# Nuclear Hydrogen Production Analysis for

# GT-HTR using HEEP Software

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**Abstract**

Hydrogen demand is expected to sharply increase shortly as technology development uses hydrogen as a new energy source. Currently hydrogen production relies primarily on fossil fuels, which are neither environmentally friendly nor economically efficient. In order to establish a hydrogen economy, it is imperative to produce a large amount of hydrogen in a clean, safe, and efficient manner. Nuclear production of hydrogen could enable a massive production of hydrogen at affordable prices while also reducing environmental pollution by cutting down on carbon dioxide emissions. Otherwise, both the need for using low-carbon energy sources and the significant advantage of SMRs lies in their adaptability to be coupled with other energy systems, like hydrogen production plants, to generate a cogeneration plant, which can efficiently produce both electricity and hydrogen while reducing overall emissions. A Gas-Turbine Modular-Helium Reactor (GT-MHR600) is an efficient reactor that can be used with the thermo-chemical Sulfur Iodine (SI) cycle to produce hydrogen. To evaluate the economy of the nuclear hydrogen production system, the International Atomic Energy Agency (IAEA) has developed software tools such as HEEP (Hydrogen Economy Evaluation Program) [2, 3]. This paper uses HEEP to calculate the Levelized cost of Hydrogen (LCOH) for a nuclear hydrogen production plant consisting of four modules of 600 MWth GT-MHR coupled with the SI process.

## INTRODUCTION

The worldwide need for energy rises in line with increasing population and prosperity. As a result, energy plays a vital part in shaping the policies of both local and international governments, as well as their economic strategies, environmental policies, sustainability efforts, and social development **[1]**. Energy systems reliant on fossil fuels are viewed as unsustainable due to their limited reserves and impact on the environment. The transition from fossil fuels to nuclear and renewable resources is anticipated due to the growing demand for energy and mounting concerns regarding environmental issues such as global warming. Hydrogen is anticipated to emerge as the primary solution for addressing our current energy and environmental challenges, according to numerous energy experts and stakeholders. It is free of carbon, does not release greenhouse gases, and does not contribute to global warming. Hydrogen is viewed as a promising option for serving as an excellent energy carrier, expanding markets for renewable and nuclear energy resources, promoting sustainability, and addressing environmental issues **[2]**. Although hydrogen is naturally abundant in the form of water, it is not found in its pure form, necessitating its production in a sustainable and eco-friendly manner. Various methods for producing this include thermochemical water decomposition, water electrolysis, coal gasification, and steam reforming of natural gas **[3]**.

The main methods for production of hydrogen from diverse energy sources are displayed in **Fig. 1**.



*FIG. 1. Techniques used for Hydrogen production [3].*

Nuclear hydrogen production can be achieved through different methods, such as low-temperature electrolysis, high-temperature electrolysis, thermochemical, and hybrid processes. Low-temperature electrolysis involves using electrical power to split water into hydrogen and oxygen, but it consumes a high amount of electricity (~1.23 V/molH2O). On the other hand, high-temperature electrolysis, also known as steam electrolysis, requires less electrical energy compared to low-temperature electrolysis when splitting steam into hydrogen and oxygen. This method can achieve higher efficiencies by using heat as an energy source, although it is not yet commercially available. However, Idaho National Laboratory (INL) has demonstrated a lab-scale solid oxide electrolysis cell (SOEC) [4]. Thermochemical processes use a series of chemical reactions to split water into hydrogen and byproducts using high and/or medium-grade heat. Although heat is the primary energy source for these processes, additional electrical power is often necessary for certain electrolytic processes.

The development of small modular reactors (SMRs) has been advancing significantly in recent years, with some reactors and demonstration projects currently under construction [4]. Nearly all companies in the nuclear power industry have introduced their own SMRs, based on the structural features of their larger, already deployed nuclear reactors, as well as other specialized SMR designs. Most of these reactors are water-cooled typical or integral pressurized water reactors, and several high-temperature gas-cooled, sodium, and lead alloy-cooled fast SMRs are in the research and development stage [5]. In addition to their small size, the innovative and unique properties of SMRs enhance the safety margins and reliability of nuclear energy use. Ultimately, these characteristics support the public acceptance of nuclear energy in countries and regions planning for the construction of nuclear power plants (NPPs). The main characteristics of SMRs that have generated interest in these nuclear reactors are their modular construction, size, and the possibility of being connected to other energy-generating systems.

