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Sustainable Combined Production of Hydrogen and Energy from Biomass in Malaysia

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This work relates to a comparison between process solutions for the production of H_2 and the co-production of H_2 and energy by means of a zero emission biomass integrated gasification and a combined cycle (BIGCC) power plant. The energy production is 10 MWe, in agreement with the Small Renewable Energy Power Plant (SREP) Program, promoted by the Government of Malaysia. H_2 is obtained by supercritical water gasification (SCWG), a technology of interest for the processing of biomass with high moisture content. An economic analysis has been carried out in order to demonstrate the feasibility of the process solutions and to compare their convenience. The feedstock is 280,000 t/y of Empty Fruit Bunch (EFB), a biomass obtained in the Palm Oil Industry. The location of the site is Teluk Intak District in the State of Perak (Malaysia). The processes are designed with Aspen Plus® V7.2. The aim of this work is to develop detailed process flow diagrams for the supercritical water gasification technology in order to study and compare the convenience and the sustainability of different scenarios that can be adopted in an industrial context. The processes have been developed to reach zero emissions and zero wastes. CO_2 and solid residuals are recycled inside the palm oil lifecycle. A cost analysis has been performed to find out the convenience of the proposed solutions.

1. Introduction

Environmental issues and large usage of fossil fuels have led the Government of Malaysia to develop an energy plan which is aiming to reduce 40 % of its greenhouse gases emissions by 2020. To achieve this goal Malaysia has promoted the usage of renewable sources in power generation, launching the Small Renewable Energy Power Plant Program in May 2001. Power producers can use every kind of renewable sources in energy production with an income tax exemption of 70 % on the statutory income for five years (EC-ASEAN, 2002).

Since Malaysia has a significant amount of agricultural activities and is one of the leading manufacturers and exporters of palm oil worldwide, biomass is a very promising alternative source of renewable energy in Malaysia’s energy policy (Mohammed et al., 2011; Sumathi et al., 2008).

In 2008 the Malaysian land covered with palm oil plantations was 4.5 Mha (MPOB, APOC, 2010). It has been estimated by Kelly-Yong et al. (2007) that a hectare of palm oil can yield 21.625 t/y of biomass residues and Empty Fruit Bunches (EFB) are the 20.44 %. Biomass from palm oil industries also shows great reactivity due to its chemical composition. It can be used as a raw material for the production of a large variety of chemicals: biofuels, biodiesel, resins, bioethanol, fertilizers and H_2, although also ashes and wastes obtained during palm oil biomass processing can be reused as soil conditioners or fertilizers, due to their good content of micro and macro nutrients (Shuit et al., 2009).

H_2 is widely used in different industrial sectors already present in Malaysia: petroleum refining, petroleum chemistry and food processing.

The aim of this work is to develop detailed process flow diagrams for the SCWG technology in order to study and compare the convenience and the sustainability of different solutions that can be adopted in an industrial scenario for the production of H_2 and the co-production of H_2 and 10 MWe of energy, according

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to the Malaysia SREP project, on the basis of a real palm oil plantation (Maju Intan Biomass Energy Power Plant Project, 2009).

2. SCWG operating conditions

Before simulating the scenarios, a preliminary study on the effect of operating conditions (temperature, pressure and water to biomass ratio) for the SCWG reaction has been performed.
The problem has been carried out using the Gibbs free energy minimization method (Tang and Kitagawa, 2005; Castello and Fiori, 2011; Freitas and Guirardello, 2012) and the Peng-Robinson equation of state, since it shows a good agreement with the experimental data (Castello and Fiori, 2011).
The characterization of the EFB biomass has been taken from the work by Omar et al. (2011). The moisture content has been set to 60 % by weight (Maju Intan Biomass Energy Power Plant Project, 2009). The results are reported in Figure 1.

