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# TECHNO-ECONOMIC FEASIBILITY STUDY OF BIOETHANOL PRODUCTION FROM A COMBINED CELLULOSE AND SUGAR FEEDSTOCK IN NIGERIA: 1-MODELING, SIMULATION AND COST EVALUATION

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**ABSTRACT**
***Bioethanol, as a renewable energy, is vital for energy security and pollution control; but its large scale uses need to be studied for different regions. In this study, a bioethanol plant with a processing capacity of 148 million liters/annum was modelled and simulated. This was done with the aid of a process simulator. The study involved process modelling and simulation, material and energy balances, energy efficiency evaluation, and total capital and manufacturing cost estimation. The study shows that the simulated plant will be 63 % energy efficient and that the plant will yield 148 million liters of bioethanol from the processing of 402 metric tonnes of crushed sugarcane with a capital of $ 51 million and manufacturing cost of $ 89 million per annum. Thus, this suggests that the modelled plant would be able to produce 368 thousand liters of bioethanol from a metric tonne of crushed sugarcane with a capital of 0.34 $/liter and manufacturing cost of 0.61 $/liter per annum, based on the conditions adopted for the study.***

***Keywords****: Process, Modelling, Simulation, Biofuel, Bioethanol, Cellulose, Sugar*

## 1 INTRODUCTION

The recent rapid growth of industries and technological advancement in the world has necessitated the development of the chemical sector and biofuel programmes, especially as it has been suggested that the investment in the production of industrial chemicals and biofuel will further enhance the economic growth of any nation [1, 2]. Thus, there is an urgent need for the Nigerian government to diversify its investment into other sectors, such as agriculture and renewable energy, to survive any energy and environmental crisis, as well as enhance rural development, job creation and industrialization. Bioethanol fuel is an attractive substitute to gasoline [3 - 5]. Also, it has been suggested that in seeking for ways of combating the current environmental pollution problems, bioethanol can be used as one of the best tools to fight vehicular pollution [6]. This is due to the 35 % oxygen content of bioethanol fuel, which enhances combustion of fuel and decreases harmful tail pipe emissions and particulate emissions that pose a health hazard [7].

Several studies have established optimum condition(s)/yield(s) for bioethanol production. These studies include the establishment of optimum conditions for producing bioethanol from groundnut shell and maize cob [1], optimum condition for bioethanol production from starch kernel [8], and bioethanol production from elephant grass stem [9]. An economic feasibility study established feasible condition(s) for bioethanol production from sugarcane and/or molasses for plants located in Kanchanaburi and Khonkaen province (in Thailand) with a production capacity of 150,000 liters per day [10]. Another study showed that there is a high economic potential for bioethanol production from rice straw in Vietnam [11]. Economic feasibility of producing bioethanol fuel from sugarcane was also established by [12] and [13] in South Africa and Tanzania respectively. Research in Nigeria also deduced that the bioethanol project using cassava in rural communities will only be feasible if the plant is sited in or next to the farm, such that there is no transportation cost for the feedstock [14]. The latter studies show that although the environmental and other benefits of bioethanol production are well known; there are no categorical conclusions on its energy efficiency and cost evaluation for large-scale production in Nigeria.

