Integration of Renewable Energy into Oil & Gas Industries: Solar-aided Hydrogen Production

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Abstract

In this paper, methods of integrating solar energy into oil and gas industries are proposed. There are numerous applications of solar energy in oil and gas industries; however, this paper particularly aims to utilize solar energy for producing hydrogen, which required in hydrothreater unit of heavy crude oil upgrader process. Each proposed method is designed to have hydrogen production capacity equals to that required in the upgrader process. Three hydrogen production processes from solar energy are proposed, namely, solar steam reforming of natural gas using a volumetric receiver reactor, solar steam reforming of natural gas using molten salt as a heat carrier, and electrolysis of water using solar thermal energy. The three methods were compared with conventional process, steam reforming of natural gas. Process designs were carried out using Aspen Plus and System Advisor Model (SAM) to determine proper capacity of the technologies in the process, as well as required raw materials and utilities. Based on the process design, economic analyses on all processes were performed and the levelized cost of hydrogen production for different pathways (LCHP) was calculated. The result show that the solar steam reforming of natural gas process using a volumetric receiver reactor has the minimum LCHP of 2.514 $ per kg H_2, which is 46% higher than that of the conventional process.

Keywords
Crude oils upgrader, Electrolysis of water, Hydrogen production from solar energy, Levelized cost of hydrogen production, Solar steam methane reforming, simulation.

1. Introduction

1.1 Current situation in global energy demand and rising problems

At the present time, the most concerned issue is rising in global energy demand. According to report by OPEC [1], the global demand in energy is expected to increase by 60%, from 256 to 410 million barrels of oil equivalent per day (mboe/d) in 2040. Throughout 2040, fossil fuels (i.e., oil, coal and gas) will remain the primary source for world energy demand. However, over the recent decades, there has been an increase in concern over the impact of fossil fuels on the environment. From the available data and continued usage of fossil fuels as the main energy source, Absi Halabi et al. [2] pointed out that the amount of CO_2 emitted will increase by virtually 40% in the next two decades.

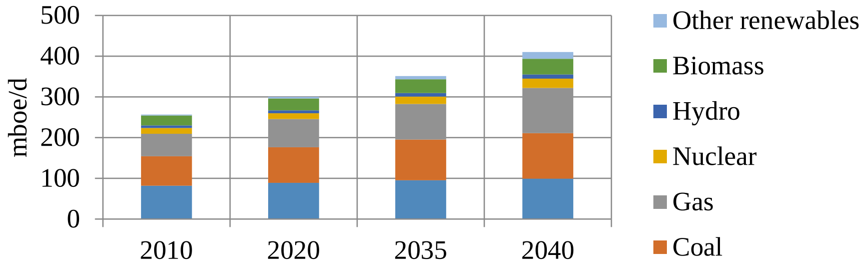

Figure 1. World energy demand [1]

To prevent global temperature from rising, the current emissions must be reduced significantly. From these concerns, a number of environmental measures to control emissions were introduced, for instance, Kyoto Protocol which restricts the amount of CO_2 emissions. These environmental measures have direct impact upon oil and gas industry due to its high energy consumption during production process, which is commonly supplied from fossil-fuels. Furthermore, because conventional oil reserves are depleting, oil industries must resort to produce from unconventional reserves such as heavy oils, oil-sand. These reserves require more energy to both produce and process which will be resulted in higher environmental impact. Due to these preceding events, the CO_2 emissions are expected to increase dramatically [2].

1.2 Heavy crude oils, reserves for future oil productions

Unconventional reserves, such as heavy crude oils, are expected to have more contribution in achieving world demand in 2030 [2]. Heavy crude oils are more viscous, have higher boiling ranges and densities. In addition, they are usually rich in aromatics and tend to have more residual material, e.g., sulfur, nitrogen, asphaltene [3]. Normally, heavy oils cannot be processed directly in petroleum refineries, thus, oil industries will usually set up an upgrader close to the oil fields that generally consist of distillation unit, residual oil processor and hydrotreater. Synthetic crude oils are obtained from the upgrader that satisfies the requirements for processing in downstream.