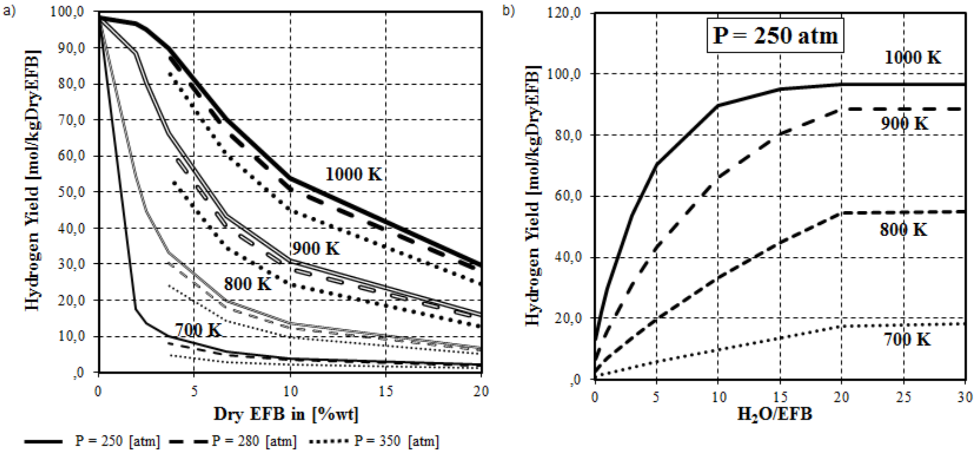

Figure 1. a) Effect of pressure, temperature and EFB biomass dry content in the reactor's feed on the H_2 yield. b) Effect of temperature and water/EFB ratio in the reactor's feed on the H_2 yield at 250 [atm].

The obtained results show that H_2 yield decreases with pressure and increases with temperature. At a given pressure and temperature, the H_2 yield of reaction decreases with the biomass dry content of the reactor's feed. The highest yields are realized at 1,000 K and a subsequent temperature increase does not affect H_2 yield anymore (Lu et al., 2007). 250 atm is the pressure level that guarantees the highest H_2 yield. A water/EFB ratio of 10 (3.6 – 4 % by weight of dry EFB content) has been selected for the SCWG reactor, since a higher value for this parameter does not lead to a significant change in the H_2 yield of reaction.

3. Process description and simulation

Two possible cases are studied: the H_2 production without energy sales and the H_2 production coupled with 10 MWe of energy sold to the Malaysia National Grid.
The proposed scenarios are four and they can be described using two process flow diagrams (PFDs) (Figure 2). In the first PFD a combined-cycle power plant coupled with the H_2 production plant is proposed, whereas in the second PFD a turbogas plant is used for the energy production.
35,000 kg/h of EFB (60 % by weight moisture content) are fed to a crusher and mixed with water to obtain a slurry. The slurry is then pumped above the water's critical pressure, heated and fed to the gasifier. Ashes obtained from the process are separated from the product gas. The obtained raw syngas is cooled to be purified. Heat recovery between the produced gas from the reactor and the inlet feed is required to improve the thermodynamic efficiency of the process. The efficiency of the heat recovery is 96.61 %. Since the SCWG reaction is endothermic, 4,076.71 kg/h of additional EFB are necessary to completely satisfy the reaction's heat requirements. The gas is then cooled to 38 °C and expanded to 37 bar (UOP, 2009) for the removal of acidic components (CO_2 and H_2S). Water and condensates are subsequently expanded to the atmosphere, mixed with other sour water streams and fed to the sour water stripper to recovery and recycle the water into the process. The syngas from the first flash drum is sent to the Selexol^{TM} unit, while the acid gas from the atmospheric flash drum is mixed with other sulfur-containing gas streams and sent to

the Claus unit for sulfur recovery. In the first column of the Selexol^{TM} plant H_2S removal occurs, while in a second absorption column CO_2 is captured. The Selexol^{TM} solvent is then regenerated. For the H_2S section a distillation column is used, while for the CO_2 section an air stripper is adopted (Sweney, 1973; Burr and Lyddon, 2008). The obtained H_2S is mixed with the streams that come from both the atmospheric flash drum and the sour water stripper to be fed to the Claus unit (Kohl and Nielsen, 1997).

The H_2 from the Selexol^{TM} unit is divided into two streams: the former is used as fuel, whereas the latter is upgraded in a PSA unit. Pure H_2 is ready for the market, while impurities are compressed again to 37 bar and mixed with the H_2 fuel stream.

