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ARTICLE

Process Simulation and Total System Efficiency Evaluation of Integrated VOYGR^{TM} Plant and Solid Oxide Electrolysis Cell for Nuclear-Hydrogen Production

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An integrated plant comprising a VOYGR^{TM} plant and a solid oxide electrolysis cell facility was modeled using process simulation to determine the advantages and disadvantages of such an integrated plant. Three different process configurations for supplying heat to the solid oxide electrolysis cell facility from various sources in the VOYGR^{TM} plant, that is, extraction steam from the steam turbine, main steam from the steam generator, and electric power from the generator, were studied and compared. The results indicated that the two steam supply cases had higher total system efficiencies than the all-electric case had. After comparing not only the total system efficiencies but also the plant engineering and operability of the two steam cases and identifying their relative advantages and disadvantages, this study concluded that the most preferrable configuration could not be determined intrinsically since it depended on the particular requirements of the project being considered. Furthermore, the study found that if the total system efficiency of the solid oxide electrolysis cell exceeded some threshold value, then the hydrogen production efficiency of an integrated plant could significantly exceed that of a VOYGR^{TM} plant operating alone and the carbon-free hydrogen production of such an integrated plant could surpass the system efficiency of a conventional nuclear power plant.

KEYWORDS: carbon neutrality, nuclear power plant application, hydrogen production, SMR, NuScale, VOYGR, NExIP and total system efficiency

I. Introduction

To mitigate the effects of global climate change, energy transition from conventional hydrocarbons to carbon-free energy sources is necessary. To achieve the reduction of CO_2 emissions, new carbon-neutral energy solutions have been developed and are already in use. In particular, the use of carbon-free hydrogen is expected to expand in a wide variety of sectors, such as in industry, refineries, and power plants. In addition, carbon-free hydrogen can be substituted for conventional fossil fuels. Although hydrogen is now mainly produced on-site through the reforming of fossil fuels, hydrogen production from water electrolysis will drastically rise in the coming decades. According to an IEA report, almost 80% of hydrogen will be produced by water electrolysis in 2050.[1)] To contribute to the reduction of CO_2 emissions, water electrolysis should use carbon-free electric power, and nuclear power plants are a source of carbon-free electric power.

Therefore, Small Modular Reactors (SMR), one of the types being developed as the next generation of nuclear power reactors, are attracting attention, and being developed worldwide for commercialization. NuScale Power, LLC is one of the leading SMR suppliers.[2)] NuScale's VOYGR^{TM} plants comprise multiple NuScale Power Modules^{TM} (NPM), which are integral pressurized light water reactor (PWR) modules. VOYGR^{TM} plants come in three standard configurations to meet demand, with 4, 6, or 12 NPMs. Thus, since a VOYGR^{TM} plant comprises multiple NPMs, each of which operates independently, a VOYGR^{TM} plant can be operated flexibly to meet variations in demand and can easily be integrated with various other facilities. In addition, because SMRs were originally developed to be applicable not only for electric power supply but also for non-electrical applications,[3)] VOYGR^{TM} plants are especially well suited for hydrogen production by integrating it with other technologies, such as solid oxide electrolysis cells (SOEC).

SOEC is a water electrolysis technology, and its efficiency is higher than that of other competing technologies, such as alkaline electrolysis (AEL), proton exchange membranes (PEM) and anion exchange membranes (AEM).[4)] The electrolysis reaction in SOEC occurs at a much higher temperature (700–850ºC) than in other electrolysis technologies.[5)] A SOEC facility is designed to make steam from feedwater and then heat the steam to the required temperature by both heat recovery inside the SOEC facility and electric heaters. However, preheating the feedwater before it enters the SOEC facility is desirable since it reduces the heat needed to generate the steam in the SOEC facility. Hence, preheating the feedwater through heat recovery outside facilities can reduce the heat required inside the SOEC facility, resulting in improved energy efficiency. Since the VOYGR^{TM} plant can supply electric power and steam to the SOEC facility on demand thanks to its flexible operability,

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integration of a SMR and a SOEC facility can be considered. In addition, the hydrogen produced is completely carbon-free in this case since both the electric power and the steam from the SMR are generated by carbon-free processes. Furthermore, the total system efficiency of the system can be improved by integrating the SMR and SOEC facility. This is because the waste heat from the turbine in the SMR nuclear power plant, which would normally be lost, can be utilized for heating the feedwater of the SOEC. This utilization of waste heat helps improve the overall efficiency of a nuclear power plant.

