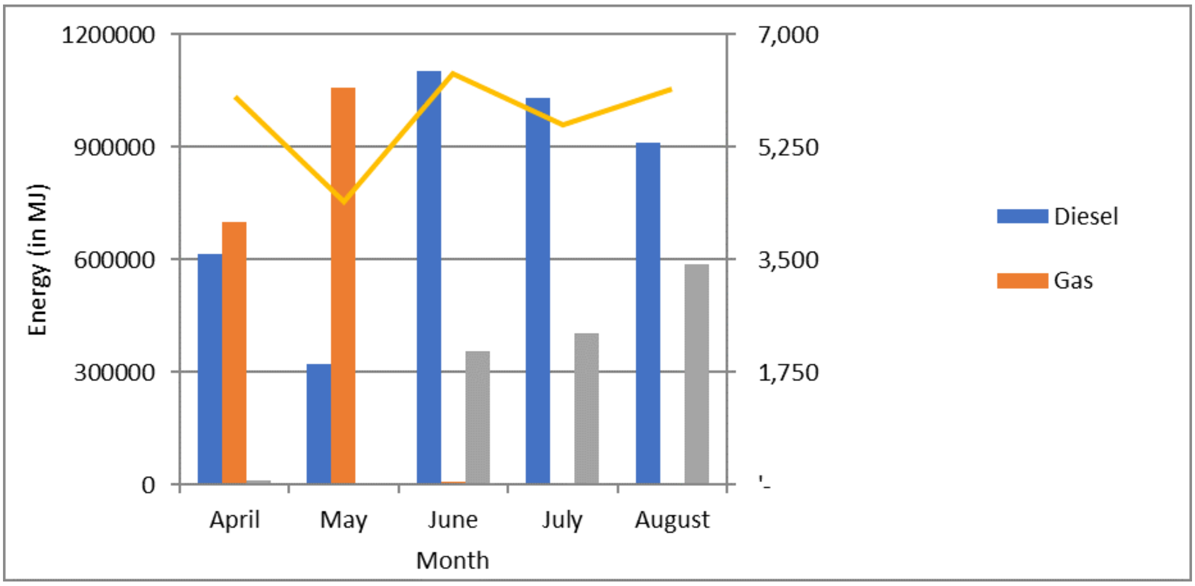

Figure 10 Comparison of total energy utilized by all sources and energy cost per tonnage

4.3 Exergy analysis

In this study, comprehensive exergy analysis of the milling process of flour production from wheat was carried out. Table 21 presents detailed results of parameters calculated for exergy analysis, including the values of the specific heat capacity (KJ/kgK), enthalpy (KJ/kg), specific exergy Ψ (KJ/Kg), exergy in rate form $\dot{E}x$ (kW) computed from equations (16), (18), (20), and (22) respectively. Table 21 presents the detailed results from the exergy analysis of components in the mill. The mass and energy balance according to the laws of conservation of mass and thermodynamics are the basis on which exergy analysis was conducted.

From the energy balance equation (24), the rate of heat lost to the environment (kW) was obtained for each machine considered and presented in Table 21. From the exergy balance equation (25), the rate of exergy destroyed (kW) for each machine considered, was obtained and can be found in table 21. The work rate (kW), exergetic efficiency η, and improvement potential IP for each machine considered were calculated from equations (23), (23), (26), (27) respectively and are found in table 22.

