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Techno-Economic Analysis of Biogas Power Plant from POME (Palm Oil Mill Effluent)

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Abstract

In this study, POME (Palm Oil Mill Effluent) was used as a source of biogas for electrical energy sources. POME was processed by anaerobic digestion using a digester with anaerobic lagoon type. Anaerobic digestion process model until the power plant was built using SuperPro Designer 9.0 software. Simulation results for oil palm plant with 30 ton capacity of fresh fruit bunch (TBS)/hour obtained biogas with ratio CH_4: CO_2 equal to 60:41. The construction of a biogas power plant requires an investment of 1,979,000 US $ with IRR = 12.5% and PBP for 6.6 years indicated that the construction of the plant is feasible but less attractive for investment in the energy sector economically.

INTRODUCTION

The potential of new renewable energy sources in Indonesia is abundant. New renowned renewable energy sources include geothermal energy, wind energy, water energy, ocean currents energy, solar energy and biogas energy. As one of the new renewable energy sources, biogas is one of the alternative sources of energy which is currently being widely researched and developed. With the target energy mix for new renewable energy sources are expected to meet more than 31% of national energy needs [1], the research and development of biogas as a source of energy becomes very interesting to be implemented as a reliable source of energy.

From 2011 to 2015 Indonesia and Malaysia expanded their palm oil plantation area by 29.80% and 12.86%, respectively, making the total 17.3 million hectares for both countries [2, 3]. The increasing growth in global palm oil industry is at least represented by these top global crude palm oil producers [4]. The enormous wet process of CPO extraction result in the gigantic quantity of palm oil mill effluent (POME), with the ratio of POME per CPO produced is 3.05 [5]. Both countries generate around 155.7 million tonnes of POME, which has high organic contents and very much a burden and problematic to the palm oil industries [6].

POME as one source of biogas is currently being studied and developed. POME is a liquid waste from palm oil processing that has characteristics with BOD 2800 mg/L, COD 64000 mg/L, TSS 24000 mg/L, oil and fat 6950 mg/L, and total N content 750 mg/L [7]. The main components contained in every 100 grams of total solids in POME are carbohydrate (MW = 162.14) 16.95 g, protein (MW = 352.38) 7.48 g, and lipid (MW = 787.24) 10.90 g [8].

POME is a good source of methane generation via anaerobic digestion due to its highly biodegradable organic content [9]. Many CPO mills utilize conventional pond to treat POME due to low operating cost [10]. Pond system system comprises of de-oiling tank, acidification ponds, anaerobic ponds and facultative or aerobic ponds [3]. Because of the difficulties in operational control and the unused biogas produced which lead to global warming, the pond system is not recommended [11, 12, 13, 14]. The handling and treatment of POME are therefore very important. Anaerobic digestion is relatively the best available technology from different aspects, which mostly came from the energy recovery through biogas generation [10, 15].

Palm oil processing plants in Indonesia have various processing capacity. Assuming that capacities of 30 tons FFB (Fresh Fruit Bunch) per hour with 6000 hours per year estimated POME produced about 90,000 – 135,000 every year. Other studies have been done on producing biogas from POME using the anaerobic digestion system, obtained the final product consisting mostly of biomethane (CH_4) and carbondioxide (CO_2) with a ratio of 65:35 and an estimated 28 m^3 of gas produced for each ton POME [16, 17]. In general, biogas has heating value about 22 MJ/m^3.

This study aims to use POME as a source of energy for power generation. In this study, the process of degradation of POME into biogas is simulated using SuperPro Designer 9.0 software by detailing the degradation that occurs in each stage of the process. This study was conducted to evaluate economic feasibility of developing power plants from POME-based biogas as an alternative substitution for the provision of electrical energy needs for palm oil processing operations and communities around the plant.

PROCESS DESCRIPTION

The main products of this process are biogas, majority consists of methane and CO_2, and digestate. In biogas production, different microbes are involved for each process. Production of biogas takes place in the digester tank at the same time. The peak production of biogas occurs in the process of methanogenesis. Ahmad et al. have reported the composition of amino acid compounds resulted from degradation of protein content and composition of fatty acid compounds resulted from degradation of lipid content from POME is shown in Tabel 1 [8].

