Thermodynamic analysis of hydrogen production using PWR-based SMRs

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1. Introduction

As global energy demand rises, environmental concerns intensify, and fossil fuels are depleting, there is a growing need to secure a sustainable energy future, and hydrogen is emerging as the next generation energy carrier. According to the Hydrogen Council, by 2050, approximately 18% of the world's energy demand is expected to be supplied by hydrogen, and the actual hydrogen production market is expected to grow at a CAGR of 9.2% to reach approximately $201.4 billion in 2025[1]. The growth of the hydrogen market is supported by advances in polymer electrolyte membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) technologies and their increasing use in hydrogen vehicles and various industrial sectors [2].

In the development of clean energy sources, nuclear power has emerged as a reliable source of electricity to compensate for the intermittency and regional limitations of renewables. Nuclear power's high energy density and ability to provide continuous power make it suitable for large-scale hydrogen production, and carbon-neutrality policies in the EU, US, South Korea and elsewhere scale back fossil fuel-based hydrogen production and accelerate clean hydrogen production from nuclear and renewable sources.

The main methods of nuclear-based hydrogen production include electrolysis, thermochemical water splitting, and hybrid methods that combine the two. In particular, the electrolysis process is considered a key technology for carbon neutrality because it can produce high-purity hydrogen using only water and electricity. Electrolysis methods include polymer electrolysis membrane (PEM), alkaline electrolysis (AEC), and high-temperature steam electrolysis (HTSE), which has the advantage of high efficiency and relatively low power consumption, but its use has been limited by the requirement for steam at 700 to 900°C. [3] Recently, Bloom Energy's solid oxide electrolyzer cell(SOEC) technology has shown that the HTSE process can be performed at relatively low temperatures, making it possible to produce hydrogen from conventional reactors such as High Temperature Gas Cooled Reactor, Very High Temperature Reactor, and even PWRs.[4] The SOEC technology has been developed by Bloom Energy.

As pressurized water reactors (PWRs) are the most commonly used nuclear reactors worldwide, there is growing interest in hydrogen production using them. While natural gas steam methane reforming can produce hydrogen at low cost, but has CO_2 emissions issues, and electrolysis based on renewable energy is not economically viable, nuclear-based HTSE has the potential to be both economically and environmentally viable, as it can use waste heat and electricity simultaneously to reduce the cost of hydrogen production to $1.5-2.5 per kilogram [5].

In this background, this study aims to perform a thermodynamic analysis of a hydrogen production system through high temperature water electrolysis (HTSE) using a pressurized water reactor (PWR) based small modular reactor (SMR). In this way, it aims to identify the economic and environmental advantages of nuclear-based hydrogen production and contribute to the construction of a realistic and competitive energy system for the future. In particular, by exploring the feasibility of implementing a hybrid system that efficiently utilizes steam and electricity from PWRs, the research aims to provide key strategic guidelines for enhancing the competitiveness of light water reactors and stimulating the hydrogen economy.

This study quantitatively analyzed the interactions between hydrogen production, power plant efficiency, and external power dependence by utilizing steam bypassed from a PWR-based SMR for high-temperature steam electrolysis (HTSE). In particular, by considering both thermoneutral and open-cell voltage conditions, this work provides a novel interpretation of the optimization of steam bypass ratios, which has previously been addressed only in a simplified manner.

2. Methodology

2.1 Description of water electrolysis

The water electrolysis reaction is an endothermic reaction that decomposes water (H_2O) into hydrogen (H_2) and oxygen (O_2), and is carried out by supplying heat energy (Q_{heat}) and electric energy ($W_{electricity}$) from the outside. The total energy input is represented by

$$E_{total} = Q_{heat} + W_{electricity} \tag{1}$$

$$H_2O + E_{total} \rightarrow H_2 + \frac{1}{2} O_2 \tag{2}$$

In the high temperature water electrolysis (HTSE) process, the total energy of the reaction (ΔH) is determined by the sum of the Gibbs free energy (ΔG), which is the minimum electrical energy, and the temperature-dependent thermal energy term ($T\Delta S$), i.e. $\Delta H = \Delta G + T\Delta S$. In ideal reversible conditions, the heat supplied is equal to $T\Delta S$. Therefore, as the temperature increases, the proportion of electrical energy decreases and the proportion of cheap and readily available thermal energy increases, reducing the overall power consumption and the cost of hydrogen production. As shown in the graph in Figure 1, as the temperature increases in the range of 0°C to 1000°C, ΔH remains nearly constant after reaching its boiling point(100°C), but ΔG decreases and $T\Delta S$ increases, indicating that thermal energy can be used instead of electricity in the high temperature region.