Table 22 Exergy Analysis Results

S/N	Machines	$\dot{Ex}_{in}$	$\dot{Ex}_{out}$	$\dot{W}$(kW)	$\dot{Q}$(kW)	$\dot{Ex}_{destroyed}$ (kW)	H	IP	RI
1	B1/B2 ROLLER	3.464475	4.757257	36	9.448339	34.55	12.05%	30.39	8.53%
2	B1/B2 PLS	4.757257	4.823336	8.8	14.03093	8.50	35.58%	5.48	2.10%
3	B3 ROLLER	4.582331	5.942034	14.8	1.492076	13.42	30.66%	9.30	3.31%
4	B3 PLS	5.942034	6.114142	8.8	7.122989	8.51	41.47%	4.98	2.10%
5	B4C/B5C ROLLER	1.390449	1.428553	29.6	29.16665	29.08	4.61%	27.74	7.18%
6	B4F/B5F ROLLER	1.875244	1.94839	29.6	28.49749	29.06	6.19%	27.26	7.18%
7	B4C/B5C BF	3.037091	3.141577	4.4	4.01198	4.23	42.24%	2.44	1.04%
8	B4C/B5C PLS	1.792491	1.871076	8.8	8.571244	8.58	17.66%	7.06	2.12%
9	BR1 BF	2.34301	2.347039	4.4	3.737537	4.33	34.81%	2.83	1.07%
10	BR3 BF	1.38353	1.529359	4.4	2.284938	4.22	26.44%	3.10	1.04%
11	BR4 BF	0.326319	0.390135	4.4	3.261086	4.28	8.25%	3.93	1.06%
12	DIV1 I.D	0.429631	0.468017	4.4	3.140851	4.31	9.69%	3.89	1.06%

13	DIV 1 PLS	0.468017	0.484416	6	5.867916	5.89	7.49%	5.45	1.45%
14	DIV 2 PLS	0.236238	0.252769	6	5.6474	5.89	4.05%	5.65	1.45%
15	DF PLS	0.046962	0.049625	6	5.93807	5.90	0.82%	5.85	1.46%
16	DBR1 PLS	0.953135	1.013218	6	4.895574	5.86	14.57%	5.01	1.45%
17	DBR2 PLS	2.0165	2.136456	6	4.049253	5.81	26.65%	4.26	1.44%
18	P1	0.458295	0.466479	0.16	0.012958	0.15	75.45%	0.04	0.04%
19	P2	0.277079	0.287867	0.16	0.064192	0.15	65.86%	0.05	0.04%
20	C1A/C2A ROLLER	0.206482	0.291374	29.6	28.11597	29.05	0.98%	28.77	7.17%
21	C1A/C2A I.D	0.291374	0.297999	4.4	4.290265	4.32	6.35%	4.05	1.07%
22	C1A/C2A PLS	0.297999	0.306906	8.8	8.751414	8.65	3.37%	8.36	2.14%
23	C1B/C2B ROLLER	0.746543	1.036883	17.6	13.17151	17.09	5.65%	16.13	4.22%
24	C1B/C2B I.D	1.036883	1.073195	4.4	3.487379	4.31	19.74%	3.46	1.06%
25	C1B/C2B PLS	1.073195	1.097751	6	5.569042	5.88	15.52%	4.97	1.45%
26	C4/C5 ROLLER	1.807506	2.126228	17.6	11.66606	17.09	10.96%	15.22	4.22%
27	C4/C5 I.D	2.126228	2.291865	12	11.83783	11.64	16.22%	9.75	2.87%
28	C4/C5 PLS	2.291865	2.512221	8.8	4.565075	8.50	22.65%	6.58	2.10%
29	C7 ROLLER	1.877702	2.699281	8.8	-1.9998	8.01	25.28%	5.99	1.98%
30	C7 I.D	2.699281	2.972264	4.4	0.582543	4.12	41.87%	2.39	1.02%
31	C7 PLS	2.972264	3.073749	8.8	6.124456	8.60	26.11%	6.35	2.12%
32	C9 ROLLER	0.501695	0.541943	8.8	7.798162	8.63	5.83%	8.13	2.13%
33	C9 I.D	0.541943	0.567113	4.4	3.050823	4.32	11.48%	3.83	1.07%
34	C9 PLS	0.567113	0.65927	8.8	7.639879	8.58	7.04%	7.98	2.12%
35	FLOUR RE-D	6.16264	6.352733	4.4	3.603139	4.15	60.14%	1.65	1.02%
36	C6 ROLLER	0.499143	0.59	12	9.983429	11.74	4.72%	11.19	2.90%
37	C6 I.D	0.59	0.608504	3.2	2.546635	3.14	16.06%	2.64	0.78%
38	C6 PLS	0.608504	0.645525	6	4.921323	5.88	9.77%	5.31	1.45%
39	C8 ROLLER	1.193857	1.477322	3.2	2.754746	2.87	33.62%	1.91	0.71%
40	C8 I.D	1.477322	1.532831	3.2	2.754746	3.10	32.77%	2.08	0.77%
41	C8 PLS	1.532831	1.596308	6	5.261681	5.85	21.19%	4.61	1.44%
42	C10 ROLLER	0.324151	0.494798	6	3.059114	5.78	7.82%	5.33	1.43%
43	C10 I.D	0.494798	0.515454	3.2	2.885684	3.13	13.95%	2.69	0.77%
44	C10 PLS	0.515454	0.545269	6	5.368669	5.88	8.37%	5.39	1.45%
45	C3A ROLLER	0.147736	0.236586	8.8	7.397536	8.59	2.64%	8.36	2.12%
46	C3B ROLLER	0.108148	0.159864	4.4	3.589169	4.29	3.55%	4.14	1.06%
47	C3A/C3B I.D	0.405145	0.425088	3.2	3.159677	3.13	11.79%	2.76	0.77%
48	C3A/C3B PLS	0.425088	0.446469	6	5.344582	5.89	6.95%	5.48	1.45%

