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Systematic Design and Analysis of Biomass Refineries for Power Generation

Lida Simasatitkul[*,a], Amornchai Arpornwichanop[b]

[a]Department of Industrial Chemistry, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Thailand
[b]Computational Process Engineering Research Unit, Department of Chemical Engineering, Faculty of Engineering, Chulalongkorn University, Thailand
lida.s@sci.kmutnb.ac.th

The depleted conventional fossil fuels coupled with an increase in price and demand of fossil fuel is regarded as a major problem for an industrial sector. Searching for renewable resources to produce alternative fuels becomes important. Biomass is a promising alternative resource for biofuel production from existing, well-developed technologies, such as gasification, anaerobic digestion of biomass and reforming processes. This study focuses on the development of a systematic design approach for the biomass refinery process to generate power using SOFC systems. Multi-objective evaluation is considered to determine the optimal process in terms of economic, efficiency and environment. Anaerobic digestion integrated with SOFC gives the best process in terms of efficiency with annual worth minimization. Based on multiple criteria consideration, the anaerobic digestion integrated with SOFC is also a sustainable process that provides the highest value by using analytical hierarchy method.

1. Introduction

Due to the depletion of conventional energy as well as rising price of fuels, development of biofuels is an interest issue for replacing conventional energy. Biomass is a major resource for producing biofuels. Hydrogen, the fuel of the future, has been produced from a wide variety of resources, such as oil, coal, natural gas and chemical substances. However, hydrogen produced from biomass is a better alternative to conventional resources when considering global warming and exhaust gas emission. Steam reforming of crude ethanol obtained from biorefinery processes is, for example, an attractive process for hydrogen production. Such process involves the pretreatment processes of biomass, such as hydrolysis, fermentation of glucose and lignin removal, to produce ethanol (Ni et al., 2006).

Use of hydrogen to produce electricity using solid oxide fuel cells (SOFCs) has been received considerable attention (Aguilar et al., 2004). In general, a hydrogen production process and SOFC combined system is usually analyzed based on simple criteria, such as system efficiency, exergy analysis and life cycle assessment (Young and Cabezas, 1999). The methodology for determining the sustainable process based on the economic and environment consideration was developed by Soorathep and Masahiko (2004). Pilavachi et al. (2009) performed a multi-criteria decision making by using the analytic hierarchy process (AHP) to choose suitable hydrogen and natural gas-fueled power plant technologies. Tzeng et al. (1992) studied the effect of weighting indicators, such as technology, environment, economy and society, in the AHP method on design of alternative energy processes. Lee et al. (2011) showed that the hydrogen production from natural gas for fuel cells was the most energy efficiency. Although a multi-criteria decision making has been applied to evaluate and analyze alternative energy processes, few studies concern about the use of renewable resources (e.g., biomass) for alternative energy production.

The aim of this study is to develop a design methodology for determining a suitable hydrogen production process. Oil palm frond, a by-product from palm oil industries, is considered a biomass feedstock. All possible flowsheets of hydrogen production processes are generated and the process assessment is performed based on the multi-evaluation of efficiency, economic and environmental impacts.

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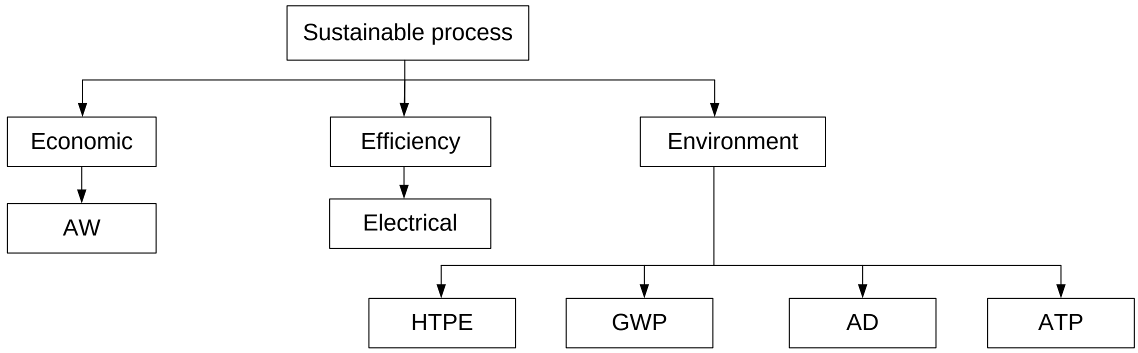

Figure 1: Multi-criteria evaluation to determine the sustainable biorefinery process integrated with SOFC.

