Economic Analysis and Optimization for Bio-Hydrogen Production from Oil Palm Waste via Steam Gasification

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ABSTRACT:

Biomass steam gasification with in-situ carbon dioxide capture using CaO exhibits good prospects for the production of hydrogen rich gas. In Malaysia, due to abundance of palm waste, it is a good candidate to be used as a feedstock for hydrogen production. The present work focuses on the mathematical modeling of detailed economic analysis and cost minimization of the flowsheet design for hydrogen production from palm waste using MATLAB. The influence of the operating parameters on the economics is performed. It is predicted that hydrogen cost decreasing by increasing both temperature and steam/biomass ratio. Meanwhile, the hydrogen cost increases when increasing sorbent/biomass ratio. Cost minimization solves to give optimum cost of 1.9105 USD/kg with hydrogen purity, hydrogen yield, hydrogen efficiency and thermodynamic efficiency are 79.9 mol%, 17.97 g/hr, 81.47% and 79.85% respectively. The results indicate that this system has the potential to offer low production cost for hydrogen production from palm waste.

KEYWORDS: bio-hydrogen; palm waste; steam gasification; economic analysis; optimization

1. INTRODUCTION

Due to the energy crises and environmental problems associated with the fossil fuel usage, the utilization of hydrogen as a clean and sustainable energy is now attractive (Pudukudy et al. 2014). Biomass gasification is recently receiving increasing attention as renewable source for the hydrogen production (Udomsirichakorn and Salam 2014). The potential for hydrogen production from biomass in Malaysia is attractive due to the abundance of biomass (Mohammed, Salmiaton, Wan Azlina, Mohammad Amran,

Fakhru'l-Razi, et al. 2011). Malaysia is the largest exporter of palm oil with the production of palm waste is more than 80 million tones/year (Shuit et al. 2009).

The use of pure steam as gasification agent for hydrogen production is not only in favor of more hydrogen but also economical than other conventional gasifying agents and pyrolysis (Balat 2008). Furthermore, hydrogen purity can be increased in the product gas with in-situ CO_2 capture technique using CaO as sorbent (Florin and Harris 2008). In addition, CaO played dual role, as absorbent and catalyst by moving gasification reactions in forward direction (Guoxin and Hao 2009).

It is believed that hydrogen economy is as important factor and biomass can become an important source of hydrogen in future. Several studies have been reported on economic analysis for biomass gasification process. Iwasaki (2003) reported the hydrogen economic efficiency using woody biomass via pyrolysis. He reported the capital cost of the plant is 3950 USD/kW of H_2 and product supply cost is 0.108 USD/kWh of H_2. John et al. (2006) developed an economical model for heat and power application from advanced biomass gasifier in New Zealand by wood industry, and got conclusion that wood gasification for power and heat application on New Zealand is economically not feasible. Dowaki et al. (2007) presented economic analysis of biomass energy system for hydrogen production from Japanese ceder. They reported bio hydrogen production cost using experimental data would be 5.75-7.86 UDS/kg-H_2. Tinaut et al. (2008) describes the approach for techno economic analysis of hydrogen production by biomass gasification. The primary elements are resource analysis, process evolution, flow sheet development, sensitivity analysis, economic analysis and barriers to commercialization. Lv et al. (2008) studied economics for hydrogen production based on the air-steam gasification of biomass in China. The results shows hydrogen production cost is 1.69 USD/kg-H_2 based on the flowsheet includes downdraft gasifier, gas cleaning system, CO shift reactor and construction expenditure.

Hydrogen production cost highly depends on the operating conditions of the process especially temperature, steam/biomass ratio, pressure and sorbent/biomass ratio (Corella, Toledo, and Molina 2008). The literature review showed that there is several work has been done for economic analysis for hydrogen

production through biomass gasification, but these studies were carried out using the fixed values of operating conditions. So there is need to develop a flexible economic model which should be able to calculate hydrogen production cost at different operating conditions, size of reactors and simultaneously with the utilities demand. Furthermore, there is also need to calculate and investigate the hydrogen production cost via biomass steam gasification with CaO as sorbent for CO_2 capture.