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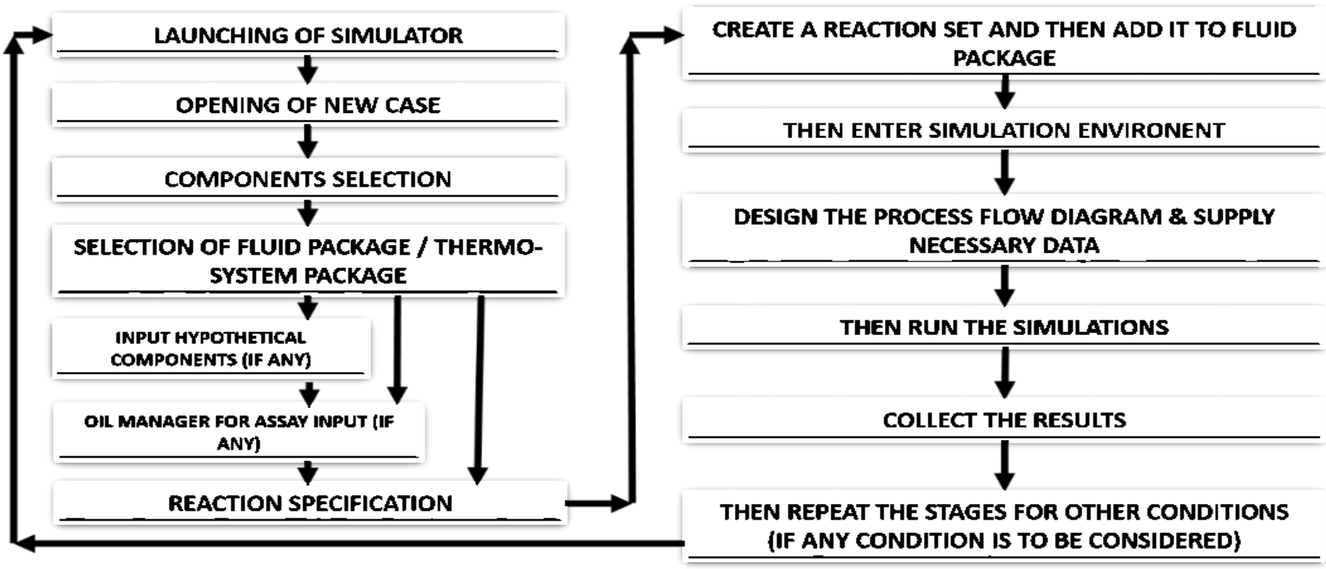


*Figure 1: Flow Chart for Process Simulation* [16].

Therefore, based on energy and environmental concerns in Nigeria, it is of interest to model and simulate the viability of building a bioethanol plant, which will convert one of the nation's agricultural waste (sugarcane bagasse) and product (sugarcane juice) into bioethanol. A combined sugar-cellulosic biochemical process, with the aid of a process simulator (Aspen HYSYS V8.0) was utilized for the research.

## 2. MATERIALS AND METHODS

### 2.1 Process Modelling and Simulation

This research employed the use of Aspen HYSYS in the modelling and simulation of the process technology to produce bioethanol from sugarcane juice and bagasse. Aspen HYSYS, being an efficient simulator with reasonable accuracy, was adopted as it offers a comprehensive thermodynamics foundation for accurate determination of physical properties, transport properties and phase behavior, along with a comprehensive library of unit operation models [15].

In particular, the non-random two-liquid (NRTL) model was employed. This model fits best to equilibrium because the components involved in the process have characteristics of polarity (like water and ethanol) and the vapour phase behaviour can be compared to that of an ideal gas due to the low operating pressures (1-5 atm) [17, 18]. The required binary interaction parameters that were not available in Aspen HYSYS were estimated with a predictive model found in the fluid package. In simulating the process plant technology, the stage-wise procedure, as shown in Figure 1, was adopted.

### 2.2 Process Descriptions

The production of bioethanol begins with a crushed and pretreated sugarcane feed, which is composed of cellulose, hemicellulose, lignin, sucrose, dextrose and water, as shown in Table 1. This composition was fed into the modelled plant.

The processes of the plant were subdivided into four stages, namely:

- Extraction of juice from sugarcane bagasse;
- Hydrolysis of sucrose, hemicellulose and cellulose;
- Fermentation of glucose and xylose; and
- Purification of raw bioethanol.