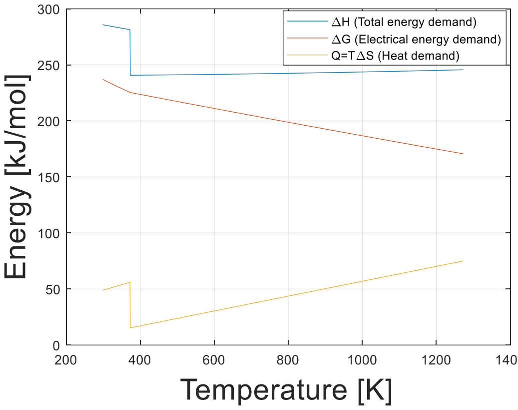

Figure 1. Energy required for water electrolysis as a function of temperature (Pressure = 1atm)

2.2 Modelling High-Temperature Water Electrolysis

To produce hydrogen from water via electrolysis, a voltage greater than the steady-state open circuit voltage (Vo) must be applied to the cell. The steady-state open circuit voltage is defined as follows

$$V^O = \frac{\Delta G_R^O}{jF} \tag{3}$$

where ΔG_R^O is the steady-state Gibbs free energy change of the reaction and j is the number of electrons transferred per hydrogen molecule. In a water vapour-hydrogen system using a Solid Oxide Electrolyte, j=2 because the reaction is driven by the migration of oxygen ions (O^{2-}). F is the Faraday constant (96,485 C/mol). However, this equation is only applicable when the reactants and products are pure and completely separated in an idealized steady state at 1 atm.

In actual high-temperature steam electrolysis (HTSE) systems, the steam supplied may contain small amounts of hydrogen or inert gases, and the oxygen generation side may also use a sweep gas such as air to reduce the partial pressure of oxygen to about 21% of the operating pressure. In addition, the system may be operated at higher pressures in general. Therefore, the opening voltage (Nernst voltage) according to the actual operating conditions is calculated using the Nernst equation

$$V_N = V^O - \frac{R_u T}{jF} \ln \left[\left(\frac{y_{H2O}}{y_{H2} y_{O2}^{\frac{1}{2}}} \right) \left(\frac{P}{P_{std}} \right)^{-\frac{1}{2}} \right] \tag{4}$$

where R is the gas constant (8.314 J/mol·K), T is the absolute temperature (K), y is the mole fraction of each gas, and P and P_{std} are the actual operating pressure and steady-state pressure, respectively. The voltage obtained from the Nernst equation is the equilibrium voltage, which varies according to the actual conditions (temperature, pressure, gas composition), and represents the minimum voltage that needs to be supplied for the electrolysis reaction to occur. In addition, unlike the fuel cell mode, the electrolysis of SOEC cells is based on an endothermic reaction, which means that the net heat generation in the stack can be negative (endothermic), zero (thermally neutral), or positive (exothermic) depending on the operating voltage. The thermoneutral voltage, where the reaction is performed purely with electrical energy without an external heat supply, is

$$V_{th} = \frac{\Delta H_R}{2F} \tag{5}$$

and typically has a value of around 1.292 V.

In this study, two scenarios are modelled for a pressurized water reactor (PWR) based HTSE system. The first is the case of supplementing TΔS with an external heat source and injecting only the minimum electrical energy (ΔG), and the second is the case of operating on electricity alone without external heat supply under thermoneutral voltage conditions. Along with this, Faraday's law is used:

$$I = 2 \times F \times \dot{N}_{H_2} \tag{6}$$

to establish the relationship between the molar flow rate of hydrogen produced and the current, the efficiency and performance of each scenario is quantitatively evaluated.