The objective of the present work is to develop a mathematical economics model for hydrogen production from palm waste via steam gasification with CO_2 capture in a single pass fluidized bed gasifier. The economics feasibility of the process is investigated via parametric studies of temperature, steam/biomass and sorbent/biomass ratio on the hydrogen cost using MATLAB. Furthermore, optimization approach is next employed to determine minimum hydrogen production cost within bounds.

2. TECHNICAL APPROCH

2.1 PROCESS DESCRIPTION

The flowsheet development, modelling and simulation have been presented by authors in earlier work (Inayat et al. 2012; Inayat, Ahmad, Mutalib, et al. 2010). The pervious study focuses on the mathematical modeling of the simplified process design for hydrogen production from palm waste using MATLAB. The flowsheet includes steam generation, gasification and gas cleaning unit as shown in Figure 1.

The flowsheet model incorporated with the mass and energy balances. The developed model is used as a platform to investigate the effects of process parameters: temperature, steam/biomass ratio and sorbent/biomass ratio on the hydrogen production and efficiency using MATLAB (Inayat et al. 2012).

Figure 1. Flowsheet for hydrogen production from palm waste via gasification
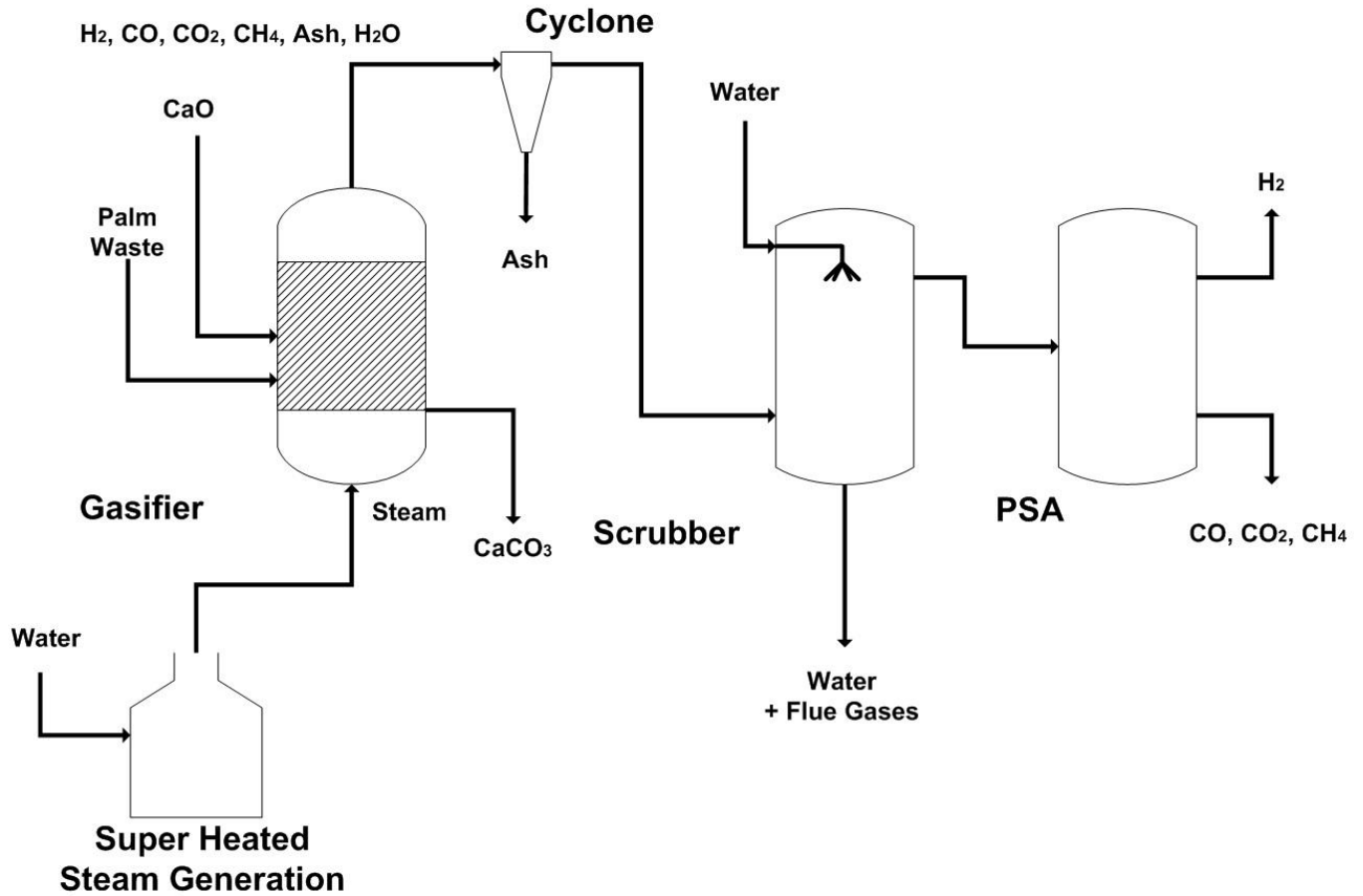
2.2 MODEL FORMULATION FOR ECONOMICS ANALYSIS