It has been established from the exergy balance that the total exergy entering the mill is equal to the total exergy exiting it. Figure 11 shows that only 16% of exergy input into the flour mill exits the process through product streams, 1% was lost through waste streams and 83% was destroyed due to irreversibilities. It was observed that the B1/B2 rolling bench was the major exergy destruction unit, generating the most irreversibility and destroying 7.1% of the total exergy input as shown in figure 12. Although direct comparison of the results of this work is not possible because of the lack of reports on similar processes, the present results show a good trend with the results of some previous related works. For example, 83% of exergy input due to irreversibility compares well to the 73.1% observed in the exergetic diagnosis of a sugar plant [23].

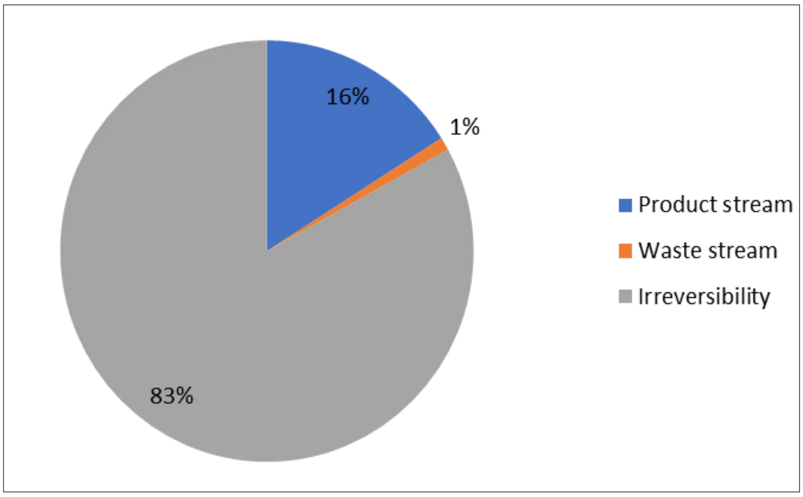

Figure 11 Exergy input into the flour mill

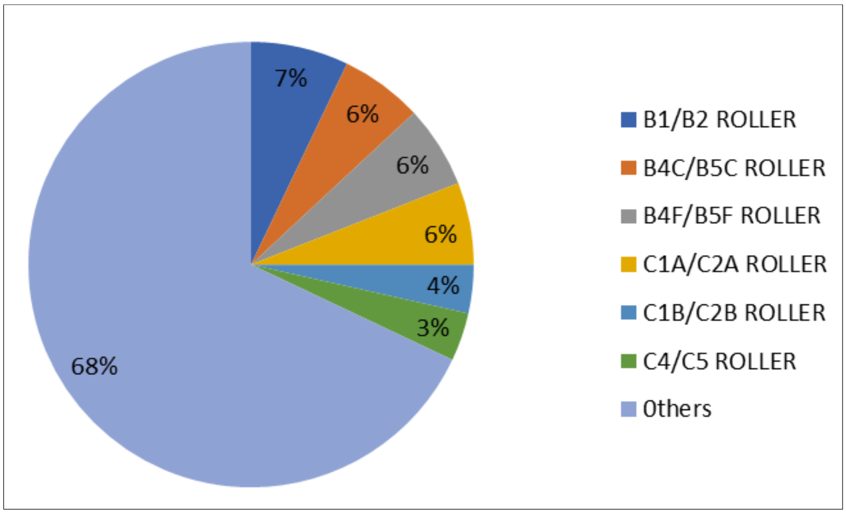

Figure 12 Major exergy destruction units

From the results obtained it is observed that the most efficient machines were the purifiers P1 and P2 with exergetic efficiency of 75.45% and 65.86% respectively, followed by the flour redresser at 60.14%. This reflects how much the input exergies were utilized in processing, thus producing