*Table 1: Feedstock Composition and Operating Conditions*

| Component Name | Mole Fractions |
|---|---|
| Cellulose | 0.049 |
| Hemicellulose | 0.046 |
| Lignin | 0.026 |
| $H_2O$ | 0.700 |
| Sucrose | 0.145 |
| Dextrose | 0.034 |
| Vapour / Phase Fraction | 0.000 |
| Temperature [C] | 25.000 |
| Pressure [atm] | 2.000 |
| Mass Flow [kg/h] | 50,000.00 |

Adopted from: [19, 20, 21].

The extracted juice containing sucrose was hydrolyzed in the presence of glucanase (enzymes), while the bagasse was hydrolyzed in the presence of cellulase and xylanase (enzymes). After hydrolysis, the fermentable sugar produced were pretreated to meet the fermentation operating conditions and then passed to the fermenter, where the sugars were converted into bioethanol and carbon dioxide, in the presence of yeast (enzymes). The bioethanol from the fermenter were then purified in a flash, absorber and distillation columns, as illustrated in Figure 2.

The energy constraint for both heating and cooling duties for different unit; material resource that would be needed for efficient production, and bioethanol production quantity were determined.

### 2.3 Components

To model the process plant, pure components, as proposed by the Aspen HYSYS components library and shown in Table 2, as well as other components that are not in the library, were used in the model and simulation.

The components not found in the library, known as hypothetical components, were developed using their normal boiling point, molecular weight, ideal liquid density or density, diameter and molecular formula, obtained from literature. Other useful properties, such as specific heat capacity, enthalpy and acentricity, were estimated with the aid of Aspen HYSYS estimator. A summary of the hypothetical components is given in Table 3.

### 2.4 Chemical Reactions

The major reactions in the model were divided into two, as detailed below. Heats of reaction(s) were calculated from standard enthalpies of formation at 298.15 K.

#### 2.4.1 Hydrolysis Reaction(s)

Hydrolysis reaction(s) involve the breaking down of sucrose, hemicellulose and cellulose into glucose and xylose, in the presence of water at a temperature of 323 K, using enzyme/feed ratio of 67.3 g/kg [22]. The reactions are shown in Table 4.