In analyzing the economics of the hydrogen production process, economic analysis work structure by National Renewable Energy Laboratory (NREL), USA guidelines has been followed which clearly defines the structure of conducting technical and economic evaluations for process and utilities industries (Parks et al. 2011). Process equipment designs and costing guidelines suggested by Peters et al. (2003) (Peters, Timmerhaus, and West 2003), Douglas (1988) (Douglas 1988), Smith (2005) (Smith 2005), and Biegler et.al. (1997) (Biegler, Grossmann, and Westerberg 1997) were adopted in this work. USA NREL report by Spath et al. (Spath et al. 2005) also being referred for methodology of hydrogen costing based on process flow diagrams of biomass gasification.

This section consists of each equipment design and assumptions taken into consideration to adopt simple yet practical design methodology. This sizing of this equipment will be an important point to determine the other economic factors such as Total Capital Investment (TCI) and Total Product Cost (TPC). The estimation of Total Capital Investment (TCI) and Total Product Cost (TPC) of the project are determined by using the methods suggested by Peters et al. (2003) (Peters, Timmerhaus, and West 2003). The equipment cost is estimated using the Guthrie's Cost Correlation (Douglas 1988).

The following set of major equations (1-6) used to calculate the cost of hydrogen from the flowsheet by programming in MATLAB.

$$Cost\ of\ hydrogen\ production = \frac{\sum Total\ cost}{\sum Total\ hydrogen\ produced} \tag{1}$$

$$Total\ \cos t\ (TC)\ =\ \sum Total\ caital\ investment\ (TCI)\ +\ \sum Total\ product\ \cos t\ (TPC) \tag{2}$$

$$Total\ capital\ investment\ (TCI)\ =\sum Fixed\ capital\ investment\ (FCI) \\ +\sum Working\ capital\ (WC) \tag{3}$$

$$Fixed\ capital\ investment\ (FCI)\ =\sum Directe\cos t(DC)\ +\sum Indirecte\cos t(IC) \tag{4}$$

$$Direct\ \cos t\ (DC)\ =\ Distribution\ factor\ \times\ \sum Purchased\ Equipment\ \cos t\ (PEC) \tag{5}$$

$$Total\ \Pr oduct\ \cos t\ (TPC)\ =\ \sum Total\ direct\ production\ \cos t\ (TDPC) \\ +\sum Total\ Manufacturing\ cost\ (TMC)+\sum Total\ genral\ \exp enses\ (TGE) \tag{6}$$

Optimization carried out with the minimization of hydrogen cost. The objective function for the minimization is used equality constraints, non-equality constraints and bounds conditions. MATLAB optimization toolbox was used for optimization of the flowsheet with minimum hydrogen production cost within bounds.