II. Objectives

The relative advantages and disadvantages of integrating an SMR and an SOEC facility were assessed. First, several plant configurations suitable for the integration of the NuScale VOYGR™ plant and an SOEC facility were proposed and investigated considering both, their total system efficiencies and the feasibility of the plant engineering and the operational suitability. Second, the impact of the efficiency of the SOEC facility itself on the total system efficiency of the integrated plant was quantitatively evaluated.

III. Process Simulation

This study was performed using the AVEVA Process Simulation (APS) application. Several configurations of an integrated plant comprising a VOYGR™ plant with six NPMs (VOYGR-6) and an SOEC facility were modeled, and the total system efficiencies were calculated by process simulations.

1. Common Basis for Flow Scheme

In the VOYGR™ plant, one of its six NPMs, each of which produces 250 MWt / 77 MWe, was dedicated to supplying electric power and steam to the SOEC.

The efficiency of the SOEC facility was assumed to be 0.89. Four configurations, that is, an extraction steam case, a main steam case, an all-electric case, and a no-SOEC case (reference case), were modeled and compared, as shown in **Fig. 1**. In the three SOEC cases, the electric power required for electrolysis in the SOEC facility was supplied from the VOYGR™ plant. The electric power required for the house loads in the VOYGR™ plant and SOEC facility was estimated as 3,500 kW which is the same for all cases. The house load was subtracted from the generated gross electricity, and the remaining was distributed to the grid and SOEC facilities. The sources of the heat for preheating the SOEC feedwater, however, were different in each case. In the extraction steam case, steam extracted from the middle of the turbine was used for preheating the SOEC feedwater. In the main steam case, some of the steam generated by the NPM was directly used. In contrast to the two steam cases, in the all-electric case, an electric heater powered by electric power generated in the VOYGR™ plant was used for preheating the SOEC feedwater. In the no-SOEC case (reference case), the VOYGR™ plant operating alone was modeled and considered. The process scheme and heat and material balance of the turbine system in the VOYGR™ plant was modeled using design information provided by NuScale Power, LLC. The conditions of the steam and feedwater supplied to the SOEC and the performance data of the SOEC facility were based on information obtained from the SOEC supplier.

2. Input for Simulation Model Preparation

In this study, the IAPWS Industrial Formulation 1997 (IAPWS-IF97) was applied for thermodynamic data. The parameters used in this study, *Eff.* $_{SOEC}$ and total system efficiency, were defined using Eqs. (1) and (2), respectively:

$$Eff._{SOEC}\,[-] = \frac{Theoretical\ HHV\ of\ H_2\left[\frac{kWh}{kg-H_2}\right]^{(*1)}}{Actual\ Energy\ Input\left[\frac{kWh}{kg-H_2}\right]^{(*2)}} \tag{1}$$

$$Total\ System\ Efficiency\,[-] = \frac{(Electricity\ to\ Grid\ [kW] + Produced\ H_2\left[\frac{kg-H_2}{h}\right] \times Theoretical\ HHV\ of\ H_2\left[\frac{kWh}{kg-H_2}\right]}{NPM\ Thermal\ Power\ [kW]} \tag{2}$$

(*1) The reported value (39.409 kWh/kg-H_2) was applied.[6]
(*2) Actual Energy Input was the energy input required for operating the SOEC package.

