OBSAFER: Hydrogen Power Plant from Soybean Straw and Tofu Liquid Waste in Kediri District

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Abstract

Industrial developments result in higher consumption of electrical energy with considerable emissions. Efforts to develop alternative energy are carried out to overcome climate change. Hydrogen, as a clean energy, can be produced from biomass, such as soybean straw waste. The OBSAFER innovation was created to optimize the use of soybean straw and tofu liquid waste in electrical power. The process began with soybean straw waste pre-treated with NaOH and entered into a bioreactor for a dark fermentation process with Clostridium butyricum to produce hydrogen, methane, and carbon dioxide. Then, the gas is separated by a CH_4 filter and a CO_2 filter, so the main product is hydrogen. The OBSAFER technology can produce 821,751 kWh/year from 21.6 tons of soybean straw waste and Clostridium butyricum from tofu liquid waste.

Keywords: Dark fermentation; OBSAFER; Soybean straw; Tofu liquid waste

1. Introduction

In the 20th century, the world experienced a significant diversification of energy consumption where the energy widely used was fossil fuels such as oil, natural gas and coal. What is very surprising is that based on statistical data provided in the BP Statistical Review of World Energy, humanity has burned 404 gigatons of oil during the period 1965 to 2018, which has resulted in carbon dioxide gas emissions of around 1204 gigatons (Gt) into the earth's atmosphere during this time [1]. This is the cause of global warming that all countries have felt. Climate changes are characterized by increasing temperatures on the earth's surface, resulting in various disasters such as drought, sinking land due to melting icebergs, and fires. Of course, this problem must be addressed immediately. One form of treatment is to use alternative energy to overcome energy needs and climate change, one of which is biomass processed using microbes [2]. In this way, carbon emissions can be reduced while energy needs are also met.

Biomass used for energy convertion is biomass with no economic value, such as agricultural waste [3]. Most agricultural waste that contains cellulose, hemicellulose and lignin can produce energy [4]. Soy straw waste in Kediri Regency has promising potential as an environmentally friendly source of electrical energy from hydrogen because it contains 85% cellulose and is abundant in quantity. Based on data from the East Java Province Livestock Service in 2018, the amount of soy straw waste from Kediri Regency reached 674.6 tons/year [5]. On the other hand, Kediri is known as a tofu city with a total demand for soybeans of 11,600 tons and produces liquid waste of ± 875 liters per 35 kg of soybean raw materials. Based on research by Sayow et al. (2020), liquid waste from the tofu industry contains high levels of organic material, Biological Oxygen Demand levels of 5,000-10,000 ppm and Chemical Oxygen Demand of 7,000-12,000 ppm [6]. This amount is very high and if the waste is dumped directly into the river it can cause odors and environmental pollution. In fact, this waste contains Clostridium butyricum can be used to produce electrical energy from hydrogen [7].

The methods currently used for energy production from organic materials are gasification, pyrolysis, carbonization, biochemistry and dark fermentation [8]. The dark fermentation process is the most superior method in terms of hydrogen production compared to other methods because it has zero emissions, is able to produce hydrogen without the help of light so it is not affected by the weather, can use various substrates, and is low cost [9]. In addition, the maximum biohydrogen produced from soybean straw using anaerobic bacteria is 60.2 mL/g dry soybean straw [10].

Regarding the problems and phenomena that occurred, the OBSAFER innovation was created to produce electrical energy and hydrogen while reducing carbon emissions from the electricity industry by utilizing soy straw waste and tofu liquid waste using the dark fermentation method. This research aims to produce design and working mechanisms and analyse the effectiveness of OBSAFER as a hydrogen power generator from soybean straw waste and tofu liquid waste in Kediri Regency to support the realization of energy security in terms of the economic aspect.

1.1. Soybean Straw Waste

Soybean straw is a type of waste from soybean plants which has not been reused but has been thrown away or burned, causing air pollution and increasing the risk of global warming. The wider the area of soybean farming, the more soybean straw waste is produced. Soybean production in Kediri Regency reached 674.6 tons, with utility waste production of 272.54 tons/year [5].

Straw waste contains crude fibre, a mixture of hemicellulose, cellulose and lignin, which is insoluble in water [3]. Based on the research results of Dewi et al. (2019), soybean straw has a crude fibre content of 44.28%. Many things can be used from soy straw waste, one of which is as a source of electrical energy from hydrogen [11]. The cellulose content of soybean straw waste will be utilized in the hydrogen production process. Soy straw waste in Kediri contains 85% cellulose, so the soybean straw waste in Kediri Regency has promising potential as an environmentally friendly source of electrical energy from hydrogen [12].