3. RESULTS AND DISCUSSION

3.1 EFFECT OF TEMPERATURE

Effect of temperature has been investigated on fixed capital investment (FCI), purchased equipment cost (PEC), total cost (TC), total capital investment (TCI), total direct production cost (TDPC) and total

production cost (TPC) as shown in Figure 2(a). It is observed that the total cost increases by increasing temperature because more energy required at high temperature. The total cost (TC) also increases due to increase of purchased equipment cost (PEC) because cost of furnace increases by increasing temperature, which is designed based on required energy for gasification process. Figure 2(b) shows the effect of temperature on hydrogen cost (USD/kg). It is observed that by increasing temperature the cost of hydrogen production decreases. Because the hydrogen yield increased by increasing temperature due to the endothermic behavior of steam reforming and char gasification reactions, as reported in the previous work and in literature (Inayat et al. 2012; Inayat, Ahmad, Yusup, et al. 2010; Ogi et al. 2013).

Figure 2. Effect of temperature (Steam/biomass ratio: 3.0; Sorbent/biomass ratio: 1.0); **(a)** fixed capital investment (FCI), purchased equipment cost (PEC), total cost (TC), total capital investment (TCI), total direct production cost (TDPC) and total production cost; **(b)** hydrogen cost


(a) (b)
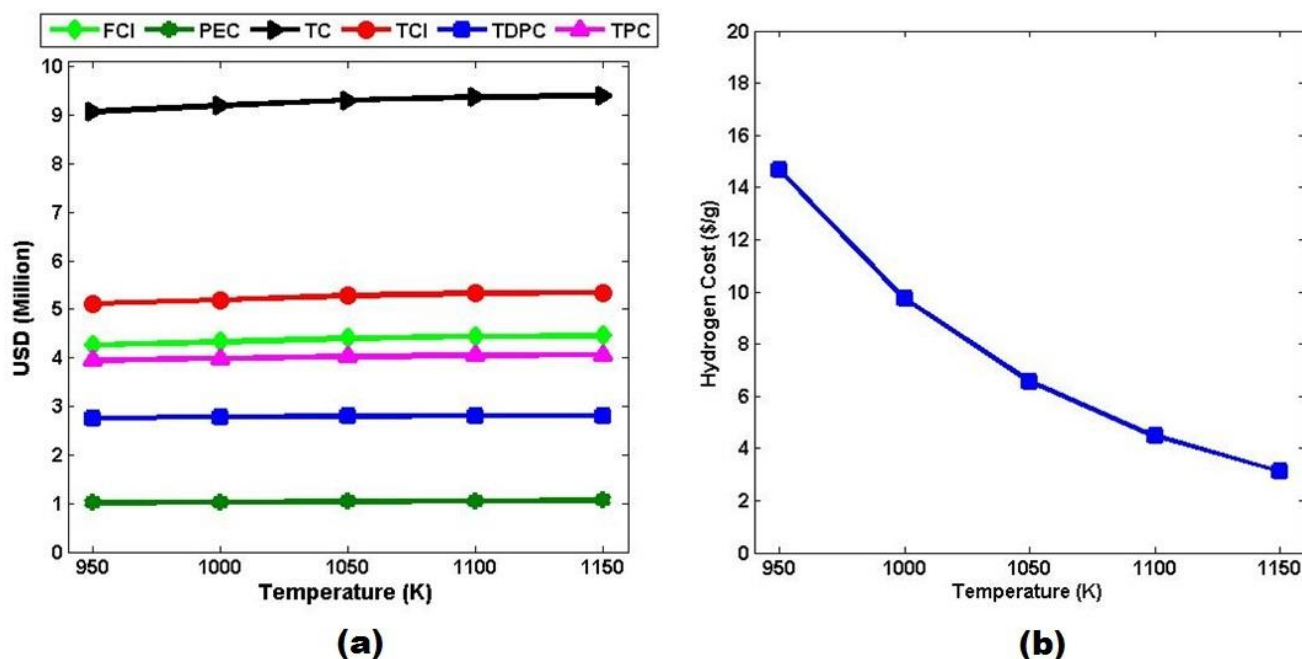
3.2 EFFECT OF STEAM/BIOMASS RATIO

Figure 3(a) shows the effect of steam/biomass ratio on the economic analysis. The figure shows that the total cost increases by increasing the steam/biomass ratio. The total cost (TC) increases from 7.90 to 9.79

million USD within the range of steam/biomass ratio of 1.5 to 3.5. The boiler has been designed based on the steam flow rate, so as steam feed rate increases the cost of steam boiler increases. Furthermore, the cost of gasifier and scrubber also increases due to high feed rate of steam. Moreover, for more steam generation more energy required which affect the total direct production cost (TDPC).

