

# Solar-aided hydrogen production methods for the integration of renewable energies into oil & gas industries

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## ABSTRACT

This paper integrates solar energy, regarded as the most abundant renewable energy in the world, into oil and gas industries to produce the hydrogen required in crude oil upgrader processes. Three alternatives of producing hydrogen from solar energy were proposed, namely, Solar Steam Methane Reforming using a Volumetric Receiver Reactor (SSMR-VRR), Solar Steam Methane Reforming using Molten Salt (SSMR-MS), and Solar Thermal Power generation coupled with Water Electrolysis (STP-WE). Simulations of all alternatives have been done to produce 2577 kmol per hour hydrogen: that is, the demand in the crude oil upgrader process. The technical, economic, and environmental analysis is performed to compare the results of the alternatives with the conventional steam reforming of natural gas. The results suggest that SSMR-VRR has the lowest levelised cost of hydrogen production, which is \$2.5 per kg of hydrogen; SSMR-MS has a highest energy efficiency of 68%, and STP-WE has the lowest greenhouse gas emissions. The economic analysis suggests that currently the thermochemical processes (SSMR-VRR and SSMR-MS) have potential for producing hydrogen required by the crude oil upgrader; however, as the renewable energy technologies progress that may lead to their capital cost decrease, solar thermal power with water electrolysis (STP-WE) will become a more promising sustainable option for hydrogen production.

## 1. Introduction

Due to the depletion of fossil resources in the future and growing concern over environmental impacts such as global warming, renewable energy and more importantly solar energy is a candidate for sustaining the world energy demand. At present, increasing energy demand is becoming the most concerning issue throughout the globe. For the next few decades, fossil fuels will likely remain as a primary source of energy to sustain these increasing demands. However, fossil fuels contribute to the global warming by producing greenhouse gas emissions. As more concern is given on the environmental impacts, oil and gas industries need to find solutions to overcome these challenges and mitigate environmental impacts. One such way is the adoption of renewables such as solar energy for the hydrogen production in the crude oil upgrader process. This article investigates several pathways of solar-based hydrogen production for oil industries, including Solar Steam Methane Reforming using Volumetric Receiver Reactor (SSMR-VRR), Solar Steam Methane Reforming using Molten Salt as a heat carrier (SSMR-MS), and Solar Thermal Power generation coupled with Water Electrolyser (STP-WE). These alternatives are compared with the

conventional steam methane reforming from the technical, economic, and environmental perspective; each of these cases has their own advantageous and disadvantageous. The economic analysis suggests that currently the thermochemical processes (SSMR-VRR and SSMR-MS) have more potential to produce hydrogen required by the crude oil upgrader. The steam methane reforming using molten salt (SSMR-MS) has the highest energy efficiency. Furthermore, the solar thermal power generation using water electrolysis (STP-WE) had lowest greenhouse gas emissions among all hydrogen production cases.

### 1.1. Importance of this research

Nearly 95% of worldwide energy is currently produced from fossil fuel resources, e.g., natural gas, hydrocarbon, and coal, which have been depleted and have a tremendous environmental impact [1]. According to the Organization of the Petroleum Exporting Countries (OPEC) [2], the global energy demand is expected to increase by 60%, from 256 to 410 million barrels of oil equivalent per day in 2040, and fossil fuels will remain the primary source for supplying this rising demand. However, over recent decades, there has been an increase in

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concern over the impact of fossil fuels on the environment [3]. Continuous production of crude oil will eventually result in the depletion of conventional oil reserves. In order to meet the demand, oil industries need to produce crude oils from unconventional reserves, such as heavy crude oils [4], and the development of such oil production plants is expected to increase [5]. These unconventional reserves require more energy to both produce and process, resulting in increasing energy consumption in oil industries. Additionally, the higher energy consumption leads to a higher environmental impact in the form of CO<sub>2</sub> emissions. Since there are more concerns to reduce environmental impacts due to new regulations for the CO<sub>2</sub> mitigation and carbon trade markets, oil industries should overcome these challenges by utilizing renewable energy in the production process [6,7].

Over the past forty years, solar energy has been used to provide electricity to off-grid communities via photovoltaic systems (PV); this was proven useful when electricity was not accessible [8–11]. Another important application of solar energy is supplying thermal energy to industrial processes [12]; the solar thermal energy is mainly used for steam and/or heat generation [13]. One notable example is a solar thermal plant constructed by Chevron and Bright Source Energy [3,14]. In addition, another potential application of solar energy is the production of hydrogen energy [15]. Solar energy can be directly used to provide high-temperature heat to meet the requirements of highly endothermic reactions. However, the technologies involved in this process are currently under development, and no industrial-scale applications have been attempted in the oil industries to date. The future prospects of solar energy in oil and gas industries is using concentrated solar energies in heavy oil upgraders in period over 20 years. Therefore, solar energy is a potential candidate for producing hydrogen due to solar abundance and sustainability [1,16]. This is because the locations of substantial heavy oil reserves are often in locations with high solar irradiance [17–19], which indicates that using solar energy in these regions can be efficient and cost effective.

Environmental regulations require that sulfur or other impurities must be removed from end use petroleum products. Crude oils are characterized based on their density and those with lower specific gravity will have higher API gravity [20]. Heavy crude oils require a special technique for extraction and recovery and cannot be processed directly in current petroleum refineries. Therefore, oil companies usually construct upgraders near oil production fields to convert bitumen into the synthetic crude oil using hydrogen, and today's refineries mostly produce hydrogen through conventional steam methane reforming [21]. Heavy crude oil from production fields is first fed to a diluent recovery unit (DRU) to separate and recover diluent from the heavy crude oil. The DRU operates at atmospheric conditions, and produce three outlet streams, namely, diluent, light gas oil (LGO) and bottoms that contain heavy components. Then, this bottom feed is subsequently cracked into smaller components in a primary cracker where the lighter components, i.e., naphtha, LGO, and heavy gas oil (HGO) are obtained. In addition, an optional secondary cracker can be employed to further crack the residuals from the primary cracker, providing additional yield. After that, each product is sent to a hydro-treater to remove sulfur; nitrogen content, aromatics and other impurities. This hydrotreater is the main source of hydrogen consumption in the upgrader process. The higher amount of nitrogen and sulfur required by crude oil upgrader, the more the hydrogen demands for their process [22].

## 1.2. Literature review

There is a large amount of ongoing research that focuses on the hydrogen production [23]. Hydrogen production via solar energy can be divided into three main groups: photochemical, electrochemical and thermochemical. Photochemical processes involve using sunlight in the hydrolysis of water to produce hydrogen. Although this process can be achieved with only heat from sunlight, it is not practical since the

temperature required to dissociate water is over 2000 °C. Many researchers have attempted to improve these processes; nonetheless, it is concluded that photochemical processes are still at the research stage of investigation [24]. Both thermochemical and electrochemical pathways offered a promising way to produce hydrogen from solar energy. The thermochemical process utilized solar energy to supply the thermal energy needed in catalytic endothermic hydrocarbon transformation reactions such as cracking, and steam reforming. Whereas electrochemical process, commonly known as electrolysis of water, was the most developed and allowed hydrogen to be produced with lower greenhouse gas emissions, however, it was not cost-effective compared to other technologies [1,25–27]. There are two different methods of hydrogen production in electrochemical process. First, solar energy can be harvested via photovoltaic (PV), directly generating electricity from sunlight [28]. Secondly, concentrated solar energy is stored in thermal energy storage before being used for electricity generation in a steam turbine cycle. Generated electricity is supplied to electrolyzers for hydrogen production. An additional benefit of this pathway compared with other production methods is that extra stored thermal energy can be provided to the crude oil upgrader process as lower grade heat [3].

