Research Article

Optimization of Integrated Solid Refuse Fuel and Solid Oxide Electrolyzer Cell System for Hydrogen Production

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In this study, a performance predictive model for hydrogen production was developed for the commercialization of the integrated solid refuse fuel (SRF) and solid oxide electrolyzer cell (SOEC) system. A SRF system was developed, and reliability was verified in the steam conditions for the SOEC application. Systems optimization according to parametric analysis was conducted in the predictive model based on the experiments. When the steam temperature varies between 973 and 1,373 K, hydrogen production increases by 14% to 64 tons per year at 1,373 K; meanwhile, when the steam pressure varies between 0.1 and 0.7 MPa, the performance deteriorates significantly. Under optimal conditions (temperature: 1,373 K; pressure: 0.3 MPa; mass flow rate: 200 kg/h), the amount of steam that can be produced by the integrated SRF–SOEC system is 1,752 tons per year, which can yield 87.6 tons of hydrogen per year. When SRF was used as a heat source, compared with the use of LNG, a total annual cost saving of approximately 2.6% was realized. The break-even point can be reduced by approximately 5 months, which reflects economic efficiency.

1. Introduction

Environmental problems caused by global warming have been a serious problem; however, it has been difficult to utilize renewable energy due to its unstable production and conflict crisis between countries [1, 2]. The recently accelerated problems are a signal that we should no longer depend on imports and exports for energy sources such as fossil fuels and that we should promote a transition to CO₂ reduction policies and renewable energy [3]. As of 2020, waste, bio, and solar energies constitute 40.2%, 25.1%, and 14.5% of South Korea’s renewable energy, respectively [4]. Among them, waste energy accounts for a high proportion despite a decrease of approximately 21% compared with that in 2016 [5]. Efforts to reduce waste are continuing; however, since it is landfilled or incinerated in a low-efficiency system [6], it requires a lot of power supply and demand, so another method should be introduced to increase the efficiency of waste energy recovery [7, 8]. Therefore, the existing methods such as landfill and incineration are not suitable for the future, and the concept of energy conversion should be introduced and treated in an eco-friendly system [9, 10]. Trainer [11] reported that the current renewable energy cannot fulfill 100% of all electricity demand unless a renewable system with improved technical performance is developed based on energy sources such as waste energy, hydrogen, solar, and biomass. This suggests that the development of an integrated system with renewable energy is inevitable. Recently, waste energy has been used in fuel conversion processes, including those pertaining to solid reuse fuel (SRF). SRF has a uniform composition and a high calorific value [12]; more importantly, it can be used in high amounts as combustible waste is processed [13, 14]. In addition, heated SRF (see Figure 1) can uniformly generate high-temperature (HT) steam due to its high calorific value, making it easy to apply to long-term operating systems [15]. The generated high-temperature steam can be applied to a bidirectional solid oxide electrolyzer cell (SOEC)
developed as an energy storage device that produces hydrogen and electricity and thus has high utility [16, 17]. Hydrogen is one of the alternatives to fossil fuels and is an energy source that can overcome limitations due to its high energy density. These characteristics stand out as an environmentally friendly method in the industrial and transportation sectors [18]. Although the proportion of hydrogen production using SOEC technology is modest, it has been implemented in the industry and is garnering significant attention as a new technology for CO₂ reduction. In particular, SOEC technology using high temperature (HT) offers a relatively high efficiency because it requires significantly less electrical energy than the low-temperature (LT) electrolysis process [19]. In addition, specific operating conditions are required to induce an SOEC reaction with high efficiency, among which the most important are high-temperature and low-pressure (HTLP) steam conditions. In terms of pressure, a low pressure (LP) is preferred over a high pressure (HP) as it is less dangerous and affords higher durability [20]. By contrast, the steam condition should be HT steam of 973 K or higher, which is opposite to the pressure condition [21]. This is because the enthalpy of combustion heat is required in the SOEC process, and as the steam temperature increases, an endothermic reaction occurs and the enthalpy increases [22]. This reduces the demand for electric energy [23] and enables, in principle (theoretically), electric energy to be converted into hydrogen with 100% efficiency. However, research pertaining to SOECs using waste energy, including SRF, is still nascent. Research on HTLP steam generation for SOEC using SRF has not been conducted, and furthermore, variable optimization and economic evaluation have not been performed based on experimental results [24]. Oh et al. [25] conducted a laboratory-scale experiment to verify the possibility of HT steam generation using SRF. In a basic study, liquified natural gas (LNG) was used instead of SRF, and optimal steam conditions (steam temperature of 773 K and steam pressure of 0.3 MPa) were derived. Pressure-drop predictions and thermal analysis based on the steam conditions were performed; additionally, it was verified that the thermal efficiency was governed by the steam conditions when the atmosphere inside the second combustion furnace (CF) was maintained constant. In addition, when SRF was used instead of fossil fuel, the energy harvesting rate was 33%, which increased the effectiveness of SRF. However, Oh et al.’s study pertaining to the possibility of using SRF is still in the nascent stage, and because it involves the generation of simple HTLP steam, the stability of the system must be confirmed using actual SRF. To commercialize an integrated SRF–SOEC system, a performance prediction model for hydrogen production through experimental verification is required. Through the economic evaluation based on the performance prediction model, the characteristics of the integrated system are identified, and the applicability is increased in industry. Duffie and Beckman [26] demonstrated through simulations that the integrated waste energy and solar system model reduced electricity costs by 25% compared to the conventional systems. Operational optimization was realized by performing numerical comparisons to derive the key variables such as design parameters. Saleem et al. [27] predicted the economic feasibility to increase the efficiency by more than 7.8% through the development of an optimal model of the integrated solar and hydrogen system. The development of a predictive model is a process that must be performed before an integrated system is constructed. In addition, variable optimization is crucial in terms of economic feasibility because it reduces possible losses in the system and allows factors affecting performance to be derived based on empirical input data. Therefore, an ecofriendly hydrogen production method should be studied to reduce CO₂ emissions and the system applied to the performance predictive model should be experimentally verified.