high exergy products. The DF plan-sifter has the lowest exergetic efficiency (0.82%), followed by the C1A/C2A, C3A, and C3B roller benches, with 0.98%, 2.64%, and 3.55% respectively. These unusually low exergy efficiencies can be due to the relatively high exergy demands of the components and low exergy products.

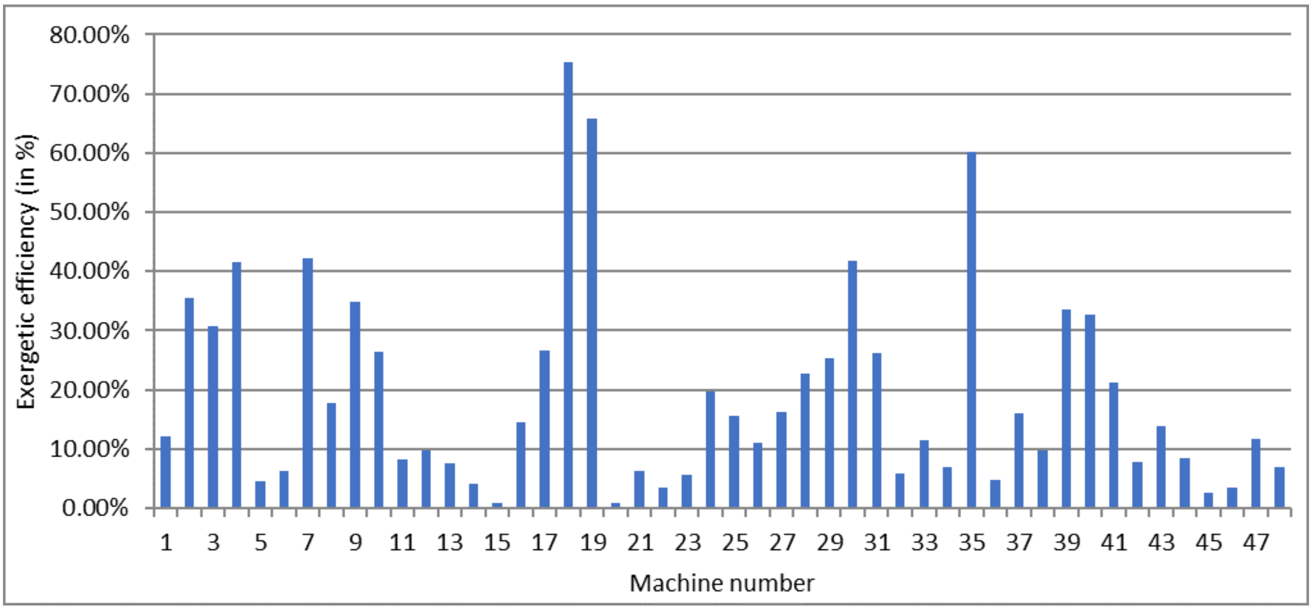

Figure 13 Exergetic Efficiency

Evaluating exergetic improvement potential provides a distinct factor for making improvement priority decisions, as it combines the effects of both irreversibility and functional exergy efficiency in the improvement process. The figure below presents the exergetic improvement potential of each component relative to its irreversibility. The highest improvement potential $\dot{IP}$ 30.39KW was found for the B1/B2 rollers, representing about 8.53% of the mill's irreversibility. Followed by the C1A/C2A, B4c/B5C, and B4f/B5f roller grinding benches with values of 28.77, 27.74, and 27.26KW, representing 7.18%, 7.18%, and 7.17% of total irreversibility respectively. The components with the lowest improvement potential are purifiers P1, P2, with values 0.04KW and 0.05KW representing 0.04% of mills irreversibility. It is observed that high exergetic improvement potential is associated with components with high irreversibility.