Table 1. Composition of amino acid and fatty acid compound [8]

No.	Amino acid (gr/100 gr Protein)	Molecul	Amount (gram)	Fatty acid (gr/100 gr Lipid)	Molecul	Amount (gram)
1	Aspartic Acid	HOOC-CH_2-CH(NH_2)-COOH	9.66	Capric Acid	CH_3-(CH_2)$_8$-COOH	4.29
2	Glutamic Acid	HOOC-(CH_2)$_2$-CH(NH_2)-COOH	10.88	Lauric Acid	CH_3-(CH_2)$_{10}$-COOH	9.22
3	Serine	HO-CH_2-CH(NH_2)-COOH	6.86	Myristic Acid	CH_3-(CH_2)$_{12}$-COOH	12.66
4	Glycine	NH_2-CH_2-COOH	9.43	Palmitic Acid	CH_3-(CH_2)$_{14}$-COOH	14.45
5	Histidine	NH_2-CH=N-CH=CH-CH_2-CH(NH_2)-COOH	1.43	Heptadecanoic Acid	CH_3-(CH_2)$_{15}$-COOH	1.39
6	Arginine	HN=C(NH_2)-NH-(CH_2)$_3$-CH(NH_2)-COOH	4.15	10-heptadecanoic Acid	CH_3-(CH_2)$_8$-CH=CH-(CH_2)$_5$-COOH	1.12
7	Threonine	CH_2-OH-CH(NH_2)-CH-COOH	2.58	Stearic Acid	CH_3-(CH_2)$_{16}$-COOH	11.41
8	Alanine	CH_3-CH(NH_2)-COOH	7.70	Oleic Acid	CH_3-(CH_2)$_7$-CH=CH-(CH_2)$_7$-COOH	8.54
9	Proline	NH_2-(CH_2)$_3$-CH-COOH	4.57	Linoleic Acid	CH_3-CH_2-(CH=CH-CH_2)$_3$-(CH_2)$_6$-COOH	4.72
10	Tyrosine	OH-Ph-CH_2-CH(NH_2)-COOH	3.26	Linolenic Acid	CH_3-CH_2-(CH=CH-CH_2)$_3$-(CH_2)$_6$-COOH	4.72
11	Phenylalanine	Ph-CH_2-CH(NH_2)-COOH	3.20	Arachidic Acid	CH_3-(CH_2)$_{18}$-COOH	7.56
12	Valine	(CH_3)$_2$-CH-CH(NH_2)-COOH	3.56	Eicosatrienoic Acid	CH_3-CH_2-(CH=CH-CH_2)$_3$-(CH_2)$_8$-COOH	1.49
13	Methionine	CH_3-S-(CH_2)$_2$-CH(NH_2)-COOH	6.88	Arachidonic Acid	CH_3-(CH_2)$_4$-(CH=CH-CH_2)$_4$-(CH_2)$_2$-COOH	1.12
14	Cystine	HS-CH_2-CH(NH_2)-COOH	3.37	Eicosapentaeoic Acid	CH_3-CH_2-(CH=CH-CH_2)$_5$-(CH_2)$_2$-COOH	0.36
15	Isoleucine	CH_3-CH_2-CH(CH_3)-CH(NH_2)-COOH	4.53	Behenic Acid	CH_3-(CH_2)$_{20}$-COOH	2.62
16	Leucine	(CH_3)$_2$-CH-CH_2-CH(NH_2)-COOH	6.86			
17	Lysine	H_2N-(CH_2)$_4$-CH(NH_2)-COOH	5.66			
18	Tryptophan	Ph-NH-CH=CH-CH_2-CH(NH_2)-COOH	1.26			

As shown in Figure 3, POME-based biogas generator circuit was conducted using SuperPro Designer simulation software for simulation purposes.

In the SuperPro software simulation, feed flow rate was 15,000 kg/hour. This flow rate is equivalent to the number of POME produced by palm oil processing plants with a capacity of 30 Ton TBS per hour. All the reaction in this simulation was assumed to be stoichiometric reaction at 30˚C. Based on the POME characteristic data from the literature, the POME feed composition used in the simulations can be seen in Table 2.

