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Techno-economic Assessment of Integrated Power Plant with Methanation

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Greenhouse gaseous (GHG) emissions increment is driven by economic and population growth which are getting higher. This has led to the increase of atmospheric concentration of CO_2. Due to this situation, carbon capture utilisation and storage (CCUS) seems to be promising approach to reduce emission of CO_2. Among all the carbon utilisation strategies available, methanation is promising. In the perspective of integrated power plant with methanation, the process is appropriate and relatively simpler due to availability of hydrogen as its main constituent. Prior to the goal of abatement of greenhouse gases emission, hydrogen production by using renewable energy technology which is electrolysis seems to be one of the solution towards future energy security. This study performed a techno economic assessment of integrated power plant with methanation with a case study in Iskandar Malaysia. From the economic assessment results, highest profit is generated when PEM is used in electrolysis process and CIS is used as solar panel due to its high efficiency and low capital expenditure (CAPEX). This cost competitiveness can be enhanced selling O_2 by product produced from electrolysis process and recycling the catalyst for methanation process. Further studies can be extended by including variation of parameter for a better optimisation superstructure.

1. Introduction

The increment of greenhouse gaseous emission driven by economic and population growth remain one of the main concerns worldwide. As of 2010, among all the GHG constituents, carbon dioxide contributes to the highest percentage of content which is 76 % (IPCC, 2014). EPA (2016) reported that CO_2 emission in United State is mainly caused by electricity generation activities followed by transportation, industrial and residential while Safaai et al. (2010) discussed in his studies that CO_2 emission in Malaysia mainly originated from electricity and heat production. The same trend shows the importance of this study on reducing the emission of CO_2 emitted to the atmosphere. Research and development together with application has been devoted on reducing CO_2 emission. Carbon capture and storage (CCS) technologies is the pioneer efforts towards CO_2 abatement. Recently, CO_2 conversion and utilisation is more preferable and promising solution which overlapping the CCS technologies. This is because of the attractiveness of CO_2 in term of its functionality, availability, inexpensiveness, renewable source origin potential, and environmentally friendly as chemical reagent. There are many products of CO_2 conversion depending of the type of industrial process for instance, methanol and dimethyl ether (DME) which are excellent fuels in internal combustion engines. Hydrogenation of CO_2 to methane (CO_2 methanation) presents several advantages over other chemicals because it can be injected directly into existing natural gas pipelines and it can be used as a fuel or raw material for the production of chemicals. In addition, methane formation from CO_2 is a simpler reaction able to generate methane under atmospheric pressure. The formation of CH_4 from CO_2 at (low) room temperature has become an important breakthrough in the knowledge of the role and in the use of CO_2 (Aziz et al., 2015). As a solution and strategy to tackle the issues CO_2 reduction, this work aimed to study the feasibility of utilising CO_2 released from the power plant in Malaysia and converting it into methane by using renewable energy as source of hydrogen (H_2).

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2. Integrated power plant with methanation

According to the energy outlook projected by Energy Commision (2016), the growth rate of Renewable Energy (RE) by 2020 will be more than 11 % to reach capacity of at least 2,080 MW. The implementation of RE unfortunately is not expected to replace the fuel mix, but only complementing the role of fossil fuel especially in Malaysia due to the limitations of implementing renewable energy system. The concept of integrated power plant with methanation has potential to tackle the issues by capturing CO_2 emitted from power plant and converting it into methane as source of energy. Apart from the application of CCUS concept, the integration plays a role as energy storage if excess energy is utilised when electricity is generated in peak hours. According to Aresta and Curulla-ferre (2014) for a better utilisation of energy, electricity produced should not be originating from fossil fuel based for the reduction of CO_2. At the same time, the source of H_2 for methanation should not come from fossil fuel resources (Schaaf et al., 2014).

Around 10 t of CO_2 are generated to produce 1 t of H_2 if fossil fuel resource is used in the H_2 production process. Prospectively, renewable H_2 is able to decarbonise various range of industrial process and act as energy vector simultaneously (Saric et al., 2014). The integrated process may involve various technologies for carbon capture, methanation, and technologies to generate hydrogen as source of methanation. Producing renewable H_2 by electrolysis has a potential to provide effective solution for hydrogen production.

In this work, techno economic review of methanation with H_2 production by electrolysis and solar power as source of electricity for electrolysis is performed. A matrix of different technology is evaluated and the cost for each pathway is being compared. For future possible extension of the study, economic analysis is performed with a specific case study.