The thermochemical process with fossil feed stocks is the well-developed and most commercially exploited technology to produce hydrogen. A total of 96% of the hydrogen production is currently from fossil resources, while 4% is from electrolysis of water. Current steam methane reforming (SMR) is the most widely used process (48%) in which natural gas is reformed with steam, producing syngas that mainly consists of hydrogen [1,29].

Some studies reviewed the solar thermal reforming of methane feedstock for hydrogen and syngas production [30–32]. The authors of the aforementioned studies concluded that significant progress has been made in solar aided steam reforming of methane, which are demonstrated at the pilot scale. Combining solar energy with conventional steam reforming of methane would be the first step to the production of hydrogen in a sustainable way. However, these technologies require public and financial support for their deployments into the market.

De Falco et al. [33] utilized solar energy to provide the heat required for hydrogen enriched methane production through heat carrier and molten salt. Reactors configurations were proposed and modeled. The effects of the operating parameters, e.g., gas hour, space velocity and the inlet reactants temperature, were investigated. The results demonstrated the process can produce enriched methane with 20% vol of hydrogen. This indicated solar energy could be successfully integrated into the low-temperature reforming reaction [34].

He and Li [35] evaluated three different hydrogen product schemes, including conventional steam methane reforming, solar steam methane reforming, and hybrid solar-redox processes. The authors mentioned that solar steam methane reforming (SSMR) shared many similarities with conventional steam methane reforming (CSMR); the key differences are the use of solar energy to provide heat for reforming reaction and recycle of off-gas from the hydrogen purification unit to the reformer (normally off-gas is combusted to provide heat for reforming reactions). The results indicated that SSMR possessed higher energy efficiency since solar energy was directly used to supply heat. Moreover, the produced hydrogen was higher due to additional feed from recycled off-gas. Another advantage of SSMR was 40% lower in CO<sub>2</sub> emissions compared to the conventional process according to life cycle analysis. The authors concluded that the use of solar energy to assist methane reforming represented a promising way to improve energy efficiency the conversion process while lowering CO<sub>2</sub> emissions.

Giaconia et al. [36] introduced the utilization of solar energy as a heat source to drive endothermic steam reforming reactions in hydrogen production process. Solar energy was transferred to hydrogen production process by molten salt which had been long tested as a solar heat carrier and a heat storage medium. The results demonstrated higher methane conversion could be obtained with both process configurations compared to the conventional process. Furthermore, solar

energy coupled with steam reforming process could save the natural gas consumption rate and, thus lower CO<sub>2</sub> emissions.

Möller et al. [29] proposed process configurations of hydrogen production by solar reforming of natural gas. The authors designed and simulated two process configurations for SSMR, which differed in methane to steam ratio (1.5 and 3.0).

The economic results indicated that the hydrogen production cost of SSMR was only 20% more expensive than that of the conventional process.

Al-Subaie et al. [37] modeled the electrolytic hydrogen production for refinery applications. They found that off-peak hydrogen production by the electrolysis results in emissions reduction compared to hydrogen production from steam methane reforming.

### 1.3. Contribution of the research

Various researchers are exploiting solar energy for hydrogen production. In particular, steam methane reforming is the most interesting subject of development. However, the utilization of solar energy to produce hydrogen has not been attempted at the industrial scale. Consequently, this paper aims to model a process to integrate solar energy into the oil and gas industries by using solar energy to aid in the hydrogen production required in the hydrotreater units of a crude oil upgrader. This paper proposes and conceptually designs the solar-aided hydrogen production pathways and evaluates them from the technical, economic, and environmental points of view at the industrial scale. In summary, the current paper succeeds in achieving the following milestones:

- (1) It studies the integration of renewable energies in the oil and gas industries (crude oil upgrader processes) by utilizing solar energy for hydrogen production.
- (2) It investigates the different methods for solar-based hydrogen production including, Solar Steam Methane Reforming of natural gas using Volumetric Receiver Reactor (SSMR-VRR), Solar Steam Methane Reforming of natural gas using Molten Salt as a heat carrier (SSMR-MS), and Solar Thermal Power generation using Water Electrolysis (STP-WE).
- (3) It compares alternatives compared from the technical, economic, and environmental points of view with the Conventional Steam Methane Reforming process (CSMR).

The remaining sections of this paper are organized as follows. The second section explains the methodology for the modeling and taking results. Next, the simulations of process design are described in detail. The fourth section presents the results and compares the various alternatives. The final section presents our concluding remarks. ”

## 2. Methodology

This paper investigates different methods for solar-based hydrogen production alternatives including, Solar Steam Methane Reforming of natural gas using Volumetric Receiver Reactor (SSMR-VRR), Solar Steam Methane Reforming of natural gas using Molten Salt as a heat carrier (SSMR-MS), and Solar Thermal Power generation using Water Electrolysis (STP-WE) for crude oil upgraders as shown in Fig. 1. The alternatives compared from technical, economic, and environmental points of view with Conventional Steam Methane Reforming process (CSMR).

In this paper, the authors employ System Advisor Model (SAM) software to design and simulate the solar components in the process, e.g., solar concentrators [38]. In order to determine the amount of hydrogen demand, the crude oil upgrader process is simulated using Aspen HYSYS [39]. The data regarding the simulation of the crude oil upgrader process is obtained from and verified by Ref. [22], considering 150,000 barrels of bitumen per day.

Fig. 2 presents the simplified process diagram of the simulated crude oil upgrader. Crude oil upgraders usually consist of a distillation unit and a residual oil processor, e.g., vacuum distillation and delayed coker. The main objective of upgraders is to convert the bitumen into the synthetic crude oil to be processed in refineries. The synthetic crude oil contains lighter components such as naphtha, diesel, and heavy gas oil. The simulated upgrader also includes hydrogen treater units to recover hydrogen from the hydrotreater purge gas. Based on the process simulation of bitumen upgrader, the hydrogen demand estimated to be 2577 kmol per hour [22].

According to the simulation output, four cases are proposed for the production of hydrogen as follow:

- **Conventional steam reforming of natural gas process (CSMR)-base case**
- **Solar Steam Methane Reforming of natural gas using volumetric receiver reactor (SSMR-VRR):** a solar volumetric receiver reactor is used to directly absorb concentrated sunlight and produce the syngas. However, the conventional reformer is needed for the rest of operation due to its limitation that allows it operates only 2000 h per year [1].
- **Solar Steam Methane Reforming of natural gas using Molten Salt as a heat carrier (SSMR-MS):** 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, the main reformer is still essential in this process as the molten salt provides the temperature up to only 500 °C, which is not enough to achieve good conversions of natural gas. The advantage of this case is that the duty of the main reformer can be reduced [30].
- **Electrolysis of water using solar thermal power generation (solar power to gas pathway):** 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.

**Technical Analysis:** With all essential data acquired from process design and simulation, each proposed case was evaluated on several aspects. Process analysis can be carried out in many different ways. In this paper, energy efficiency is mainly used for the technical comparison in evaluating chemical systems from the point of First Law thermodynamics as defined in Eq. (1).

$$\text{Energy efficiency} = \frac{\text{Total Energy Input}}{\text{Total Energy Output}} \times 100\% \quad (1)$$

where: the total energy input is the summation of different energy carriers supplied to the process, e.g., heat, electricity, solar, fuel based on the lower heating value (LHV), similarly, the total energy output is the summation of all energy carriers leaving the process, which is calculated based on the LHV of produced hydrogen.

