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Economic analysis of hydrogen production by methane thermal decomposition: Comparison to competing technologies

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ABSTRACT

This study is a comparative analysis of hydrogen production costs in current and potential future market environments. The economic feasibility of hydrogen production by thermal decomposition of methane was compared to two other technologies, namely steam methane reforming and water electrolysis. According to the results, thermal decomposition of methane would be most suited for on-site demand-driven hydrogen production in small or medium industrial scale. Hydrogen production by thermal decomposition of methane would be economically competitive with steam reforming with a product carbon value of at least 280–310 EUR/tonne. By contrast, the main benefit of thermal decomposition of methane in comparison with water electrolysis is the feedstock availability via the current natural gas infrastructure, whereas electrolysis is highly dependent on the cost and availability of renewable electricity. The major factors affecting the economic feasibility were identified as product carbon value in thermal decomposition of methane, natural gas cost in steam reforming, and electricity cost in electrolysis. Thus, the effect of these variables on the hydrogen production costs was analyzed. Additionally, the specific carbon dioxide emissions in hydrogen production by thermal decomposition of methane ($40\,kg_{CO_2}/MWh_{H_2}$) were found to be much less that by steam reforming coupled with carbon dioxide capture from the syngas ($133\,kg_{CO_2}/MWh_{H_2}$).

1. Introduction

The International Energy Agency (IEA) estimates that the global energy demand will rise by 30% to 2040 and especially the transportation sector will undergo a fuel switch from oil to alternative energy sources [1]. In order to respond to the growing energy demand and limit the global CO_2 emissions, a transition from the current fossil-based economy to low-carbon economy is required. A possible future option would be the H_2 economy since H_2 has been identified to be one of the few potential energy carriers in the low-carbon economy. [2] However, the current H_2 production is based on steam methane reforming (SMR) of natural gas (48%), or utilization of other fossil fuels (48%) whereas the water electrolysis accounts for 4% of the H_2 production [3]. The usage of fossil fuels for H_2 production causes annually 500 million tonnes of CO_2 emissions, which corresponds to around 2% of the global energy-related CO_2 emissions [4].

In the future, the H_2 production is proposed to occur by electrolysis that is powered by renewable electricity [5]. However, due to the electrolyzer technology costs and the cost of renewable electricity, electrolytic H_2 is predicted to remain expensive the next decades [2]. The IEA predicts that the renewable electricity production capacity increases rapidly in the future [1]. Despite the fast growth, it is estimated that electrolysis cannot be applied to wide-scale H_2 production that would be required in the H_2 economy before the second half of the 21st century [6]. In order to begin developing the H_2 infrastructure and promoting the transition to the H_2 economy, alternative solutions that enable H_2 production with low CO_2 emissions are required as soon as possible.

Applying thermal decomposition of methane (TDM) to natural gas to produce H_2 and solid carbon has been proposed as a potential transition-period technology towards the H_2 economy [7]. A life-cycle analyses of TDM and SMR conducted by Dufour et al. [8,9] have revealed that TDM has a lower fossil energy consumption and total environmental impact than SMR even when carbon capture and storage (CCS) is coupled to SMR. Moreover, a study of the whole energy system reveals that the H_2 economy where H_2 is produced by TDM and used in fuels cells assuming that the natural gas leakages would be in control, can potentially reduce the global CO_2 equivalent emissions up to 27% in comparison with the current situation [10]. A benefit of TDM is the exploitation of the current natural gas infrastructure, and thus, it could provide a near-term solution for less polluting H_2 production. Moreover, H_2 production by TDM could be utilized to promote the H_2

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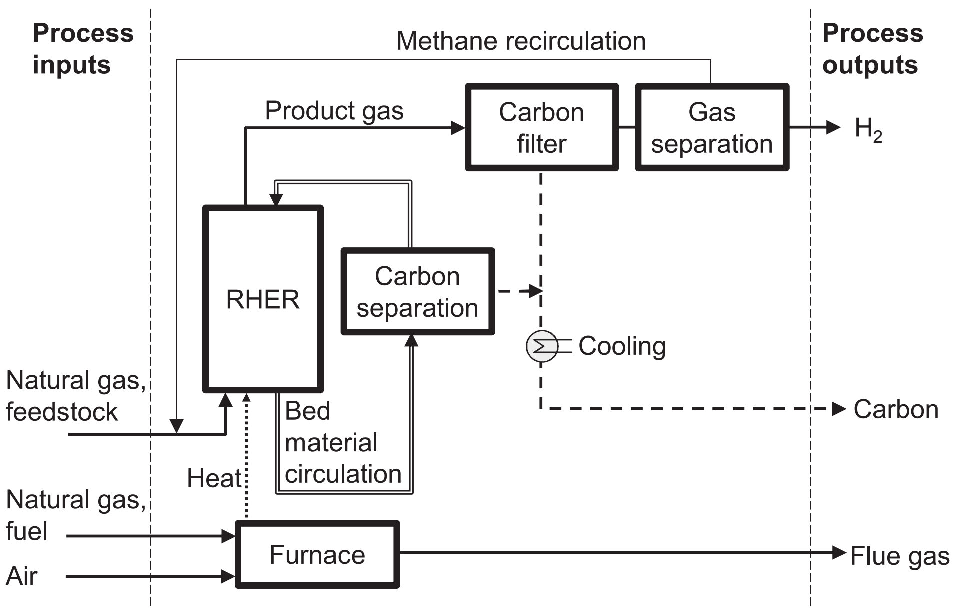

Fig. 1. Flow chart of the TDM process.

infrastructure development, and thus, smoothen the transition to the H_2 economy in the future.