2. Design methodology

The design methodology starts from the generation of all possible alternative hydrogen production flowsheets. These flowsheets are simulated using ASPEN PLUS process simulator. In this study, the hydrogen and SOFC process is designed for electrical power of 100 kW. The operating conditions of each process are specified using data from literatures. The sustainability of the process is determined using a multiple criteria analysis, as shown in Figure 1. The economic analysis is based on the annual worth (AW) consisting of capital cost and operating cost. Environmental criteria consists of human toxicity potential by inhalation exposure (HTPE), global warming potential (GWP), acidification potential (AD) and aquatic toxicity potential (ATP). The potential environmental impact (PEI/h) is used as an environmental indicator. Each criteria (i.e., economic, environment and efficiency) is weighted and then categorized in two groups (high value high desire and low value high desire). The weighting factor is normalized into scale 0 to 1. All profitability indicators are aggregated by ranking scale 1 to 9 in the matrix. In the final step, the sustainable process is determined by using analytic hierarchy process (AHP).

3. Superstructure

Figure 2 shows the superstructure of the conversion process of oil palm frond to electricity using a biorefinery process integrated with SOFC. The proximate and ultimate analysis of oil palm frond are reported in Guangul et al. (2012). All possible routes consist of four pathways. The first is gasification process of oil palm frond integrated with SOFC. Oil palm frond is decomposed and sent to gasifier to react with gasifying agent (e.g., steam and air). Equilibrium reactor (RGibb module) is used to represent the gasifier. Ash is separated from the synthesis gas product which is sent to water gas shift reactors (WGS1 and WGS2) to improve the quality of synthesis gas. The base conditions of this process are gasifying temperature of 750 °C, steam to carbon ratio of 1.5 and ER ratio of 0.5. The second flowsheet involves biomass to ethanol production and reforming process integrated with SOFC. Oil palm frond is sent to pretreatment unit, such as steam explosion and enzymatic hydrolysis. Steam explosion is operated at pressure of 2,000 kPa and temperature of 190 °C. Then, cellulose and hemicelluloses are hydrolyzed to glucose and xylose which is further converted to furfural. It is assumed that 90 % of cellulose is converted to glucose. Lignin and furfural are eliminated by separator. The fermentation reactor with 98 % conversion of oil palm frond to produce crude ethanol is assumed Eq(1) and Eq(2).

$$C_6H_{10}O_5 \rightarrow 2C_2H_5OH + 2CO_2 \quad (1)$$

$$C_5H_8O_4 \rightarrow 1.68C_2H_5OH + 2CO_2 \quad (2)$$

Unreacted sugar (xylose and glucose) is eliminated from crude ethanol by using distillation column. 98 % of crude ethanol is reformed with steam to produce hydrogen at operating temperature of 800 °C and steam to carbon ratio at 2. The third process is the anaerobic digestion of biomass integrated with SOFC. Anaerobic digester is operated at pressure of 101.3 kPa and temperature of 45 °C. Buswell equation is used to compute biogas yields obtained from anaerobic digestion Eq(3). The effect of parameters, such as temperature, pressure and amount of substrate is neglected in this study. The oil palm frond ($C_cH_hO_oN_nS_s$) is considered the substrate in the Buswell equation where the products are CO_2, CH_4, NH_3 and H_2S. Biogas product is fed into the steam reforming process to produce synthesis gas products.