In this study, a performance predictive model for hydrogen production based on experiments was firstly developed for the commercialization of an integrated solid refuse fuel (SRF) and solid oxide electrolyzer cell (SOEC) system. To do this, the high-temperature steam must be stably supplied to the solid oxide electrolysis cell (SOEC), and this process was experimentally/numerically studied. As the first attempt to increase the effectiveness of the integrated system, a high-temperature steam generation system for SOEC is developed using SRF. The drivability and reliability of the system are verified at the steam conditions (temperature: 973 K; pressure: 0.3 MPa; and mass flow rate: 100 kg/h). The experimental data are applied to the newly proposed performance
prediction model, and optimal conditions are derived to predict hydrogen production for one year. The performance prediction model will be a guideline to increase the effectiveness of the integrated SRF-SOEC system as it can be applied to the design stage and the economic evaluation for system scale-up. Moreover, it is expected that a highly efficient hydrogen production system will be constructed using the SRF, considering the optimization strategy.

2. Experiments

2.1. Experimental Apparatus and Procedure. Combustible wastes were selected from households and workplaces. They comprised shredded primary and secondary wastes, and their processing can be categorized into formed and non-formed processing, as shown in Figure 2. In this study, non-formed SRF was used as fuel for steam generation. The energy density of the SRF was 15–21 MJ/kg, and the energy density of the LNG used was 53.6 MJ/kg. The energy consumption rate can be reduced by approximately 50% using the SRF. In addition, energy can be harvested based on the difference in heat supplied; therefore, it is highly useful from an industrial perspective [28]. In this experiment, a 100 kg-class industrial pilot plant system was established, as shown in the schematic diagram of Figure 3, and its specifications are summarized in Table 1. The system is composed of a hopper for the SRF inlet, first CF, second CF, one-through boiler, water-cooled heat exchanger (HX), and dust collector system. Other devices include ignition and supporting burners, a forced draft (FD) fan, an induced draft (ID) fan, pumps, and measuring devices. The operating conditions of the HTLP steam system are listed in Table 2. In the first CF, the SRF was burned, and the gas temperature was approximately 1,300 K. After combustion, the bottom fly ash was discharged to the bottom. The primary gas heat flowed to the second CF, and the gas temperature was approximately 1,100 K. The low calorific value of the SRF input was 122.04 MJ/kcal, which is sufficient for generating HTLP steam. A reactor that can withstand high combustion heat is necessitated to convert LT steam to HT steam. A high-temperature steam generator (HTSG), which is a reactor, was installed in the second CF. Because the gas temperature in the first CF was higher, installing the HTSG in the first CF allowed the vapor temperature to reach the target value more rapidly. However, in the SRF, ash is generated when it is burned at HT. When the HTSG was installed in the first CF, ash was adsorbed on the surface of the HTSG and fouling occurred, which can damage the device. As such, it is an unproductive method in industrial systems because it must be operated stably for a long duration and adversely affects operational economy, e.g., fuel wastage, equipment repair, and heat loss during generation. Therefore, the gas heat of the second CF was transferred to the surface of the HTSG, and the steam temperature inside the HTSG reached the targeted value owing to radiation and convection. The low-temperature and low-pressure (LTLP) steam inside the HTSG was supplied from a one-through boiler using city water. The steam condition generated by the boiler was LTLP, the steam temperature was 453 K, the steam pressure was 0.4 MPa, and the steam flow rate was 100 kg/h. The LTLP steam became HTLP steam at 973 K owing to the gas heat from the second CF, which was discharged after it was transferred to the HTSG. The temperature of the discharged gas, which included ash and harmful elements, was approximately 900 K. Therefore, it should be discharged appropriately by performing the necessary posttreatments. In this study, the exhaust gas temperature was reduced using a one-through boiler and water-cooled HX. The one-through boiler not only supplies LTLP steam but also functions as a heat exchanger to cool the gas heat discharged.

Figure 2: Simplified process of SRF production. (a) Combustible waste. (b) 1st shredding. (c) 2nd shredding. (d) Solid refuse fuel.
from the second CF. The established industrial pilot plant system is shown in Figure 4. Because the system was installed outdoors, it was significantly affected by ambient air during the winter. As it is essential to prevent heat loss in all devices and pipes in the system, an insulating material with a thermal conductivity of 0.23 W/m-K or less was used.

Because SRF contains significant amounts of impurities such as KCl and NaCl, an efficient dust collector system was used to prevent deposit formation during combustion [29, 30]. In this experiment, a bag filter was used owing to its excellent separation efficiency through filtration; moreover, it can achieve a dust collection efficiency exceeding 99% for ultra-fine particles [31].

