# Economic Analysis for Nuclear Hydrogen Production System Based on HyS Process

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## 1. Introduction

The current promising base for massive hydrogen production on high temperature environment derives primarily from three sources: the commercial production of chemicals for the sulfur-iodine (SI) process, the development of solid-oxide fuel cells (SOFC), and the hybrid method of chemicals and fuel cells [1, 2]. The three kinds of process requires high temperature heat energy over 850~950℃ for the efficient and economic hydrogen production. One of the clean, economic, and moreover promising heat sources supplied to the process is nuclear plants. The nuclear plants producing high temperature heat energy over 950℃ are well known as Very High Temperature Reactors (VHTR) which could have two types of prismatic and pebble-bed cores along reactor core shape. In this paper, we report on the Hybrid Sulfur Process (HyS), and the estimated costs for the system which composes of VHTR of prismatic core type and HyS plant. Nuclear hydrogen production system based on HyS process has been configured to optimally use the thermal energy from VHTR and electric energy to produce hydrogen and oxygen from clean water. High temperature thermal energy is transferred to the HyS process by way of intermediate heat exchanger (IHX) with associated piping and.

In this paper, the hydrogen production costs for a system composed of a VHTR with six 600MWth module, a power conversion unit (PCU) and a HyS plant are presented, where the thermal energy produced in two module was converted to electric energy in PCU and then transferred to the electrolysis cells for hydrogen production and circulating units on HyS plant, and the remaining thermal energy was supplied to chemical process on HyS plants. As a preliminary study of cost estimates for nuclear hydrogen systems, the hydrogen production costs of the nuclear energy sources benchmarking GT-MHR are estimated in the necessary input data on a Korean specific basis. G4-ECONS was appropriately modified to calculate the cost for hydrogen production of HyS process with VHTR as a thermal energy source.

## 2. HyS Process

The hydrogen production system based on HyS process has two major parts of units of power conversion and electrical and chemical plant as shown in Fig. 1. High temperature heat energy generated in VHTR is supplied to PCU and HyS plant for electricity generation and chemical reaction, respectively, by way of IHX. High temperature helium heat transfer loops between the VHTR primary loops, steam generator in PCU and the HyS $H_2SO_4$ decomposition reactors. The HyS is a hybrid process that uses both thermal energy and electrical energy to produce hydrogen from clean water. Fig. 2 shows a block diagram of the HyS process, where heat energy in sulfuric acid decomposition unit designated in Fig. 2 is supplied from the IHX loop. The feed to the process is sulfur in the form of sulfuric acid ($H_2SO_4$). High pressure is maintained in the decomposition reactor to minimize the pressure differential between the helium and process sides. Using the thermal energy from the IHX loop, the sulfuric acid is thermally reduced to form tetravalent sulfur dioxide ($SO_2$) plus oxygen and water. Oxygen is separated from the $So_x$ stream and makeup feed water and $SO_2$ are added. And then, the water-Sox mixture is then electrolyzed to generate $H_2$ gas. In the electrolysis process, sulfur is reoxidized to hexavalent sulfur as $H_2SO_4$. Using the results of calculations of mass and energy balances [3], order of magnitude capital costs and allowances for operating costs could be prepared to allow a provisional economic review.