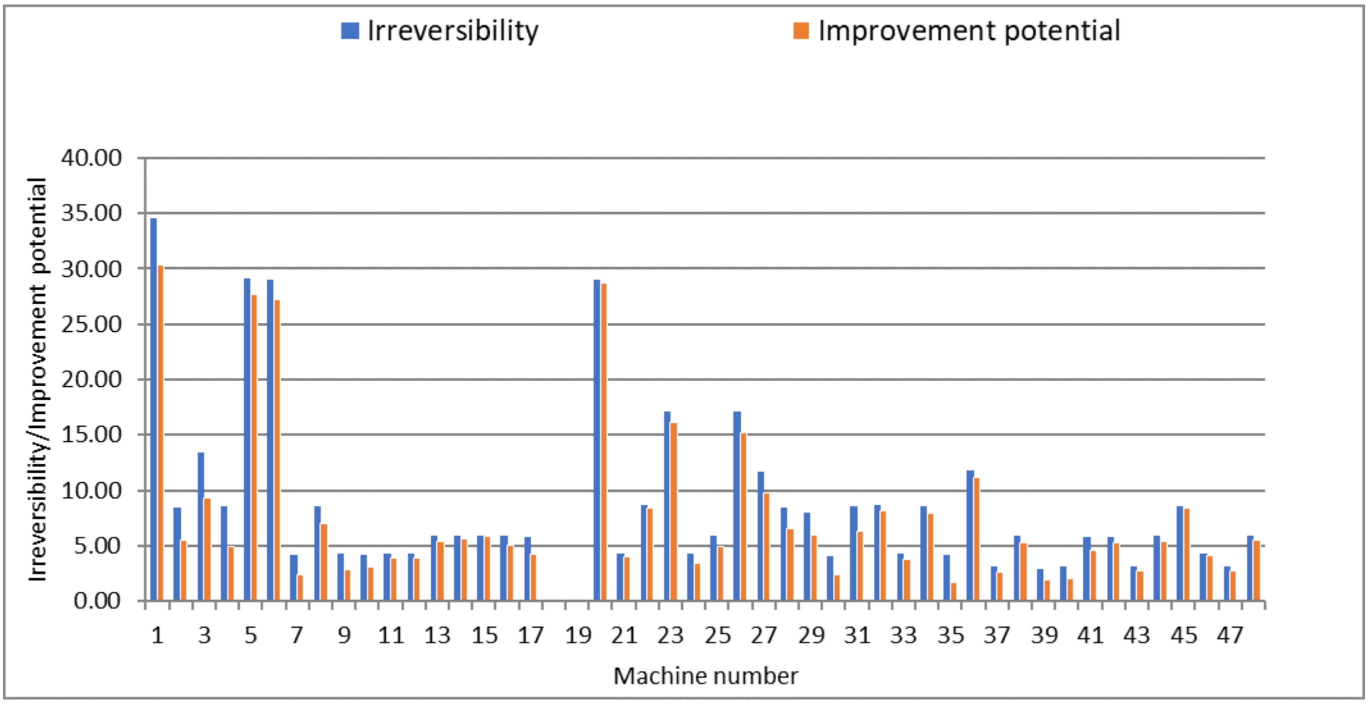

Figure 14 Exergetic improvement potential

The main sources of irreversibility were identified as the B1/B2, C1A/C2A, B4C/B5C, B4F/B5F, C1B/C2B, C4/C5 roller benches with values 34.55, 29.05, 29.08, 29.06, 17.09. 17.09 Respectively. The machines with the least irreversibility were the purifiers P1, P2 with values 0.15 and 0.15 respectively. A reduction in irreversibilities is required to minimize energy utilized for flour production in the mill.