Small and mid-sized nuclear reactors serve as an alternative to traditional fossil fuel-based power plants and can be installed independently or as part of a larger complex. However, some countries are seeking to reduce their reliance on nuclear power plants, particularly large-scale ones, in favor of developing renewable energy-based power plants **[6]**. Many experts have proposed using renewable energy sources for hydrogen production due to their environmental benefits. However, the intermittent nature and lower intensity of renewable energy sources make it difficult to use them as the primary energy source for large-scale hydrogen production plants **[6,7]**. One potential solution is to combine renewable energy sources with nuclear or other power plants to take advantage of different energy sources. A gas turbine modular helium reactor (GT-MHR) is considered as an efficient reactor to couple with the thermo-chemical Sulfur Iodine (SI) cycle to achieve the hydrogen economy.

HEEP, short for Hydrogen Economy Evaluation Program, is a software tool developed by the IAEA **[8]** to assess the economic viability of nuclear hydrogen production by estimating the cost of unit hydrogen production. The research paper calculates the Levelized cost of Hydrogen (LCOH) using HEEP for a nuclear hydrogen production plant, comprising 4 modules of 600 MWth GT-MHR coupled with the SI process. The study examines various scenarios for hydrogen storage (compressed gas, liquefaction, metal hydrides) and transportation (pipeline and truck).

## methods and materials

### GT-MHR applications

The gas turbine modular helium reactor (GT-MHR) couples a HTGR with a Brayton power conversion cycle to produce electricity at high efficiency **[5]**. GT-MHT is expected for many applications taking advantage of their high temperature helium coolant of maximum 850 °C. Electricity generation, hydrogen production, process steam supply, and waste heat utilization are anticipated utilizing heat of various temperature ranges. **Fig. 2** illustrates examples of heat applications.



*FIG. 2. GT-MHR applications.*

As the reactor unit can produce high coolant outlet temperatures, the modular helium reactor system can also efficiently produce hydrogen, e.g. by high temperature electrolysis or thermochemical water splitting.

### HEEP software

The HEEP software package, developed by the IAEA, is a newly released tool for evaluating the economic aspects of large-scale nuclear hydrogen production, including storage and transportation options **[9]**. It can assess various hydrogen production methods, such as low and high-temperature electrolysis, thermo-electro-chemical hydrogen production, and steam methane reforming, in terms of their economic viability. The software includes details such as capacities, total capital cost, initial and annual fuel costs for cost estimation **[10]**. The technical details and specific case studies about the HEEP software package, including cost items (capital or fixed cost, operational costs, decommissioning cost), and an execution module for levelized costs of hydrogen production, can be found in other sources **[9-11]**.



*FIG. 2. Scenarios of hydrogen storage and transportation [3].*

The study compares the costs of producing hydrogen using GT-MHR. It considers different scenarios for storing and transporting hydrogen, as shown in **Fig. 2**. Each nuclear plant is assumed to have one type of hydrogen generation plant. The study evaluates the cost of producing hydrogen and storing it using different storage and transportation methods, except for metal hydride storage and liquefaction, which cannot be transported through pipelines. The levelized cost of hydrogen is calculated by the HEEP, which considers the present value of generated hydrogen, storage, and transportation compared to the present value of gross hydrogen generated **[9]**.

$$C\_{H\_{2}} = \frac{G\_{NPP}\left(t\_{0}\right) + G\_{H\_{2}GP}\left(t\_{0}\right) + G\_{H\_{2}T}\left(t\_{0}\right)}{G\_{H\_{2}}\left(t\_{0}\right)} \left[\$USD/kg\right]$$

where E, C, and G refer to expenditures, subscripts NPP, H2GP, and H2T refer to nuclear power plant, hydrogen generation and storage, and hydrogen transportation, respectively. The present values of expenditures are calculated with the following definition **[9,10]**:

$$E\left(t\_{0}\right) = \sum\_{t\_{start}}^{t\_{end}}\frac{CI\_{t}}{\left(1+r\right)^{t-t\_{0}}} + \sum\_{t\_{start}}^{t\_{end}}\frac{R\_{t}}{\left(1+r\right)^{t-t\_{0}}} + \sum\_{t\_{start}}^{t\_{end}}\frac{DC\_{t}}{\left(1+r\right)^{t-t\_{0}}} $$