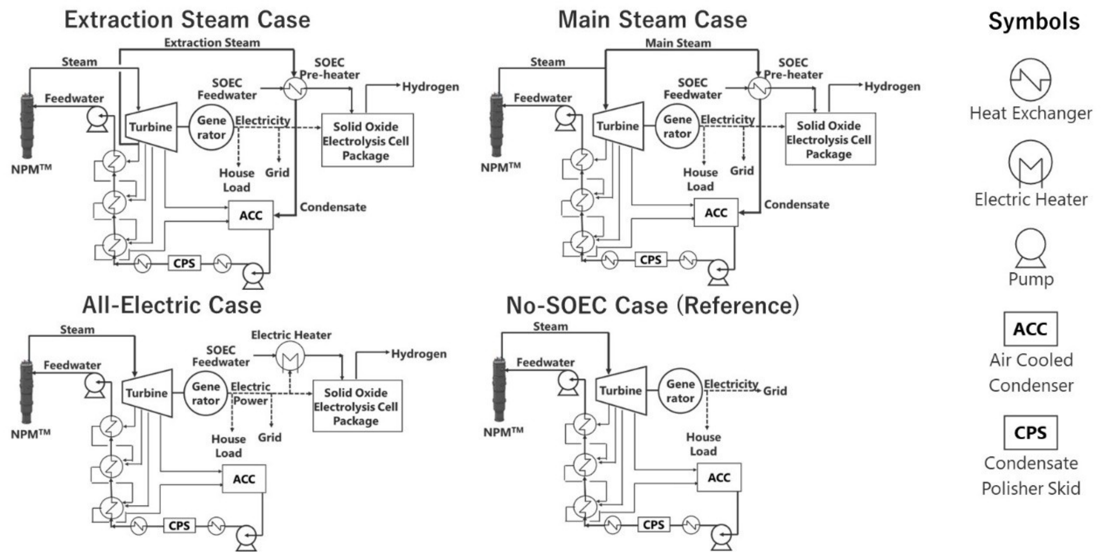

Fig. 1 Configurations of Integrated VOYGR™ Plant and SOEC Facility Modeled

IV. Results and Discussion

1. Comparison of Configurations Modeled

(1) Total System Efficiency

The relation between the total system efficiency and the hydrogen production rate for each case is illustrated in **Fig. 2**. The vertical axis represents the relative system efficiency, normalized to the reference case (i.e., the case without SOEC), while the horizontal axis indicates the relative hydrogen production rate, normalized to the highest rate observed in the main steam case. The relative hydrogen production rate is varied for each case because the branched steam flowrate supplied to SOEC preheater is varied. Fig. 2 clearly shows that the total system efficiency decreased in the following order, from highest to lowest: no-SOEC case (reference case) > extraction steam case > main steam case > all-electric case.

The total system efficiency of the extraction steam case was slightly higher than that of the main steam case. This was mainly because the electric power generated by the turbine in the main steam case was less than that generated in the extraction steam case, owing to drawing off some of the main steam instead of passing it through the turbine. Since the electric power required for the house loads in the VOYGR™ plant and SOEC facility was the same for all cases, the ratio of the electric power exported to the grid to that generated by the turbine was relatively lower for the main steam case than for the extraction steam case.

Another point illustrated in Fig. 2 is that the total system efficiencies in all three cases in which an SOEC facility was integrated with the VOYGR™ plant were lower than that in the no-SOEC case (reference case) and that they decreased directly with the hydrogen production rate. This indicated that producing hydrogen with an SOEC facility by supplying steam or electric power from a VOYGR™ plant was less efficient than operating a VOYGR™ plant alone.

In addition, Fig. 2 shows that, for hydrogen production with an SOEC facility, supplying steam was better than using electric power, regardless of the steam conditions. This was because in the two steam supply cases the feedwater for the SOEC facility was heated directly by the supplied steam, so there was no energy loss at the turbine for converting thermal energy to electric power, as there was in the all-electric case.

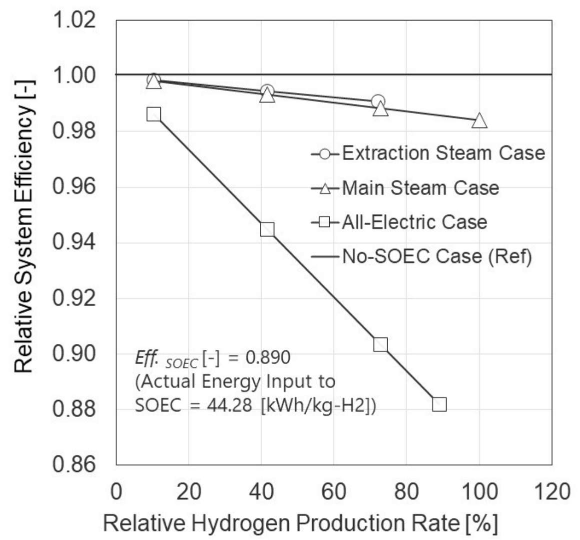

Fig. 2 Total System Efficiency Behavior for each case (*Eff.* $_{SOEC\ Package}$ = 0.890 [-] (Actual Energy Input = 44.28 kWh/kg-H_2.))