2.3 Cycle Modelling

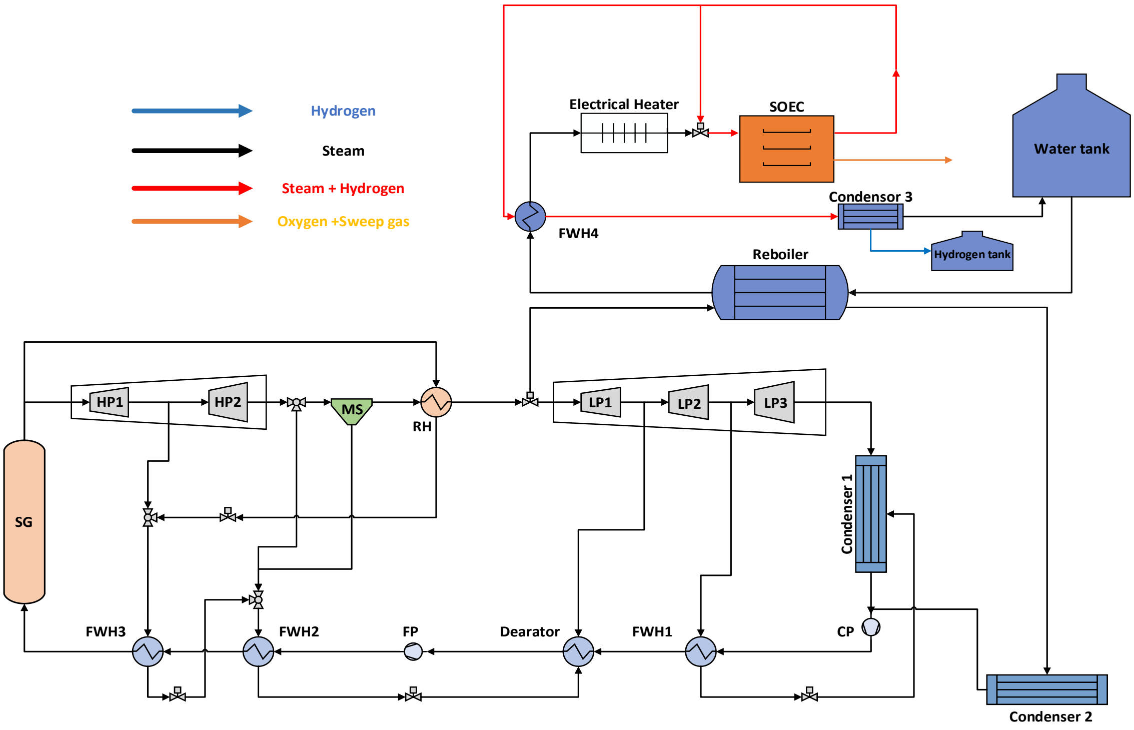

Fig.2 Schematic diagram of a cycle integrating PWR-based SMR and high-temperature water electrolysis

In order to simulate the behavior of the power plant at partial load (quasi-steady state) rather than at 100% rated output, the main boundary conditions of the turbine and auxiliary systems are modelled with fixed values. Specifically, the outlet temperature and pressure of the steam generator, the inlet and outlet conditions of the condensor, and the efficiency of the moisture separator and the reheater flow rate are kept constant despite load variations. This is a conservative assumption that reflects the controlled feedwater, cooling, and heat exchange processes in actualoperation.

Part-load operation is mainly implemented by reducing the steam mass flow rate through the throttling valve, while the volumetric flow rate is kept constant under the assumption of isenthalpic process. The modelling was performed to keep the volumetric flow constant with a concomitant reduction in density as the mass flow rate decreased. These modelling prevented efficiency degradation in steam turbine due to pressure ratio changes, even in off-design operating conditions, using the same steam turbine design pressure ratio and design efficiency. In addition, the increase in exhaust losses at the lower pressure end of the turbine (LSB) due to the temperature-pressure drop is reflected in the model through Expansion line and point(ELEP) and exhaust loss curves.