1.2. Tofu Waste Water

The tofu industry is a small industry that can support the economy in Kediri Regency. However, this industry has the potential to harm the environment. Based on research conducted in Wonosari Hamlet, Papar District, Kediri Regency, each craftsman produces more than 2,500 litres of tofu liquid waste daily. In the process of making tofu, the industry usually produces a lot of liquid trash. This waste comes from the washing, soaking, clumping, pressing, spills and cleaning processes [13].

Based on research by Sayow et al. (2020), it is known that liquid waste from the tofu industry contains high levels of organic material, Biological Oxygen Demand (BOD) levels of 5,000-10,000 ppm and Chemical Oxygen Demand (COD) of 7,000-12,000 ppm [6]. This amount is very high, and if the waste is dumped directly into the river, it can cause odours and environmental pollution. Almost all tofu industries in Kediri Regency do not have waste processing units. Thus, it is dangerous for the environment. Tofu liquid waste can be utilized as electrical energy from hydrogen using the dark fermentation method. The yield of hydrogen obtained from the fermentation method reaches 107.5 ml-H_2/g COD at a temperature of 35°C and pH 5.5 – 6.0 [14].

1.3. Hydrogen

Hydrogen is a chemical element that has been widely developed as an alternative energy because it is abundant. Hydrogen can be found in plants because the body has four main components: carbon, hydrogen, nitrogen and oxygen [15]. Hydrogen has several advantages compared to other fuels because the heating value of hydrogen is 120–142 MJ/kg, higher than methane and ethanol, which respectively have a heating value of 50 MJ/kg and 26.8 MJ/kg [10].

Hydrogen production can be done using the dark fermentation method. The hydrogen yield produced through the dark fermentation method is 4 mol H_2/mol glucose [16]. Then, using hydrogen as a source of electricity generation has great potential with Microbial Fuel Cells (MFC). Microbial fuel cells have several advantages: low cost and large storage capacity. However, the efficiency only reaches 45-50%, so further development and proper control are needed when using MFC. The use of microbial fuel cells can produce 0.3 kW for a volume of 600 litres [17].

2. Method

This research method uses a meta-analysis, a literature study carried out by reviewing several scientific journals, and a simulation method using Autodesk Fusion 360 software to determine the safety level of OBSAFER technology as a hydrogen power plant from soybean straw waste and tofu liquid waste in Kediri Regency in an effort to support the realization of energy security.

This research combines qualitative and quantitative data types. In describing the data obtained and needed, a qualitative method was used to compare this research with other research nationally and internationally. The research sources were obtained from journals published by official publishers. Meanwhile, the quantitative method is carried out by calculating the amount of hydrogen produced from dark fermentation data and electricity that can be converted from hydrogen to electricity and calculating the BCR (Benefit-Cost Ratio). Then, the results are compared with existing research. The data obtained is then compiled, analyzed and concluded to obtain conclusions regarding the results of literature studies and process simulations. The overall research stages were carried out based on the flow diagram in Figure 1.

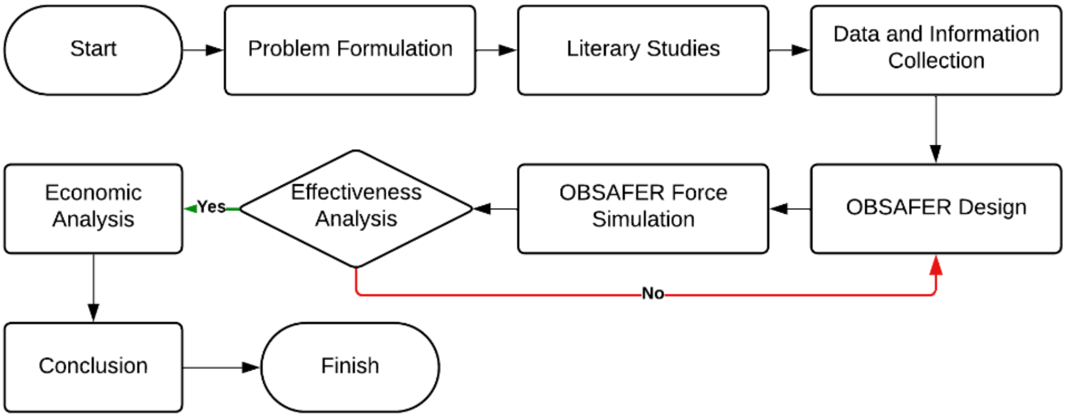

Figure 1. OBSAFER Research Flow

The materials used for OBSAFER technology as hydrogen power plants are straw waste as a substrate, liquid tofu waste containing Clostridium butyricum for the dark fermentation process, reactors, hydrogen tanks, hydrogen fuel cells, and generators.