Therefore, this study focused on the comparison between the steam supply cases to determine a suitable configuration for integrating a VOYGR™ plant and an SOEC facility.

(2) Plant Engineering and Operability

Both the plant engineering, including process and equipment design, and the operability of the two steam supply cases were compared, and their relative advantages and disadvantages were identified.

(a) Total System Efficiency Study

As already noted, the total system efficiency of the extraction steam case was slightly higher than that of the main steam case.

(b) Maximum Hydrogen (H_2) Production Rate

As shown in Fig. 2, the maximum hydrogen production rate in the extraction steam case (~72%) was lower than that in the main steam case (~100%). For the extraction steam case, the maximum hydrogen production rate was limited by the amount of heat supplied to the SOEC preheater. This heat supply was governed by the flow rate of the extraction steam, which in turn depended on the mechanical design of the steam turbine.

The conceptual balance limiting the maximum hydrogen production rate for each case was as shown in **Fig. 3**. When the extraction steam rate to the SOEC preheater was at 100%, 66% of the electric power generating capacity was consumed by the SOEC to make hydrogen, leaving 30% of the

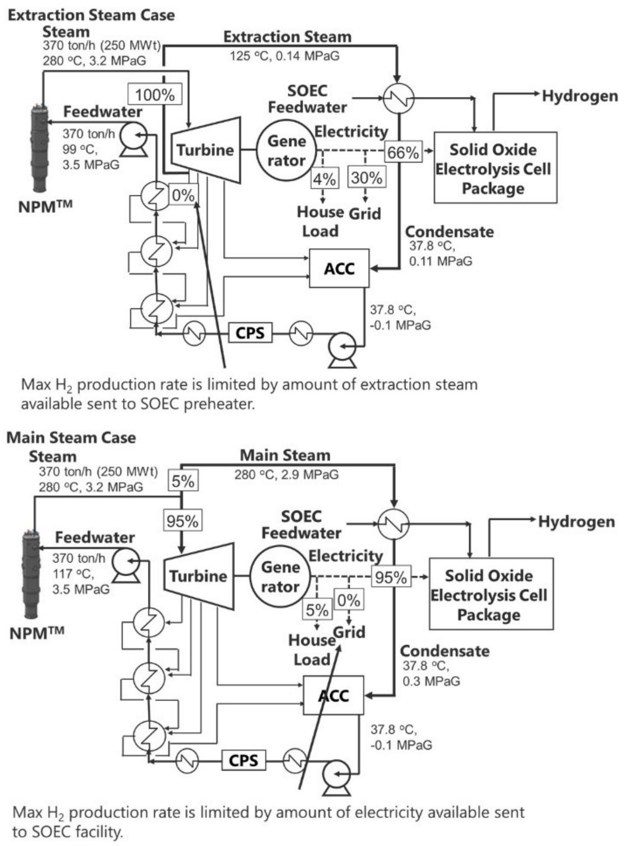

Fig. 3 Conceptual Balance Limiting Maximum Hydrogen Production Rate for each case

generating capacity for export to the grid and 4% of that was consumed as the house load. According to the original heat and material balance around the turbine, the flow rate of the extraction steam available to be sent to the SOEC preheater was less than 4% of that of the total steam generated by the NPM, and almost all the heat of the extracted steam was already being consumed at the turbine before extraction. Hence, the heat provided to the SOEC preheater was less than that in the main steam case, which resulted in a lower hydrogen production rate.

However, the maximum hydrogen production rate in the main steam case was limited by the amount of electric power available for the SOEC. When 95% of the electric power required, leaving 5% of the generated electricity was necessary for the house load, was used by the SOEC, 5% of the main steam was consumed by the SOEC preheater to heat the feedwater. The higher the hydrogen production rate was, the lower the electric power generated by the turbine was, due to the reduction of steam supplied to the turbine. When all the electric power generated was used by the SOEC facility, no electric power could be exported to the grid, and the hydrogen production rate reached a ceiling and could not be increased any further.