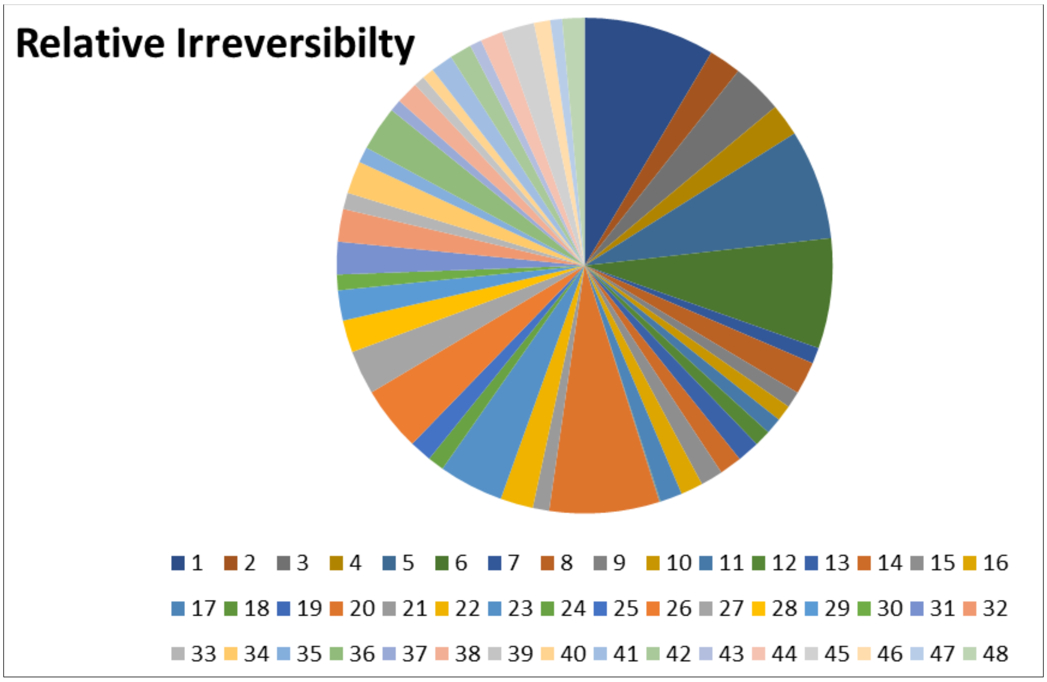

Figure 15 Relative Irreversibility

When comparing results and prioritizing components for improvement, prioritizing based on irreversibility and exergy efficiency can be tricky but ideally, the components with the highest irreversibilities are considered first.

4.4 Nomenclature

Symbol	Description	Unit
EP	Electrical energy	kWh
η	Motor efficiency	%
P	Motor power	kW
t	Operational time	hours
E_m	Manual energy input	kWh
N_m	Number of workers	
E_t	Total energy input	kWh
E_I	Energy intensity	MJ/ton
$\sum \dot{m}$	Sum of mass flow rate	Kg/s
$\sum \dot{E}$	Sum of rate of energy transfer	kW
$\dot{W}$	Work rate	KW
$\dot{Q}$	Heat transfer rate	KW
$\sum \dot{Ex}$	Sum of exergy rate	KW
Ψ	Specific flow exergy	KJ/kg

T_0	Reference temperature	K
Ex	Exergy	KJ
$\dot{Ex}_D$	Rate of exergy lost to irreversibilities	KW
$Ex_{physical}$	Physical exergy	KJ
Ex_{mix}	Mixing exergy	KJ
$Ex_{chemical}$	Chemical exergy	KJ
W_m	Moisture fraction	%
W_p	Protein fraction	%
c_p	Specific heat capacity	KJ/kgK
T	Temperature	K
h	Enthalpy	KJ/kg
s	Specific entropy	kJ/kgK
IP	Improvement potential	KW
RI	Relative irreversibility	%