**Economic Analysis:** Since each proposed hydrogen production pathway utilizes different methods and technologies, a means of equally comparing cost between each case should be used.

For economic evaluations, the term Levelized Cost of Hydrogen Production (LCHP) is used for comparing how much cost is needed to produce an equivalent amount of hydrogen. LCHP is calculated based on the amortized total cost and the total amount of hydrogen produced during the lifetime of the system, as in Eq. (2). The four cases are analyzed and compared over the expected 20-year lifecycle of a hydrogen production facility. This method allows comparison between the processes that are significantly different from each other, as included in this paper.

$$\text{LCHP} (\text{"$/kg}) = \frac{\sum_{y=1}^n \frac{(C_{\text{Capital}} + C_{\text{Production}})}{(1+r)^{y-1}}}{F_{H_2} \times 8000 \times n} \quad (2)$$

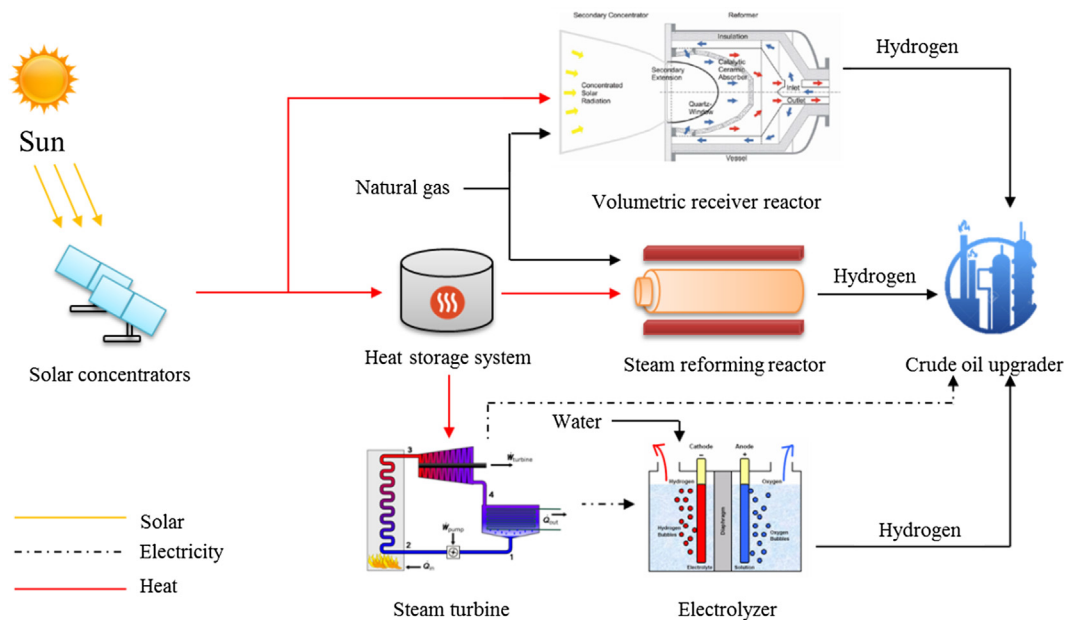


Fig. 1. Proposed hydrogen production cases using solar energy [40].

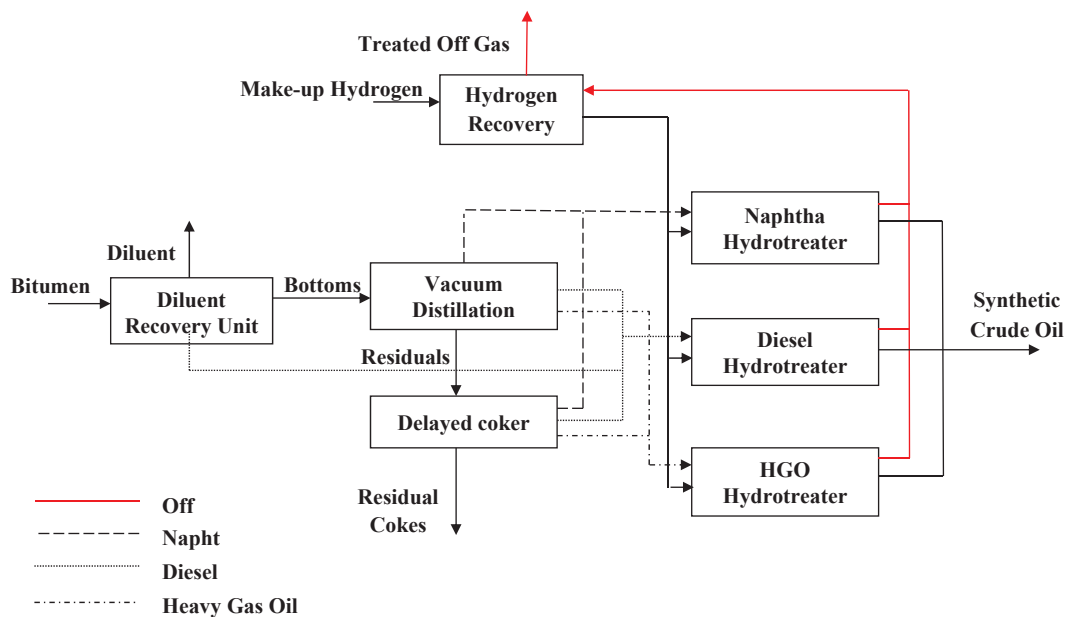


Fig. 2. Simplified crude oil upgrader process diagram [40].

where  $C_{\text{Capital}}$  is the total capital cost per year and  $C_{\text{Production}}$  is the total production cost of hydrogen including operational, maintenance, and fuel costs.  $F_{H_2}$  is the hydrogen production rate (kg per hour), which is equal to the hydrogen demand in the crude oil upgrader process i.e., 5154 kg per hour. The annual hours of the system operation is assumed to be 8000.  $n$  and  $r$  are life time of the project and discount rate, respectively.

In this work, the size and capacity of each equipment is used to estimate the purchased costs of the process equipment [41]. The cost study estimation method is developed based on the overall factor method similar to that of Lang [42]. The purchased cost of solar-related equipment is estimated following the method provided by SAM [38]. The purchased cost of the electrolyzers and its components are taken from H2A model [43], developed by National Renewable Energy Laboratory (NREL).

**Environmental impact analysis:** since there are more concerns on

reducing environmental impact, an analysis should be carried out to indicate the benefit of using solar energy for different cases. Thus, the  $CO_2$  emissions of each hydrogen production case is investigated by calculating the  $CO_2$  from flue gas and removed  $CO_2$  from an Amin plant.