1.3 Solar energy and oil and gas industry

As the global energy demand is increasing and more concern is focused on the environmental impact, oil and gas companies will need to overcome these challenges. These can be approached by providing more efficient energy usage or the utilization of renewable energy whenever possible. Among various renewable energies, solar energy is the most abundant resource and can be harvested and utilized in different ways, such as, electricity generation via photovoltaic cells or thermal energy by concentrating panels [4]. Moreover, the locations of substantial heavy oil reserves are in the area with high solar irradiance, which indicates that using solar energy in these regions can be efficient and cost effective [2].

In this paper, methods of integrating solar energy into oil and gas industries are proposed. There are numerous applications of solar energy in oil and gas industries; however, this paper particularly aims to use solar energy for producing hydrogen that required in hydrothreater unit of crude oil upgrader process. Each proposed method will be designed to have a hydrogen capacity that satisfies a demand in the crude oil upgrader process. Aspen Plus® and System Advisor Model (SAM) [5] are used to aid in the process designs. After proper equipment size and process requirements are obtained, each method is compared in both process efficiency and economic aspects in order to determine the most applicable way of using solar energy to produce hydrogen for the crude oil upgrader process.

2. Literature review

Over the recent decades, there have been many applications of solar energy in petroleum industry as presented in the review by Absi Halabi et al. [2]. One notable example was using solar concentrators to concentrated solar energy; this solar thermal energy was then used to produce steam required in the oil production process. The authors also mentioned that there were potentials of using solar energy the petroleum industry since most of oil reserves were located at isolated area, where land were available for solar energy plants. Therefore, it is possible to use solar energy to produce hydrogen for the crude oil upgrader. For the method of producing hydrogen using solar energy, Ngoh and Njomo [6] suggested that currently there were three possible processes, including, photochemical, thermochemical, and electrochemical process, as shown in Figure 2. Among these processes, the photochemical process was under a stage of investigation; leaving the possible candidates to be two other processes.

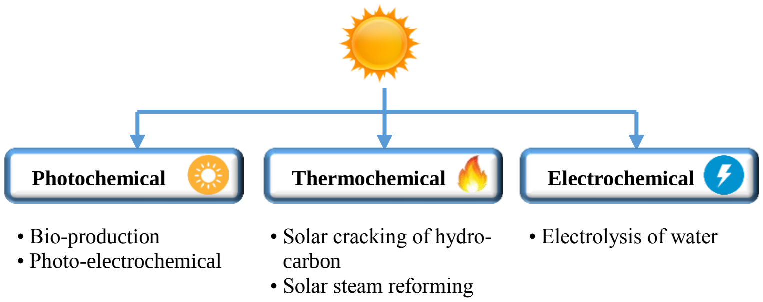

Figure 2. Hydrogen production from solar energy (adapt from [6])

In the thermochemical process, solar energy was concentrated and used to provide heat required in endothermic hydrocarbon cracking reactions, such as steam reforming of natural gas. Recent works on this thermochemical process are available; for example, Möller et al. [7] proposed process configurations of hydrogen production by solar reforming of natural gas. In their process, conventional reformer was replaced by the new innovative volumetric reactor receiver (VRR) (Figure 3). This VRR can be heated with concentrated solar energy to more than 900 °C which was adequate for steam methane reforming reaction. However, the process could only operate during the full load hours of solar energy, restricting the operating hours to 2,038 hours per year. Detailed economic evaluation was carried out; the authors claimed that the hydrogen production cost of this process in only 20% more expensive compared to the conventional steam reforming of natural gas process.

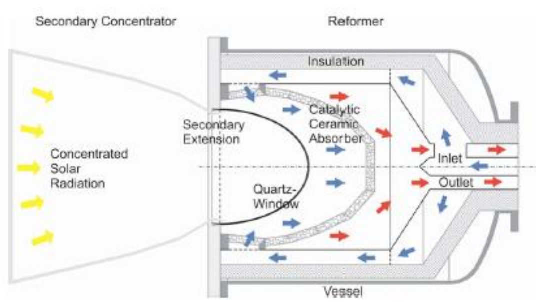

Figure 3. Volumetric receiver reactor [7]

More example of thermochemical process was demonstrated by Giaconia et al. [8]. In their work, solar energy was transferred to hydrogen production process by molten salt which had been long tested as solar heat carrier and heat storage medium. The advantage of this process over the previous process by Möller et al. [7] is that it can operate during an absence of sunlight. However, due to temperature limit of molten salt that could only provide temperature up to 565 °C, resulting in a low conversion of methane, the authors proposed a steam reforming process coupled with membrane reactors. The use of membrane reactor could drive the steam reforming reactions forward at low temperature (<565 °C), increasing methane conversion thereby. The authors also carried out an economic analysis by estimating hydrogen production cost from each proposed process; the results showed the cost was 40 – 80% higher than conventional steam reforming process. These were because of additional equipment installed, increasing capital cost. However, the cost could be reduced in the future as solar equipment become less expensive, and natural gas price increases.