Table 2. General feed POME composition used in simulation

Nr.	Component	Molecule	kg/h
1	Carbohydrat	$C_6H_{10}O_5$	101.70
2	Protein	$C_{16}H_{24}O_5N_4$	65.40
3	Lipid	$C_{50}H_{90}O_6$	44.88
4	Water	H_2O	14788.02

In the biogas production process, there are four main processes:

1. Hydrolysis

The process occurs in hydrolysis is complex organic compound decomposed into smaller units (mono- and oligomers). Hydrolysis microorganisms excrete hydrolysis enzymes. The assumptions used in this simulation are degradation of all carbohydrate into glucose with hydraulic retention time (HRT) 5 days. Reaction occurred in this process are shown:

$$Lipid \xrightarrow{lipase} fatty\ acid, gliserol$$

$$polysaccharide \xrightarrow{cellulase, cellobiase, xylanase, amilase} monosaccharide$$

$$Protein \xrightarrow{protease} amino\ acid$$

2. Acidogenesis

In this process, the hydrolysis product is converted to methanogenic substrates (acetate, H_2 and CO_2). Simple sugars, amino acids, and glycerol are degraded to acetate, CO_2 and H_2 (70%) as well as volatile fatty acids (VFA, which consists of lactic acid, propionate acid, butyric acid and valeric acid) and alcohol (30%). The assumptions used in this process are degradation of glucose to 70% acetic acid dan 30% etanol, gliserol to propionic acid with HRT of 10 days.

The amino acid degradation can be seen in Table 2. The amino acid degradation reaction shows the yield of hydrogen sulfide and ammonia. Thus, for aerobic digestation is required to break down the nitrate to reduce the odor.

3. Acetogenesis

The acidogenesis product, which is not directly converted to methane by ascdogenesis bacterial, is converted to a methanogenic substrate in the process of acetogenesis. Fatty acids, VFAs and alcohols are oxidized to methanogenic substrates, namely acetate. The assumptions used in this simulation are degradation of fatty acid to acetic acid with HRT of 10 days. The fatty acid degradation can be seen in Table 3. Hydrogen production increases the hydrogen partial pressure. This can be considered as waste of acetogenesis and inhibit the metabolism of acetogenic bacteria.

4. Methanogenesis

Mostly, 70% of methane is formed from acetate and the rest is produced from the conversion of hydrogen and carbon dioxide by reaction:

$$Acetic\ acid \xrightarrow{methanogenic\ bacteria} methane + carbon\ dioxide$$

$$hydrogen + carbon\ dioxide \xrightarrow{methanogenik\ bacteria} methana + water$$

The process of methanogenesis is a critical process that occurs slowly. This process is influenced by operating conditions, raw material composition, flow rate, temperature and pH. Excess digestate, changes in temperature, and oxygen entry may cause a cessation of the reaction. In this simulation, the assumptions used are degradation of acetic acid to CH_4 and CO_2, decomposition of CO_2 and H_2 to CH_4 dan H_2O with HRT of 20 days. Acetat reaction to methane is the main methanogenic route, so theoretical calculations are conducted on this reaction.