### 3. Process design simulation

The process simulation of all cases are carried out in Aspen Plus, whereas System Advisor Model (SAM) software is used to design the solar concentrators system. The details of each process simulation is given as follows:

#### Case 1: Conventional steam reforming of natural gas process (CSMR)

Treated natural gas and steam are supplied into the reformer where

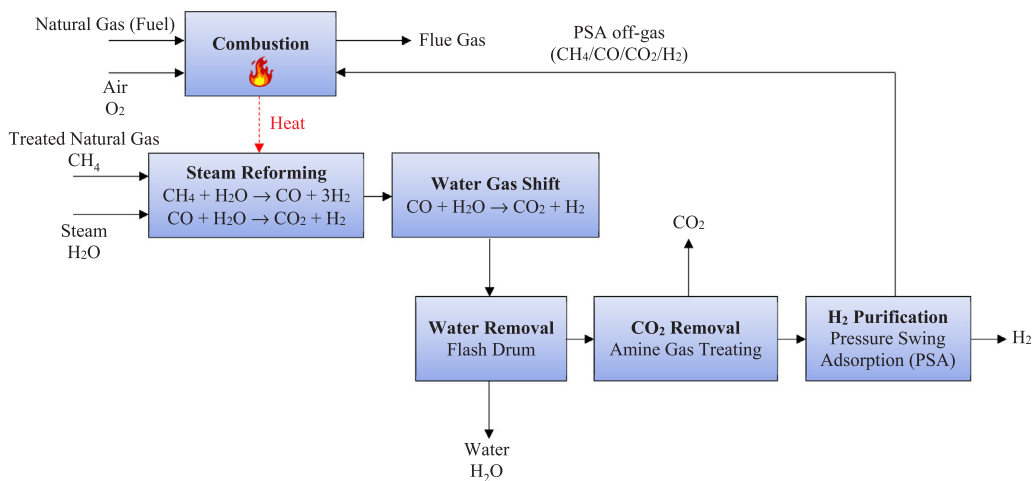


Fig. 3. Simplified block diagram of conventional steam reforming of natural gas (CSMR).

the reactions of steam methane reforming occur; the high temperature (900 °C) of the reformer is provided by combusting fuel, i.e., natural gas. Then, syngas leaving the reformer is cooled down and enters water-gas shift reactor to convert carbon monoxide (CO) into additional hydrogen product through water-gas shift reaction. After that, the syngas passes through a train of purifications unit to purify the hydrogen product. The first unit is water separator; in this case, the flash drum is employed. The second unit removes carbon dioxide (CO<sub>2</sub>) from the product stream by amine gas treating process. Finally, hydrogen is purified in pressure swing adsorption (PSA) unit, achieving the purity up to more than 99.9 vol%. However, only 90% of hydrogen is recovered from this unit. The off-gas from PSA unit is recycled back as a fuel for providing heat to the reformer. Fig. 3 shows the process diagram of conventional steam reforming of natural gas.

**Case 2: Solar steam reforming of natural gas using Volumetric Receiver Reactor (SSMR-VRR)**

This process is similar to the conventional steam reforming of natural gas process with an addition of the volumetric receiver reactor and solar concentrators systems. A key difference is the PSA off-gas is recycled back as a raw material instead of fuel to steam methane reforming. The cause is that the heat is directly provided by concentrated

solar energy and it can reduce natural gas consumption rate (Fig. 4).

**Case 3: Solar steam reforming of natural gas using molten salt as a heat carrier (SSMR-MS)**

The third process is almost identical to the conventional process; the additional unit is the pre-reformer unit that utilize molten salt, heated by concentrated solar energy, as a heat carrier. This pre-reformer partially converts natural gas into hydrogen. Therefore, this will reduce a heat duty required in the main reformer. The rest of the process are in no difference as depicted in Fig. 5.

The complete specifications of all equipment, which are implemented in Aspen Plus, is summarized in Table 1.

**Case 4: Solar Thermal Power Generation coupled water Electrolysis (STP-WE)**

This process is different from the first three processes in term of method used to produce hydrogen. In this process, electricity is generated by heat cycle, usually steam turbine, which receives heat from solar concentrators. This electricity is then used to produce hydrogen in the electrolyzer through electrolysis of water reactions. The alkaline electrolysis technology is selected due to the higher hydrogen

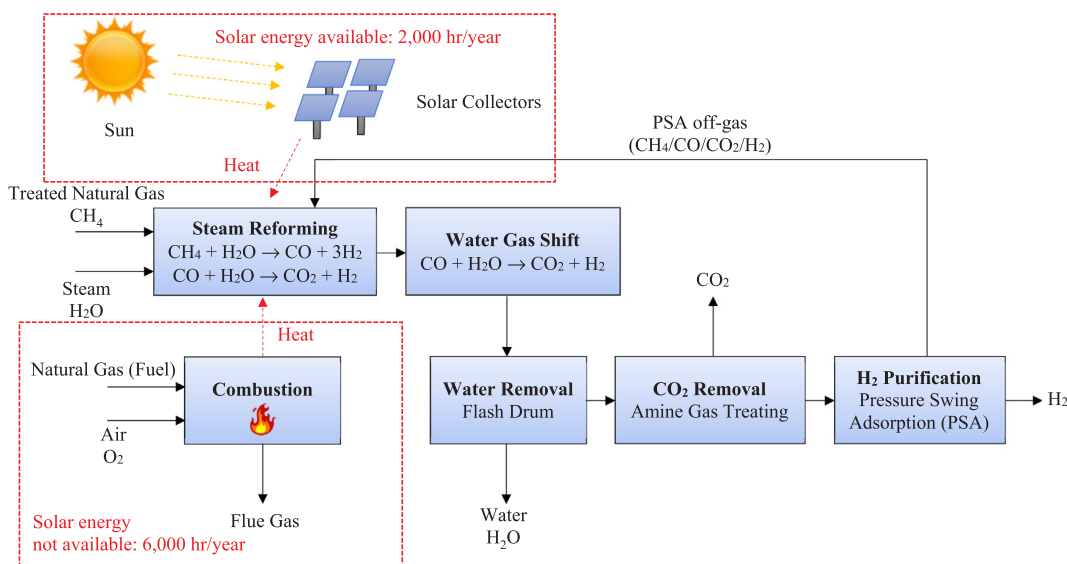


Fig. 4. Process diagram of solar steam reforming of natural gas using volumetric receiver reactor (SSMR-VRR).

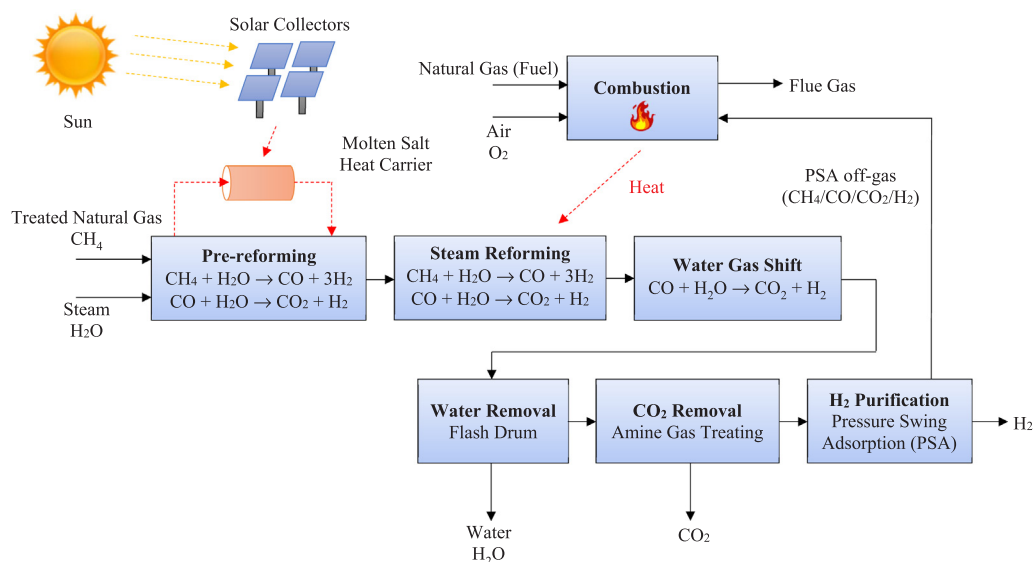


Fig. 5. Process diagram of solar steam reforming of natural gas using molten salt as a heat carrier (SSMR-MS).

production capacity than its alternatives [47]. The existing commercial electrolyzer Norsk Hydro Atmospheric Type No.5040 is employed for this work [35]. Note that using photovoltaic cells to generate electricity is relatively expensive compared to the other processes. Hence, this alternative is not considered further in this work (see Fig. 6).