For electrochemical process, the most well-known process is electrolysis of water where electricity is used to decompose water in hydrogen and oxygen. It is the most developed and useful method in industries for hydrogen production [2]. it is not cost-effective on the economic viewpoint unless the electricity is generated from renewable energy, such as solar energy. In addition, utilizing renewable energy for electricity generation will allow hydrogen to be produced without CO_2 emissions.

According to the literature, there had been numerous efforts in exploiting solar energy for hydrogen production. Particularly, steam reforming was the most interested subject of development. However, utilization of solar energy to produce hydrogen had not been attempted in industrial scale. Consequently, this work aim is to use solar energy to produce hydrogen required in the crude oil upgrader process.

3. Methodology

The first procedure is determining a demand of hydrogen in the crude oil upgrader process. This demand will be a design target for each proposed hydrogen production process using solar energy. The details can be addresses as follows

3.1 Crude oil upgrader process simulation

In the process, bitumen (150,000 barrel/day) is upgraded and converted into synthetic crude oil. The simplified process diagram is shown in Figure 4 [9].

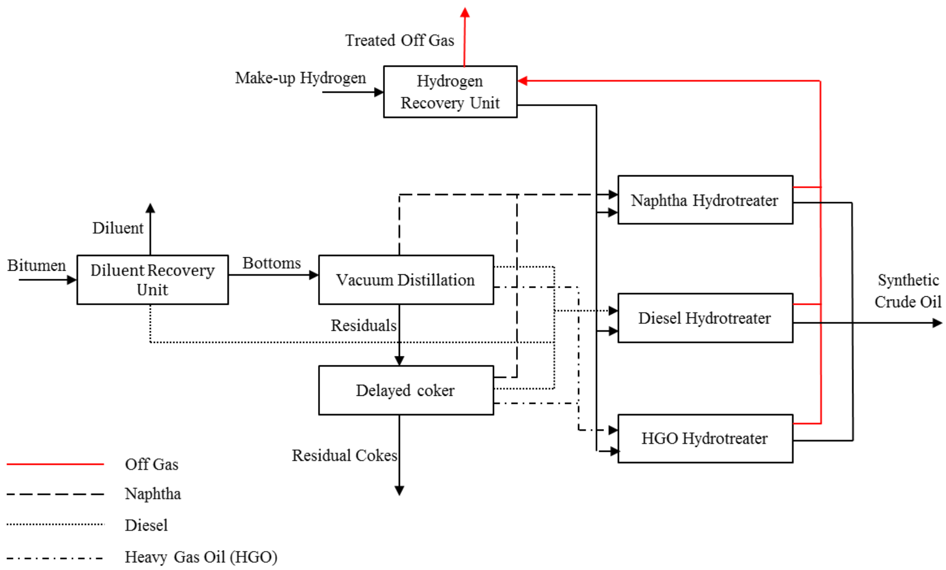

Figure 4. Crude oil upgrader process diagram [9]

The process consists of 5 main units: diluent recovery unit, vacuum distillation, delayed coker, hydrogen recovery unit and three hydrotreaters. According to simulation results, the amount of hydrogen demand (flow rate of make-up hydrogen stream) is found to be 2,577 kmol/h. Additional simulation results are summarized in Table 1 [9].

Table 1. Crude oil upgrader simulation results [9]

Parameter	**Process stream**		
	Bitumen feed	**Synthetic crude oil**	**Make-up hydrogen**
Temperature (°C)	21.11	430.40	37.78
Pressure (kPa)	689.50	7,791	4,137
Molar flow rate (kmol/h)	-	-	2,577
Std ideal liquid vol. flow rate (barrel/day)	150,000	97,000	-
Sulfur content (% wt)	3.58	0.02	-
°API	19.84	28	-
Heat requirement (kW)	3.18×10^{5}		
Electricity requirement (kW)	1.70×10^{4}		

3.2 Proposed methods of producing hydrogen using solar energy

In this paper, there are three proposed hydrogen production processes using solar energy, as illustrated in Figure 5.