Here, CI, R, and DC refer to capital investment expenditures, facility running expenditures and decommissioning expenditures

for the year t, respectively. Subscript 0 is for the base year, and r is the real discount rate. The present value of the gross hydrogen generation for the time t0 is given as follows:

$$G\_{H\_{2}}\left(t\_{0}\right) = \sum\_{t\_{start}}^{t\_{end}}\frac{G\_{H\_{2}}\left(t\_{0}\right)}{\left(1+r\right)^{t-t\_{0}}} $$

### Configuration of Nuclear Hydrogen Production

The nuclear hydrogen production system consists of four major sub-systems as explained below.

#### NHSS (Nuclear Heat Supply System)

NHSS is a GT-MHR reactor with a core outlet temperature higher than 850°C, which transfers energy in the form of either heat or electricity to the hydrogen production plant.

#### PCS (Power Conversion System)

PCS is a system that produces electricity from the high temperature heat from the reactor. PCS produces electricity using reactor high heat with gas turbine or steam turbine.

*2.2.3 HTS (Heat Transport System)*

The thermal heat generated from GT-MHR should be transported to the SI process to be used directly in hydrogen production. The pressurized helium gas is used as a working fluid to transfer heat from GT-MHR to SI process through the heat transport system.

*2.2.4 HPS (Hydrogen Production System)*

There are three potential nuclear hydrogen production processes, namely SI (Sulfur Iodine) process, THE (High Temperature Electrolysis) process, and Hybrid Process. The original Sulfure-Iodine (SI) process has been proposed by General Atomics (GA) and 75 L/h production is achieved through three key reactions.

The iodine-sulfur (IS) process is selected as the candidate hydrogen production method considering its potential to produce hydrogen with high thermal efficiency from water, which does not emit CO2 from neither material source nor heat source. The IS process consists of the following three chemical reactions **[12,13]**. H2O is decomposed thermally into H2 and O2 in total; iodine (I) and sulfur (S) compounds cycle within the process.

I2 + SO2 + 2H2O→ H2SO4 + 2HI (Bunsen reaction)

H2SO4 → H2O+ SO2 + 0.5O2

2HI → H2 + I2

The highest temperature requirement in the process is 800-900 °C for H2SO4 decomposition. The demand matches the maximum temperature of the GT-MHR helium coolant of 850 °C.

### Input data in HEEP software

*2.4.1 Model Nuclear Hydrogen Production Plant*

The four prismatic modular reactors coupled with SI cycle (GT-MHR, 4ⅹ600MWth) were chosen as a nuclear hydrogen production plant model for the LCP calculation using HEEP software. The specifications of the nuclear hydrogen production plant are shown in **Table 1**. The hydrogen production rate for four 600MWth prismatic modular reactors is calculated to be about 7.2 kg/s (205,000 tons/year), assuming a plant capacity factor of 0.9 and thermal efficiency of 48 %.

*2.4.2 Input Data to HEEP Software*

The Levelized cost of Hydrogen (LCOH) was calculated using HEEP software. The costs for nuclear hydrogen production plant are summarized on an annual basis in **Table 2** and this will be used as an input to the HEEP software to calculate LCOH. The total capital cost includes all direct and indirect costs, nuclear fuel cost for the initial core plus interest during construction. The fuel cycle costs include nuclear fuel fabrication cost plus spent fuel waste handling and disposal cost. Table 3 displays the time periods and financial features of GT-MHR, hydrogen production plant, storage using liquefaction, and transportation by pipelines. Table 4 illustrates the pipelines features.

TABLE 1. Nuclear POWER Plant AND HYDROGEN GENERATION PLANT COSTS

|  |  |
| --- | --- |
| Designation  | Value |
| **Nuclear power plant**  |  |
| Thermal ratting per unit  | 600 |
| Number of units | 2 |
| Electricity rating (MWe/unit)  | 288 |
| Efficiency (%) | 48 |
| Thermal heat of H2 plant (MWth/unit) | 340 |
| Max specific capital cost ($/kWe) | 5400 |
| Capital cost (M$) | 1050 |
| O&M cost (% of CC) | 5.8 |
| Fuel cost ($/kg) | 270 |
| Decommissioning cost (% of CC) | 10 |
| **Hydrogen generation plant (per unit)** |  |
| Annual hydrogen generation (ton/year) | 32,000 |
| Thermal energy required (MWth)/unit | 340 |
| Electric energy required (MWe)/unit | 25.4 |
| Capital cost (M$/unit) | 209 |
| Energy usage cost (M$) | 13.27 |
| O&M cost (%) | 7.78 |
| Decommissioning cost (%) | 10 |