Case study designed for this work is focusing on the current available power plant in Malaysia for future possible implementation of the integrated system. For this case study, calculation is made based on the carbon emitted at the power plant that is available in Malaysia which is Tanjung Bin Power Plant. The detail of Tanjung Bin Power plant is as showed in Table 1. Tanjung Bin Power Plant is the first private coal fired power plant in Malaysia with net capacity of 2,100 MW. The coal for this plant is imported from Australia, Indonesia, Russia and South Africa which came in various types of bituminous and sub-bituminous coal. According to annual report provided by Malakoff Corporation Berhad, in 2015 the average capacity factor of the power plant is about 76.9 % which able to supply about 14,157 GWh of electricity to national grid (Malakoff Corporation, 2015).

Table 1: Tanjung Bin Power Plant Technical Data

Type of data	Data
Type of Plant	Conventional Coal Fired Power Thermal Power Plant
Main Fuel	Pulverised coal (Bituminuous)
Nett Capacity	3 x 700 MW
Average Capacity Factor	76.9 %
Grid Supply Voltage	500 kV
Cooling water supply	Sea Water

Total amount of CO_2 emitted annually is calculated by multiplying fuel consumption at Tanjung Bin Power Plant and emission factor for coal. Environmental Protection Agency provided emission factor for every greenhouse gases inventory (EPA, 2014). Given that the emission factor for coal is 2.5633 t CO_2/t fuel and the coal consumption is 5.9 MTPA. The calculated amount of CO_2 emitted for Tanjung Bin Power Plant is 15 million t/y. The parameters used to calculate CO_2 emitted is summarised in Table 2.

Table 2: Parameters for Carbon Dioxide Emitted

Parameter	Value	Unit	Sources
Coal Consumption (2015)	5.9	MTPA	(Energy Commision, 2016)
Fuel emission factor	2.563	t CO_2/t fuel	(Idris et al., 2017)
Carbon dioxide emitted	15.12 Million	t/y	Calculated

2.1 Technology review

This section reviews on the methanation process together with the parameter required for mass balance calculation prior to the economic analysis performed in the next section.

2.1.1 Methanation process

As comparison of various type of catalyst upon methanation reaction, 4 types of catalyst with different types of metal support are selected. The catalysts are Ru–TiO_2, Ni/Al_2O_3, Ni/CeO_2 and Ru-Mn-Ni/Al_2O_3. Table 3 listed the catalyst chosen with its conversion percentages. The most ordinarily used catalyst for CO_2 methanation is Nickel based catalyst due to its high activity, high CH_4 activity, and low in price. Ruthenium (Ru) is found to be more active and stable at operating temperature of methanation reaction compared to nickel. Combination of Ru–TiO_2 was studied to be most active combination (Garcia-Garcia et al., 2016) but found to be more expensive reducing the preference for this catalyst especially for large scale application (Wang and Gong, 2011).

Table 3: Catalyst for CO_2 methanation

Catalyst	Conversion (%)	Source
Ru–TiO_2	85.5	(Sahebdelfar and Takht Ravanchi, 2015)
Ni/Al_2O_3	98.9	(Sahebdelfar and Takht Ravanchi, 2015)
Ni/CeO_2	93.0	(Aziz et al., 2015)
Ru-Mn-Ni/Al_2O_3	99.7	(Younas et al., 2016)

The methanation reaction occurs as following chemical reaction mentioned in Eq(1), known as Sabatier Reaction.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (1)$$

By performing mass balance calculation, the amount of hydrogen gas required to convert the CO_2 into methane can be determined as presented in Table 4.

Table 4: Parameter for methanation process

Catalyst	Production of CO_2 (kg/h)	Efficiency (%)	Required H_2 (kg/h)	Produced CH_4 (kg/h)	Produced water (kg/h)
Ru–TiO_2	1,717,033	85.5	365,132	624,376	1,404,845
Ni/Al_2O_3	1,717,033	98.9	315,660	631,320	1,420,470
Ni/CeO_2	1,717,033	93.0	335,686	671,372	1,510,586
Ru-Mn-Ni/Al_2O_3	1,717,033	99.7	313,127	626,254	1,409,072

2.1.2 Electrolysis process

Electrolysis process uses water and electricity to split the water into H_2 and oxygen (O_2). The efficiency of water splitting is found to be ranging from 63 % up to 93 % depending on the efficiency of the technology being used (Heinisch, 2014). Recently researchers agreed that, the current interest on choosing electrolysis as hydrogen production method is mainly due to its capability as energy storage and carrier (Lehner et al., 2014). The technology of electrolysis for hydrogen production is progressing and has reached maturity level. Hence, there are many technological option commercially available and technologies that are still in the pre-commercial state to be chosen from (Heinisch, 2014).