The effect of steam/biomass ratio on hydrogen cost is shown in Figure 3(b). It has been observed and discussed in previous studies (Inayat et al. 2012; Acharya, Dutta, and Basu 2010) that more steam is in favor of more hydrogen yield as it shifts the water gas shift and methane reforming reactions to forward side. Therefore, by increasing steam/biomass ratio the cost of hydrogen production decreased. It also shows that steam plays very important role in the hydrogen production economy.

Figure 3. Effect of steam/biomass ratio (Temperature: 1150 K; Sorbent/biomass ratio: 1.0); **(a)** fixed capital investment (FCI), purchased equipment cost (PEC), total cost (TC), total capital investment (TCI), total direct production cost (TDPC) and total production cost; **(b)** hydrogen cost


(a)   (b)
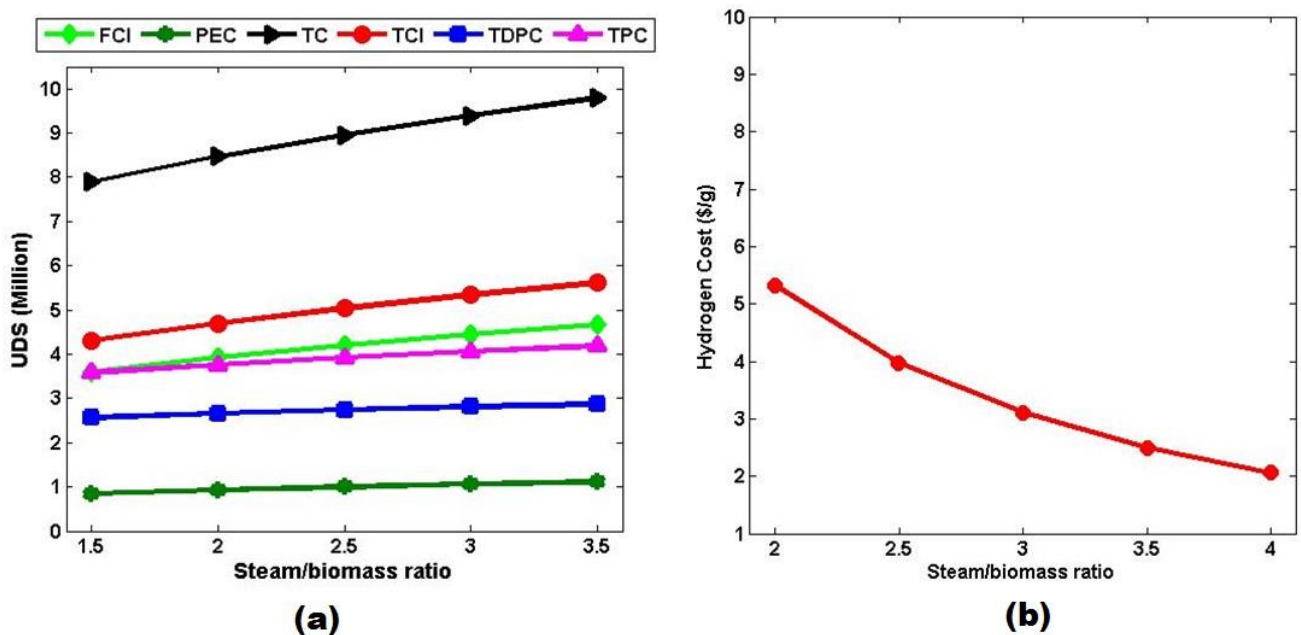
3.3 EFFECT OF SORBENT/BIOMASS RATIO