TABLE 2. TIME PERIODS AND FINANCIAL PARAMETERS

|  |  |
| --- | --- |
| Designation  | Value |
| **General cost and operating parameters** |
| Discount rate  | 10% |
| Inflation rate | 6% |
| Interest rate | 10% |
| Tax rate  | 20% |
| Equity/debt | 70%/30% |
| Borrowing interest | 6% |
| Depreciation period | 20 years |
| Construction period | 4 years |
| Operation lifetime | 60 years |
| Cooling before decommissioning | 1 year |
| Decommissioning  | 9 years |
| Refurbishment | 30 years |
| Fuel cycle | 24 months |
| Waste cooling period | 24 months |
| Capacity factor | 90% |
| Availability factor | 100% |
| Unit cost of grid electricity (c$/kWh) | 6.6 |
| **Hydrogen generation plant**  |
| Construction period | 4 years |
| Operating life | 60 years |
| Cooling before decommissioning  | 1 year |
| Decommissioning period | 9 years |
| Capacity factor | 90% |
| Availability factor | 100 % |
| **Storage** |  |
| Hydrogen storage period, (h) | 168 |
| Unit cost of cooling water for storage ($/ML) | 0.00022 |
| O&M cost for hydrogen storage (%) | 5 |
|  **Liquefaction** |  |
|  Cooling water flow rate of liquefaction (L/kg H2) | 209 |
|  Daily boil-off rate (%) | 0.1 |

TABLE 3. TRANSPORTATION OPTIONS

|  |  |
| --- | --- |
| Designation | Value  |
| **Pipelines** |  |
| Transportation distance (km)  | 600 |
| Pipe equivalent radius (mm) | 125 |
| Inlet pressure of hydrogen (bar) | 52.3 |
| Delivery pressure (bar) | 50.0 |
| Temperature of hydrogen (K) | 293 |
| Friction factor | 0.01 |
| Decommissioning cost (%) | 1 |
| O&M cost (%) | 1 |

## PRELIMiNARY RESULTS

The Levelized cost of Hydrogen (LCOH) was calculated by the HEEP software, and it was 3.01 $/kg for the model system including storage and transportation as shown in Fig. 5.



*FIG. 3. SMR and H2 production features inside HEEP*

  

*FIG. 4. Storage method and H2 transportation features inside HEEP*



*FIG. 5. HEEP Calculation Result for the model system*

TABLE 4. DETAILS ABOUT HEEP RESULTS

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Capital cost (Debt) | Capital cost (Equity) | O&M + Refurbishment | Decommissioning cost | Facility total |
| Nuclear Power Plant | 0.3 | 0.22 | 1 | 0.09 | 1.62 |
| Hydrogen Generation | 0.12 | 0.1 | 0.72 | 0.02 | 0.96 |
| Hydrogen storage | 0.06 | 0.05 | 0 | 0 | 0.11 |
| Hydrogen Transportation | 0.14 | 0.13 | 0.04 | 0 | 0.32 |
| Total of all facilities | 0.62 | 0.5 | 1.76 | 0.12 | 3.01 |

## conclusion

Coupling a hydrogen production plant with a nuclear energy system presents numerous benefits. For instance, integrating a Gas-Turbine Modular Helium Reactor (GT-MHR) with a Sulfur-Iodine (SI) process for hydrogen production takes advantage of the heat generated by the reactor, reducing carbon dioxide emissions by substituting gas fuel with nuclear heat. Furthermore, this coupling enhances the thermal efficiency of the nuclear power plant (NPP). The economic analysis in this study offers valuable insights into the cost breakdown, showing a competitive hydrogen production cost of $2.52/kg when using nuclear heat from the GT-MHR. This cost rises to $3.01/kg when storage and transportation are factored in. The study also highlights the importance of evaluating the sensitivity of capital costs for each facility to determine the levelized cost of hydrogen.

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