Table 2. Degradation of amino acid and fatty acid

Degradation of amino acid [18]	:	Degradation of fatty acid [19]	:
Aspartic Acid + 2 H_2O	→ Acetic Acid + 2 CO_2 + NH_3 + 2 H_2	Capric Acid + 8 H_2O	→ 5 Acetic Acid + 8 H_2
Glutamic Acid + H_2O	→ Acetic Acid + ½ Butanoic Acid + NH_3 + CO_2	Lauric Acid + 10 H_2O	→ 6 Acetic Acid + 10 H_2
Serine + H_2O	→ Acetic Acid + NH_3 + CO_2 + H_2	Myristic Acid + 12 H_2O	→ 7 Acetic Acid + 12 H_2
Glycine + ½ H_2O	→ ¾ Acetic Acid + NH3 + ½ CO_2	Palmitic Acid + 14 H_2O	→ 8 Acetic Acid + 14 H_2
Histidine + 4 H_2O	→ Acetic Acid + ½ Butanoic Acid + Formamide +2 NH_3 + CO_2	Stearic Acid + 16 H_2O	→ 9 Acetic Acid + 16 H_2
Arginine + 3 H_2O	→ ½ Acetic Acid + ½ Propionic Acid + ½ Valeric Acid + 4 NH_3 + CO_2	Oleic Acid + 16 H_2O	→ 9 Acetic Acid + 15 H_2
Threonine + H_2O	→ Propionic Acid + NH_3 + CO_2 + H_2	Linoleic Acid + 16 H_2O	→ 9 Acetic Acid + 14 H_2
Alanine + 2 H_2O	→ Acetic Acid + NH_3 + CO_2 + 2 H_2	Linolenic Acid + 16 H_2O	→ 9 Acetic Acid + 13 H_2
Proline + H_2O + H_2	→ ½ Acetic Acid + ½ Propionic Acid + ½ Valeric Acid + NH_3	Heptadecanoic Acid + 14 H_2O	→ 7 Acetic Acid + Propionic Acid + 14 H_2
Phenylalanine + 2 H_2O	→ Phenyl acetate + NH_3 + CO_2 + 2 H_2	Arachidic Acid + 18 H_2O	→ 10 Acetic Acid + 18 H_2
Valine + 2 H_2O	→ Butanoic Acid + NH_3 + CO_2 + 2 H_2	Eicosatrieonic Acid + 18 H_2O	→ 10 Acetic Acid + 15 H_2
Methionine + 2 H_2O	→ Propionic Acid + NH_3 + CO_2 + Methanetiol + H_2	Arachidonic Acid + 18 H_2O	→ 10 Acetic Acid + 14 H_2
Cystine + 2 H_2O	→ Acetic Acid + NH_3 + CO_2 + H_2S + ½ H_2	Eicosapentaeonic Acid + 18 H_2O	→ 10 Acetic Acid + 13 H_2
Isoleucine + 2 H_2O	→ Valeric Acid + NH_3 + CO_2 + 2 H_2	Behenic Acid + 20 H_2O	→ 11 Acetic Acid + 20 H_2
Leucine + 2 H_2O	→ Valeric Acid + NH_3 + CO_2 + 2 H_2		
Lycine + 2 H_2O	→ Acetic Acid + Butanoic Acid + 2 NH_3		
Tryptophan + 2 H_2O	→ Indole + Acetic Acid + NH_3 + CO_2 + H_2		