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \quad (3)$$

The last flowsheet is based on biomass reforming process integrated with SOFC. Oil palm frond is first introduced to a high-pressured hydrolysis reactor Eq(4) where the product yield is fixed at pressure of 3,039 kPa and temperature of 150 °C. Then, the aqueous phase reforming of hydrolysis products (Eq(5)) is carried out at high pressure to produce synthesis gas products consisting of H_2, CO, CO_2, CH_4 and small trace of C_2H_6. The synthesis gas is sent to WGS reactors Eq(6) to remove CO prior to sending to SOFC. The composition of the synthesis gas at the end of each biomass conversion process is shown in Figure 3. It shows that methane is consumed completely for all processes. The remaining steam can be further used in WGS reactors.

$$C_{48.59}H_{7.33}O_{36.3} + H_2O \leftrightarrow C_6H_{12}O_6 \quad (4)$$

$$C_nH_{2y}O_n \leftrightarrow nCO + yH_2 \quad (5)$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \quad (6)$$

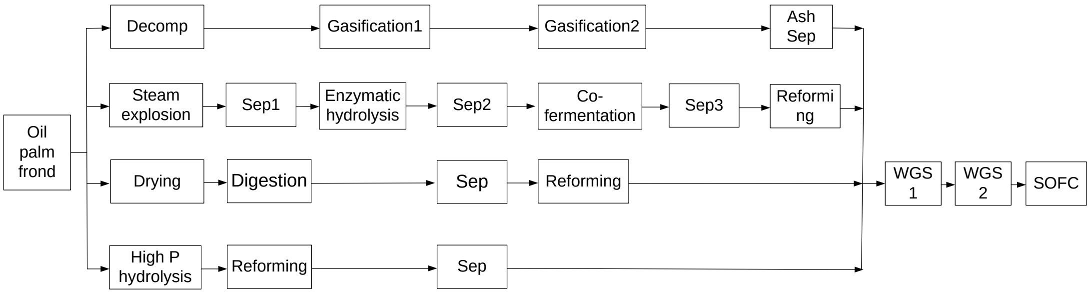

Figure 2: Superstructure of the conversion process of oil palm frond to electricity.

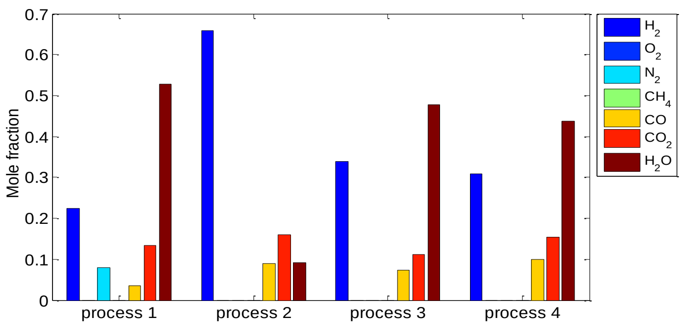

Figure 3: Compositions of the synthesis gas obtained from each biomass conversion process (Process 1 = gasification, Process 2 = fermentation and reforming, Process 3 = anaerobic digestion and reforming, and Process 4 = hydrolysis and reforming).

4. SOFC model

SOFC stack consists of anode, cathode and electrolyte. To simulate the SOFC in ASPEN PLUS, the equilibrium reactor (RGibbs module) is used as the anode where the overall electrochemical reaction occurs, whereas a separator unit represents the cathode where oxygen is separated from air and sent to the anode. A Fortran subroutine is developed to predict a complete electrochemical model of the SOFC stack. The amount of air flow rate sent to cathode and amount of O_2 consumption in the anode are specified using a Design Spec tool in ASPEN PLUS.

The effluent streams from the anode and cathode are sent to an afterburner. Therefore, excess H_2 and CO can be reacted with O_2 in the afterburner to produce high temperature exhaust gas Eq(7) and Eq(8)

$$H_2 + 0.5O_2 \rightarrow H_2O \quad (7)$$

$$CO + 0.5O_2 \rightarrow CO_2 \quad (8)$$

Table 1: Comparison of the model prediction and experimental data (Tao et al., 2005)

Current density (A/cm^2)	Cell voltage (model prediction) (V)	Cell voltage (experiment) (V)
0.1	0.84	0.86
0.2	0.77	0.76
0.3	0.7	0.68
0.4	0.65	0.62