In this way, by fixing the key design conditions, the energy balance and flow-pressure characteristics of each turbine stage are simplified, enabling quantitative analyses of the change in performance of the entire plant at partial load.[6]

Table 1 summarizes the main operating parameters. As shown in Fig. 2, a portion of the steam exiting the reheater (RH) is diverted just before entering the low-pressure turbine (LP1) and sent to the reboiler. In the reboiler, the diverted steam is used to convert water from the water tank into steam, with the water flow rate set equal to the diverted steam flow. The steam produced in the reboiler then passes through the feedwater heater, where it exchanges heat with a hydrogen–steam mixture, and is further heated to approximately 750°C by an electric heater. Since the solid oxide electrolysis cell (SOEC), a high-temperature water electrolysis device, requires steam mixed with hydrogen in a certain proportion (about 15% mole fraction) rather than simple steam, the steam + hydrogen mixture generated in electrolysis was merged with steam to make a mixture of 15% hydrogen and 85% steam. After electrolysis, part of the gas mixture is diverted to the steam supply system, while the remainder goes through the feedwater heater to the condenser, where hydrogen and water are separated into their respective tanks. This process, which recycles heat and water, maximizes energy efficiency and enables the determination of the optimal bypass ratio for hydrogen production using only the electrical and thermal energy from the SMR.

Table.1 Assumed nuclear part cycle parameters

Parameters	Value
SG thermal power	520MWth
Net efficiency	33.70%
SG inlet temperature	230℃
SG outlet temperature	297.8℃
SG inlet pressure	5.335MPa
SG outlet pressure	5.25MPa
Turbine efficiency	85%
Pump efficiency	82%
HX effectiveness	90%
Hot side pressure drop	3% of inlet

Table.2 Assumed hydrogen production part cycle parameters

Parameters	Value
SOEC operating temperature	750℃
Electrical heater efficiency	100%
Reboiler effectiveness	90%
Reboiler pressure drop	3% of inlet

3. Result

As the bypass ratio increases, the amount of steam directed to the High Temperature Steam Electrolysis (HTSE) process increases, leading to a proportional increase in both the corresponding water supply and hydrogen production. This tendency results from the design of the system, where the amount of water supplied is modelled to match the diverted steam flow. A higher bypass ratio results in a greater proportion of steam bypassing the power cycle, thereby enhancing the hydrogen production reactions. However, this also leads to a reduction in turbine output and a potential increase in dependence on external electricity. Therefore, it is crucial to strike a balance between maximizing hydrogen production and maintaining power plant electricity generation. Therefore, an integrated design and operating strategy that considers both water and steam diversion (bypass ratio) is essential for efficient system performance.