2.2. Data Reduction. The chemical composition of the SRF was analyzed to calculate the inlet heat of the system. The accuracy varied depending on the size of the sample during analysis, and it was generally 1.5–2 mm. Table 3 shows the chemical composition of the SRF; elements C, H, N, S, and O constituted 88.3%, whereas ash constituted 11.8%. The noncombustible material remained as ash and was regarded as an inorganic component or a trace metal component in the form of an oxide. Furthermore, the proximate composition of moisture, ash, volatile content, and fixed carbon was 100% on a dry basis. The mass flow rate of the SRF used in the experiment was 48 kg/h, and the SRF and air temperatures were assumed to be 293 K. Hence, the total calorific value of combustion was 976 MJ/h based on the lower calorific value. The amount of heat supplied to the steam was calculated based on the SRF, as shown in [32]

\[
\dot{Q}_s = \dot{m}_s \cdot (h_o - h_i),
\]

where \(\dot{Q}_s\) is the steam heat transfer rate, \(\dot{m}_s\) the steam flow rate, \(h_i\) the enthalpy of the inlet steam, and \(h_o\) the enthalpy of outlet steam.

2.3. Uncertainty Analysis. The data evaluated 30 min after the steady state was attained are shown in Figures 5(a)–5(d). The experiment was conducted for 2 h, and it was

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**Table 1: Specification of high-temperature steam generation system using SRF.**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st combustion furnace</td>
<td>Φ1,280 × 2,065 H</td>
</tr>
<tr>
<td>2nd combustion furnace</td>
<td>Φ940 × 1,445 H</td>
</tr>
<tr>
<td>HTSG (high-temperature steam generator)</td>
<td>100 kg/h</td>
</tr>
<tr>
<td>Ignition burner</td>
<td>100,000 kcal/h</td>
</tr>
<tr>
<td>One-through boiler</td>
<td>200 kg/h</td>
</tr>
<tr>
<td>Bag-filter dust collector</td>
<td>14 m³/min</td>
</tr>
<tr>
<td>FD fan</td>
<td>15 m³/min</td>
</tr>
<tr>
<td>ID fan</td>
<td>25 m³/min</td>
</tr>
<tr>
<td>Stack</td>
<td>Φ240 × 7,000 H</td>
</tr>
</tbody>
</table>

**Table 2: The operating conditions of HTLP steam system.**

<table>
<thead>
<tr>
<th>Systematic characteristics</th>
<th>Operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam inlet condition (MPa)</td>
<td>Saturated vapor state (0.4)</td>
</tr>
<tr>
<td>Steam inlet flow rate (kg/h)</td>
<td>100</td>
</tr>
<tr>
<td>Steam outlet temperature (K)</td>
<td>973</td>
</tr>
<tr>
<td>1st combustion gas temperature (K)</td>
<td>1,300</td>
</tr>
<tr>
<td>2nd combustion gas temperature (K)</td>
<td>1,100 K</td>
</tr>
</tbody>
</table>

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Because SRF contains significant amounts of impurities such as KCl and NaCl, an efficient dust collector system was used to prevent deposit formation during combustion [29, 30]. In this experiment, a bag filter was used owing to its excellent separation efficiency through filtration; moreover, it can achieve a dust collection efficiency exceeding 99% for ultra-fine particles [31].
confirmed that the steady state was maintained during the entire experiment. The uncertainty of the system was calculated using the methods of Abernethy et al. [33].

\[
U_c = \left[ 4 \sum_{n=1}^{N} \left( \frac{\partial X}{\partial x_n} \cdot B_{Pn} \right)^2 + \sum_{n=1}^{N} \left( \frac{\partial X}{\partial x_n} \cdot A_{Pn} \right)^2 \right],
\]

\[
B_p = \frac{\sigma}{\sqrt{N}},
\]

\[
X = X(x_1, x_2, x_3, \ldots, x_n),
\]

\[
\sigma = \sqrt{ \frac{1}{N-1} \sum_{n=1}^{N} (X_n - \bar{X})^2 }.
\]

where \( U_c \) is the experimental uncertainty, \( A \) is the bias uncertainty, \( B \) is the random standard uncertainty, and \( \sigma \) is the standard deviation of the experimental values \((x)\) of the steam temperature, steam pressure, and steam flow rate. The measurement devices used in the system are summarized in Table 4 [34], and the errors are listed in Table 5. In regard to the gas temperature of the first CF and the second CF inlet in Figure 5(a), a temperature fluctuation occurred in a specific section, which was caused by the heat supply when the SRF was input. A certain amount of SRF was injected at a time to maintain a constant pressure and temperature inside the combustion furnace to achieve complete combustion. In addition, proportional integral differential controller (PID) control was applied to prevent deviation from the temperature range, thereby enabling stable operation. Meanwhile, because the gas heat was transferred to the HTSG in the second CF directly, its fluctuation would affect the steam condition, rendering it difficult to generate homogeneous steam. When the steady state was reached, the gas heat of the second CF was evenly distributed; therefore, the gas temperature remained constant in the steady state even when fuel was supplied. Therefore, the HTLP steam of Figures 5(b)–5(d) was uniformly generated at 100 kg/h, and its feasibility to be integrated with an SOEC was validated. The experimental uncertainty of the steam heat transfer rate is 13%.