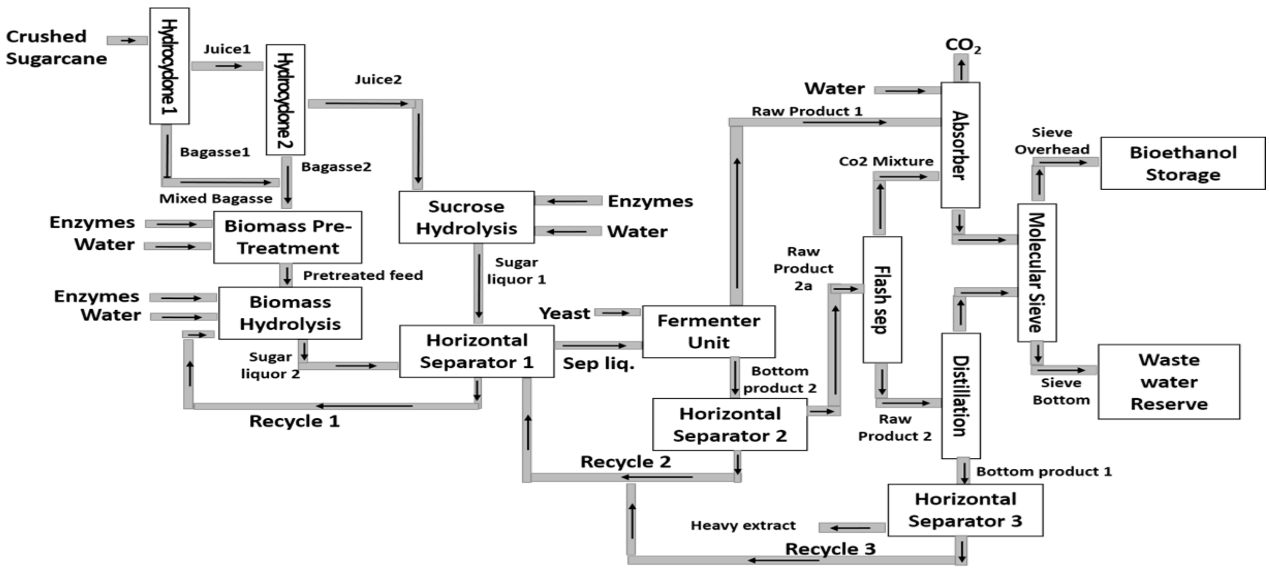


*Figure 2: Block Flow Diagram for Bioethanol Production from Sugarcane Juice & Bagasse*

*Table 2: Components involved in the simulation process*

| Name | Chemical Formula | CAS Number | Process Application |
|---|---|---|---|
| Carbon dioxide | $CO_2$ | 123-38-9 | Fermentation product |
| Ethanol | $C_2H_6O$ | 64-17-5 | Fermentation product |
| Glucose/Dextrose | $C_6H_{12}O_6$ | 50-99-7 | Hydrolysis product |
| Water | $H_2O$ | 7732-18-5 | For hydrolysis and washing |
| Sucrose | $C_{12}H_{22}O_{11}$ | 57-50-1 | Feedstock |
| Xylose | $C_5H_{10}O_5$ | - | Hydrolysis product |
| Cellulose | $(C_6H_{10}O_5)_n$ | - | Feedstock |
| Hemicellulose | $(C_5H_8O_4)_n$ | - | Feedstock |
| Lignin | $(C_{31}H_{34}O_{11})_n$ | - | Feedstock |
| Enzyme | $CH_{1.57}N_{0.29}O_{0.31}S_{0.007}$ | - | Enzymatic hydrolysis |
| Furfural | $C_5H_4O_2$ | 98-01-1 | By product of hydrolysis |
| Yeast | Unknown | - | Fermentation bacteria |
| Z.mobilis | $CH_{1.8}O_{0.5}N_{0.2}$ | - | Fermentation bacteria |

*Table 3: Hypothetical Components and some of their properties*

| Component | Specified Properties |
|---|---|
| Xylose | Chemical Formula: $C_5H_{10}O_5$<br>NBP, Ideal Liquid Density, Molecular Weight(E) |
| Cellulose | Chemical Formula: $(C_6H_{10}O_5)_n$ where n = 100 units<br>Density, Molecular Weight(E), Diameter(A) |
| Hemicellulose | Chemical Formula: $(C_5H_8O_4)_n$ where n = 10 units<br>Density(A), Molecular Weight(E), Diameter (A) |
| Lignin | Chemical Formula: $(C_{31}H_{34}O_{11})_n$ where n = 10 units<br>Density(A), Molecular Weight(E), Diameter (A) |
| Enzyme *(Cellulase, B-glucosidase, Endo-glucanase, Xylanase)* | Modeled as Glucose, Chemical Formula: $CH_{1.57}N_{0.29}O_{0.31}S_{0.007}$<br>Density, Molecular Weight(E), Diameter(A) |
| Z.mobilis | Modeled as Glucose, Chemical Formula: $CH_{1.8}O_{0.5}N_{0.2}$<br>Density, Molecular Weight(E), Diameter(A) |
| Cellubiose | Chemical Formula: $(C_6H_{10}O_5)_n$ where n = 200 units<br>Density, Molecular Weight(E), Diameter(A) |

*Note*: (E) represents estimated property while (A) represents assumed property.