3. Results and Discussion

3.1. OBSAFER Design

Figure 2 shows the 3D modelling of OBSAFER designed using Sketch Up. It consists of several components, such as a pre-treatment tank, bioreactor, power storage, CO_2 filter, CH_4 filter, and hydrogen tank. Based on straw waste substrate data in Kediri Regency, there are 21.6 tons of straw waste per year, so the estimated straw waste produced is 60 kg/day. The pre-treatment tank and bioreactor capacity are designed to be 75 kg with a 1000 L hydrogen gas tank capacity.

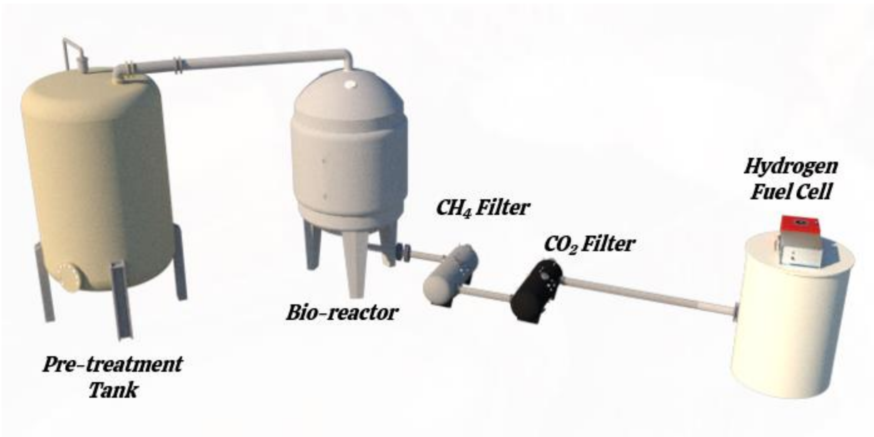

Figure 2. OBSAFER Design

The simulation was carried out by simulating static and thermal loads on the bioreactor. In the dark fermentation process the operating temperature is 30°C. Then, the simulated weight is 750 N. The material used in this reactor is Stainless Steel 316 L. This material was chosen because it has good corrosion resistant properties.

3.1.1 The Calculation of Electricity Production

The chemical reactions that occur during dark fermentation of soybean straw waste substrate using Clostridium butyricum bacteria which can produce biohydrogen are as follows:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (1)$$

From the reaction above, acetic acid is also obtained which can decompose and produce methane gas as a side product of the following reaction:

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2)$$

Biohydrogen production from each use of 20 grams of reducing sugar/liter can produce a maximum of 0.011 mol H_2/mol of reducing sugar [16]. Thus, it is possible to calculate the hydrogen gas yield resulting in 2 liters of substrate. The following is a calculation to determine the amount of soy straw waste needed for biohydrogen production and how much electrical energy can be produced using OBSAFER technology:

$$\text{Amount of waste} = (V1/V2) \times 20 \text{ grams} \quad (3)$$

$$\text{Amount of waste} = (2/0.1) \times 20 \text{ grams} \quad (4)$$

$$\text{Amount of waste} = 400 \text{ grams} \quad (5)$$

Calculation of the assumed hydrogen gas yield every hour:

$$\text{Yield } H_2/12 \text{ hours} = (400/100) \times \text{yield } H_2/100\text{gram} \quad (6)$$

$$\text{Yield } H_2/12 \text{ hours} = 4 \times 0.011 \text{ mol } H_2/\text{mol sugar} \quad (7)$$

$$\text{Yield } H_2/12 \text{ hours} = 0.044 \text{ mol } H_2/\text{mol sugar} \quad (8)$$

$$\text{Yield } H_2/\text{hour} = 0.0037 \text{ mol } H_2/\text{mol sugar} \quad (9)$$