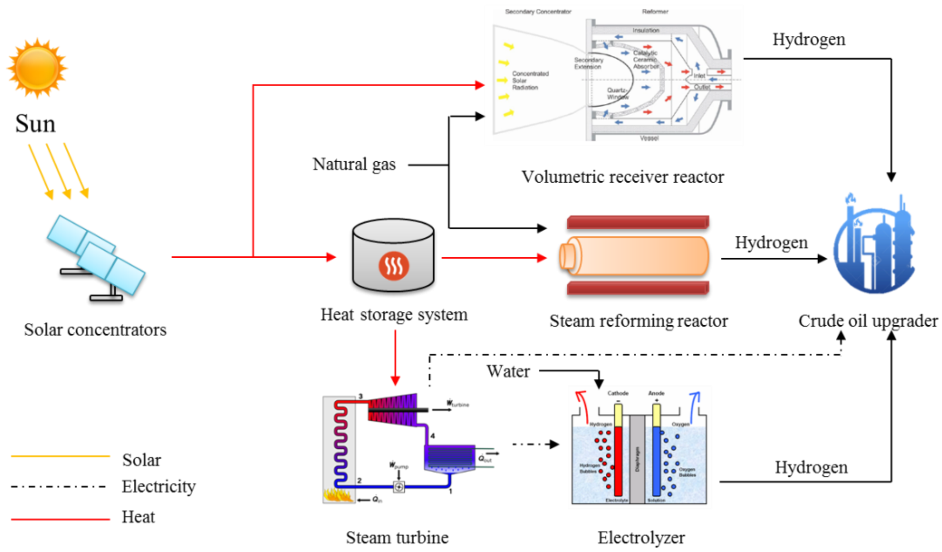

Figure 5. Proposed hydrogen production processes using solar energy

The details of each process are as follows.

1. Solar steam reforming of natural gas using volumetric receiver reactor

This process is based on Ref. [7]; the volumetric receiver reactor is used to receive concentrated solar energy and convert natural gas into syngas rich in hydrogen. However, due to its limitation that allows it operates only 2,000 hours per year, the conventional reformer is needed for the rest of operation.

2. Solar steam reforming of natural gas using molten salt as a heat carrier

This process is an adaptation of Ref.[8]; the heat carrier, i.e., molten salt, is heated by concentrated solar energy and transferred its thermal energy to steam reforming reactor, driving the reactions forwards. However, since the molten salt can provide the temperature up to only 500 °C, not enough to achieve good conversions of natural gas, the main reformer is still essential in this process. The advantage is that the duty of the main reformer can be reduced.

3. Electrolysis of water using solar thermal power generation

This process utilizes concentrated solar energy to provide heat required in steam turbine. Electricity generated from steam turbine is then supplied to electrolyzer to produce hydrogen.

These three processes will be compared with the conventional steam reforming of natural gas process which results in the total of four cases considered in this paper.

3.3 Economic analysis

Method used for economic analysis is Levelized cost of hydrogen production (LCHP); it is the sum of annualized cost of capital investment cost and operating cost divided by the amount of hydrogen produced per year. This method allows comparison between the processes that are significantly different from each other, as included in this paper.

4. Result and discussion

4.1 Process design

Simulations with Aspen Plus® on the first three processes are carried out. The heat duty required by the volumetric receiver reactor and for heating molten salt heat carrier will be the design point for the solar concentrator (designed by SAM). As for the fourth process, the calculated power consumptions by the electrolyzer unit are the design target for designing the solar thermal power plant. The energy input and output of each process is shown in Figure 6.

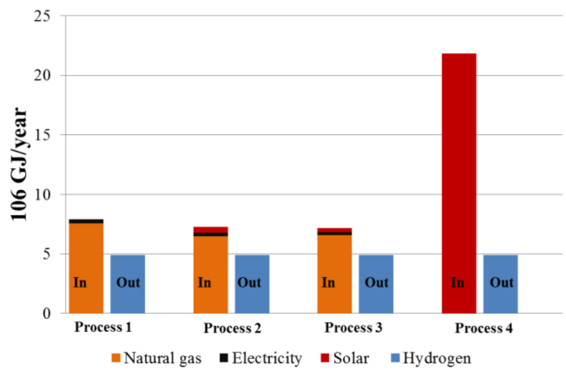

Figure 6: Input and output energy summary (LHV basis).