*Table 4: Set of hydrolysis reactions*

| Reaction | Chemical Equation | Reactant | Conversion |
|---|---|---|---|
| Sucrose hydrolysis | Sucrose+$H_2O$→2 Glucose | Sucrose | 1.000 |
| Hemicellulose hydrolysis | Cellulose+$H_2O$→90 Glucose | Cellulose | 0.077 |
| | Cellulose+0.5$H_2O$→Cellobiose | Cellulose | 0.007 |
| | Hemicellulose+$H_2O$ →6.4 Xylose | Hemicellulose | 0.925 |
| | Hemicellulose→Furfural+47 $H_2O$ | Hemicellulose | 0.050 |
| Cellulose hydrolysis | Cellulose+$H_2O$→90 Glucose | Cellulose | 0.940 |
| | Cellulose+ 0.5$H_2O$→0.5 Cellobiose | Cellulose | 0.012 |
| | Cellobiose+$H_2O$→90 Glucose | Cellobiose | 1.000 |

*Table 5: Set of fermentation reactions*

| Reactions / Chemical Equation | Reactant | Conversion |
|---|---|---|
| Glucose→3 Ethanol+$CO_2$ | Glucose | 0.950 |
| 3 Xylose→2 Ethanol+$CO_2$ | Xylose | 0.850 |
| Glucose+ 2$H_2O$→1.2 Glycerol+$O_2$ | Glucose | 0.004 |
| Xylose+ 5$H_2O$→Glycerol + 4.6$O_2$ | Water | 0.030 |

### *2.4.2 Fermentation Reaction(s)*

Fermentation reaction(s) in Table 5, convert glucose and xylose to ethanol and carbon dioxide, in the presence of yeast at a yeast/feed ratio of 33 g/kg and temperature of 303 K [22].

### *2.5 Energy Efficiency of the Bioethanol Production Process*

The efficiency of the bioethanol production process, $E_f$, was evaluated using Equation 1.

$$E_f = \frac{E_b}{E_{cs} + W_{in}} \quad (1)$$

Where, $E_{cs}$ is the Total energy of the feed in Watt, $W_{in}$ is the Electricity input requirement for pumps in the plant in Watt, $E_b$ is the Energy content of bioethanol fuel in Watt.

### 2.6 Total Capital Investment and Manufacturing Cost

Using Marshall and Swiss cost correlation and indices [23, 24], each unit equipment cost was estimated as $C_p = C_o S^n$ and the resulting cost was escalated to evaluate the updated cost of each unit equipment as $C_x$.

$$C_x = C_o S^n \left(\frac{MS_x}{MS_n}\right) \quad (2)$$

Where $C_o$ is the Bare Cost at i year, S is the Equipment Size, n is the Cost index, MS is the Marshall & Swiss Cost Index at n and x year.

The total plant equipment cost was used to estimate the total capital investment using the factorial method, as stated in literature [25]. While the cost of manufacturing was estimated with the aid of MATLAB.

## 3. RESULTS AND DISCUSSION

### 3.1 Simulated Process Flow Diagram

The process flow diagram modelled for the process information presented on the block flow diagram (Figure 2) is shown on Figure 3.