2.4. Thermogravimetric Analysis (TGA). TGA is a method of measuring the change in weight of organic and inorganic materials, including polymers, in a thermal environment. Additionally, it can be used to determine the composition of a sample or verify its thermal stability. In this study, the weight of the sample and its change rate as a function of temperature were observed. The temperature range used for the analysis was 273–973 K as shown in Figure 5. The weight remained constant at approximately 90% at 573 K. When the temperature exceeded 773 K, the weight decreased rapidly to approximately 40%, whereas it decreased by
approximately 20% at 873 K. The SRF decomposed the most smoothly above 873 K; below this temperature, adsorption may occur, which can cause ash to adhere to the surface of the device and result in contamination. Therefore, the CF should be designed such that its internal temperature is 873 K or higher in the configuration stage of the experimental device. In this study, the internal temperature of the CF was 1,100 K or higher; therefore, the decomposition rate of ash was high, and stability against contamination was confirmed. Steam generated using SRF can be used for industrial and domestic use; additionally, it can be reused for heating absorption systems. Industrial plants produce HT steam using renewable energy or fossil fuels. The operating conditions of the HT steam for each heat source are shown in Table 6, and the reliability has been verified experimentally [35–38]. When LPG was used, the maximum steam temperature reached was 1,233 K; however, because fossil fuels were used, a higher steam temperature was recorded. Using fossil fuels is not an ecofriendly method as it increases CO₂ emissions. In addition, the HP steam generated during the operation is not suitable to be supplied to the SOEC. Hence, SRF is suitable for SOEC applications compared with other parameters.

### Table 4: The specifications of the measuring devices.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Type</th>
<th>Operating range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam temperature (K)</td>
<td>K-type</td>
<td>-473–1,523</td>
<td>±0.02</td>
</tr>
<tr>
<td>Steam pressure (kPa)</td>
<td>Pressure transducer</td>
<td>0–1,000</td>
<td>±4.71</td>
</tr>
<tr>
<td>Steam flow rate (kg/h)</td>
<td>Volumetric flowmeter</td>
<td>10.0–47.6</td>
<td>±0.35</td>
</tr>
</tbody>
</table>

### Table 5: Experimental uncertainty of HTLP steam generation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A (%)</th>
<th>B (%)</th>
<th>Uc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam temperature</td>
<td>0.014</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Steam pressure</td>
<td>0.032</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Steam flow rate</td>
<td>1.75</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Steam heat transfer rate</td>
<td>13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6: Comparison of steam generation according to heat sources.

<table>
<thead>
<tr>
<th></th>
<th>SRF</th>
<th>Solar energy</th>
<th>Coal-fired</th>
<th>LPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam temperature (K)</td>
<td>973</td>
<td>654–794</td>
<td>839</td>
<td>823–1,233</td>
</tr>
<tr>
<td>Steam pressure (MPa)</td>
<td>0.3–0.6</td>
<td>7.4–9.5</td>
<td>&lt;24.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

3. Performance Predictive Model for Integrated SRF-SOEC System

In this study, a system that is applicable to SOECs based on the generation of 100 kg/h of HTLP steam using SRF in a pilot plant system was developed. It is clear that the steam conditions and technologies applicable to the SOEC have been established, and the resulting system is highly efficient. However, since this is the first attempt to integrate this system directly with an SOEC, many limitations were encountered, e.g., the separation and appropriate integration between hydrogen production and storage [39, 40]. Therefore, the long-term operation performance of an integrated system must be predicted through simulation before it is developed; additionally, a restrictive approach must be applied, and the component types and functions must be selected rationally. In this study, simulation was conducted based on empirical data obtained from the abovementioned experimental system, and Transient System Simulation (TRNSYS), a commercial program, was used. TRNSYS is a dynamic simulation program that focuses on evaluating the performance of the thermal and energy systems of a system; it is used in various fields because it can predict performance by determining variables. It is one of the best programs for optimizing the system process and deriving key factors. A schematic diagram of the modeling system is shown in Figure 6. The steam generation region using SRF was configured in the same manner as the experimental system. The SOEC was modeled as a hydrogen system in TRNSYS [41]. Additionally, the performance of the system, such as the hydrogen production rate and gas volume, was predicted based on the supplied steam condition. The characteristics of each component are described as follows:

3.1. HTLP Steam Generation

3.1.1. HTSG (Type 636). This device heats the LT steam supplied from the boiler. A pinch-point temperature differential approach is used to identify impossible or impractical heat exchange conditions. The pinch point temperature difference, which allows heat transfer, is defined as the minimum temperature difference between the heat source fluid and water vapor.

3.1.2. CF (Type 967). The furnace was modeled using the heating input ratio and a time constant that describes the time required for the CF to reach its maximum capacity. Depending on the gas heat output, the CF can reach its maximum supply temperature and be regulated internally such that the temperature is not exceeded.

3.1.3. Feed SRF (Type 14). The fuel input cycle and the amount of fuel input per hour or day were calculated repeatedly.

3.1.4. One-Through Boiler (Type 659). The auxiliary heater increases the fluid temperature; when the outlet temperature of the heater is lower than the maximum value ($T_{max}$) specified by the user, the heater heats the fluid at the speed specified by the user. By providing control between 0 and 1 in the controller, this routine is performed in the same manner as a CF that provides heat at a rate of $Q_{max} \times Y$ without exceeding a specified outlet temperature ($T_{set}$).

3.1.5. Water-Cooled HX (Type 652). This model maintains the gas heat discharged from the one-through boiler at LTs. A constant (efficiency/$T \times C_{min}$) HX that can automatically bypass the hot-side fluid around the heat exchanger is modeled to maintain the cold-side outlet temperature above a specified time-dependent set point.

3.1.6. Supply and Feed Water Pump (Type 114). This is a single-speed pump that can maintain the flow rate of a fluid. The downstream flow is set based on the rated flow parameter and the current value of the control signal input.