The process designs of the first three processes are carried out in Aspen Plus® by developing a process flowsheet. Using the design target, i.e., hydrogen production rate is 2577 kmol per h; process simulations are carried out to obtain equipment size and the other requirements in the process. As for the solar concentrator systems, it is designed using SAM and the selected technology is solar tower since it could provide temperature up to 1000 °C [36], adequate for providing heat required by a steam reforming reaction.

## 4. Result and discussion

### 4.1. Process design results

Simulations with Aspen Plus® on the first three processes are carried out as the results are summarized in Table 1. The heat duty required by the volumetric receiver reactor and for heating molten salt heat carrier is 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.

Comparison between all hydrogen production processes considered in this paper are summarized in Table 1; the fuel consumption, CO<sub>2</sub> emissions, the specifications of solar systems, and the required lands by each case are shown in Table 1. The size of heliostats reflective area of Solar Thermal Power Generation coupled water Electrolysis (STP-WE) is extremely large compared to those required in Solar steam reforming of natural gas using Volumetric Receiver Reactor (SSMR-VRR) and Solar steam reforming of natural gas using molten salt (SSMR-MS) cases. This will incur a large capital investment cost and very large land area for the implementation of STP-WE case, which can become a problem in the region where land area is limited.

From the simulation results derived that around one third of the total natural gas was used to provide the heat required for the steam reforming reactions. Therefore, it could be possible to reduce the natural gas consumption by using solar energy to provide the heat for the steam reforming reactions instead. In addition to the natural gas consumption, water consumption is also an important factor to be considered, since most of the crude oil upgraders are located in an isolated

area where a limited amount of water is available. Because, the amount of water consumed is proportional to the amount of the inlet natural gas feed, the water consumption can be reduced with the reduction of inlet natural gas feed.

As can be seen, in solar thermal power generation coupled with electrolysis water (STP-WE) process, the water consumption is the highest due to the nature of electrolysis of the water reaction. The great benefit of STP-WE process is no CO<sub>2</sub> emissions during the hydrogen production process.

In addition, high purity oxygen by-product is also obtained from the process; these can be used for a specific purpose, or sold for additional credits. However, STP-WE process cannot produce steam for the crude oil upgrader process. More disadvantages of STP-WE process are large requirements of the solar-related equipment as summarized in Table 2.

The first and important parameter is the natural gas consumption in each process as shown in Fig. 7. It is clear that utilizing solar energy can reduce the natural gas consumption rate in both feed and fuel. For SSMR-VRR process, the reduction occurs mostly in the feed section, because the PSA off-gas is recycled back as the inlet feed, whereas in the SSMR-MS process, natural gas in the fuel part significantly decreases because of lower heat duty in the main reformer unit. Overall, both SSMR-VRR and SSMR-MS cases can save an equal amount of natural gas consumption. Note that the STP-WE does not have any natural gas consumption due to the differences in the hydrogen production process. SSMR-VRR and SSMR-MS achieve 14% and 12% reduction in natural gas consumption, compared to conventional steam methane reforming (CSMR) case.

As displayed in Fig. 7, employing solar energy into the steam reforming of natural process reduces the electricity consumption. For both SSMR-VRR and SSMR-MS processes, the electricity used by the air compressor decrease notably. However, for SSMR-VRR process, the electricity consumed by the PSA off-gas compressor also increases by 10.4 GWh per year when compared to the consumption rate in CSMR process. This is because the PSA off-gas needs to be re-pressurized back to higher pressure. In SSMR-MS process, the PSA off-gas is re-compressed back to the process (for using as a fuel), therefore resulting in no increment in the electricity consumption. The lowest electricity consumption rate belongs to the SSMR-MS process as shown in Fig. 7. SSMR-VRR and SSMR-MS achieve 13% and 21% reduction in electricity consumption, respectively, compared to the conventional steam methane reforming (CSMR) case. The electricity consumption of the electrochemical case (STP-WE) are the highest, due to the electrolytic hydrogen production. Note that solar aided steam turbines generated

**Table 1**  
Equipment specifications summary of steam reforming of natural gas process.

Equipment	Model used in Aspen Plus®	Equipment specifications	
Natural gas feed compressor	Compr	Type	Polytropic using ASME method
		Discharge pressure	30 bar
		Polytropic efficiency	80%
		Mechanical efficiency	98%
Air feed compressor PSA off-gas compressor	Compr	Type	Polytropic using ASME method
		Discharge pressure	5 bar
		Polytropic efficiency	80%
		Mechanical efficiency	98%
Combustor of reformer	RGibbs	Temperature	1000 °C
		Pressure	3 bar
Heat exchanger	HeatX	Flow direction	Countercurrent
		Type	Design
		Hot stream outlet temperature	200–400 °C
Heat exchanger	HeatX	Flow direction	Countercurrent
		Type	Design
		Heat exchanger area	1000 m <sup>2</sup>
Heat exchanger	HeatX	Flow direction	Countercurrent
		Type	Design
		Hot stream outlet temperature	50 °C
Flash separator (water removal)	Flash2	Coolant	Cooling water
		Heat duty	0 kW (adiabatic)
		Pressure drop	2 bar
Heat recovery steam generator	HeatX	Flow direction	Countercurrent
		Type	Design
		Cold stream outlet temperature	400 °C
High-temperature water gas shift reactor	RPlug	Reactor type	Reactor with specified
		Temperature	400 °C
		Pressure drop	2 bar
		Tube diameter	0.019 m
		Tube length	6.096 m
		Number of tubes	2000 tubes
		Bed voidage	0.5
		Catalyst particle density	1250 kg/m <sup>3</sup>
		Reactor type	Reactor with specified
Low-temperature water gas shift reactor	RPlug	Temperature	200 °C
		Pressure drop	2 bar
		Tube diameter	0.019 m
		Tube length	6.096 m
		Number of tubes	3250 tubes
		Bed voidage	0.5
		Catalyst particle density	1360 kg/m <sup>3</sup>
		CO <sub>2</sub> spilt fraction	0.95
Amine gas treating unit (CO <sub>2</sub> removal)	Sep		
Water feed pump	Pump	Discharge pressure	30 bar
		Pump efficiency	72.5%
		Driver efficiency	96%
Pressure swing adsorption (H <sub>2</sub> purification)	Sep	H <sub>2</sub> product split fraction	0.9
		Outlet pressure of H <sub>2</sub> product	20 bar
		Outlet pressure of PSA-off gas	1 bar
Reformer	RPlug	Reactor type	Reactor with specified
		Temperature	900 °C
		Pressure drop	2 bar
		Tube diameter	0.1 m
		Tube length	10 m
		Number of tubes	135 tubes
		Bed voidage	0.5
		Catalyst particle density	1150 kg/m <sup>3</sup>
Volumetric receiver reactor	RGibbs	Temperature	900 °C
		Pressure drop	2 bar
		Product calculation	RGibbs considers all components as products
Molten salt	Molten salt is a mixture between Sodium Nitrate (NaNO <sub>3</sub> ) and Potassium Nitrate (60/40%w). In this simulation, component NaNO <sub>3</sub> , available in Aspen Plus®, is used to represent the molten salt.	Molecular weight	90.794 kg/kmol [44]
		Heat capacity	145.27 kJ/(kmolK) [44]