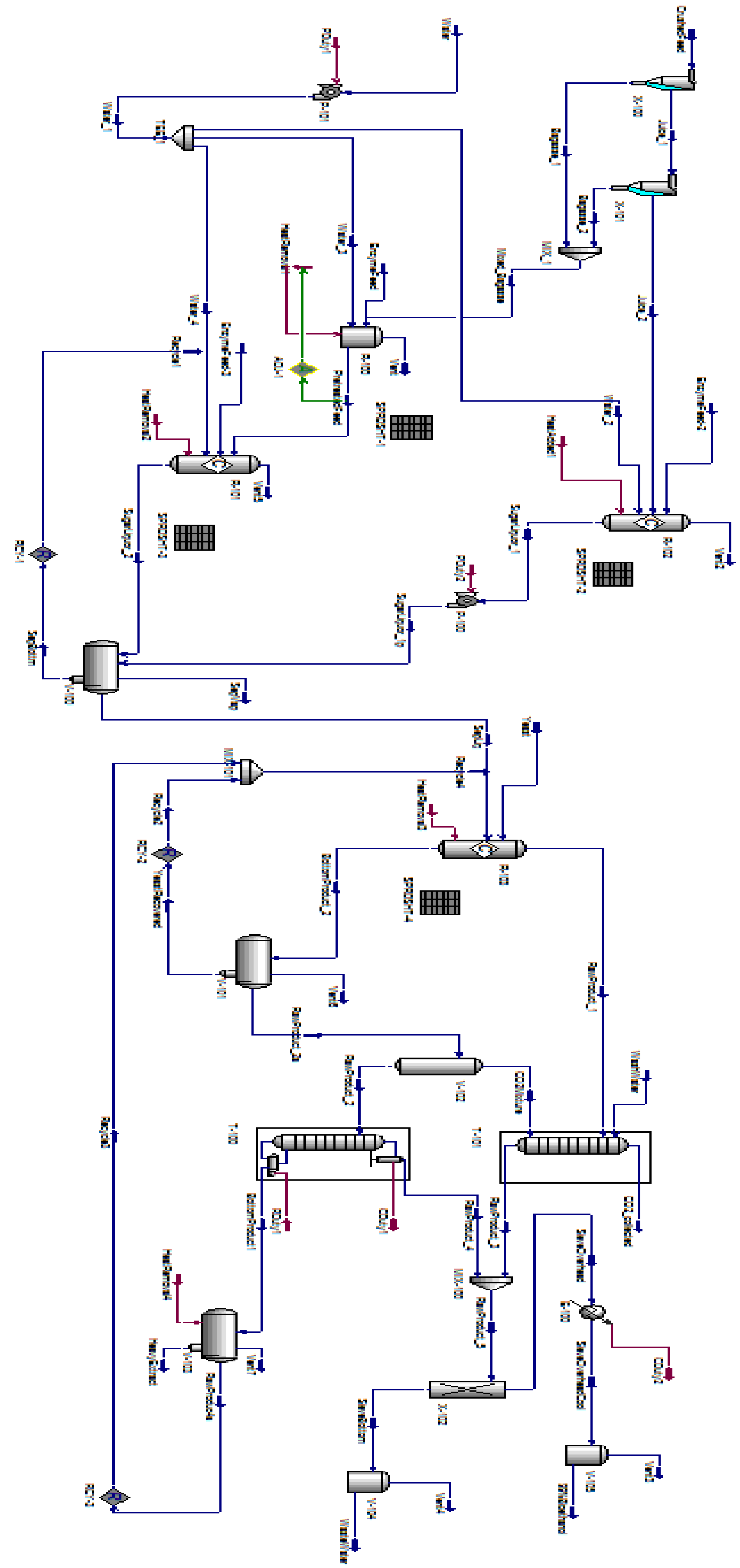

*Figure 3: PFD for Bioethanol Production*

### 3.2 Material Balance and Requirement Analysis

From the material balance analysis of the proposed plant, as shown in Table 6, it can be deduced that 14,618 kg/h (equivalent to 148 million L/yr) of fuel grade bioethanol can be produced from 50,000 kg/h pretreated crushed feed of sugarcane, using 6,905 kg-enzyme/hour (to aid the breaking down of large molecules of sugar such as cellulose, hemicellulose and sucrose to monosaccharides) and 717 kg-yeast/hour (to convert the monosaccharides to bioethanol) at a moderate temperature of 303 K.

*Table 6: Summary of Results of the Overall Material balance*

| Inlet Material Stream | Mass Flow (kg/h) | Outlet Material Stream | Mass Flow (kg/h) |
|---|---|---|---|
| Yeast | 717 | $CO_2$collected | 5,378 |
| EnzymeFeed-3 | 3,538 | 99%Bioethanol | 14,618 |
| EnzymeFeed | 3,314 | WasteWater | 177 |
| EnzymeFeed-2 | 53 | Recycle1 | 35,219 |
| Water | 50 | Recycle4 | 2,353 |
| CrushedFeed | 50,000 | Vent3 | 0 |
| WashWater | 72 | SepVap | 0 |
| Total Flow of Inlet Streams | 57,745 | Total Flow of Outlet Streams | 57,745 |
| | | Error (%) | 0.00 |