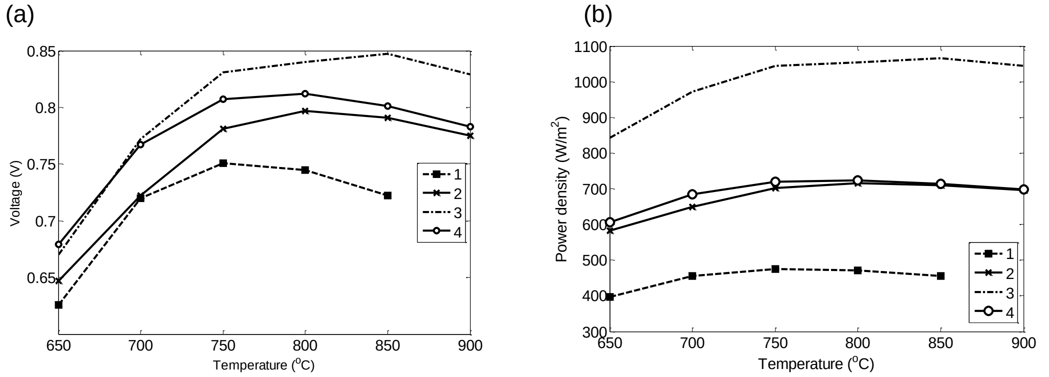

Figure 4: Effect of the cell operating temperature (°C) on (a) cell voltage (V) and (b) cell power density (W/m^2) (Process 1 = gasification, Process 2 = fermentation and reforming, Process 3 = anaerobic digestion and reforming, and Process 4 = hydrolysis and reforming).

The SOFC model developed in ASPEN PLUS is validated against experimental data (Tao et al., 2005). Inlet fuel to fuel cell is the synthesis gas consisting of 21 % of CH_4, 40 % of H_2, 20 % of CO, 18 % of CO_2 and 1 % of N_2. A comparison of the model prediction and experimental data is shown in Table 1. It is observed that the model can reasonably predict a cell voltage at different current density values.

5. Results and discussions

5.1 Effect of temperature SOFC

In this section, the suitable of temperature of SOFC is determined when the amount of oil palm frond is fixed at 80 kg/h and fuel utilization in the SOFC is 0.85. Figure 4(a) and (b) shows the effect of operating cell temperature on the performance of SOFC in the four proposed processes. The results show a similar trend even the composition of fuel entering the SOFC is changed. Low temperature operation of the SOFC causes low voltage and power density produced. The optimum temperature of SOFC varies with the applied biomass conversion process. The use of biomass anaerobic digestion integrated with SOFC gives the highest voltage and power density at temperature of 850 °C, compared with other biomass processing. This is because high composition of H_2 is obtained with low purity. This optimum temperature is used to evaluate the economic, environment and multiple criteria.

5.2 Single criteria: Economic evaluation

The biomass refinery plant is designed for 100 kW and its lifetime of 20 y is assumed (MARR is 15 %). Table 2 shows details in the economic evaluation of the proposed process, including capital cost, operating cost, number of cell and annual worth (AW). The electrical efficiencies of the biomass to electricity process with different biomass conversion paths are approximately 55 %, 33.92 %, 72 % and 42.92 %, respectively. The results show that the anaerobic digestion of biomass integrated with SOFC (process 3) is the most preferable process because it has the lowest annual worth. This is because the anaerobic digestion is operated at mild conditions. In addition, hydrogen content obtained from this process is high, leading to high power generation and efficiency of the SOFC. Therefore, a lower number of SOFC cells is required. The biomass hydrolysis process integrated with SOFC (process 4) is the worst case because of high capital cost as a large volume of reactors at the pretreatment (high pressure operation) and reforming sections is required. The amount of hydrogen from this process is lower than other biomass conversion processes. From the economic analysis, the most significant parameter affecting the process capital cost is the SOFC cost, approximately 50 % of fixed capital cost. To compare with other studies, a number of SOFC cells used here is still high for all the processes. Saebea et al. (2012) studied the ethanol reforming integrated with SOFC and used 1,000 SOFC cells in producing the power of 120 kW. Piroonlerkgul et al. (2009) investigated the performance of SOFC run on methane. They reported that for the power generation of 120 kW, 1,152 SOFC cells are needed. High number of SOFC cells is required in this study because the ratio of hydrogen to carbon of biomass is lower than ethanol and methane and thus, hydrogen is less produced.