Several techno-economic assessments of various H_2 production technologies have been published. Mueller-Langer et al. [11] evaluated the H_2 production costs by SMR, coal and biomass gasification, and water electrolysis. They hypothesized that at the early stages of the H_2 economy, H_2 would be produced in large-scale fossil fuel based units combined with CCS. Thus, they proposed that SMR would be the most feasible H_2 production technology in the near future and calculated that the production costs would be 36 EUR/MWh without CCS and 39.6 EUR/MWh with CCS [11]. Similarly, Simbeck and Chang [12] found SMR as less expensive H_2 production technology than coal partial oxidation, biomass and petroleum coke gasification, or water electrolysis. In their analysis, the H_2 production costs by SMR varied from 30 EUR/MWh to 67 EUR/MWh depending on the sequential H_2 delivery solution [12]. Less mature technologies were studied by Khojasteh Salkuyeh et al. [13] who analyzed economics of H_2 production from natural gas by two chemical looping processes in comparison with existing SMR and auto-thermal reforming of natural gas. According to the results, chemical looping reforming technology is promising when the energy efficiency, emissions, and H_2 production costs are considered. However, due to the technical challenges related to the heat transfer inside the process, catalyst durability, and continuous operation, further research is required until the chemical looping reforming technology is commercially available [13]. Furthermore, Yao et al. [14] conducted a techno-economic assessment of H_2 production by biomass gasification, biogas reforming, and water electrolysis. As a result, the economic feasibility of the three processes was about the same when the H_2 production capacity was 1000 Nm^3/h [14].

Yaun et al. [15] evaluated the H_2 production costs of various thermochemical processes using different feedstocks, i.e., natural gas, diesel, methanol, and biomass. One of the technologies in the analysis was applying catalytic methane decomposition to natural gas in order to produce H_2 and carbon nanotubes. According to the results, the H_2 production by methane decomposition would be economically competitive with SMR when the value of the product carbon from methane decomposition would be more than 440 USD/t_C and the CO_2 emission allowance cost would be 35 USD/t_{CO_2} [15]. Parkinson et al. [16] analyzed the cost of H_2 production by TDM that is conducted in a molten metal process. According to the results, H_2 production by TDM was competitive with SMR with the product carbon value of 200 USD/t_C and a carbon tax of 78 USD/t_{CO_2}. Moreover, decreasing the TDM reaction temperature below 1300 K by applying a suitable catalyst would further improve the economic feasibility of TDM [16]. A recent study [17] discussed the status and perspectives of three alternative technologies for H_2 production with low CO_2 emissions, namely fossil-based H_2 production plant coupled with CCS, thermal decomposition on various hydrocarbons, and H_2 processes integrated with nuclear or solar energy. The competitiveness of thermal decomposition process was highlighted to depend on the technology development of the process, market development for the product carbon from process, and tightening of the carbon dioxide emission regulation [17].

This paper is a continuation of a previous techno-economic analysis of four commercial scale process concepts for TDM that was conducted by some of the authors [18]. One of the concepts presented in that study was taken as a starting point in the current study and the analysis was complemented by applying the technology development work presented in [19] in the reactor design. Thus, this paper combines the previously conducted technical analysis of TDM with an economic analysis. As a result, this paper illustrates the market conditions where TDM would be an economically feasible technology for H_2 production in comparison with SMR and electrolysis. In addition to the evaluation of the current market situation, i.e. where the current natural gas and electricity costs are applied, the future market environment is discussed as well. In order to take into account the environmental aspects, the specific CO_2 emissions in H_2 production in each process were calculated.

2. Analyzed processes

This section introduces the four processes for H_2 production that were analyzed in this study. The processes are outlined and the process flow charts are presented.

2.1. Thermal decomposition of methane process

In TDM, methane is converted to gaseous H_2 and solid carbon. The global reaction equation for methane decomposition is [20]:

$$CH_4(g) \rightarrow C(s) + 2H_2(g) \quad \Delta H_r^0 = +76\ \text{kJ/mol} \tag{1}$$

The methane conversion and the properties of the product carbon depend on the reaction conditions e.g. temperature, reaction time and catalyst properties if one is applied. The influence of the reaction conditions on the TDM reaction and product carbon quality have been