The two configurations adopted differ in the energy production plant. In the first scheme (Figure 2b) a combined-cycle power plant is used: H_2 is diluted with CO_2 (Natarajan et al., 2007), burned and expanded in a gas turbine. Flue gases are sent to the DeNOx-SCR reactor (NOx and SOx removal) and the heat of the clean flue gases is used for steam production to drive a steam cycle with three pressure levels (150, 30, 5 bar) and as utility (1.5 bar steam) for the plant.

In the second scheme (Figure 2a) only a gas turbine is used for power generation and the heat of the flue gases is used only to produce low pressure steam (1.5 bar) as utility.

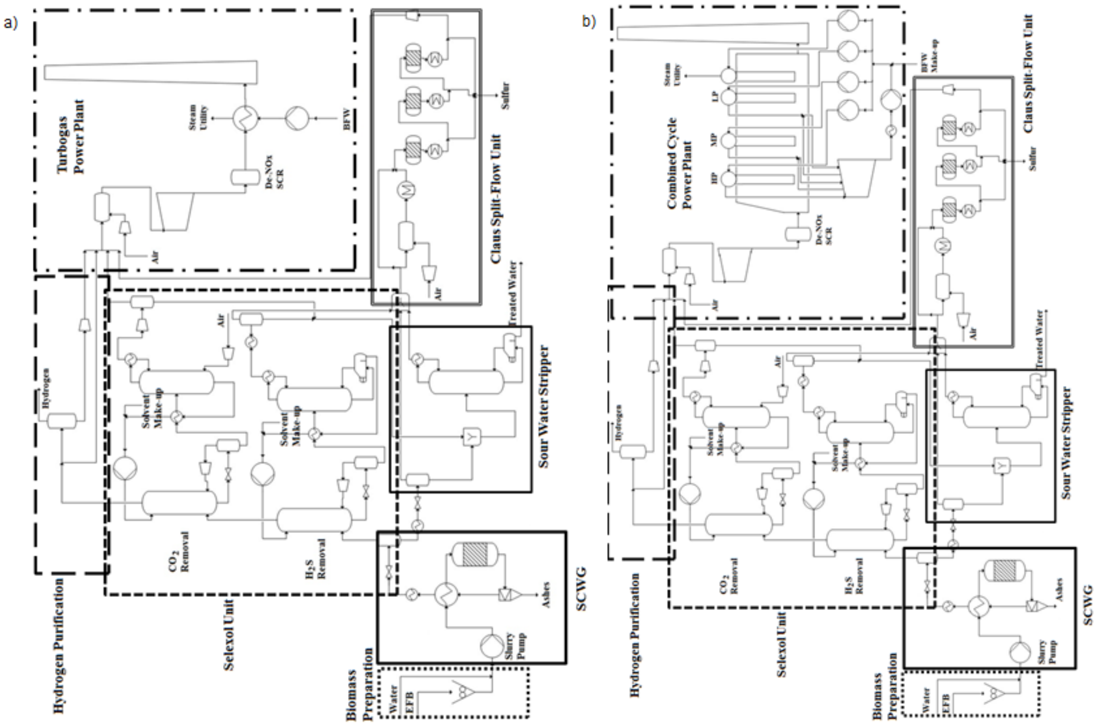

Figure 2. PFDs for the production of H_2 and the co-production of H_2 and energy, using a) a turbogas power plant and b) a combined-cycle power plant.

When only H_2 is produced, the fraction of H_2 burned is reduced to satisfy only the plant requirements (heat and power), while when the production of H_2 is coupled with the production of 10 MWe of energy, this ratio is increased to both satisfy the plant's energy requirements and produce the desired amount of electrical power. For the co-production of H_2 and 10 MWe of power with a combined-cycle power plant (scenario 1) the H_2 stream used as fuel is 41.8% of the total gas stream coming out from the Selexol^{TM} unit. For the production of only H_2 with the fulfillment of the plant's energy requirements with a combined-cycle power plant (scenario 2), the value of this parameter is 24.3 %. For the co-production of H_2 and 10 MWe of power using a gas turbine (scenario 3), the H_2 used as fuel is the 51 % of the total stream from Selexol^{TM} unit. At last, for the production of only H_2 and energy to satisfy the plant's requirements (scenario 4), the value of this parameter is 18.1 %.