Utilizing solar energy in the steam reforming process can reduce natural gas consumptions in the process. Furthermore, the electricity consumptions are also decreased; this is due to the lower amount of natural gas and fuel required making compressors load become lower. Both process 2 and 3 have higher process efficiency than the conventional steam reforming process as shown in Figure 6. As for the process 4, the process efficiency is very low because the solar thermal energy needs to be converted to electricity through heat cycle, which is commonly known to have low efficiency.

4.2 Economic analysis

The levelized cost of hydrogen production (LCHP) requires three cost components, including, capital investment cost, production cost, and hydrogen production rate. To determine the LCHP, all processes are assumed to have a lifetime of 25 years with 3 years construction period; the capital investment cost is divided and invested equally in this period. The discount rate is taken as 5%; the deprecation method used is MACRS, 20 years. The capital investment cost is estimated from overall factor method of Lang [14]. This method required an estimation of all purchased cost of all process equipment; this can be done following procedures given in [14]. The purchased cost of solar-related equipment is estimated following the method provided by SAM [15]. As for the purchased cost of the electrolyzer and its components, their costs are taken from H2A model [16], developed by National Renewable Energy Laboratory (NREL).

The production cost comprises cost of raw materials, utilities, operations, maintenance and overhead. Estimations of these costs follow method given in [14]. Table 2 summarizes all estimated costs associated with the LCHP of each process.

Table 2. Summary of estimated cost associated with LCHP

Cost details	Cost (M$)			
	Process 1	**Process 2**	**Process 3**	**Process 4**
Capital investment cost				
Purchased cost of all process equipment	25.86	25.64	26.61	243.85
Purchased cost of all solar-related equipment	-	41.02	98.82	1853.16
Land	1.55	6.62	10.87	78.99
Working capital	22.24	60.20	113.27	201.79
Total capital investment cost	154.51	406.48	756.11	3962.79
Production cost				
Raw materials	24.68	20.51	24.83	2.74
Utilities	17.12	16.35	12.97	4.80
Operations	2.80	4.48	4.48	12.00
Maintenance	10.43	27.15	51.11	105.65
Overhead	5.61	13.96	25.37	44.84
Total production cost	60.64	82.44	118.764	170.03

Amount of hydrogen produced	41,232,000 kg/year			
Levelized cost of hydrogen production (LCHP) ($/kg H_2)	**1.7**	**2.5**	**3.8**	**7.9**

Results of economic analysis show that the process 2 has the most competitive LCHP among three proposed processes. The most expensive LCHP belongs to the process 4; most of the costs are from the capital investment cost. The cost of solar thermal power plant is very high due to its high power output. However, in the future, cost of solar thermal power plant can become cheaper in the future; therefore this method could be promising for the future. The process 2 and 3 utilize the same method of producing hydrogen; the LCHP of process is considerably higher than that of process. The factor that affects the LCHP in the process 3 is an adoption of solar thermal storage system; this is the key difference between process 2 and 3 and it results in higher LCHP. The thermal storage system is also the main cost of the process 4 as well. Therefore, if the cost of thermal storage system was reduced in the upcoming future, the LCHP of these processes could become more competitive compared to the conventional process.

5. Conclusion

In this work, the methods of integrating of solar energy into oil and gas industry are presented. The solar energy is used to aid in the producing hydrogen that required in the crude oil upgrader process. Three hydrogen production processes using solar energy are proposed, and these process are compared with the conventional steam reforming of natural gas process. Process designs were carried out, and according to the simulation results obtained from Aspen Plus, all proposed processes consumed less natural gas feeds, as well as had lower CO_2 emission rates compared to the conventional process. However, the economic analysis using the levelized cost of hydrogen production (LCHP), showed that all proposed process had higher LCHP compared to the conventional process. The lowest LCHP is 2.514 $ per kg H_2 which belongs to the process 2: steam reforming of natural gas process using a volumetric receiver reactor, and it is 46% higher than the conventional process. For these finding, it is concluded that using solar energy to aid in the hydrogen production could lower the environmental impact; however, in term of economic point of view, these methods are currently not economic since the solar-related equipment are still expensive. In the future, the cost of this equipment could be less expensive, making these methods become applicable and promising.

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Biography

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