(c) Pressure of Condensate Returned from SOEC Preheater to VOYGR™ Plant

Since the steam and condensate in a VOYGR™ plant circulate in a closed loop, the condensate from the steam supplied to the SOEC preheater must be returned to the VOYGR™ plant circulation loop to maintain the mass balance. Therefore, the condensate must have sufficient pressure for return to the VOYGR™ plant.

While pressure of the steam supplied to turbine was about 2.9 MPaG, pressure of the extraction steam was about 0.14 MPaG as shown in Fig. 3. However, it is required a sufficient pressure of the steam condensate, which is typically 0.3 MPaG at the battery limit of VOYGR™ plant but the higher pressure at the discharge from the SOEC preheater, to be returned to the air cooled condenser (ACC) in the VOYGR™ plant.

In addition, the nuclear power plant and the SOEC have to be located at a sufficient distance from each other to meet safety concerns.[7)] The specific requirements for this distance depend on the project requirements, and the head losses in the supply and return lines generally need to be taken into consideration.

Additionally, the extraction steam used for preheating the SOEC feedwater needs to be taken from an earlier stage of the turbine. This differs from the original design, which serves as the basis for the heat and material balance of the turbine system in the VOYGR™ plant. As a result, the electric power generated by the turbine is reduced. This reduction is due to the decreased amount of steam passing through the subsequent stages of the turbine. This change of extraction stage should be confirmed with the turbine vendor.

(d) Rating of Piping and Equipment for the Steam Supply System

Considering the differences in the steam conditions (280°C, 2.9 MPaG for the main steam case, and 125°C, 0.14 MPaG for the extraction steam case) the main steam case may require a higher rating for piping, equipment, and other components of the steam transportation line than in the extraction steam case. Since the steam transportation line may be long, owing to the long distance required between the VOYGR™ plant and the SOEC facility for safety reasons, this higher rating may increase the plant cost.

(e) Impact on VOYGR™ Turbine System

The effects of drawing off steam from the closed loop of the turbine system have to be considered. In the extraction steam case, extraction of steam that is originally intended to be used to heat the feedwater of the turbine system changes the heat balance in the loop and causes a loss of preheating of the NPM feedwater. Unless this loss can be compensated in the NPM by increasing the heat load, it may result in insufficient energy in the generated steam, eventually leading to a failure of the turbine system.

In the main steam case, in contrast, this loss of steam has only a minor impact on the turbine operation because only 5% at most of the main steam is used for the SOEC preheater, and the remaining 95% of the steam is still circulated in the loop. It is therefore assumed that such a limited loss of steam could be accommodated by turbine load adjustment without any other modification.

(f) Operability of SOEC

When the turbine load is changed, the steam available to be supplied to the SOEC preheater fluctuates. When the turbine load is reduced for only a short time, the flow rate of the steam to the turbine is reduced, but the steam generator is maintained at its normal production capacity by sending the excess steam directly to the air cooled condenser (ACC), bypassing the turbine entirely.

Therefore, in the extraction steam case, the available extraction steam decreases with the reduction of steam passing through the turbine. This directly leads to a reduction of the hydrogen production rate at the SOEC. Thus, the SOEC production rate depends on the turbine load.

However, since the steam generator remains at its normal production rate in the main steam case, steam is still available to be sent to the SOEC preheater. Even when the turbine load is reduced, a static condition can be achieved as the steam sent to SOEC preheater is maintained, and the excess steam due to the turbine load reduction bypasses the turbine and cooled by the condenser. Therefore, in the main steam case, as long as electric power for the SOEC operation is available, the SOEC continues to produce hydrogen independently from the turbine load.

(g) Simplicity of Configuration

When integrating the VOYGR™ plant and the SOEC facility, the process schemes inside the VOYGR™ plant needs to be reviewed since the design will become more complicated.