Pumps isentropic efficiencies have been set to 75 %, compressors isentropic efficiencies are equal to 80 %. Gas turbine isentropic efficiency is 90 %, whereas for the steam cycle the efficiencies of the high pressure stage, medium pressure stage and low pressure stage are respectively 84 %, 89 % and 77 % (Aspen Plus$^{®}$, 2008). To better perform the simulations, also machineries drivers efficiencies and parasitic load consumptions have been taken into consideration. Compressor drivers, pump drivers and EFB mill have an efficiency of 92 % (Schiferl, 2003), while the alternator 95 % (Pellegrini et al., 2011). For parasitic loads the following assumptions have been considered: steam turbine auxiliary equipment consume the 0.1 % of the gross electric power produced by the steam turbine (Gülen, 2011), service water pump and De-NOx SCR circulating pump require the 0.1 % of the gross electrical power of the combined cycle (ABB, 2009), the plant instrumentation and transformer need the 0.5 % of the gross electrical power of the combined cycle (ABB, 2009; Gülen, 2011), the cooling tower fan uses the 0.2 % of the gross electric power of the combined cycle (ABB, 2009) and the gas turbine auxiliary equipment absorbs the 0.25 % of the gross electrical power from gas turbine (Gülen, 2011). The belt conveyor for biomass transport requires 1.5 kWe (Clénet, 2010). For scenario 1 and scenario 2 a 0.1% loss of the total BFW used in the steam cycle has been considered (Pellegrini et al., 2011). The plant operability is 8,000 h/y.

4. Economic and Sustainability Analysis Assumptions

To make a comparison between the four scenarios considered in this work, a cost analysis has been performed, taking into account both capital and operating costs.
Capital costs have been calculated according to Eq. (1):

$$C=\frac{M\&S2011}{M\&Syear}\,C_0\left(\frac{S}{S_0}\right)^n \tag{1}$$

where C is the actual cost of the plant's units, C_0 is the reference cost. S is the actual size of every process unit and S_0 is the reference size. n is the scale factor and $M\&S2011$, $M\&Syear$ are the Marshall and Swift indexes respectively at year 2011 and at the year at which the reference unit cost is given. The reference costs and sizes and the scale factor are taken from the work by Kreutz et al. (2005) and General Atomics (2005). General facilities, contingencies, land, site specific factor, engineering, permits and start-up costs have been calculated as percentages of total capital costs (Pellegrini et al., 2011).
Operating costs have been calculated assuming 0.001 \$/kg for BFW (Pellegrini et al., 2011), 4.32 \$/kg for the Selexol^{TM} solvent (Rubin et al., 2007), whereas EFB cost has been considered zero, since the plant is thought to be installed next to the palm oil plantations and mills.
For revenues, electricity selling price has been considered 0.062 \$/kWh (UNDP, 2007), H_2 value is 0.84 \$/kg (Kelly-Yong et al., 2007) and the price of sulfur is 0.285 \$/kg (Alibaba, 2013).
The economical comparison between the four studied scenarios has been carried out evaluating the pay-back time (assumed as the ratio between capital costs and the difference between revenues and operating costs).
The environmental sustainability of the proposed plant solutions has been investigated. Palm oil is established to be a very sustainable plantation and it is considered capable to have a high efficiency in CO_2 emissions mitigation (Sumathi et al., 2008; Shuit et al., 2009; UNDP, 2007). Palm Oil cultivations can absorb 44 t of dry matter per hectare per year and up to 64.5 t of CO_2 per hectare per year, while typical rainforests can only absorb 25.7 t of dry matter per hectare per year and 42.2 t of CO_2 per hectare per year (Sumathi et al., 2008; Shiut et al., 2009). It has been estimated by Kelly-Yong et al. (2007) that a hectare of palm oil can yield 21.625 t/y of biomass residues and Empty Fruit Bunches (EFB) are 20.44 % of the total biomass produced from palm oil wastes. The environmental sustainability of the four case studies has been discussed in terms of land requirements for the CO_2 and ashes reabsorption by the palm oil cultivations in the area where the four scenarios are located.