In this study, alkaline electrolysis, proton exchange membrane (PEM) and Solid Oxide electrolysis (SOE) or known as high temperature electrolysis are chosen for production of H_2. Table 5 showed parameters and result of mass balance calculation performed to determine the amount of electricity required for electrolysis to occur.

The electrolysis process runs according to the following equation shown in Eq (2) using hydrogen low heating value (LHV) as basis

$$H_2O \rightarrow H_2 + ½\, O_2 \quad (2)$$

The electrolysis process requires 187,876 kg/h to 219,079 kg/h of water. The electricity required for this process ranges from 848,300 kW to 1,169,280 kW.

Solar energy has promising potential compared to other power sources. Directing sun to solar panel can generate energy in term of electricity or heat. Solar photovoltaic (PV) system is used to directly produced electricity from sun.

The amount of electrical power that the system able to deliver after sun is directed overhead on a sunny day are rated in peak kilowatts (kWp) (Parida et al., 2011). The theoretical solar power able to be generated by PV globally is about 1,700 TW (Iskandar Malaysia, 2013) while total solar radiation in Malaysia is about 4,000 – 5,000 Wh/m^2 daily (Ali, 2012). The current state and progress of solar PV is critically reviewed by Mekhilef et al. (2012). From his studies, Malaysia is found to has high solar energy potential with daily solar radiation of 4,000 – 5,000 Wh/m^2

Table 5: Parameters for electrolysis process

Process	Alkaline	PEM	SOE	Unit	Remarks/Sources
Required H_2 flowrate (Lowest)	20,875	20,875	20,875	kg/h	Calculated
Required H_2 flowrate (Highest)	24,342	24,342	24,342	kg/h	Calculated
Chemical Conversion	100	100	100	%	Assumption
Water required (Lowest)	187,876	187,876	187,876	kg/h	Calculated
Water required (Highest)	219,079	219,079	219,079		Calculated
O_2 by product produced (Lowest)	167,001	167,001	167,001	kg/h	Calculated
O_2 by product produced (Highest)	194,737	194,737	194,737		Calculated
Electricity efficiency	82	82	86	%	(Zhang et al., 2016)
Required electricity - Lowest	848,300	848,300	848,300	kW	Calculated
Required electricity - Highest	1,169,280	1,169,280	1,169,280	kW	Calculated
Energy lost as heat - Lowest	152,694	152,694	152,694	kW	Calculated
Energy lost as heat - Highest	210,470	210,470	210,470	kW	Calculated

In 1980's, PV solar penetrates the market of RE in Malaysia and up to current date, there are four different types of PV solar panel available in market. All of these panels are distributed by three major companies which are First Solar, Q-Cells and Sun Power. Mono- crystalline Silicon, Poly-crystalline Silicon, Copper-Indium-Diselenide (CIS) and thin film Silicon (using Amorphous Silicon) are the four available solar panels with different properties and efficiencies. The comparison between efficiencies and performance ratio of the four panels are listed in Table 6.

Table 6: Efficiency and performance ratio of PV solar panels (Parida et al., 2011)

	Mono-crystalline Si	Poly-crystalline Si	Amorphous silicon	CIS
Average output efficiency (%)	30.1	30.34	33.74	35.31
Average module efficiency (%)	6.87	5.14	2.23	3.99
Performance ratio	0.933	0.941	1.046	1.094

The electricity and area required is then being calculated and showed in Table 7. The total area of solar panel required to supply the electricity is estimated to be between 4.15 km^2 to 8.99 km^2. This area of solar panel is required to ensure that all CO_2 emitted can be converted to methane. According to research done by Tan et al. (2014) the total available area for solar energy system in Iskandar Malaysia, Johor, Malaysia is 315.8 km^2 which is double the calculated area, indicating that there is sufficient area to invest on solar.