### 3.3 Energy Balance and Requirement Analysis

It can be deduced from the energy balance analysis, shown in Table 7, that hydrolysis reaction(s) of hemicellulose and cellulose are highly exothermic reactions, which release large amount(s) of heat. The heat(s) released denoted by 'HeatRemoval1' (hemicellulose) and 'HeatRemoval2' (cellulose) are worth 12.3 and 109 million kJ/hour respectively. The fermentation reaction of monosaccharides is also an exothermic reaction, which release heat of 17.5 million kJ/hour and is denoted by 'HeatRemoval3'. On the other hand, the hydrolysis of sucrose is an endothermic reaction process, which requires energy worth 668,000 kJ/hour and is denoted by 'HeatAdded1'.

The overall plant energy balance infers that the process 'energy flow in', which represents the total amount of heat that flows into the plant, is worth 1.08 billion kJ/hour. An error of 0.01 % was found in the course of the analysis; this error was found to be as a result of the presence of hypothetical components in the simulation.

### 3.4 Energy Efficiency of Bioethanol Production Process

From Table 8, the total energy input ($E_{cs}$) into the bioethanol process was estimated from the energy content of crushed sugarcane (feed) in terms of mass flow rate and calorific value, which is 190.37 MW.

*Table 7: Summary of Results of the overall Energy Balance*

| Inlet-Streams | Energy Flow kJ/h | Outlet-Streams | Energy Flow kJ/h |
|---|---|---|---|
| Yeast | 3.00E+03 | $CO_2$Collected | -4.68E+07 |
| HeatRemoval3 | -1.75E+07 | 99%Bioethanol | -8.85E+07 |
| HeatRemoval2 | -1.09E+08 | WasteWater | -2.74E+06 |
| HeatRemoval1 | -1.23E+07 | CDuty1 | 1.21E+09 |
| HeatAdded1 | 6.68E+05 | CDuty2 | 1.51E+07 |
| PDuty1 | 4.43E+00 | Recycle1 | 3.73E+06 |
| CrushedFeed | -4.61E+06 | Recycle4 | -9.84E+06 |
| WashWater | -1.14E+06 | Vent4 | 0 |
| PDuty2 | 2.10E+00 | SepVap | 0 |
| HeatRemoval4 | -8.93E+05 | Vent7 | 0 |
| RDuty1 | 1.23E+09 | | |
| Total Flow of Inlet Streams | 1.08E+09 | Total Flow of Outlet Streams | 1.08E+09 |
| | | Error (%) | 0.01 |

*Table 8: Results of the Energy Efficiency (Ef)*

| Description | Symbol | Mass Flow [kg/h] | HHV [kJ/kg] | E [MW] | In [MW] | Out [MW] |
|---|---|---|---|---|---|---|
| Feed | $E_{cs}$ | 50000 | 13706.42 | 190.37 | 190.37 | 0 |
| PDuty1 | Win1 | 0 | 0 | 1.23E-06 | 1.23E-06 | 0 |
| P-100 | Win2 | 0 | 0 | 1.41E-05 | 1.41E-05 | 0 |
| Product | $E_b$ | 14663.33 | 29428.52 | 119.87 | 0 | 119.87 |
| Sum | | | | | 190.37 | 119.87 |
| Efficiency | | | | | | 62.97 % |

The electricity input requirement ($W_{in}$) for pumps is 0.0015 kW. The energy content ($E_b$) of bioethanol fuel in terms of its higher heating value (HHV) and mass flowrate is computed to be 119.87 MW. Therefore, the energy efficiency of bioethanol production process, $E_f$ is determined as 63.0 %.