(continued on next page)

Table 1 (continued)

Equipment	Model used in Aspen Plus®	Equipment specifications	
Pre-reformer	RPlug	Density	1.87 kg/m <sup>3</sup>
		Temperature	565 °C
		Pressure	8 bar
		Flow rate	150 kg/s
		Composition	Pure molten salt
		Methane to steam ratio	1:4
		Reactor type	Reactor with specified temperature
		Thermal fluid	Molten salt
		Tube dimensions	
		Length	6.096 m (20 ft) <sup>a</sup>
		Diameter	0.019 m (0.75 in.) <sup>a</sup>
		Number of tubes	12,500 tubes <sup>b</sup>
		Pressure drop	2 bar
Bed voidage	0.5		
Catalyst particle density	1150 kg/m <sup>3</sup> [45]		

<sup>a</sup> Typical tube size of heat exchanger is used [46].

<sup>b</sup> Sensitivity analysis is carried out to find this number of tubes.

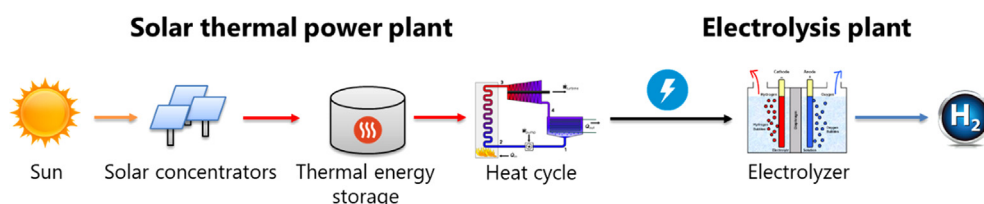


Fig. 6. Process diagram of Solar Thermal Power Generation coupled water Electrolysis (STP-WE).

this electricity.

#### 4.2. Technical analysis results

Process energy efficiency of different cases (computed by Eq. (1)) are used for technical comparison as shown in Fig. 8. The overall energy input and output of all hydrogen production processes are also presented in Fig. 9. The energy of the natural gas and hydrogen were calculated from the lower heating value (LHV) of  $5.003 \times 10^4$  and  $11.996 \times 10^4$  kJ/kg, respectively.

Solar thermal power generation by water electrolysis (STP-WE) has the lowest process energy efficiency, because more energy conversion steps are involved. Furthermore, converting thermal energy to power possesses low energy conversion efficiency, resulting in low process energy efficiency of STP-WE process. Both SSMR-VRR and SSMR-MS processes have higher process energy efficiencies than CSMR process. This is because in CSMR process, the energy was lost through the flue gas of combustion; however, in SSMR-VRR and SSMR-MS, the solar

energy was utilized to provide the heat, thus reducing the heat loss through the flue gas. From the comparisons, SSMR-VRR process has the highest process energy efficiency because the heat is directly absorbed by the volumetric receiver reactor and used for steam reforming reaction, whereas, in SSMR-MS process, the heat from the concentrated solar energy is exchanged through molten salt heat carriers.

As given in Fig. 8, solar steam methane reforming using molten salt (SSMR-MS) has the highest energy efficiency: that is, 10% greater than conventional steam methane reforming. solar steam methane reforming using volumetric receiver reactor (SSMR-VRR) for hydrogen production results in 9% increase in energy efficiency compared to the conventional steam methane reforming.

#### 4.3. Economic analysis

The levelized cost of hydrogen production (LCHP) requires three cost components, including, capital investment cost, production cost, and hydrogen production rate. The production cost comprises cost of

Table 2  
Process design result summary.

Results	Case 1 (CSMR)	Case 2 (SSMR-VRR)	Case 3 (SSMR-MS)	Case 4 (STP-WE)
Natural gas consumption (kt/yr) (Raw materials and fuel)	150.35	129.85	132.36	–
Water consumption (kt/yr)	455.95	417.19	454.16	462.14
Electricity consumption, (GWh)	106.61	92.72	83.73	2218.01 (280 MW) <sup>a</sup>
CO <sub>2</sub> emissions (kt/yr) (Flue gas and removed CO <sub>2</sub> )	411.25	355.19	356.83	–
Required heat duty for designing solar concentrators system (MW)	–	65.95	43.79	–
Solar thermal energy design point (MW)	–	66.00	44.00	909 <sup>b</sup> .00
Solar concentrators area (m <sup>2</sup> ) <sup>c</sup>	–	173,000.00	187,000.00	1,800,000.00
Land area required (acre)	–	281.00	297.00	3946.00
Solar tower height (m)	–	112.00	93.00	214.00
Thermal storage heat duty (MW) (15 h of heat storage)	–	–	792.00	6816.00

<sup>d</sup> Typical value from Canada is used for solar irradiance.

<sup>a</sup> The solar thermal power plant is designed to have capacity of 140 MW; therefore, 2 solar thermal power systems are required.

<sup>b</sup> The solar thermal energy design point of case 4 is calculated by assuming thermal to electricity power conversion efficiency of 37%, given by SAM [29].

<sup>c</sup> Solar concentrators, i.e. heliostats, area are designed based on the direct normal irradiance of 950 W/m<sup>2</sup>.



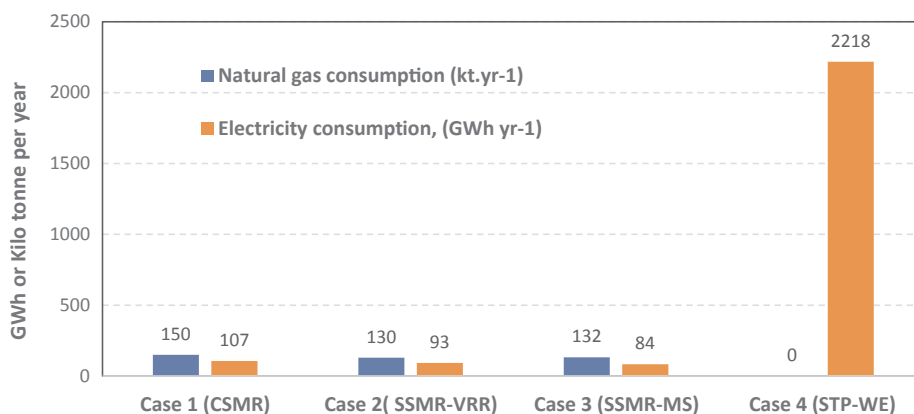


Fig. 7. Comparison between natural gas/Electricity consumption in different cases.

raw materials, utilities, operations, maintenance and overhead. Table 3 summarizes all estimated costs associated with the LCHP of each process, and Fig. 10 shows the LCHP summary of all cases.

It can be clearly seen that the highest production cost component is the raw materials cost, followed by the utilities cost. The reason behind these high costs is the large amount of natural gas being consumed in the process. Therefore, it is possible to reduce these costs by utilizing the solar energy as in the SSMR-VRR and SSMR-MS processes.