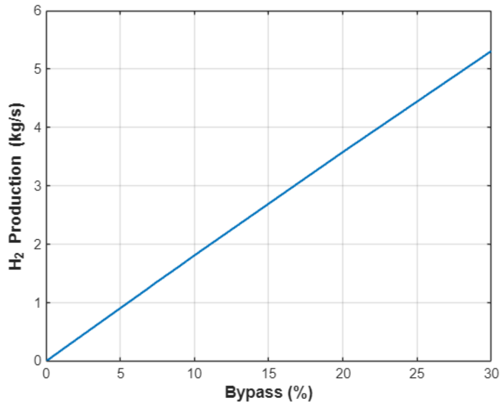

Fig.3 Effect of Bypass Percentage on Hydrogen Production Rate

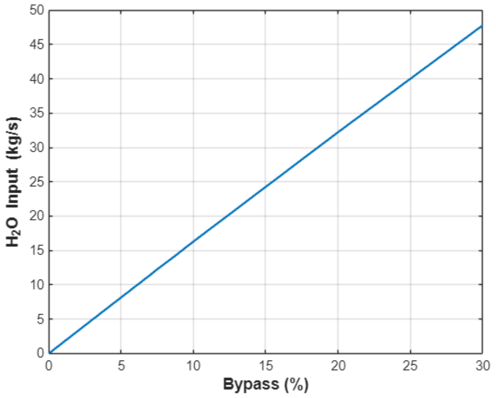

Fig.4 Variation of Water Input with Increasing Bypass Fraction

The comparison of power generation and high-temperature steam electrolysis (HTSE) operating Power as a function of the bypass ratio (%) can be categorized into three key indicators. First, represents the amount of electricity generated by the SMR-based steam power cycle (depicted by the blue curve). Second, $P_{\mathrm{thermoneutral}}$ indicates the power required for operating the HTSE process under thermoneutral voltage conditions (depicted by the red curve). Lastly, P_{opencell} refers to the power demand for electrolysis under open-cell voltage conditions (depicted by the yellow curve). This represents the minimum power required for hydrogen production. Therefore, depending on the capacity of the external heat source, power must be supplied between P_{opencell} and $P_{\mathrm{thermoneutral}}$.

Fig. 5 shows that as the bypass ratio increases, the electricity generated by the SMR (P_{SMR}) gradually decreases, whereas the power required for the electrolysis process ($P_{\text{thermoneutral}}$, P_{opencell}) increases linearly. Notably, the intersection between the SMR power curve and the open-cell voltage electrolysis curve occurs around a bypass ratio of 7.38%, while the intersection with the thermoneutral voltage curve appears at approximately 9.47%.

In the low bypass region (below 7.38%), the electricity generated by the SMR is sufficient to fully meet the power demand for electrolysis under open-cell conditions, leaving surplus electricity within the power plant. In the intermediate region (7.38% to 9.47%), the SMR power can still meet the open-cell electrolysis demand but falls slightly short of the thermoneutral voltage requirement, requiring a small amount of additional external electricity. In contrast, when the bypass ratio exceeds 9.47%, the power demand for electrolysis surpasses the available SMR power, requiring significant external electricity input to sustain thermoneutral operation. These results show that increasing the amount of steam bypassed to the electrolysis process leads to higher hydrogen production but simultaneously reduces the net power output of the plant and increases dependence on external electricity. Thus, the bypass ratio serves as a crucial factor in balancing hydrogen production and electricity sales, and the selection of the optimal bypass ratio should be based on the system's operational objectives of the plant, such as self-sufficiency in power, hydrogen demand, and overall economic feasibility.

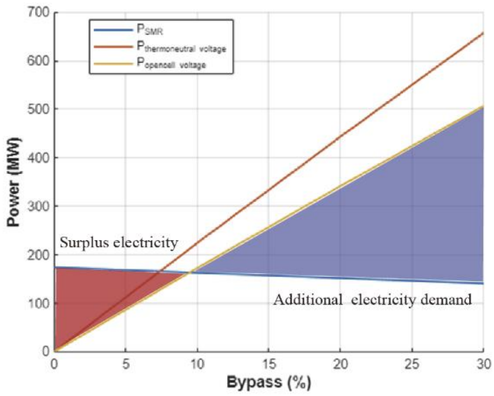

Fig.5 Power Balance between SMR Generation and SOEC Demands (Thermoneutral/Open-Cell) as a Function of Bypass