5. Results and Discussion

The results of the four process simulations are summarized in Table 1. The plant overall efficiency is calculated according to Eq. (2):

$$\eta=\frac{\dot{W}_{el,NET}+\dot{W}_{H_2,PROD}}{\dot{W}_{IN,EFB}} \tag{2}$$

as the ratio between the total power output (electrical and contained in the produced H_2) and the EFB biomass input power.

For the evaluation of the revenues, the excess heat produced has not been taken into account, since the aim of these scenarios is to produce only H_2 and/or, electrical power.

Table 1: Results obtained in this work

	SCENARIO1	SCENARIO2	SCENARIO3	SCENARIO4
H_2 Production [t/y]	11671.29	15180.71	9826.35	16424.04
Electric Power Requirement [MWe]	16.86	17.40	22.76	14.38
Gross Power Production [MWe]	26.84	17.40	32.83	14.38
Net Power Production [MWe]	10.08	0.0	10.07	0.0
Thermal Requirement [MW]	44.97	45.0	45.0	45.0
Thermal Production [MW]	44.97	45.0	120.0	45.0
Net Thermal Production [MW]	0.0	0.0	75.0	0.0
Plant Overall Efficiency [%]	41.4	44.7	36.0	48.25
Investment Costs [M$]	65.8665	60.0199	58.1042	47.4123
Income [M$/y]	13.484	11.451	11.915	12.495
Payout Time [y]	4.88	5.24	4.88	3.79
CO_2 Produced [t/y]	189,313.74	190,543.28	190,318.54	189,313.74
Ashes Produced [t/y]	9,428.49	9,428.49	9,428.49	9,428.49
Land Covered by The Palm Oil Plantation [ha]	70,724.67	70,724.67	70,724.67	70,724.67
Land Required for CO_2 Absorption [ha]	2,935.10	2,954.16	2,950.67	2,935.10
Land Required for Ashes Absorption [ha]	214.28	214.28	214.28	214.28

The plant overall efficiency is usually higher when only H_2 is produced and scenario 4 allows to reach the highest value. In scenario 3 a surplus of heat is produced, since the heat of the flue gas from the turbine is not completely recovered and losses are significant, while in scenario 4 the amount of fuel burned for energy production is lower and the excess heat of the flue gas is recovered completely as steam, balancing the plant's thermal requirements. Scenario 1 has the highest investment costs. In scenario 4 the cost for the CO_2 compressor is different, since the amount of CO_2 used for dilution inside the turbine is lower due to the lowest consumption of H_2 as fuel.

The comparison shows that for the production of H_2 scenario 4 is the most suitable solution. For the co-production of H_2 and 10 MWe of energy scenario 1 and scenario 3 have the same payout time. However scenario 1 is the best solution, since in scenario 3 the energy efficiency is lower, a huge amount of heat is not recovered (75 MW) and the produced H_2 is lower.

Results obtained from the sustainability analysis show that the land required for the absorption of ashes and CO_2 is quite the same for the four scenarios and is less than the area covered with oil palms. In this way all the wastes produced during the biomass processing are completely recycled into the EFB life cycle and the four cases are sustainable.

6. Conclusions

A comparison between process solutions for the production of H_2 and the co-production of H_2 and 10 MWe energy (in agreement with the Malaysia Small Renewable Energy Power Plant Program) has been made. An economic analysis has been carried out in order to demonstrate the feasibility of the process solutions and to compare their convenience. The obtained results show that, when only H_2 is produced, the most suitable solution is the coupling of the SCWG plant with a gas turbine for the production of plant utilities, whereas for the combined production of H_2 and power an integration of the SCWG plant with a combined-cycle power plant is more convenient. Detailed process flow diagrams for the SCWG technology have been developed and the process simulations have been performed with Aspen Plus®. The designed processes can be considered at zero emissions and zero wastes. CO_2 and solid residuals are recycled inside palm oil lifecycle. The study demonstrates the great potential of palm oil biomass as a renewable energy source.

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