3.1.7. Input Data (Type 9). This model inputs the calorific value of the SRF or the data on city water temperature. Information is transmitted to each component using a specified input value.

3.1.8. Pressure-Reducing Valve (Type 596). The steam entering the valve is expanded to a user-specified outlet pressure. If the specified outlet pressure is higher than the inlet...
pressure, the steam passes through the device without a state change. The steam inlet conditions (temperature, minimum pressure, mass flow rate, and enthalpy) were provided, whereas the outlet pressure was specified by the user. The steam’s attribute subroutine from TRNSYS was used to fully determine the imported attribute. Subsequently, the steam’s attribute routines were reused along with $h_s$ and $P_o$, as shown in Equations (3) and (4), [41], respectively. The model provides the steam outlet conditions (temperature, pressure, mass flow rate, and enthalpy).

$$h_o = h_s,$$

$$P_o = \text{Min} (p_f, p_s).$$

3.1.9. Pressure Drop and Thermal Loss (Type 605 and Type 201). The heating load imposed on the steam flow is modeled. A specified amount of energy is removed from the steam stream based on the specified inlet steam condition, load, and outlet steam pressure. In addition, this model checks if the outlet steam temperature is higher than the specified minimum temperature (pinch point calculation, etc.). When the calculated outlet temperature is below the user-specified minimum temperature, steam flows at the specified minimum temperature. The pressure drop in the simulation is determined according to the inlet and outlet conditions of the pipeline by the basic equation. Since the thermal loss starts in balance over the pipe volume, the outlet temperature and overall loss conductance are calculated. In addition, the heat transfer coefficient, conductance, and insulation of the outside of the pipe can be specified by the user, and through this, heat loss that may occur during system integration can be overcome.

3.1.10. Water Tank (Type 156). The water tank is a tank that can store a certain amount of city water, and an HX is installed inside it. The fluid in the tank is maintained at a set temperature via its interaction with the fluid in the HX.

3.1.11. ID fan and FD Fan (Type 147). A fan that can spin at any speed between 0 (complete stop) and its rated speed. The volumetric flow rate of air yielded by the fan exhibits a linear relationship with the control signal.

3.1.12. PID Controller (Type 23). A PID controller is a control device for inputting the air volume of the ID and FD fans; it calculates the control signal required to maintain the control variable at the set point. In general, a short time step is used in the simulation; however, in the proposed model, the control signal is adjusted by setting the repeat mode for a long-term operation.

3.2. Hydrogen Production (SOEC).

3.2.1. Controllers (Type 100a). This model comprises a set of control functions for an electrolyzer in an integrated minigrid-connected wind/electrolyte/H$_2$ storage/fuel cell system. The electrolyzer is designed to operate in the variable power mode.

3.2.2. Power Conditioning (Type 175). A mathematical model of a power-conditioning unit based on an empirical efficiency curve for an electrical converter (DC/DC) or inverter (DC/AC or AC/DC). An empirical relationship was first proposed by Laukamp H [42], and was subsequently improved by Ulleberg [43]. The output power is calculated using the available input power.

3.2.3. Electrolyzer (Type 160). A model for generating high-temperature steam electrolysis (HTSE) based on a combination of basic thermodynamics, heat transfer theory, and empirical electrochemical relationships includes dynamic thermal models. The temperature-dependent current–voltage curve for a specified pressure and the Faraday efficiency relationship, independent of temperature and pressure, form the basis of the electrochemical model. The electrolyzer temperature can be used as an input or calculated from a simple or detailed thermal model [44].

According to Faraday’s law, the rate of hydrogen production in an electrolytic cell is directly proportional to the rate of electron transfer at the electrode, which translates to the current in the external circuit. Therefore, the total hydrogen production rate of an electrolyzer composed of several cells connected in series can be expressed as shown in [45].

$$\dot{n}_H = \eta_f \cdot N_{cell} \cdot \frac{I_{cell}}{n \cdot F}.$$  \hspace{1cm} (5)

The rate of oxygen production can be obtained readily based on stoichiometry (cathode); on a molar basis, it can be expressed as shown in [46].

$$\dot{n}_{O_2} = 0.5 \cdot \dot{n}_H.$$  \hspace{1cm} (6)

The heat generated in the electrolyzer is primarily due to electrical inefficiency, and the energy efficiency ($\eta_e$) can be calculated as shown in Equation (7) [47], where the thermoneutral voltage ($U_{tn}$) and cell voltage ($U_{cell}$) are involved.

$$\eta_e = \frac{U_{tn}}{U_{cell}}.$$  \hspace{1cm} (7)

3.2.4. Compressed Gas Storage (Type 164). The compressed gas storage model is based on the van der Waals equations of state for real gases [48, 49].

Figure 7 shows the TRNSYS modeling of the integrated SRF–SOEC system. For HTLP steam, the steam properties calculated from the Engineering Equation Solver were used. The mass flow rate of the SRF was 48 kg/h and was implemented for 24 h. For the water data supplied to the once-through boiler and water-cooled HX, the water temperature of Cheong-ju, which is in close proximity to the experimental location, was applied, and the input of the component in the HTLP steam generation region was input based on the experimental data. In particular, the steam condition to be supplied to the SOEC was identical to the experimental value, and the pinch point temperature difference at the steam outlet was set to 15 K, considering system fluctuations.
that may occur during the process. Furthermore, it was assumed that steam was supplied to the SOEC using a steam turbine. The system variables are presented in Table 7. A corresponding model for postprocessing gas heat is not available in TRNSYS. Therefore, the efficiency of the device used in the actual system was input; it is noteworthy that the temperature of the exhaust gas was reduced and discharged into the ambient environment via the device.