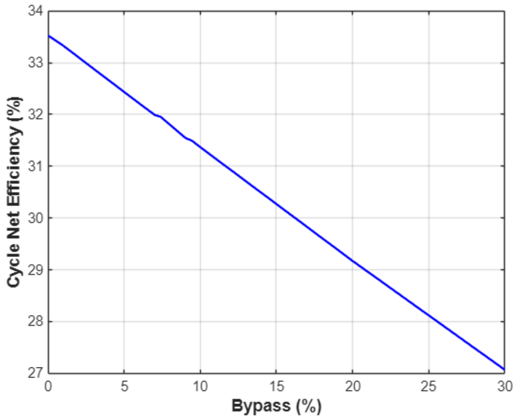

Fig.6 Effect of Bypass Ratio on Cycle Net Efficiency

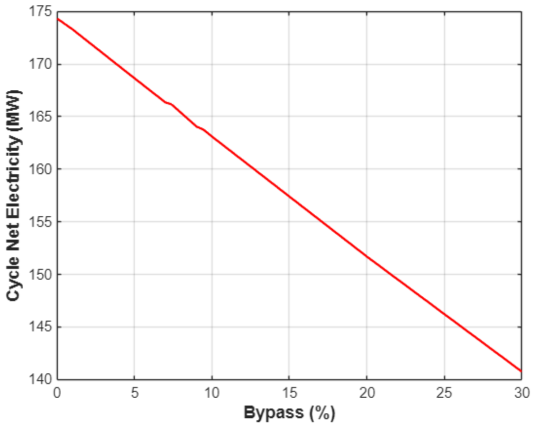

Fig.7 Effect of Bypass Ratio on Cycle Net Electricity

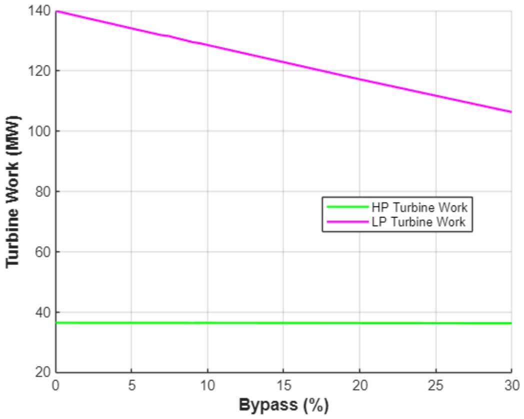

Fig.8 Effect of Bypass Ratio on HP and LP Turbine Work

As shown in Figures 6 and 7, increasing the bypass ratio causes a linear decrease in the turbine's net electricity output (Cycle Net Electricity), which in turn reduces the plant's cycle efficiency (Cycle Net Efficiency). This occurs because, at higher bypass ratios, a greater proportion of the steam bypasses the turbine and is instead directed to the high-temperature steam electrolysis process, thereby reducing the steam available for turbine work.

Figure 8 shows that while the high-pressure (HP) turbine output remains relatively stable, the low-pressure (LP) turbine power decreases significantly. This is due to the significant steam extraction at the reheater (reboiler) stage, generally located downstream of the HP turbine, which leaves less steam available for the LP turbine. Consequently, as the bypass ratio increases, the drop in LP turbine output becomes more pronounced, with a direct impact on overall net power production and cycle efficiency.

4. Conclusions

This study conducted a thermodynamic analysis of hydrogen production through high-temperature steam electrolysis (HTSE) integrated with a pressurized water reactor (PWR)-based small modular reactor (SMR) system. The results highlight the critical impact of the bypass ratio on system performance, including cycle efficiency, power generation, electrolysis power demand, hydrogen production, and water input requirements.

As the bypass ratio increases, a more portion of the steam is directed to the HTSE process, improving hydrogen production but simultaneously reducing power plant efficiency and net power output. The analysis shows that while low bypass operation (below 7.38%) allows surplus electricity to be available for external use, intermediate bypass operation (7.38%–9.47%) ensures that SMR-generated electricity can fully supply electrolysis under open-cell conditions but requires partial external electricity input for thermoneutral operation. In contrast, high bypass operation (above 9.47%) requires significant external power input to meet the electrolysis demand, as the power generated by the SMR becomes insufficient.

These results highlight the trade-off between maximizing hydrogen production and maintaining power generation for external supply. While a high bypass ratio increases the hydrogen yield, it also increase system dependency on external power, which affects economic feasibility and operational strategy. Therefore, the optimal bypass setting should be carefully determined based on system objectives, considering factors such as energy self-sufficiency, hydrogen market demand, and economic constraints.

As a future research direction, an economic analysis that integrates operational considerations—such as using a single SMR to supply both heat and electricity for hydrogen production versus employing multiple SMRs, where only one unit provides steam while the others focus on electricity generation—could determine which approach yields a more favorable outcome. Through such an approach, nuclear-based HTSE can be further refined as a sustainable and competitive hydrogen production pathway, contributing to the transition toward a clean hydrogen economy.

Acknowledgements

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