Then, calculations are carried out using the ideal gas equation:

$$V=(n \times R \times T)/P \quad (10)$$

$$V=(0.0037 \times 0.082 \times (273+35))/1 \quad (11)$$

$$V = 0.094 \text{ liters } H_2 \quad (12)$$

With the assumptions above, the amount of electrical energy produced in 1 year with a hydrogen fuel cell efficiency of 70%:

$$0.094 \text{ L/hour} \times 8760 \text{ hours} = 820.577 \text{ L } H_2 \text{ gas/year} \quad (13)$$

$$\text{Electricity} = \text{fuel cell ratio} \times 820, 577 \text{ L } H_2 \text{ gas/year} \quad (14)$$

$$\text{Electricity} = 1{,}430.615 \text{ Wh/liter} \times 820\text{L } H_2 \text{ gas/year} \quad (15)$$

$$\text{Electricity} = 1{,}173{,}930 \text{ kWh} \quad (16)$$

$$\text{Electricity with 70\% efficiency} = 821{,}751 \text{ kWh} \quad (17)$$

So the electricity obtained by converting hydrogen that has been produced into electricity using 21.6 tons of soy straw waste as a substrate is 821,751 kWh.

3.1.2 Economic Analysis

Economic analysis is carried out with several parameters starting with calculating capital expenditure or capital costs. Once identified, OBSAFER capital expenditure can be seen in Table 1.

Table 1. Capital Expenditure Of OBSAFER

Item	Qty	Price per Unit (IDR)	Total (IDR)
Bioreactor	1	56,733,809.00	56,733,809.00
Hydrogen Fuel Cell	1	200,521,656.00	200,521,656.00
CH_4 Filter	1	2,000,000.00	2,000,000.00
CO_2 Filter	1	2,290,000.00	2,290,000.00
API 5L GR X52 Pipe	4	2,595,000.00	10,380,000.00
Hydrogen Tank	1	38,529,000.00	38,529,000.00
Power Storage	1	105,876,000.00	105,876,000.00
Wiring System & Others	1	20,000,000.00	20,000,000.00
Total			436,330,465.00

When implementing the OBSAFER system, operational costs are also calculated to determine the costs incurred during the operational process. Operational costs consist of Cost of Goods Sold (COGS) and Operational Expenditure (OpEx) which can be seen in Table 2 and Table 3.

Table 2. First Year Cost Of Goods Sold

Item	Qty	Price per Unit (IDR)	Total (IDR)
Soybean Straw	21,600	2.000.00	43,200,000.00
Liquid Tofu Waste	43,200	2,000.00	86,400,000.00
NaOh	540	52,000.00	28,080,000.00
Distiribution	4	5,000,000.00	20,000,000.00
Total			177,680,000.00

Table 3. First Year Operational Expenditure

Item	Price (IDR)
Advertising & Promotion	12,000,000.00
General & Administrative	8,000,000.00
Marketing	12,000,000.00
Operation, Testing, & Maintenance	87,266,093.00
Office Rent	108,000,000.00
Professional Fees	300,000,000.00
Total	527,345,093.00

From the analysis that has been carried out, net earnings in the first year were IDR 155,205,184.51; second year amounting to IDR 157,092,488.20; third year amounting to IDR 158,987,117.96; and so on which comes from electricity sales of IDR 1,100.00/kWh. After that, a complex economic analysis was carried out which produced several economic parameters in Table 4.

Table 4. Economic Analysis Results

Item	Value
Payback Period	2.936
Net Present Value(NPV)	IDR 527,009,748.10
Internal Rate of Return (IRR)	34%
Benefit-Cost Ratio (BCR)	1.14

OBSAFER is an innovative hydrogen power generation system that uses cellulose from biomass as a hydrogen source. The cellulose used comes from soybean straw waste which will then be converted into hydrogen using the dark fermentation method with microorganisms originating from liquid tofu waste. Based on Figure 2, shows that the working mechanism of OBSAFER is that soy straw waste is pre-treated first using NaOH. Next, the soy straw waste is put into a bioreactor for a dark fermentation process with Clostridium butyricum for 14 hours to produce hydrogen, methane, and carbon dioxide. Then, the fermentation gases are separated using a CH_4 filter and a CO_2 filter, so the main product is hydrogen. Next, the hydrogen is converted into electricity using a hydrogen fuel cell.