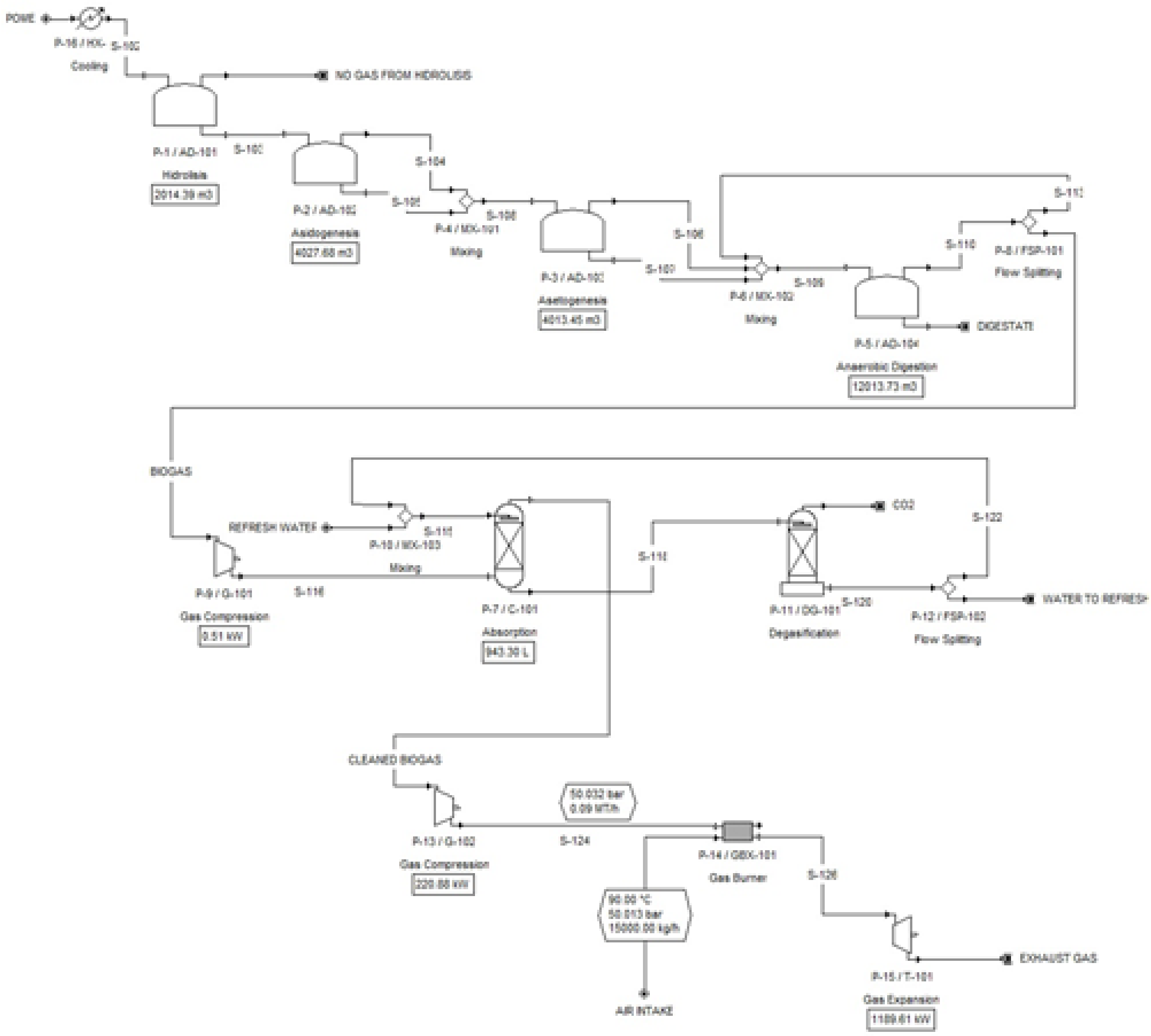

Figure.1. Biogas power plant from POME simulation using Superpro software.

Table 3. Potential source of biogas [8]

Component	Methanogenic Reaction	Biogas (lg^{-1})	CH4 (%)
Carbohidrat	$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$	0.830	50.0
Protein	$C_{16}H_{24}O_5N_4 + 14.5\ H_2O \rightarrow 8.25\ CH_4 + 3.75\ CO_2 + 4\ NH_4^+ + 4\ HCO_3^-$	0.921	68.8
Lipid	$C_{50}H_{90}O_6 + 24.5\ H_2O \rightarrow 34.75\ CH_4 + 15.25\ CO_2$	1.425	69.5

Table 4. Simulation Result of Product Composition

Component	POME		Carbohydrat		Protein		Lipid	
	mol/h	%	mol/h	%	mol/h	%	mol/h	%
CH_4	5188.04	59.80	3530.35	50.00	3889.15	50.65	8079.87	71.13
CO_2	3634.81	41.20	3529.98	50.00	3788.83	49.35	3279.87	28.87
	8822.85		7060.33		7677.98		11359.74	

RESULTS AND DISCUSSION

Biogas Production Result

From the literature, it is known that the biogas production potential is highly dependent on the feed components. For components of carbohydrates, proteins and lipids, each has the potential for production of different methane gas. This can be seen in Table 4. The gaseous composition of the methanogenesis step obtained from this simulation has a molar ratio between CH_4 and CO_2 as shown in Table 5.

By comparing simulation and literature data on potential biogas production, it can be seen that the process stages used in the simulations give the final result of biogas products with the composition of CH_4: CO_2 close to the literature data for the main components of carbohydrates and lipids. Especially for the potential of biogas production with the main components of protein there is a significant difference, because in the literature there are HCO_3^- products separated calculations from CO_2 products.