3.3. Model Validation. To optimize the SRF–SOEC system, the variables affecting the system performance should be identified [50]. In this study, the steam temperature, steam pressure, and steam flow rate were specified as variables, and the performance of the system was predicted based on changes in the variables. Experimental results from the same period were used to validate the simulation results. The results included those of the steam generation region (temperature, pressure, flow rate, etc.) and hydrogen production region (total hydrogen production rate, efficiency, hydrogen gas pressure, etc.) from the experiment.

Figure 8 shows a comparison between the experimental and simulation results in terms of the steam heat transfer rate. The model was verified to be valid based on its error of approximately 2.6% in the simulation. The annual hydrogen production calculated based on modeling was 43.8 tons. The average efficiency was approximately 79.2%, and the simulation was assumed to exhibit high efficiency because it was operated under ideal conditions [51].

**Figure 7: Flow diagram of hybrid SRF–SOEC system.**

**Table 7: System parameters of the parametric study.**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRF (MJ/h)</td>
<td>976</td>
</tr>
<tr>
<td>1st CF gas (K)</td>
<td>1,300</td>
</tr>
<tr>
<td>2nd CF gas (K)</td>
<td>1,100</td>
</tr>
<tr>
<td>Air flow rate (Nm$^3$/kg)</td>
<td>5.1</td>
</tr>
<tr>
<td>Air temperature (K)</td>
<td>298</td>
</tr>
<tr>
<td>One–through boiler efficiency (K)</td>
<td>80</td>
</tr>
<tr>
<td>Water tank volume (m$^3$)</td>
<td>1.6</td>
</tr>
<tr>
<td>Water–cooled heat exchanger efficiency (K)</td>
<td>65</td>
</tr>
<tr>
<td>HTSG pinch point temperature (K)</td>
<td>15</td>
</tr>
<tr>
<td>Steam inlet temperature (K)</td>
<td>450</td>
</tr>
<tr>
<td>Steam inlet pressure (MPa)</td>
<td>0.4</td>
</tr>
<tr>
<td>Steam flow rate (kg/h)</td>
<td>100</td>
</tr>
<tr>
<td>Pressure drop of HTSG inlet and outlet</td>
<td>0.1</td>
</tr>
<tr>
<td>Steam outlet temperature (K)</td>
<td>973</td>
</tr>
<tr>
<td>Steam outlet pressure (K)</td>
<td>0.3</td>
</tr>
<tr>
<td>Turbine efficiency (%)</td>
<td>70</td>
</tr>
<tr>
<td>Electrode area (m$^2$)</td>
<td>0.25</td>
</tr>
<tr>
<td>Number of cells</td>
<td>21</td>
</tr>
<tr>
<td>H$_2$ tank volume (m$^3$)</td>
<td>5</td>
</tr>
</tbody>
</table>
4. Results and Discussion

Kazepoor and Braun [52] reported the importance of operating conditions that affect the performance of SOECs. The energy density of SOECs increases with the supplied steam temperature. In addition, unlike other energy sources, SOECs require LP steam owing to its durability and risk. Therefore, the HTLP conditions must be precisely controlled. In the experiment, the system was validated by generating HTLP steam; however, the performance must be predicted via a parametric study because the temperature and pressure of steam may increase or change. Hence, the factors that impose the most significant effect on the integrated SRF–SOEC system should be derived, and the variables should be optimized. The detailed variable parameters are presented in Table 8.

4.1. Effect of Steam Temperature. An SOEC using HT steam typically operates at 973–1273 K. This is because the total energy demand during electrolysis is reduced by the heat of vaporization and can be provided at a low cost. Yadav and Banerjee [53] experimentally demonstrated an increase in the energy efficiency from a minimum of 9.1% to a maximum of 12.1% based on the variation in the steam temperature (temperature range: 873–1,273 K). The results proved that the steam temperature affects electrolysis. In this section, the performance based on the variation in the steam temperature obtained numerically is discussed, and the results are shown in Figure 9. The steam temperature range was 973–1,373 K, and the steam pressure and steam flow rate were fixed at 0.3 MPa and 100 kg/h, respectively. As shown in Figure 9, as the steam temperature increased, the annual hydrogen production rate and overall efficiency increased linearly, where the rate of increase was approximately 14% at 1,373 K. Herein, the overall efficiency refers to the average

![Figure 8: TRNSYS modeling of hybrid SRF–SOEC systems. (a) HTLP steam generation system using SRF. (b) SOEC system for hydrogen production.](image-url)

| Table 8: Variable parameter of hybrid SRF–SOEC system. |
|--------------------|---------|
| Parameters         | Value   |
| Steam temperature (K) | 973–1,373 |
| Steam pressure (MPa)   | 0.1–0.7  |
| Steam flow rate (kg/h) | 100–200  |
value. The steam heat transfer rate supplied to the SOEC increased with the steam temperature, and the average energy efficiency obtained from the simulation deviated by only approximately 2% from that of Yadav and Banerjee. In particular, the effect of the increase in steam temperature is depicted in Figure 9; as shown, the cell voltage decreased with the heat of vaporization of the HT steam. As the steam temperature increased, the current density continued to increase without an inflection point, and the density improvement in the temperature range of the simulation was not limited. However, the HT thermal energy constituted only a small portion of the total energy. In other words, because the energy efficiency did not differ significantly in the operating range, the effects of other system variables must be confirmed [54].

