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Techno-Economic Analysis of Grid-Connected Hydrogen Production via Water Electrolysis

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Abstract: As the global energy landscape transitions towards a more sustainable future, hydrogen has emerged as a promising energy carrier due to its potential to decarbonize various sectors. However, the economic competitiveness of hydrogen production by water electrolysis strongly depends on renewable energy source (RES) availability. Thus, it is necessary to overcome the challenges related to the intermittent nature of RESs. This paper presents a comprehensive techno-economic analysis of complementing green hydrogen production with grid electricity. An evaluation model for the levelized cost of hydrogen (LCOH) is proposed, considering both CO_2 emissions and the influence of RES fluctuations on electrolyzers. A minimum load restriction is required to avoid crossover gas. Moreover, a new operation strategy is developed for hydrogen production plants to determine optimal bidding in the grid electricity market to minimize the LCOH. We evaluate the feasibility of the proposed approach with a case study based on data from the Kyushu area in Japan. The results show that the proposed method can reduce the LCOH by 11% to 33%, and increase hydrogen productivity by 86% to 140%, without significantly increasing CO_2 emission levels.

Keywords: hydrogen production; water electrolysis; renewable energy; operation strategy; CO_2 emission; levelized cost of hydrogen (LCOH)

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1. Introduction

Nowadays, the high levels of greenhouse gas emissions resulting in global warming are regarded as one of the major issues worldwide [1]. Green hydrogen, produced through water electrolysis using renewable energy sources (RESs), has gained significant attention in recent years as a promising solution to address global energy and climate challenges. Its potential applications span across various sectors, including transportation, power generation, and industrial processes, making it a versatile and attractive energy carrier [2]. However, despite the considerable progress made in the development of green hydrogen production technologies, its large-scale deployment still faces several barriers, primarily due to the intermittent nature of RESs and the high costs associated with electrolysis processes.

Among all RESs, the most used are photovoltaic (PV) and wind power generation, which mainly depend on weather conditions [3]. Thus, the availability of electricity from RESs is uncertain, affecting both the economy and the safety of water electrolysis. On the one hand, a hydrogen production plant cannot work when the input power is unavailable, which will reduce the operating hours of the plant and increase total production costs [4]. On the other hand, the direct use of fluctuating power from RESs will cause several problems such as crossover gas and electrolyzer degradation, challenging the normal operation of electrolysis [5]. Therefore, it is necessary to overcome these issues related to the intermittent nature of RESs.

Water electrolysis is an electrochemical process that splits water into hydrogen and oxygen. Regarding water electrolysis technologies for hydrogen production, currently, there are three main methods available or under development: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs). In this paper, we only focus on the first two as SOECs have not yet been commercialized, although individual companies are now aiming to bring them to market [6]. Alkaline electrolysis is the most mature and commercial technology with over 100 years of history. It is highly durable, and already available at large scale, with relatively low capital cost [7]. However, this conventional technology is not designed to be operated with fluctuating power sources, and it shows a very poor performance when the power supply is switched off [5]. PEM electrolysis is relatively resistant to fluctuating power due to its fast response and flexible operation, which allows it to provide a service with a larger load range than alkaline electrolysis, especially in the low load range, and to take advantage of dynamic electricity prices [8]. Moreover, PEM electrolysis shows less performance degradation when power interruption occurs [5]. Thus, it is beneficial in operations with intermittent power sources like RESs. However, the high cost of precious metal electrode catalysts and the shorter lifetime of PEM electrolyzers hinder the wide deployment of this technology [9].

Theoretically, the influence of RES power fluctuations on electrolyzers should be considered when modeling to avoid security risks. However, the existing literature usually ignores this issue to simplify the model [7], or just advocates for PEM technology by highlighting the limits of alkaline technology without a specific techno-economic analysis [10], leading to misestimation of the actual benefits brought by alkaline electrolysis [11]. The authors in [12] adopt the engineering model of an alkaline electrolyzer in a green hydrogen production system without any constraints for the uncertain input power. Few authors explicitly model the impacts of fluctuating power supply. In [13], the limitation of alkaline technology is modeled as ramp-up constraints during the start-up period by setting the needed time for electrolyzers to be operational. However, the influence of uncertain power input on electrolyzers is ignored. In [14], the authors compared the cost of an off-grid hydrogen production plant when using alkaline and PEM electrolyzers. The differences between alkaline and PEM technologies are considered but only in terms of economics, ignoring environmental and safety factors. In [15], the low dynamic load range restriction is modeled for alkaline technology. The authors analyzed both the economic and environmental impacts of complementing green hydrogen production with grid electricity in an average pricing scheme. Therefore, how to model the fluctuations' influences on electrolyzers is still a challenge.