4.5 Abbreviations

Abbreviation	**Meaning**
NEFM	Nigeria Eagle Flour Mill
PFM	Premier Feed Mill
IBEDC	Ibadan Electricity Distribution Center
LED	Light Emitting Diode
PLS	Plan-sifter
I.D	Impact Detacher
BR	Bran
BF	Bran Finisher
DBR	Deep Bran
P	Purifier
RE-D	Redresser
T/s	Temperature/Entropy
KW	Kilowatt
KWh	Kilowatt-hour
Kg	Kilogram
Kg/s	Kilogram per seconds
KJ/kg	Kilojoules per Kilogram
oC	Degree Celsius
K	Kelvin
%	Percentage

5 Conclusion

The project presented a comprehensive energy, cost and exergy analysis of the flour milling process using Nigeria Eagle Flour Mill as a case study with a daily production capacity of 500 tonnes. It can be concluded that the components with the highest waste streams also have the highest irreversibilities. Minimizing waste streams reduces the amount of exergy lost and increases the exergetic efficiency of components. Before building any plant, energy, cost, and exergy analysis should be performed to create the most energy and cost-efficient plan. Existing factories or plants must also conduct energy, cost, and exergy analyses to identify and implement the most effective energy and cost-saving measures.

Recommendation

- Energy management approaches

Energy efficiency can be approached in a variety of ways. Flour milling uses energy-intensive equipment such as motors, and efficient monitoring and control of plant equipment can improve energy efficiency and productivity. Process optimization is another method of ensuring that the most productive technology is in place to realize energy savings in plant operations. Finally, synchronizing the efficiency and operation of both mills are required to generate energy savings. One existing energy-saving solution in the plant is the employment of a capacitor bank to raise the power factor of loads to 0.98. This means that electric motors can operate at up to 98 percent of their capacity. Several energy-saving strategies and improvements can be implemented to increase plant energy efficiency, some of which are described below:

- Proper sizing of motors

Inadequately sized motors result in excessive energy losses. Motor size can be adjusted where peak loads can be minimized. Correcting for motor oversizing saves 1.2 percent of their electricity, and significantly more for smaller motors. Monitoring, in conjunction with operations and maintenance, can be used to detect problems and determine remedies to produce a more efficient system.

- Limiting the use of compressed air

Compressed air is utilized in pneumatic lines, packaging lines, and aspiration in milling. Because of its inefficiency, compressed air is the most expensive kind of energy accessible in an industrial operation. Because of its inefficiency and high running costs, compressed air should be utilized in the smallest amount possible for the shortest amount of time, constantly checked, and reweighed against alternatives. Lower leaks (in pipes and equipment) to reduce the amount of compressed air consumed. Conveyors and elevators are recommended for product transport where applicable.

- Lighting controls

Illumination controls are used to offer overall ambient light across the refining, storage, and office spaces, as well as low bay and task lighting to specified locations. Automatic controls, such as occupancy sensors, which turn off lights when an area becomes vacant, can be used to switch off lights during non-working hours. Manual controls can be used in conjunction with automatic controls to save even more energy. Increased levels of daylight within rooms can lower electrical lighting demands by up to 70%, therefore efficient use of natural light is advocated. Additionally, as discovered during the lighting study, replacing fluorescent and halogen lights with LED bulbs can save more than 40% of the energy consumed by lighting.

- HVAC (Heating, Ventilation, and Air Conditioning) improvements

During non-operational hours, electronic controls such as on/off switches can be utilized to operate HVAC systems. The vaporizer in the liquefied gas plant exchanges heat with the surrounding environment. Heat transfer can be used to conserve energy in HVAC systems. Because of the significant flammability of natural gas, extensive research is required to establish the economic advantage and practicality.

In addition to the exergy analyses and solutions presented, the economic ramifications of these exergy solutions must be assessed through exergoeconomics studies before their implementation. Finally, the occurrence of minor discrepancies in the data evaluated was owing to the impossibility to capture all machines in the study because only machines with electrical motors were included, as well as inaccuracies associated with manual data collection. This error can be corrected for future studies by using automated data gathering.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors declare they have no conflict of interest.

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