4.2. Effect of Steam Pressure. Henke et al. [55] analyzed the performance of an SOEC based on a steam pressure of 0.05–2 MPa to ensure an effective operation and emphasized the necessity of LP steam for achieving stable hydrogen production and durability. This is because the steam outlet pressure significantly affects the system performance. In this section, the effect on the SOEC analyzed through a simulation of the steam pressure was presented. The range of the steam pressure was 0.1–0.7 MPa, the steam flow rate was 100 kg/h, and the steam temperature was 1,373 K selected as the optimum temperature (as presented in Section 4.1). Figure 10(a) shows that the hydrogen production rate and overall performance decreased as the steam pressure increased. Owing to the characteristics of the integrated system, the steam heat transfer rate decreased as the steam pressure increased because it was affected by the steam condition. Therefore, the power generated in the steam generation affected the hydrogen production rate. In particular, when the steam pressure was 0.25 and 0.4 MPa, an inflection point was observed, where the performance significantly decreased. A similar trend was observed in the current density, as shown in Figure 10(b). It is known that at high pressures, the internal cell resistance is reduced owing to increased mass transport and decreased diffusion over potential [56]. Therefore, in the low current density range, the thermodynamic reaction on the stack and cell performance imposed a greater effect than the electrochemical reaction. In addition, the higher the current density, the greater the effects of electron conduction, activation, and diffusion resistance on the cell performance. It was discovered that LP steam was suitable for the process.

4.3. Effect of Steam Flow Rate. The optimal operating conditions for temperature and pressure were derived. The scale-up of a system is essential for its commercialization. As the scale of the system increases, the amount of steam produced increases because it is directly associated with hydrogen production. The maximum steam flow rate that can be produced in the system was selected, and the hydrogen production based on the steam flow rate was defined. The range of the steam flow rate was selected to be 100–200 kg/h, based on the capacity of the HTSG installed in the system. As shown in Figure 11, the steam heat transfer rate increased with the steam flow rate, and the hydrogen production rate indicated a linear increase. This indicates that hydrogen production is correlated with the steam supply. In the proposed model, the SRF input was fixed at 976 MJ/h; it was expected that the SRF input would be limited by the increase in the steam flow rate. However, when the steam flow rate was 200 kg/h, the effectiveness of the SRF was validated by the stable hydrogen production. The increase in steam flow rate was primarily due to the one-through boiler, which generated LTLP steam, and the HTSG, which received the LTLP steam. The boiler can generate up to 200–250 kg/h of LTLP steam, and the capacity of the HTSG was 200 kg/h; therefore, steam and hydrogen can be generated uniformly. Furthermore, the system constructed in this study can stably generate up to 200 kg/h of steam, with an annual hydrogen production of up to 87.6 tons and an average overall efficiency of approximately 80%.

5. Life Cycle Cost Analysis

As discussed in Section 4, the simulations conducted in this study were based on experiments, and the optimal operating conditions were derived from the performance prediction model to increase the utilization of the integrated SRF–SOEC system. When the system is operated for one year, it is possible to predict the performance of hydrogen production under the optimal conditions. However, long-term operations of 10 or 20 years are difficult to predict, particularly in terms of the economics of the system. To increase the effectiveness of SRF for its use in the SOEC, economic feasibility in terms of the lifetime and cost of the system should be considered [57]. Therefore, the economic evaluation of the integrated SRF–SOEC system was conducted during the long-term operation. In the LCC analysis method, management costs, HTLP steam generation, and the SOEC are considered and analyzed from the industrial perspective. The LCC is calculated as a cost governed by the operating period and can be used as an important index for evaluating
and comparing the integrated SRF–SOEC systems. The initial cost used to construct the system accounts for most of the total cost and includes the material costs, installation costs, management costs, and fuel costs. In addition, to improve reliability, all equipment costs are calculated based on the amount suggested by the contractor when building the system. In the LCC analysis, \( CTA \) is the total amount required for the annual system and is expressed as shown in Equation (8), where \( CM \) is the maintenance cost.

\[
C_{IC} = CE + CB + C_{ME}, \tag{9}
\]

\[
CE = C_{CF} + C_{HTSG} + C_{DS} + C_{SOEC}. \tag{10}
\]

The operation and maintenance costs of the system \( C_{OM} \) were calculated using Equation (11). The operating cost \( C_{OP} \) based on the cost of the power of the gas burner \( C_{BN} \) used to initially burn the SRF and that of the one-trough boiler \( C_{OB} \) used for the production of LTLP steam were estimated using Equation (12). The operating
conditions were used based on the simulation, where the inlet pressure and flow rate were set to 0.3 MPa and 200 kg/h, respectively. The pumping power was calculated based on the pressure drop that occurred at the inlet and outlet of the HTSG, and it was included in the operating cost. The fuel cost \( (C_{FE}) \) required to operate the integrated SRF–SOEC system is expressed as shown in Equation (13).