OBSAFER technology has a high level of effectiveness and safety in producing electrical energy from hydrogen obtained from the dark fermentation process. Based on the static load simulation results, the maximum stress obtained at 1.722×10^{-4} MPa and the minimum stress at 2.365×10^{-10} MPa. Then the maximum strain obtained was 7.894×10^{-10} and the minimum strain was 9.359×10^{-16}. As for the safety factor value from the simulation results, it shows the number 15, so this bioreactor is very safe to use with a load of around 75 kg. Furthermore, from the results of thermal simulations at a temperature of 30°C the bioreactor is safe to use. The maximum heat flux value is 9.794×10^{-8} W/mm^2 and the minimum heat flux is 4.54 × 10-12 W/mm^2. Meanwhile, the maximum thermal gradient is 1.749×10^{-6} C/mm and the minimum thermal gradient is 8.107×10^{-11} C/mm. Apart from that, OBSAFER can produce electrical energy of 821,751 kWh/year from 21.6 tons of soy straw waste and Clostridium butyricum obtained from liquid tofu waste.

Economic analysis is carried out with several parameters starting with calculating capital expenditure or costs. Capital expenditure uses several assumptions such as the bioreactor cost, API 5L GR X52 pipe, filters, hydrogen gas tank, and power storage. Once identified, OBSAFER's capital expenditure is IDR 64,069,215.00. The operational costs are also calculated to determine the costs incurred during the operational process. Operational costs include the Cost of Goods Sold (COGS) and Operational Expenditure (OpEx). COGS in the first year of product sales reached IDR 177,680,000.00 which came from the purchase of tofu liquid waste, soy straw, NaOH, and distribution services. This value will continue to increase as production increases every year. The OpEx required in the first year reached IDR 527,345,093.00, which came from production site rental costs, worker salaries, operation & maintenance costs, administration and marketing costs. So, the total operational costs required in the first year of sales are IDR 705,025,093.00. This value will continue to increase as the nominal COGS and OpEx increase yearly.

The OBSAFER system's estimated profits are determined based on the net earnings value obtained each year. The net earnings obtained have gone through a complex financial analysis stage taking into account the electricity price of IDR 1,100.00/kWh, with an increase in the processing of tofu liquid waste and soybean straw every year (2%/year), an increase in COGS which adjusts for the increase in waste processing, increase in Operational Expenditure (OpEx) which adjusts the percentage increase in each parameter, income taxes by 22%, up to 10 years of business continuity. From the analysis that has been carried out, net earnings in the first year were IDR 155,205,184.51; the second year amounted to IDR 157,092,488.20; the third year amounted to IDR 158,987,117.96; and so on.

In the OBSAFER system, complex financial projections can be made by calculating several economic parameters, such as payback period value, Net Present Value (NPV), Internal Rate of Return (IRR), and Benefit Cost Ratio (BCR). Some of these parameters can indicate the feasibility of the OBSAFER business in the next few years. The revenue that will be obtained when OBSAFER is implemented in the first year is IDR 903,926,100.00. This value comes from electricity production of 821,751 kWh. Revenue will continue to increase because every year there is a projected increase in the processing of liquid waste from tofu and soybean straw by 2%.

OBSAFER achieved a payback period of 2,936 years. In the first 10 years, the Net Present Value obtained was IDR 527,009,748.10, and the Internal Rate of Return was 34% by applying a discount rate of 10%. NPV and IRR projections from businesses that show positive value make the OBSAFER system a hydrogen-producing innovation feasible to implement as a long-term business (at least the next 10 years). OBSAFER also has a benefit-cost ratio (>1), 1.14.

4. Conclusions

The OBSAFER technology is designed with a simple design to reduce production costs to produce electricity. The working mechanism of OBSAFER consists of soy straw waste being pre-treated using NaOH and then fermented in a bioreactor with Clostridium butyricum for 14 hours to produce hydrogen, methane, and carbon dioxide. Then, the fermentation gas is separated using a CH_4 filter and a CO_2 filter to obtain hydrogen from the product. Next, the hydrogen is converted into electricity using a hydrogen fuel cell. OBSAFER has a high level of effectiveness in the process of converting biomass into hydrogen and electrical energy because it can produce electricity of 821,751 kWh/year from 21.6 tons of soy straw waste and Clostridium butyricum which comes from liquid tofu waste. Apart from that, this technology is very safe because the safety factor value reaches 15 with a load of around 75 kg. Also, this technology is worth investment in the energy conversion sector because based on the benefit-cost ratio analysis, a BCR ratio of 1.14 is obtained after 10 years of use.

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