Assuming the conversion rate power plants of 35% and the plant works for 8000 hours/year, the calculation of the potential generating power capacity is as follows:

Plant capacity	=	240	thousand Ton (alm Fresh Fruit Bunch)
POME produced	=	120	thousand Ton
Biogas produced	=	3,360	thousand m^3
Potential energy	=	73,920	Giga J
Electricity generated	=	7,187	MWh
Generating Capacity	=	0.898 ~1	MW

Economic Analysis

In this study, the economic analysis is needed to see the feasibility of developing POME-based biogas power plant with absorption process of H_2S and CO_2 gas with water absorbent using the SuperPro simulation. The following results are obtained:

- Total Investment = 1.979.000 US$ (~2 Million $)
- Annual operating cost = 455.000 US$
- Annual cash inflows = 298.000 US$
- Electricity generated = 7.537.400 kWh/year

From the simulation SuperPro Designer software results obtained the cost of electricity production are:

Cost of electricity production per kWh

= 455.000 US$/year: 7.537.400 kWh/year

= 0,06 US$/kWh

While the economic analysis calculation was done with the assumption 15 years and the interest rate used by 12%, obtained the value of economic parameters as follows:

- NPV = 51,000 US$
- IRR = 12.5 %
- PBP = 6.6 year

From the results, these parameters can be stated that the construction of power plants from POME-based biogas is economically feasible. As a comparison Table 6 shows some investments for the different energy source.

Table 5. The comparison of various energy investment

Energy Source	Investment
Geothermal	US$ 360,000,000; IRR = 7.1 %; 120 MW; [20]
Natural Gas	US$ 43,100,000; IRR = 13,1 %; 35 MW; [21]
Biomass (Bioethanol)	US$ 303.000.000,00; IRR = 17,1 %; 7.8 MW; [22]
Coal	US$ 15.000.000,00; IRR =11,0%; 14 MW; [23]
Microhydro	US$ 2.250.000,00; IRR = 20,7%; 1.6 MW