In addition, the SRF cost \( (C_{SRF}) \) used as the initial fuel, the LNG cost \( (C_{WT}) \) for gas heat supply, and the water supply cost \( (C_{WT}) \) for LTLP steam generation were included.

\[
C_{OM} = C_{OP} + \frac{1}{2} C_{CP},
\]

\[
C_{OP} = C_{BN} + C_{SB} + \frac{1}{\rho} \Delta P P_{fl},
\]

\[
C_{FE} = C_{SRF} + C_{Gas} + C_{WT}.
\]

Figure 12 shows the total annual cost \( (C_{TAK}) \) of the integrated SRF–SOEC system; it was used to compare the economic feasibility of systems to be developed in the future. The lifespan of the integrated SRF–SOEC system was calculated to be 20 years, and the fuel cost required to operate the system was 43.2%, which is extremely high. By contrast, the initial cost was approximately 1.8%, and most devices to be fabricated after a detailed verification in the design stage of a pilot plant have a semipermanent lifespan. Therefore, the cost of maintenance was only approximately 17.2%, and the costs of other ancillary equipment (e.g., the burner, one-through boiler, HX, pump, and valve) can be reduced based on the operating pattern of the system. This is efficient from an economic perspective. Based on the optimal conditions of the simulation, the total amount of HTLP steam that can be generated annually is approximately 1,752 tons, and the steam can be sold for approximately $37,024 in South Korea. The total amount of hydrogen that can be converted to steam is approximately 87.6 tons per year, and the hydrogen sales price suggested by the Ministry of Science and ICT in South Korea is $3.23. Nonetheless, steam generated using fossil fuels is still being supplied to industrial sites in large quantities. Liquefied natural gas, which has a high calorific value, has reached a maximum combustion efficiency of up to 90% and is still preferred by the industry, making it difficult to convert energy use to SRF. However, it is highly affected by market fluctuations and difficult to supply uniformly; moreover, its use in commercial development is being reduced gradually. The combustion efficiency of SRF is approximately 81%, which is relatively lower than that of LNG; nonetheless, it is advantageous in terms of long-term operation and cost [28]. Figure 13 shows a comparison of the break-even point when the heat sources of the SRF and LNG were used to generate HTLP steam in the integrated SRF–SOEC system. The operating conditions and data were observed based on experiments and simulations, assuming equal fixed costs \( (C_{IC}, C_{OP}, \text{ and } C_{OM}) \). However, the fuel costs from the experiments significantly differed from the costs recorded in simulation. Compared with LNG, the use of SRF can annually yield a cost harvest of approximately 2.6%, thereby reducing the break-even point by approximately 5 months. The results indicate the possibility of integrating SRF and SOEC into a single system that can be operated economically under optimal conditions.

6. Conclusions

In this study, a performance predictive model for hydrogen production based on experiments was developed for the commercialization of integrated SRF and SOEC systems. HTLP steam for SOEC supply was experimentally verified through a pilot plant system using SRF. In addition, the variable change of the integrated SRF–SOEC system was predicted for a long period of time to derive the optimal conditions, and the economic feasibility was evaluated from an industrial plant perspective. The conclusions of this study are as follows:
(1) HTLP steam for SOEC (temperature: 973 K, pressure: 0.3 MPa, and steam flow rate: 100 kg/h) using SRF was generated in an environment above 1,073 K, the standard for complete combustion, and the supplied heat capacity of SRF is 976 MJ/h

(2) The simulation of the integrated SRF-SOEC system was performed based on the experiment, and variable optimization analysis was performed in the performance predictive model

(i) When the steam temperature was varied from 973 to 1,373 K, hydrogen production increased by up to 14% to 64 tons per year at 1,373 K

(ii) When the steam pressure varied from 0.1 to 0.7 MPa, the performance deteriorated significantly when the vapor pressure was 0.25 or 0.4 MPa. At high pressures, mass transport increased, whereas diffusion to dislocation decreased; therefore, low pressure appeared to be a suitable condition

(iii) The annual hydrogen production generated by the change in the steam flow rate (100–200 kg/h) was up to 87.6 tons, and the average overall efficiency was approximately 80%.

(iv) Optimum conditions are steam temperature of 1373 K, pressure of 0.3 MPa, and the flow rate of 200 kg/h in the integrated SRF-SOEC system

(3) The LCCA involved the initial, operation and maintenance, and fuel costs, and it was performed to evaluate the economy of the system. The amount of steam generation is 1,752 tons per year at optimum condition in the performance predictive model, which translates to the generation of 87.6 tons of hydrogen per year

(4) When SRF was used as a heat source, compared with LNG, a total annual cost saving of approximately 2.6% was realized. The break-even point can be reduced by approximately 5 months, which reflects the economic efficiency

Nomenclature

A: Bias uncertainty
B: Random standard uncertainty
h: Heat transfer coefficient, W/m²·K
F: Faraday constant
Iₑ: Transfer rate of electrolyzer
N: Number
n: Production rate, m³/hr
m: Mass flow rate, kg/hr
P: Pressure, Pa
Uc: Experimental uncertainty, %.

Greek Symbols

η: Efficiency, %
σ: Standard deviation.

Subscripts

H₂: Hydrogen production
cells: Electrolyzer cell
f: Faraday
i": Inlet
max: Maximum
min: Minimum
o: Outlet
O₂: Oxygen production
s: Steam
set: Set point
tv: Thermal voltage.

Acronyms

CF: Combustion furnace
FD: Forced draft
HP: High pressure
HT: High temperature
HTLP: High temperature and low pressure
HTSE: High-temperature steam electrolysis
HTSG: High-temperature steam generator
HX: Heat exchanger
ID: Induced draft
LCC: Life cycle cost
LNG: Liquefied natural gas
LP: Low pressure
LT: Low temperature
LTLP: Low temperature and low pressure
SOEC: Solid oxide electrolysis cell
SRF: Solid refuse fuel
TGA: Thermogravimetric analysis.

Data Availability

Data are available on request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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