The effect of sorbent/biomass ratio on total cost analysis and hydrogen cost is shown in Figure 4(a) and Figure 4(b), respectively. The Figure 4(a) shows that the total cost (TC) increases by increasing the sorbent/biomass ratio. The purchased equipment cost (PEC), fixed capital investment (FCI) and total capital

investment (TCI) decreases by increasing sorbent to biomass ratio, because by increasing sorbent/biomass ratio, more CO_2 absorbs from the gasifier and the product flowrate decreased. Furthermore, flowrate through scrubber and PSA decreases and cost decreases as well. On the other hand, by increasing sorbent/biomass ratio the total direct product cost (TDPC) and total product cost (TPC) increases due to the increase of cost of more sorbent for the system. Figure 4(b) shows that the hydrogen cost is increases by increasing sorbent/biomass ratio.

Figure 4. Effect of sorbent/biomass ratio (Temperature: 1150 K; Steam/biomass ratio: 3.5); **(a)** fixed capital investment (FCI), purchased equipment cost (PEC), total cost (TC), total capital investment (TCI), total direct production cost (TDPC) and total production cost; **(b)** hydrogen cost.

(a)   (b)
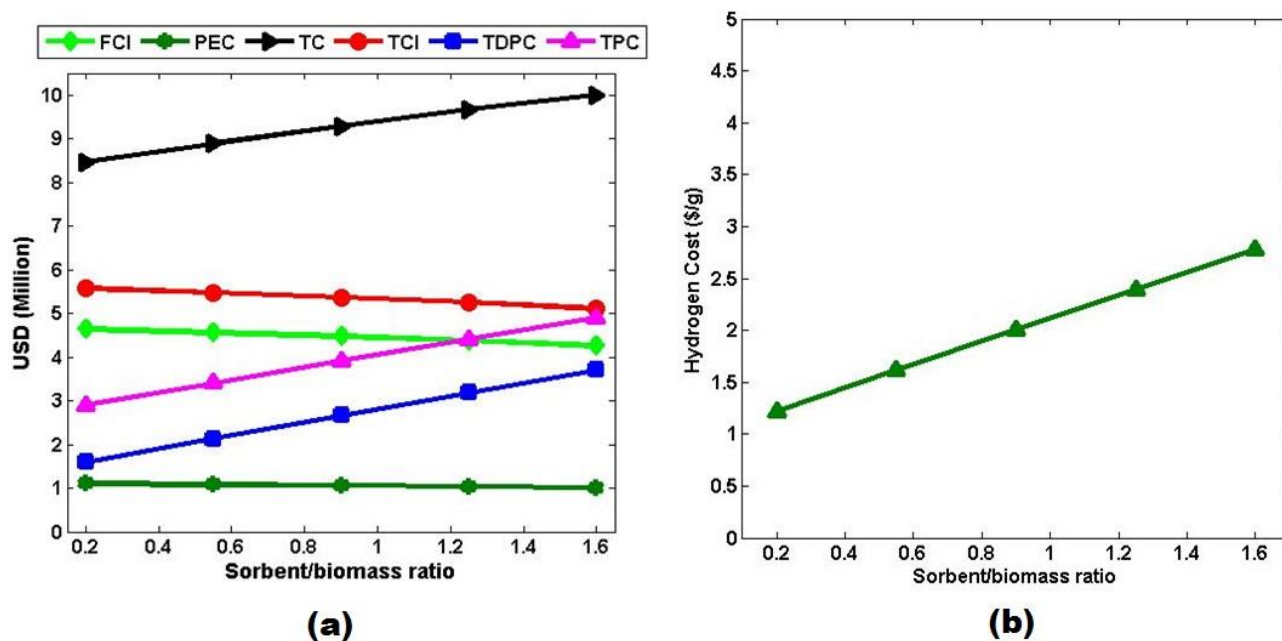
The increase in amount of sorbent in system promotes the increase of hydrogen purity in the product gas due more absorption of CO_2 from the product gas via carbonation reaction, but have minor effect on hydrogen yield as mentioned in previous work (Inayat, Ahmad, Yusup, et al. 2010; Han et al. 2011; Acharya, Dutta, and Basu 2010). The hydrogen cost is calculated with Equation (1), which based on total cost and total hydrogen yield. So the cost of hydrogen production increases by increasing sorbent/biomass ratio because the total cost is increases but very low hydrogen yield change.