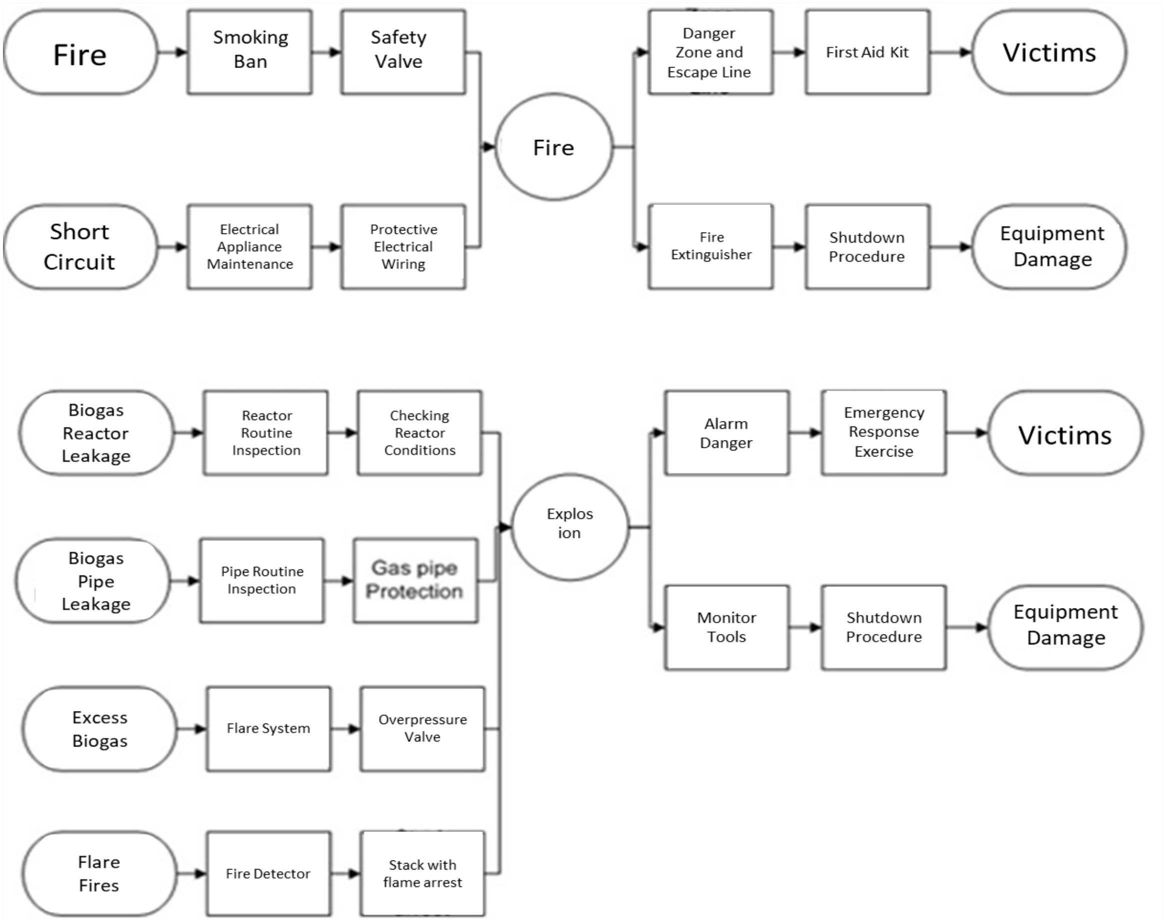

Figure 2. Bow-Tie diagram power plant from Biogas

Risk Analysis

Risk analysis was conducted to support the Techno economic review of biogas power plant from POME for biogas production plant operation. The Bow-Tie Analysis method was used to asses the risk analysis as can be seen in Figure 2.

Biogas plant processes a large number of flammable gases and toxic gases, which if exposed will cause a fire and explosion hazard in case of errors in design, material or control. Methane is highly flammable and causes explosions when mixed with oxygen in the air. Therefore blast protection is very important in biogas plants. For this reason biogas should be prevented from entering the work area. Certain security measures should be ensured during the construction and operation of biogas plants. The risk of explosion is very high close to digester and gas storage (overpressure protection device).

Areas at risk of explosion according to the probability of occurrence of explosive conditions are grouped in one zone. The source of the fire should be prevented and a small positive pressure prevents air penetration into the bioreactor. Minimum overpressure is a constant to avoid this incident. The pressure inside the biogas storage tank is measured and transmitted to the control center. The safety device used is intended to prevent an increase in pressure by an amount that can cause damage to the gas container membrane. Therefore the biogas plant is usually equipped with a hydraulic overpressure valve.

Furthermore, when there is an excess of biogas, which can not be stored or used, emergency flares are the main solution to eliminate the risk of overpressure of the gas reservoir. Safe and reliable operation of the flare requires a number of features, in addition to burner and protector. Important safety features include fire arrestor, failure safety valve and ignition system combined with fire detector.

Flares should be controlled by automated tools and when the gas reservoir pressure is less than the installed operational value, the feed biogas for the flares are automatically closed. Attention is often given for protection during maintenance. If necessary maintenance work is within the hazard zone, measurements should always be made at the beginning of this work. Particularly during welding, crude cutting and soldering, suitable fire extinguishers shall be available. These extinguishers should be immediately visible, easy to reach in case of fire and operation.

As a responsibility to ensure the safety of biogas plant facilities, the operator should assess the hazards that may be appropriate with the Regulations on Safety and implement appropriate safety. Safety equipment, building planning and technical systems (flame retention of gas reservoir membranes, etc.) shall be adjusted to certain conditions and inspected periodically. Operators should not only focus on hazard prevention, but should also consider scheduled maintenance measures (extinguishing maintenance schedules), which are often ignored.

In addition, for emergency response plans, routes for fire engines and evacuation must be accurately designed. To ensure an effective emergency response system, sensors (gas and fire detectors) must be positioned precisely, calibrated, connected and maintained. For larger factories repetitive emergency exercises are performed to show whether alarms can alert everyone in and around the facility at all times and prove the efficiency of evacuation procedures and rescue plans.

CONCLUSION

The proposed SuperPro design for the composition of the POME composition based on the literature gives the result of methanogenesis product with a mole ratio of CH_4: CO_2 composition of 60: 41. Economic results for the construction of a POST-based power plant provide NPV (12% interest) = US $ 51,000, IRR = 12.5% and PBP = 6.6 years. This shows the construction of a feasible factory but less attractive for investment in the field of economic energy. Bow-Tie analysis for the operation of biogas POME-based generating plants can be used as a benchmark for operational procedures and factory handling that takes into account hazard levels, thereby reducing losses arising from biogas explosions

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