Cost Analysis of Nuclear Hydrogen Production Using IAEA-HEEP 4 Software

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Abstract. Hydrogen is a commercially important element. Basically, there are several methods of hydrogen production that have been commercially used, such as Steam Methane Reforming (SMR), High Temperature Steam Electrolysis (HTSE), and thermochemical cycles, like Sulphur-Iodine (SI). Among these methods, SMR is the most widely used for large-scale hydrogen production, with conversion efficiency between 74–85% and it has commercially used in some fertilizer industries in Indonesia. Steam reforming is a method to convert alkane (natural gas) compounds to hydrogen and carbon dioxide (synthetic gas) by adding moisture at high pressure and temperature (35-40 bar; 800-900°C). These hydrogen production technologies can be coupled with different nuclear reactors based on the heat required in the process. The High Temperature Gas-cooled Reactor (HTGR) using helium as a coolant, has a high outlet temperature (900°C), so it can potentially be used to supply for process heat for hydrogen production, coal liquefaction/ gasification or for other industrial processes requiring high temperature heat. Hydrogen production cost from SMR method is influenced by a range of technical and economic factors. The fuel component of natural gas needed in the SMR method can be replaced by nuclear heat from a nuclear power plant (NPP) operating in cogeneration mode (i.e. simultaneous producing electric power and heat), hence contributing to the reduction of carbon dioxide in the process.

In the SMR method, fuel costs are the largest cost component, accounting for between 45% and 75% of production costs. Therefore, there is opportune to assess the economics of hydrogen production by using nuclear heat. The economic evaluation is done by using IAEA HEEP-4 Software.

The results comprise cost break up for 2 cases, coupling SMR process for hydrogen production with: (1) 2 HTGRs of 170 MWh/unit; and (2) 1 HTGR of 600 MWh/unit. The cost of hydrogen production is highly depend on the scale of the NPP as energy source and results indicated that hydrogen production cost of the 1 HTGR Unit600 MWh (Case 2) has a lower value (1.72 US$/kgH₂), than the cost obtained when 2 HTGR units of 170 MWh each (case 1) are considered (2.72 US$/kgH₂). For comparison, the hydrogen production cost by using SMR with carbon capture and storage (CCS) with natural gas as fuel is 2.27 US$/kgH₂.

Keywords: nuclear, cogeneration, hydrogen, HTGR, HEEP-4, economy, steam methane reforming
1. Introduction

As of 2019, roughly 70 million tons of hydrogen are produced annually worldwide [7] mostly used in oil refining (~25%) and for the production of ammonia (~55%) and fertilizers. Other applications are in methanol production (~10%), the steel industry, food processing and electronics sectors [1].

There is various method for hydrogen production, namely: Steam Methane Reforming (SMR), natural gas reforming/ gasification, electrolysis, renewable liquid reforming, and fermentation [2,3]. Among these methods, SMR is the most common and developed method used for large-scale hydrogen production. SMR uses natural gas both as raw material and fuel with conversion efficiency between 74–85% [4]. Ratio of natural gas used as raw material to natural gas used as a fuel is 40%:60%. Therefore, it is opportune to seek solutions to replace natural gas fuel by other energy sources, one of which being nuclear heat. This contributes to reducing the greenhouse gas emissions released in the hydrogen production process and also to the economy of natural gas reserves.

Steam reforming converts alkane (natural gas) compounds to hydrogen and carbon dioxide (synthetic gas) by adding moisture at high pressure and temperature (35-40bar; 800-900°C). The process is achieved through four main steps: desulfurization, catalytic reforming, CO conversion, and gas separation [5]. The process requires heating the gas to between 700–1100 °C in the presence of steam and a nickel catalyst. The resulting endothermic reaction breaks up the methane molecules and forms carbon monoxide CO and hydrogen H₂. The CO gas can then be passed with steam over iron oxide or other oxides and undergo a water gas shift reaction to obtain further quantities of H₂. The downside to this process is that its major byproducts are CO, CO₂ and other greenhouse gases, depending on the quality of the feedstock (natural gas, naphtha, etc.).

Therefore, considering environmental impact and a drive for saving natural gas reserves in Indonesia, investigation of replacing the natural gas used as fuel in the SMR process for hydrogen production with nuclear heat is opportune.

Nuclear energy is an excellent source of process heat for various industrial applications including desalination, synthetic and unconventional oil production, oil refining, biomass-based ethanol production, and hydrogen production. One of the nuclear power reactors that has the potential to be used to supply high temperature steam for hydrogen production process is High Temperature Gas Cooled Reactor (HTGR). HTGR is helium- cooled and graphite-moderated and uses a thermal neutron spectrum, with an outlet coolant temperature of ~800°C [8,9]. Due to a high coolant outlet temperature, HTGR can be used for the generation of hydrogen through several endothermic processes, such as steam reforming. It has also potential for cogeneration purposes, wherein part of the heat is used to produce electricity and part of the other is used to produce hydrogen, so electricity and hydrogen can be simultaneously produced. The use of nuclear power plants (NPPs) in cogeneration systems provides many economic, environmental and efficiency related benefits [10].