The raw material cost of the electrolysis plant is very small because this process only has water as a raw material. Most of the production cost come from the maintenance cost since it was estimated as a percentage of the capital investment cost, which is very high for this electrolysis plant.

The cost summary indicates the cost of heliostats dominates other equipment costs. With this additional equipment, the total capital investment cost of this process is higher than that of the conventional SMR process.

The raw materials cost of SSMR-VRR and SSMR-MS process is lower than that of the SMR process as a result of lower natural gas being used in this process. However, the maintenance cost increases significantly because of higher capital investment cost.

The results demonstrate that the levelized cost of hydrogen production of conventional steam methane reforming (CSMR) is the lowest; the LCPH of steam methane reforming using volumetric receiver reactor (SSMR-VRR) is around \$2.5 per kg hydrogen, which is 46% more than that of CSMR, while the LCPH of SSMR-MS is around \$3.8 per kg hydrogen, which is 50% more than CSMR. Solar thermal power generation coupled with water electrolysis has the highest LCPH of \$7.6 per kg; most of it is from the capital investment cost as shown in

Table 2. Solar thermal power plant requires a huge investment due to their large installation capacity. This case might be promising in very near future, when there is a reduction in the cost of solar systems and electrolyzers. Since the SSMR-VRR and SSMR-MS utilize the same method of producing hydrogen, therefore, their LCPH are very near to each other, however, using solar thermal storage system in case 3 (SSMR-MS) increases its LCPH compared to that of case 2 (LCPH-VRR).

#### 4.4. Environmental analysis

As for the environmental impact of each process, Fig. 11 illustrates the total CO<sub>2</sub> emissions rate during the hydrogen production including removed CO<sub>2</sub> from Amin plant and flue gas. It can be seen that the CO<sub>2</sub> emissions corresponds to the natural gas consumption rate, i.e., the lower the natural gas consumption rate, the lesser the CO<sub>2</sub> emissions. For both SSMR-VRR and SSMR-MS cases, the CO<sub>2</sub> emissions decrease notably in the combustion flue gas by 45.5 and 53.6 kilo-tons per year, respectively, which indicate the benefit of solar energy utilization in the conventional steam reforming of natural gas process (CSMR). Case 4 (STP-WE) does not have any CO<sub>2</sub> emissions, due to its different process for hydrogen generation using the clean renewable energy and water electrolyser.

#### 4.5. Summary

Fig. 12 demonstrates simultaneously all four hydrogen production cases in terms of economic, environmental, and technical indexes. It can be seen that case 4 is the worst (greater cost) in terms of economy and energy efficiency. Economic analysis suggests that currently the

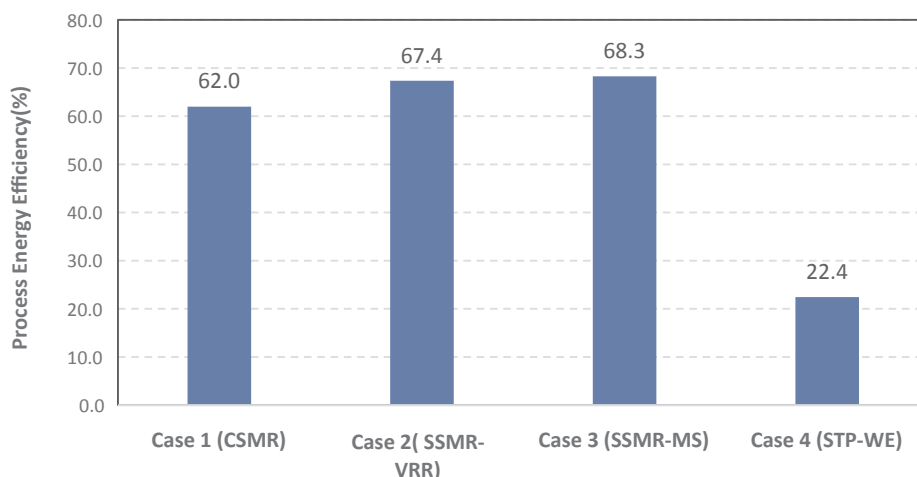


Fig. 8. Energy efficiencies of all hydrogen production cases.

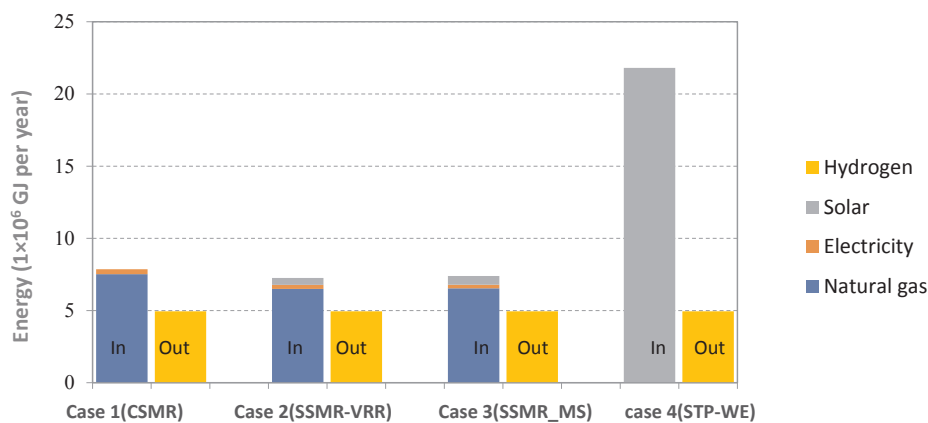


Fig. 9. Overall energy input and output of all hydrogen production cases.

Table 3

Summary of estimated cost associated with different hydrogen production cases.

Cost details	Cost (M\$)			
	Case 1 (CSMR)	Case 2 (SSMR-VRR)	Case 3 (SSMR-MS)	Case 4 (STP-WE)
<i>Capital investment cost</i>				
Purchased cost of all process equipment	25.9	25.6	26.6	243.9
Purchased cost of all solar-related equipment	–	41	98.8	1853.2
Land	1.6	6.6	10.9	79
Working capital	22.2	60.2	113.3	202
<b>Total capital investment cost</b>	<b>154.5</b>	<b>406.5</b>	<b>756.1</b>	<b>3962.8</b>
<i>Production cost</i>				
Raw materials	24.7	20.5	24.8	2.7
Utilities	17.1	16.4	13	4.8
Operations	2.8	4.5	4.5	12
Maintenance	10.4	27.2	51.1	105.7
Overhead	5.6	14	25.4	44.8
<b>Total production cost</b>	<b>60.6</b>	<b>82.4</b>	<b>118.8</b>	<b>170.</b>

thermochemical processes (SSMR-VRR and SSMR-MS) have more potential for producing the hydrogen required by the crude oil upgrader and SSMR-VRR has a lower LCHP than SSMR-MS. The steam methane reforming using molten salt (SSMR-MS) has the higher energy efficiency than the other alternatives. Solar thermal power generation using water electrolysis (STP-WE) has the lowest greenhouse gas emissions among all the other hydrogen production cases.

The advantages and drawbacks of the proposed hydrogen production cases using solar energy are summarized in the following table (Table 4).

