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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 levelized 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 Electrolysor (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_2 emissions. Since there are more concerns to reduce environmental impacts due to new regulations for the CO_2 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 hydrotreater 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_2 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_2 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