This study was conducted to analyze the economics of nuclear hydrogen using IAEA HEEP-4 Software.

2. Methodology

The economic evaluation of hydrogen production cost using cogeneration of HTGR with a SMR plant was carried out by using the IAEA HEEP Software. HEEP stands for Hydrogen Economic Evaluation Programme and is a tool provided freely by IAEA to Member States to analyze economics of the most promising processes for hydrogen production (high and low-temperature electrolysis, thermo-chemical processes including Sulphur–Iodine (S-I) process, and steam reforming). A literature review of hydrogen production by SMR was performed to determine to most representative input parameters for the economic model.
3. Theory

3.1. Hydrogen Production Methods
Hydrogen can be produced from diverse, domestic resources including fossil fuels, biomass, and water electrolysis with electricity. The environmental impact and energy efficiency of hydrogen depends on how it is produced.

There are a number of ways to produce hydrogen: [11,12,13,14]

- Natural Gas Reforming/Gasification: synthesis gas, which is a mixture of hydrogen, carbon monoxide, and a small amount of CO$_2$, is created by reacting natural gas with high-temperature steam. The CO gas is reacted with water to produce additional hydrogen. This method is the cheapest, most efficient, and most common. Natural gas reforming using steam accounts for the majority of hydrogen produced in the United States annually.

  A synthesis gas can also be created by reacting coal or biomass with high-temperature steam and oxygen in a pressurized gasifier, which is converted into gaseous components—a process called gasification. The resulting synthesis gas contains hydrogen and carbon monoxide, which is reacted with steam to separate the hydrogen.

- Electrolysis: An electric current splits water into hydrogen and oxygen. If the electricity is produced by renewable sources, such as solar or wind, the resulting hydrogen will be considered renewable as well, and has numerous emissions benefits. Power-to-hydrogen projects are taking off, where excess renewable electricity, when it's available, is used to make hydrogen through electrolysis.

- Renewable Liquid Reforming: Renewable liquid fuels, such as ethanol, are reacted with high-temperature steam to produce hydrogen near the point of end use.

- Fermentation: Biomass is converted into sugar-rich feedstocks that can be fermented to produce hydrogen.

Several hydrogen production methods are in development [12]:

- High-Temperature Water Splitting: High temperatures generated by solar concentrators or nuclear reactors drive chemical reactions that split water to produce hydrogen.

- Photobiological Water Splitting: Microbes, such as green algae, consume water in the presence of sunlight, producing hydrogen as a byproduct.

- Photoelectrochemical Water Splitting: Photoelectrochemical systems produce hydrogen from water using special semiconductors and energy from sun.

3.2. Cogeneration System
Cogeneration systems refer to energy systems that have the ability to produce two useful commodities simultaneously. Cogeneration systems are combined heat and power plants, where electricity and useful heat are both produced from one plant. Cogeneration is a highly efficient energy orientation that can achieve primary energy savings compared to conventional power and heat supply.

Furthermore, aside from electricity and heat combination, commodities include heat for desalination, hydrogen production and other applications. In essence, Cogeneration system is a process that produces electricity and heat simultaneously. The schematic diagram of Cogeneration of HTGR type reactor with hydrogen production plant of SMR is shown in Figure 1.
Figure 1. Schematic diagram of nuclear heat supply for hydrogen plant [15].

Table 1. Input data for NPP and Hydrogen Production Plant [16]

| NPP | Case-1 2 HTGRs of 170 MWth/unit | Case-2, 1 HTGR of 600 MWth/unit | Hydrogen Production Plant (Steam Methane Reforming Method) |
|-----|--------------------------------|---------------------------------|----------------------------------------------------------|
| Thermal rating (MWth/unit) | 170 | 600 | \( \text{H}_2 \) generation rate (kg \( \text{H}_2 \)/s) | 4.2 |
| Heat for \( \text{H}_2 \) plant (MWth/unit) | 65.3 | 170 | \( \text{H}_2 \) generation per unit (kg/unit) | 5.9E+7 |
| Electricity rating (MWe/unit) | 21.3 | 202 | Heat consumption (MWth/unit) | 65.3 |
| Number of units | 2 | 1 | Electricity required (MWe/unit) | 33 |
| Initial fuel load (kg/unit) | 2396 | 7090 | Number of units | 2 |
| Annual fuel feed (kg/unit) | 767 | 1773 | Capital cost (USD/kg \( \text{H}_2 \)) | 2.0E+8 |
| Capital cost (CC) (USD/unit) | 6.0E+8 | 5.47E+8 | Energy Usage cost (USD) | 6.15E+6 |
| CC fraction for electricity infrastructure (%) | 10 | 10 | Other O&M cost (% of CC) | 7.78 |
| Fuel cost (USD/kg fuel) | 22937 | 5800 | Decommissioning cost (% of CC) | 10 |
| O&M cost (% of CC) | 4 | 3.81 | Annual water consumption (L/yr) | 0 |
Case-1: 2 HTGRs of 170 MWth/unit  
Case-2: 1 HTGR of 600 MWth/unit  
Table 2. Financial Parameter