### 3.5 Plant Equipment Costing and Total Investment Estimation

The plant equipment cost employed in the estimation of capital investment cost using factorial method shown in Table 9. The total capital investment, as reported in Table 10, is $ 51 million for the production of 148 million liters of bioethanol (i.e. 0.34 $/L); this value is the sum of the fixed capital investment and working capital. This cost is 24 % higher than the reported $ 25 million for the production of 90 million liters of bioethanol (i.e. 0.28 $/L) from sugar beet and grain sorghum [26].

*Table 9: Plant Equipment Costing (PEC)*

| Description | Unit | Initial Cost, Cp | Escalated Cost, Cx |
|---|---|---|---|
| Hydrocyclone | $ | 2,820.00 | 4,176.91 |
| Vessels | $ | 222,155.03 | 305,326.55 |
| Reactors | $ | 6,225,784.77 | 8,556,625.65 |
| Column Tray & Tower | $ | 16,621.90 | 22,844.88 |
| Molecular Sieve | $ | 1,112.40 | 1,647.65 |
| Other Process Facilities | $ | 98,100.96 | 145,326.06 |
| Total Cost (PEC) | $ | 6,566,595.06 | 9,035,947.71 |

*Table 10: Total Capital Investment (TCI)*

| Description | Unit | Amount |
|---|---|---|
| Direct Plant Cost (DPC) | $ | 26,475,000.00 |
| Indirect Plant Cost (IPC) | $ | 15,885,000.00 |
| Total Plant Cost (DPC+IPC) | $ | 42,361,000.00 |
| Fixed Capital Investment (FCI) | $ | 48,715,000.00 |
| Working Capital (WC) | $ | 2,435,700.00 |
| Total Capital Investment (FCI+WC) | $ | 51,150,000.00 |
| Bioethanol production | L | 147,620,000 |
| Capital per Liter | $/L | 0.34 |

Nevertheless, the cost of the proposed plant is similar to that reported for the Southeast plant of similar capacity and cost ($ 50.8 million), and lower than the other plants (also reported) at Idaho Southwest and Panhandle [27].

### 3.6 Cost of Manufacturing Estimation

The analysis for the proposed plant, as shown in Table 11, suggests the need for up to 51 plant operators; this is higher than that reported in literature [27]. The manufacturing cost was estimated as $ 89.48 million, implying 0.61 $/L which is more than that obtained by [12] as 0.54 $/L in South Africa. This manufacturing cost (a liter of bioethanol) is again more expensive than that reported in literature [27, 28]. This manufacturing cost accounts for operating labour cost, maintenance cost, supervision cost, utilities cost and raw material cost. Further study of the results reveals that the cost of raw materials may be responsible for the high cost of manufacturing. Hence, to reduce the cost of manufacturing, the price of raw materials must be reduced.

*Table 11: Cost of Manufacturing (COM)*

| Description | Unit | Amount |
|---|---|---|
| Raw Materials | M$ | 60.31 |
| Operating Labour | M$ | 0.06 |
| Work Force | - | 51 |
| Utilities | M$ | 1.21 |
| Direct Production Cost(DPc) | M$ | 65.03 |
| Depreciation(DP) | M$ | 4.87 |
| Fixed Charges(FC) | M$ | 5.98 |
| General Expenses(GE) | M$ | 13.87 |
| Cost of Manufacturing(DPc+DP+FC+GE) | M$ | 89.48 |
| Production | ML | 147.62 |
| Cost price | $/L($/gal) | 0.61(2.42) |

## 4. CONCLUSION

This study establishes that 375,000 liters of bioethanol can be produced from a metric tonne of crushed sugarcane at a capital investment and manufacturing cost of 0.34 $/L and 0.61 $/L respectively. The plant will yield 148 million liters of bioethanol from the processing of 402 metric tonnes of crushed sugarcane with a capital of $ 51 million and manufacturing cost of $ 89 million per annum. The energy efficiency of the proposed bioethanol plant was found to be 63 %.

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