5.3 Single criteria: Environmental impact

Table 3 shows the environmental impact of each biomass conversion process in term of I_{out} (PEI/h) including waste disposal and exhausted gas of output stream. Less environment impact indicates the best environmentally friendly process. The most significant index is global warming potential (GWP) that represents the content of CO_2 in exhaust gas when all weighting factor is equal to 0.25. Carbon Footprint (CF) calculation is also applied to determine the amount of emission of green house gas (GHGs) (kg CO_2/ 100 kW). The emission of GHGs is represented by CO_2 equivalent in 100 y of GWP_{100} per kg emission (IPCC, 2007). It is found that the biomass gasification integrated with SOFC emits the lowest waste disposal; however, the highest GHG emission factor (kg CO_2/kg biomass) in the output stream is obtained. This is because the gaseous product from gasification process contains high CO content that can be combusted with oxygen in afterburner. For the anaerobic digestion integrated with SOFC, CO_2 is generated in the digestion reactor. Similarly, CO_2 is obtained in the fermentation reactor at the first step of the fermentation of biomass to produce ethanol. The reforming of ethanol and hydrolysis products generates high hydrogen content. High reaction extent of hydrogen at the afterburner in the ethanol reforming integrated with SOFC gives low content of CO_2 and high content of water in the exhaust gas. From Table 3, the biomass fermentation integrated with SOFC has the lowest PEI. However, the results of GHG emission show that this process is not the best option. It is noted that GHG gases is produced from heat and electricity generation, especially in the pretreatment process.

5.4 Multiple criteria

Three dimension matrix including economic, efficiency and environmental impact are aggregated for multi-criteria evaluation. It is assumed that all the three impact factors are equally weighted. Table 4 shows that the AHP in term of the economic impact of the biomass anaerobic digestion integrated with SOFC is equal to 1 (the highest value). The AHP in term of the environmental impact of the biomass fermentation with SOFC is largest. Therefore, the optimal biomass conversion process should be selected based on multiple criteria. It is found that the anaerobic digestion of biomass integrated with SOFC shows the highest total AHP value and thus, the sustainable process to convert biomass to electricity.

Table 2: Economic evaluation of the propose four biomass conversion processes

	Process 1	Process 2	Process 3	Process 4
Biomass (kg/h)	62	80	55	75.3
Capital cost ($\times 10^6$)	1.02	1.32	0.98	1.46
Operating cost($\times 10^5$)	4.14	2.73	2.22	4.17
Electrical efficiency (%)	55	33.92	72	42.92
Number of cell	11,394	13,974	9,900	13,085
Annual worth (\$/y$\times 10^5$)	5.78	4.85	3.8	6.51

Note: Process 1 = gasification, Process 2 = fermentation and reforming, Process 3 = anaerobic digestion and reforming, and Process 4 = hydrolysis and reforming.

Table 3: Amount of waste and gas emission and environmental impact value

	Process 1	Process 2	Process 3	Process 4
Waste (kg/h)	0.66	18.64	20.64	25.64
CH_4 out (kg/h)	0	0	3.3×10^{-5}	0
CO out (kg/h)	0	0	0	0
CO_2 out (kg/h)	83.14	44.37	53.09	73.52
I_{out} (PEI/h)	166.79	110.47	130.23	176.89
GHG emission factor(kg CO_2/kg biomass)	1.34	0.55	0.97	0.98
GHG emission of process (kg CO_2/ kW h)	0.45	0.53	0.4	0.44

Table 4: AHP with single criteria and multiple criteria

	Process 1	Process 2	Process 3	Process 4
AHP of economic impact	0.27	0.61	1	0
AHP of environmental impact	0.15	1	0.7	0
AHP of efficiency	0.53	0	1	0.24
Total AHP	0.32	0.53	0.89	0.08

6. Conclusions

This work is aimed at the evaluation of a power generation from biomass refineries processes integrated with solid oxide fuel cell (SOFC). Four biomass conversion processes, such as gasification, fermentation, hydrolysis and anaerobic digestion, to produce hydrogen for (SOFC) are considered. Process design methodology using single criteria for economic and environmental analysis is proposed. The anaerobic digestion of biomass integrated with SOFC gives the lowest cost of power generation and the highest efficiency. The biomass fermentation to produce ethanol shows greater environmental impact value than other biomass conversion processes. To find the sustainable process, multi-criteria process design is considered taking into account process efficiency, economic and environmental impact. The results show that the anaerobic digestion of biomass integrated with SOFC is the most sustainable process that gives the highest AHP value.

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