As it has not originally been expected to supply steam anywhere other than to the feedwater heaters of the turbine system of the NPM, in the extraction steam case, certain modifications, such as addition of new process lines and control systems, are necessary. In addition, modifications of some systems designed by the turbine vendor are also necessary. Since turbine vendors normally have their own standard designs, such modifications need to be discussed with the vendor.

However, since in the main steam case the steam is supplied from the main steam line, only an additional branch line and some piping are required.

It is expected that the cost impact of such modifications will be less than the cost of the modifications needed in the extraction steam case. Furthermore, unlike the extraction steam case, no changes in the turbine vendor's design would probably be needed in the main steam case.

(h) Summary

The relative advantages and disadvantages of the extraction steam and main steam cases noted above are summarized in **Table** 1, from which it is clear that the preferable case depends on the priorities of the requirements for the particular integrated plant. If the first priority is the total system efficiency, the extraction steam case seems preferrable, assuming that the pressure of the condensate returned can meet the requirements. However, if the first priority is the hydrogen production rate, then considering the simpler design and the greater flexibility of operation independent from fluctuations in the turbine load, the main steam case, instead, seems preferable.

2. Impact of the Efficiency of the SOEC Package

The simulation results in Fig. 2 show that the Actual Energy Input for evaluation of $Eff._{SOEC}$, Eq. (1), was expected to be 44.28 kWh/kg-H_2, according to information from the SOEC supplier. As this value was fixed, the parameter of $Eff._{SOEC}$ was fixed at 0.890 [-] for all cases. However, the results of simulations performed with different values of Actual Energy Input are presented in this section to evaluate the impact of the efficiency of the SOEC package alone on the total system efficiency of the integrated plant.

(1) Impact of the Efficiency of the SOEC Package on the Total System Efficiency

The relation between the total system efficiency and the hydrogen production rate at different values of $Eff._{SOEC}$ in the extraction steam and main steam cases were as shown in **Figs.** 4(a) and (b), respectively. The relative system efficiency normalized to the no-SOEC case (reference case) is shown on the vertical axis in Figs. 4(a) and (b), same as in Fig. 2.

Table 1 Advantages and Disadvantages of Extraction Steam Case and Main Steam Case

Other Considerations	**Extraction Steam Case**	**Main Steam Case**
Total system efficiency study	High	Low
Maximum hydrogen (H_2) production rate [a)]	~72%	100%
Pressure of condensate returned from SOEC preheater to VOYGR™	Need to review the stage of extraction Pressure of steam (original): 0.14 MPaG	Sufficient Pressure of steam: 2.9 MPaG
Rating of piping and equipment for the steam supply system	Low	High
Impact on VOYGR™ turbine system	Large impact. Loss of extraction steam may change the balance of the turbine system and cause a loss of preheating of feedwater to NPM, which may eventually result in failure of turbine operation.	Small impact. Loss of steam (~5%) can be accommodated by turbine load adjustment without other modifications.
Operability of SOEC	Dependent on turbine load.	Independent of turbine load.
Simplicity of configuration	Complicated. Additional process control systems, process lines, and modifications of turbine system required.	Simple. Line branches off the existing steam supply line.

a) The highest hydrogen production rate of the main steam case was defined as 100.