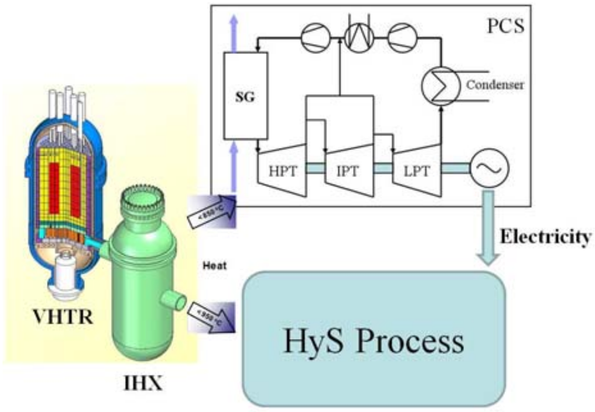


**Fig. 1** Configuration of hydrogen production system based on HyS process

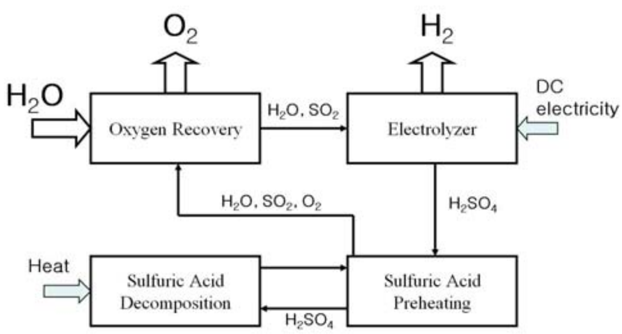


**Fig. 2** Block diagram for HyS process

## 3. Cost Estimates

G4-ECONS program was used to cost calculation for hydrogen production. Program version 2008 was appropriately modified to calculate the cost for hydrogen production of HyS process with VHTR as a thermal energy source rather than the LUEC (Levelized Unit Electricity Cost) [4, 5]. Through a preliminary study of cost estimates, we wished to evaluate the economic potential for hydrogen produced from nuclear energy, and, in addition, to promptly estimate the hydrogen production costs for an updated input data for capital costs, which compose the labor and materials costs as well as equipment costs . Although some input data were modified on the Korean specific basis, most of capital costs for the GT-MHR and E4-ECONS baseline data were available and served as the basis of our estimate [2, 6]. It is well known that the six reactor cluster makes sense from an availability basis because fueling can be staggered and the plant can be kept at high percentage of capacity at all times. On this basis, the preliminary cost estimates were performed to the multi-reactor cluster.

The economic assessments were performed for PMR (6 x 600MWth) coupled to a HyS electrical and chemical plant as a hydrogen production process. The capital costs for VHTR were referred to the GT-MHR for some account. The assumed annual fixed charge was 10%. The input data of the capital costs were based on scaling the previous reactors and HyS plant, and increasing costs of some equipment to account for the use of higher-temperature materials. Capital costs were also escalated to 2008 dollars.

The reactor and HyS plant systems were subdivided into 58 and 8 items in the cost estimates, respectively, i.e., costs shown in Table 1 are rolled-up at the level of major systems, which also shows O&M and fuel costs.

Table 1. Cost for a calculation model

| **Account Description** | **Costs, $M** |
|---|---|
| Construction costs | 3,338 |
| Test run costs | 400 |
| Total investment costs | 3,738 |
| Fixed operation costs | 32 |
| Various operation costs | 95 |
| Nuclear fuel costs | 129 |

## 4. Results and Discussion

The baseline hydrogen production was estimated to be 2.32 $/kg. If oxygen production benefit is considered in this economic evaluation, the hydrogen production cost could be 2.11 $/kg. Parameter studies were performed to determine the sensitivity of the hydrogen production costs and efficiency to construction time, fixed charge rate and HyS main equipment costs. The fixed charge rate has a significant influence on hydrogen production cost (about 0.5 $/kg increase for fixed charge rate increase of 7%). It is well known that increasing the construction time results in higher interest charges, but the increase in hydrogen production cost is only 0.05 $/kg ~ 0.23 $/kg. The projected HyS hydrogen cost with these assumptions could be in the range of 2.00 to 3.00 $/kg.

Improvements to the HyS system design have resulted in higher expectations for system efficiency and lower expected hydrogen production costs. Using preliminary order-of-magnitude capital cost allowances, a rough O&M allowances, and representative private investment financial assumptions, the HyS process was shown to be one of efficient of the hydrogen production processes analyzed. The estimated costs presented in this paper also show that hydrogen production by VHTR coupled to HyS plant system could be competitive with current techniques of hydrogen production from fossil fuels if $CO_2$ capture and sequestration is required. This favorable situation is expected to further improve as the cost of natural gas rises. Nuclear hydrogen production would allow large-scale production of hydrogen at economic prices while avoiding the release of $CO_2$. Nuclear production of hydrogen could thus become the enabling technology for the hydrogen economy. These results are only indicative what could be achieved if a number of technology development challenges are successfully addressed.

## 5. Reference

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