### 5. Conclusion

This paper has investigated the integration of renewable energies in the oil and gas industries (crude oil upgrader processes) by utilizing solar energy for hydrogen production. Today’s refineries mostly produce hydrogen through steam methane reforming, which produces high level of CO<sub>2</sub> emissions. This work proposes three hydrogen production methods using solar energy: Solar Steam Methane Reforming using Volumetric Receiver Reactor (SSMR-VRR), Solar Steam Methane Reforming using Molten Salt as a heat carrier (SSMR-MS), and Solar Thermal Power generation coupled with Water Electrolyser (STP-WE). It has compared them with conventional steam methane reforming using the technical, economic, environmental criteria. The hydrogen production cases were conceptually designed and simulated to achieve the hydrogen production capacity of 2577 kmol per hour, which the demand in the crude oil upgrader process. Economic analysis of each

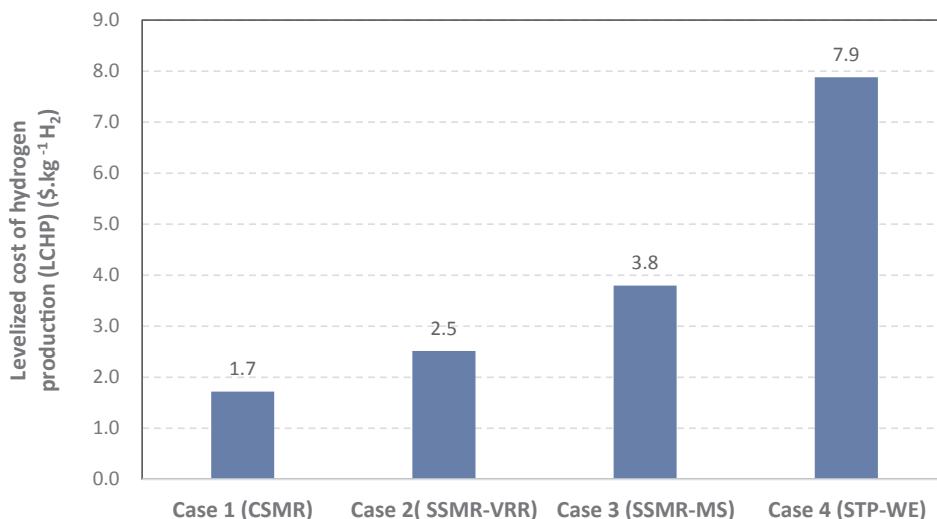


Fig. 10. Levelized cost of hydrogen production (LCHP) for different hydrogen production cases.

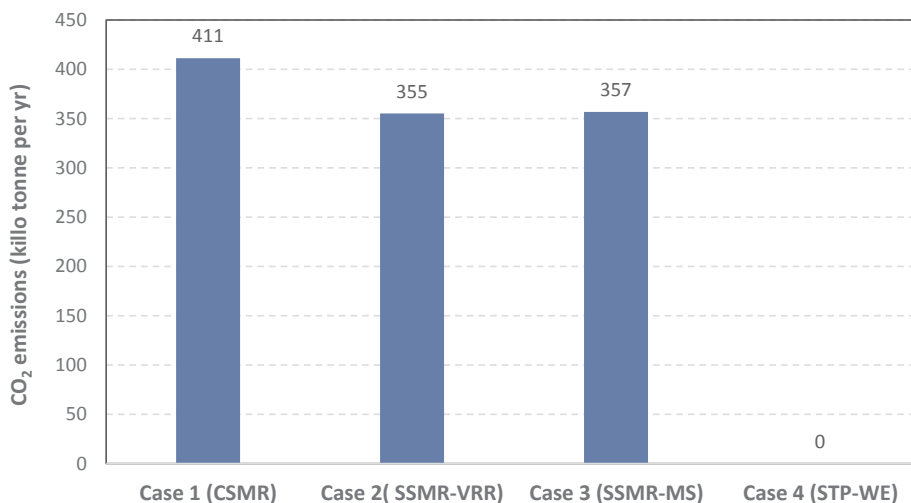


Fig. 11. Greenhouse gas emissions for different hydrogen production cases.

process was performed using the levelized cost of hydrogen production (LCHP).

The economic analysis suggests that currently the thermochemical processes (SSMR-VRR and SSMR-MS) have more potential for producing the hydrogen required by the crude oil upgrader. However, SSMR-VRR has a lower LCHP than SSMR-MS. The LCHP of the electrochemical process (STP-WE) is very high, due to its capital investment cost for the renewable energy equipment; however, when the renewable energy technologies advances enough to lead to their capital cost decrease, STP-WE process will be a more promising option for hydrogen production, since it is considered clean and sustainable. Solar thermal power generation using water electrolysis (STP-WE) has the lowest greenhouse gas emissions among the hydrogen production cases.

The solar steam reforming of natural gas using a volumetric receiver reactor (SSMR-VRR) has been shown to have the minimum levelized cost of hydrogen production, at \$2.5 per kg of hydrogen, which is 46% higher than of the conventional hydrogen production process (CSMR). However, the simulation results demonstrates that this process has benefit of lower environmental impact; the CO<sub>2</sub> emission and natural gas consumption were reduced by 14% and 14%, respectively, compared to CSMR.

The steam methane reforming using molten salt (SSMR-MS) has the highest energy efficiency, 68%, which is 10% higher than that of conventional steam methane reforming (CSMR). Moreover, the CO<sub>2</sub> emissions, natural gas, and electricity consumption have been reduced by 13%, 12%, and 21%, respectively, compared to CSMR.

Table 4  
Pros and cons of solar aided hydrogen production methods for industrial applications.

Processes	Benefits	Drawbacks
CSMR	–	–
SSMR-VRR	– Higher energy efficiency – Reduced natural gas consumption – Reduced water consumption – Lower CO <sub>2</sub> emissions – Lowest LCHP	– Limited operation hours of the volumetric receiver reactor – 2 modes of operations could lead process complexity
SSMR-MS	– Higher energy efficiency than CSMR – Reduced natural gas consumption – Reduced water consumption – Lower CO <sub>2</sub> emissions – Thermal energy storage allows constant operation	– Heat from concentrated solar can only be used to pre-reform the natural gas
STP-WE	– Virtually no CO <sub>2</sub> emissions – High purity oxygen by-product – Clean and sustainable	– Lower energy efficiency – required large land area – Expensive equipment – Highest LCHP

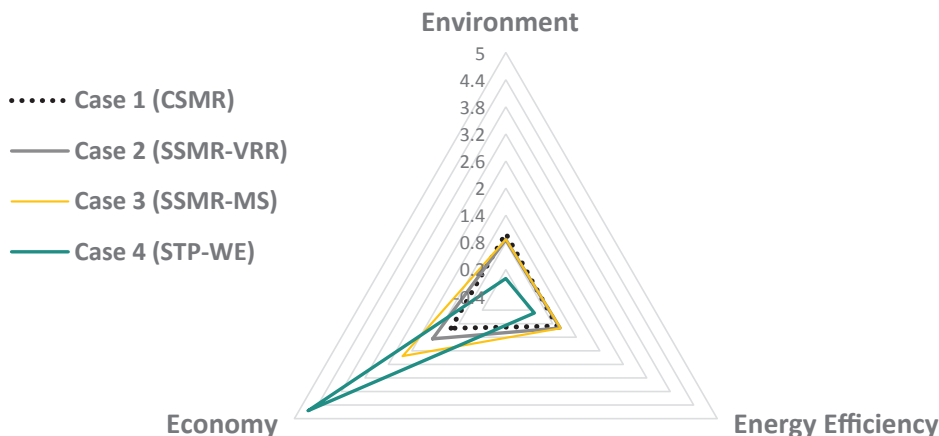


Fig. 12. Sustainability Radar chart for different hydrogen production cases.

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