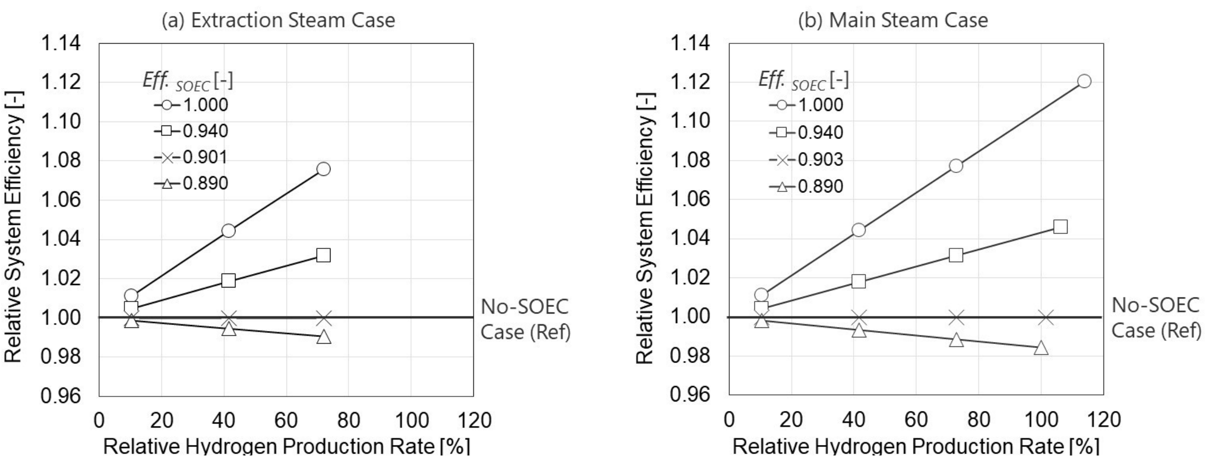

Fig. 4 System Efficiency Behavior for different $Eff._{SOEC}$ (a) Extraction Steam Case (b) Main Steam Case

Similarly, the relative hydrogen production rate normalized to the highest value of the main steam case at an $Eff._{SOEC}$ of 0.890 [-] is shown on the horizontal axis.

Figures 4(a) and (b) show that a higher total system efficiency was achieved in both the extraction steam and main steam cases when a higher $Eff._{SOEC}$ was applied. In addition, in the main steam case, the maximum hydrogen production rate was increased with a higher $Eff._{SOEC}$ value. This was because the efficiency was increased, while the electric power available to the SOEC facility was fixed, as noted above. In the extraction steam case, since the extraction steam generated from turbine is determined by design of turbine system and independent of the $Eff._{SOEC}$, the maximum hydrogen production rate is not changed by changing $Eff._{SOEC}$.

(2) Threshold Efficiency

The most important insight obtained from this result was that there was a specific value of $Eff._{SOEC}$ at which the total system efficiency of the integrated VOYGR™ plant and SOEC facility was the same as that of the no-SOEC case.

In this report, that value of $Eff._{SOEC}$ is called the "threshold efficiency."

The threshold efficiencies for the extraction steam and main steam cases were 0.901 [-] and 0.903 [-], respectively. At the threshold efficiency, the ratio of the total energy loss of the turbine and the SOEC together to the heat input from the NPM of the integrated plant was equal to the ratio of the energy loss of the turbine to the heat input from the NPM of the VOYGR™ plant alone.

It has been reported that the target efficiency of an SOEC is less than 40 kWh/kg-H_2 in 2050.[5] In terms of the $Eff._{SOEC}$ defined in this study, the target value of 40 kWh/kg-H_2 is equivalent to an $Eff._{SOEC}$ of 0.985 [-], which is much higher than the threshold efficiency calculated in this study: an $Eff._{SOEC}$ of 0.901 [-] for the extraction steam case, and 0.903 [-] for the main steam case.

If an SOEC package with a higher efficiency than the threshold efficiency is integrated with the VOYGR™ plant, the total system efficiency of the integrated plant will exceed that of a sole VOYGR™ plant (i.e., the no-SOEC case). This means that the hydrogen production of an integrated VOYGR™ plant and SOEC facility can have a greater total system efficiency than that of a power generation facility operating alone.

V. Conclusion

First, both the extraction steam and main steam cases had advantages and disadvantages. While the total system efficiency of the extraction steam case was slightly higher than that of the main steam case, the main steam case had a higher hydrogen production rate, a sufficient supply pressure, and a simpler design, which offered advantages for plant design and operation.

It is therefore suggested that the configuration be selected based on requirements of the particular integrated plant.

Second, if the efficiency of the SOEC facility itself ($Eff._{SOEC}$) is higher than the threshold efficiency, hydrogen production in an integrated VOYGR™ plant and SOEC facility can have a greater total system efficiency than operating a VOYGR™ plant alone for power generation.

The threshold efficiency presented in this study is therefore significantly lower than the reported target in 2050, making it highly achievable. Thus, although SOEC technology is still under development, the efficiency of an SOEC facility could reach the threshold efficiency in the future, which would mean that highly efficient production of carbon-free hydrogen using an integrated VOYGR™ plant and SOEC facility would be feasible.

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