3.4 COST MINIMIZATION

The constraints and bounds define for optimization is mentioned in Table 1. Furthermore, the Table 1 also showed the overall results obtained from optimization based on constraints and bounds.

Cost optimization presents the results at optimum conditions of hydrogen purity, hydrogen yield, hydrogen g/kg of EFB, hydrogen efficiency and thermodynamic efficiency are 79.9 mol%, 17.97 g/hr, 224.73 g/kg of EFB, 81.47 % and 79.85 % respectively at minimum cost of 1.9105 USD/kg of H_2.

Table 1. Optimization limitations and results

min hydrogen production cost subject to: Constraints and Bounds	
H_2 purity > 80%	Constraints
H_2 yield > 15 g/hr	
H_2 efficiency > 80%	
Thermodynamic efficiency > 80%	
850 < Temperature (K) < 1150	Bounds
2.0 < Steam/biomass ratio < 5.0	
0.2 < Sorbent/biomass ratio < 1.6	
Optimum conditions with minimum hydrogen production cost	
Minimum Cost (USD/kg of H_2)	1.9105
Temperature (K)	1150
Steam/biomass ratio	4.0030
Sorbent/biomass ratio	0.8771
Results at optimum conditions	
Hydrogen purity (mol %)	79.913
Hydrogen yield (g/hr)	17.97
Hydrogen efficiency (%)	81.47
Thermodynamic efficiency (%)	79.85

A comparison of hydrogen production cost between the current study and others on is shown in Table 2. The results indicate that this system has the potential to offer low production cost for hydrogen production from palm waste. The hydrogen production cost is higher than predicted by due to small scale system. Small scale hydrogen production plant from biomass that has been conducted by Lv et al. (Lv et al. 2008) is used in term of results of economic outcomes. Although the production capacity reported by Lv et al. (Lv et al. 2008) is for 266.7 kg/hr biomass, the estimation of hydrogen production cost of scaled-up Lv's plant has been used to compare with hydrogen production cost of steam gasification with in-situ CO_2 capture.

Table 2. Comparison of hydrogen cost

H_2 Cost (USD/kg)	Biomass Feed Rate (kg/hr)	Process	Reference
4.28	4166	Biomass (wood) pyrolysis and CO-shift with high pressure steam	Iwasaki (2003)
10	-	Electrolyzed hydrogen	Georgi (2002)
1.69	266.7	Biomass (rice husk) oxygen-steam gasification and CO shift at atmospheric pressure	Lv et al. (2008)
4.60	450	Biomass (japanese ceder) air-steam gasification with heat integration	Dowaki et al. (2007)
2.11	6	Biomass (palm waste) air gasification	Mohammed et al. (2011)
1.91	0.80	Biomass (palm waste) gasification with in-situ CO_2 capture	Current Study

4. CONCLUSION

A detailed economic analysis study on the hydrogen production cost has been performed. Influence of the temperature, steam/biomass and sorbent/biomass ratios on the hydrogen economy has been investigated. Hydrogen cost decreasing by increasing both temperature and steam/biomass ratio. On the other hand, by increasing sorbent/biomass ratio the hydrogen cost also increases. Cost minimization has been carried out using MATLAB optimization toolbox. Based on the results from optimization, the minimum cost found 1.9105 USD/kg of H_2 with optimum conditions (Temperature: 1150K, Steam/biomass ratio: 4.0030 and sorbent/biomass ratio: 0.8771) of hydrogen purity, hydrogen yield, hydrogen g/kg of EFB, hydrogen efficiency and thermodynamic efficiency are 79.9 mol%, 17.97 g/hr, 224.73 g/kg of EFB, 81.47 % and 79.85 % respectively. The results indicate that this system has the potential to offer low production cost for hydrogen production from palm waste.

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