Table 7: Parameters for solar technologies comparison

Parameter	Mono-crystalline Si	Poly-crystalline Si	Amorphous Silicon	CIS	Unit	References
Solar panel power per unit area	1,000	1,000	1,000	1,000	W/m^2	(Ito et al., 2008)
Solar panel efficiency	20.4	14	13	19.8	%	(Parida et al., 2011)
Electricity required-smallest	848,300	848,300	848,300	848,300	kW	Calculated
Electricity required-largest	1,169,279	1,169,280	1,169,279	1,169,280	kW	Calculated
Area required - Smallest	4,158,335	6,059,288	6,525,387	4,284,345	m^2	Calculated
Area required - Largest	5,731,763	8,351,999	8,994,460	5,905,454	m^2	Calculated

3. Economic analysis for power plant with methanation

The economic viability study of integrated system is conducted in term of profit by using the technological review data in previous section and the data listed in Table 8. Table 9 shows the result of economic assessment, given that the total revenue of methane is 729,270,729 USD/y with methane selling price of 400 USD/Mt. The economic assessment is done by comparing 12 different pathways. The differences between each pathway are the type of technologies used for electrolysis and solar plant. From the results, the pathways that utilised Mono-crystalline Si and Poly-crystalline Si as solar panel yield negative profit due to high capital cost. Highest profit is generated when PEM is used in electrolysis process and CIS is used as solar panel basically due to the high efficiency and low CAPEX of the technology. The profit for whole integrated system can be increased by selling the O_2 byproduct due to high production of O_2 in the electrolysis process. Apart from that, the economics of the system can be further improvised by inclusion of catalyst recycling for methanation. The economic assessment for this study does not include the variation efficiency of catalyst hence parameter variation of the optimisation is recommended in future investigation for the potential of the system to be implemented.

Table 8: Economic parameters

Process	Capital Cost (USD/MW)	References	Operation Cost (USD/MW.y)	References
Electrolysis - Alkaline (E1)	4.366×10^5	(FCH JU, 2015)	8.732×10^3	(FCH JU, 2015)
Electrolysis - PEM (E2)	2.950×10^5	(FCH JU, 2015)	5.900×10^3	(FCH JU, 2015)
Electrolysis - SOE (E3)	7.375×10^5	(FCH JU, 2015)	1.475×10^3	(FCH JU, 2015)
Solar - Mono-crystalline Si (S1)	4.670×10^6	(IRENA, 2012)	2.802×10^5	(NREL, 2011)
Solar - Poly-crystalline Si (S2)	4.670×10^6	(IRENA, 2012)	2.802×10^5	(NREL, 2011)
Solar - Amorphous Silicon (S3)	2.670×10^6	(IRENA, 2012)	1.602×10^5	(NREL, 2011)
Solar - CIS (S4)	3.000×10^6	(IRENA, 2012)	1.800×10^5	(NREL, 2011)
Capture Technologies	6.707×10^5	(Lee et al., 2008)	6.706×10^3	(Lee et al., 2008)
Methanation	4.140×10^5	(Lehner, et al., 2014)	4.140×10^3	(Chiuta et al., 2016)

Table 9: Economic Assessment Results

Network	Total capital cost (USD)	Total operating cost (USD/y)	Profit (USD/y)
E1-S1	2.392×10^{10}	1.371×10^9	-3.495×10^8
E1-S2	2.392×10^{10}	1.371×10^9	-3.495×10^8
E1-S3	1.543×10^{10}	8.623×10^8	1.595×10^8
E1-S4	1.683×10^{10}	9.463×10^8	7.550×10^7
E2-S1	2.343×10^{10}	1.361×10^9	-3.397×10^8
E2-S2	2.343×10^{10}	1.361×10^9	-3.397×10^8
E2-S3	1.494×10^{10}	8.526×10^8	1.692×10^8
E2-S4	1.634×10^{10}	9.366×10^8	8.525×10^8
E3-S1	2.495×10^{10}	1.392×10^9	-3.702×10^8
E3-S2	2.495×10^{10}	1.392×10^9	-3.702×10^8
E3-S3	1.647×10^{10}	8.831×10^8	1.387×10^8
E3-S4	1.787×10^{10}	9.671×10^8	5.477×10^7

4. Conclusions

The rise of GHG emission due to emission of CO_2 increases the concern of researchers and countries around the world. This problem was rooted from the increment of energy demand. Techno-economic potential of integrated power plant with methanation is investigated in this study as one of the strategy to tackle the issues.

Prior to the economic analysis of the system, technological review of the whole system is conducted. Methanation is a common chemical process but using hydrogen from renewable sources has a great potential towards reducing environmental impact of the system. From the economic assessment results, highest profit is generated when PEM is used in electrolysis process and CIS is used as solar panel due to its high efficiency and low CAPEX. This cost competitiveness can be enhanced selling O_2 by-product produced from electrolysis process and recycling the catalyst for methanation process. Further studies can be extended by including variation of parameter for a better optimisation superstructure.

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