|                        | Discount Rate | Inflation Rate | Equity/ Debt | Borrowing Interest | Tax rate |
|------------------------|---------------|----------------|--------------|--------------------|---------|
|                         | 10%           | 3%             | 70%/30%      | 5%                 | 25%     |

4. Results and Discussion

Hydrogen is a commercially important element. It is used for many industrial applications and to provide a lower carbon emission technology for its production, this study investigated the option of using nuclear heat to replace the fuel component of gas in the SMR process.

Hydrogen production cost will strongly depend on the price of feedstocks and process efficiency, as well as a wide variety of other parameters such as nuclear plant size and plant availability, maturity of the technology, and physical distance to end-use markets. The nuclear power plant that can produce the high temperatures steam of about 850 to 950°C required to gasify coal and convert natural gas to hydrogen may be achieved only in high-temperature gas-cooled nuclear reactors (HTGR) type reactor. The nuclear reactor coupled to hydrogen production has the potential for higher overall energy use efficiency and better utilization of capital equipment.

Results of calculations by using IAEA HEEP software are presented in Table 3 and in Figures 2 and 3, in terms of levelized cost of hydrogen production and cost breakup, respectively. Two cases were discussed for providing the heat needed for the SMR process from nuclear reactors: (1) two units HTGR (170 MWth/unit); (2) 1 unit NPP (600 MWth).
Results as shown in Figure 2 and 3 show cost break up. For case 1, the NPP cost is 1.69 USD (62.02%), hydrogen generation plant cost is 0.71 USD (26.13%), hydrogen storage 0.19 USD (7.15%) and hydrogen transportation 0.13 USD (4.7%). Cost breaks up for case 2 indicated that NPP cost is 0.65 USD (38.07%), hydrogen generation plant cost is 0.78 USD (45.64%), hydrogen storage 0.17 USD (9.6%) and hydrogen transportation 0.12 USD (6.69%). The cost of producing hydrogen depends on the capital, operation, maintenance, feedstock costs, (Kothari et al., 2008).

For instance, from feedstocks viewpoint, cost of hydrogen from fossil fuels is highly dependent on the price of natural gas and other conventional fuels, while the cost of hydrogen produced from renewable energy resources depends on the level of advancement of renewable energy technologies, and whether the system is connected or not to the electric grid.

The cost of hydrogen is highly influenced by the scale of the NPP as energy source for hydrogen production process heat and nuclear hydrogen generation plant. For example, 1 unit of 600 MWth HTGR produces hydrogen at a lower cost of 1.72
Table 3. Summary of HEEP calculation for 2 cases NPP

|                     | Case-1  | Case 2,  |
|---------------------|---------|----------|
|                    | 2 HTGRs | 1 HTGR   |
|                    | of 170  | of 600   |
| MWth/unit          |         | MWth/unit|
| Nuclear Power Plant| 1.69    | 0.65     |
| Hydrogen Generation Plant | 0.71 | 0.78     |
| Hydrogen Storage   | 0.19    | 0.17     |
| Hydrogen Transportation | 0.13 | 0.12     |
| Total of all Facilities | 2.72 | 1.72     |

US$/kgH₂ (case 2) compared to the 2 HTGR units of 170MWth each for which the hydrogen production cost obtained is 2.72 US$/kgH₂ (case 1).

5. Conclusion
Coupling hydrogen production plant to a nuclear energy system offers a multitude of advantages. One example is the coupling of HTGR with a SMR process for hydrogen production, capitalizing on the heat generated by the nuclear reactor and contributing to the reduction of the carbon dioxide emissions by replacing the gas fuel needed in the process with nuclear heat. In addition, by coupling the NPP with the hydrogen generation plant the thermal efficiency of NPP increases. The economic evaluation conducted in this study provides a good insight on the breakdown of costs and the results indicated a competitive value obtained when nuclear heat from HTGR is used (2.72$/kg H₂ – case 1, 1.72$/kgH₂ – case 2), as compared with an average value (2.3$/kgH₂) obtained for hydrogen production by SMR method using gas as a fuel, which varies from about 1.25 US$/kg for large systems to about 3.50 US$/kg for small systems.[19]

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