Moreover, electricity pricing schemes are diverse according to the electricity market and the employed model. In the wholesale market, electricity prices are available 24 h ahead ("day-ahead prices") and 1 h ahead ("real-time prices"). Some papers omit dynamic prices to facilitate calculation. For example, the authors in [15] use the average electricity price to calculate hydrogen production cost, simplifying the optimization problem. Generally, a hydrogen production plant can reduce its operating cost by extending production capacity during periods of cheap electricity. In [16], GAMS optimization is used based on day-ahead electricity prices to compare the electricity cost with different operation times only for PEM electrolysis. In [17], yearly historical data are utilized to determine the electricity price at which the levelized cost becomes minimal. The authors in [18] consider both flat-rate pricing schemes and real-time pricing schemes for grid-connected hydrogen production.

The levelized cost of hydrogen (LCOH) is usually used to analyze the economic performance of hydrogen production. The LCOH is a measure of the average net present cost of hydrogen production for a plant over its lifetime [15]. It is used to account for all the capital and operating costs of producing hydrogen and to compare different methods on a consistent basis.

This paper aims to analyze the techno-economic benefits of complementing green hydrogen production with grid electricity. An evaluation model for LCOH is proposed, including the CO_2 penalty, under a wholesale electricity market. The proposed model allows the hydrogen production plant to perform the following:

- Determine the bidding process in the grid electricity market to reduce the LCOH.
- Improve hydrogen productivity without significantly increasing CO_2 emission levels.
- Ensure the load of the electrolyzers meets the requirements of safe operation.

Different capital expenditures (CAPEX) and different operating expenses (OPEX) are evaluated in the proposed model. And the features of alkaline and PEM electrolysis are also considered in our analysis. Moreover, an optimal operation strategy is developed to solve this nonlinear evaluation model. It can calculate the optimal amount of grid electricity required in each time step to cover the intermittency of RESs.

The main contributions of this paper compared with the existing literature are as follows:

- An evaluation model for LCOH is proposed, including CO_2 emission costs in a wholesale electricity market. It considers both the economic and environmental impacts of grid-connected systems and can take advantage of dynamic electricity prices.
- The influences of RES fluctuations on alkaline and PEM electrolyzers are considered. A minimum load restriction is required to avoid explosion due to high crossover gas concentrations.
- A novel operation strategy for hydrogen production plants is developed to determine optimal bidding in the grid electricity market to minimize the LCOH. It can simplify the above optimization problem and solve it without any complex algorithms.

Some recent research also focuses on grid-connected hydrogen production systems. In [19], the authors aimed to smooth the wind farms' output fluctuation to produce hydrogen constantly with the grid-connected system, but they ignored the characteristics of electrolyzers. The evaluation model for the LCOH with CO_2 emissions and a low load range restriction is applied in [15] as well. However, it calculates the LCOH with the average electricity price, ignoring the advantages brought by dynamic electricity prices. The wholesale electricity market is considered in [17,18]. However, in [17], it only focuses on transforming grid electricity into hydrogen, excluding RESs. The CO_2 penalty is not discussed in [18], and it requires the prediction of hydrogen production demand and assumes that hydrogen plants do not produce more than the forecasted demand. To the best of the authors' knowledge, an evaluation model for the LCOH in the wholesale electricity market, considering CO_2 emission costs and the influences of RES fluctuations on electrolyzers, has not yet been discussed in any literature.

The remainder of this paper is organized as follows: Section 2 introduces the off-grid system and grid-connected system for producing hydrogen by electrolysis. Section 3 presents the LCOH model employed and the optimal operation strategy to minimize the LCOH for hydrogen production plants. A case study in the Kyushu area is performed to illustrate hydrogen production with alkaline and PEM electrolyzers. The simulation results are shown in Section 4 to evaluate the performance of the proposed LCOH model. Finally, conclusions are drawn in Section 5.

2. Hydrogen Production by Water Electrolysis

Green hydrogen production by water electrolysis requires 100% RES electricity, which can be achieved with an off-grid production plant, as shown in Figure 1. The power supply is usually wind power or solar power. However, directly using RES electricity may cause some problems. For RES electricity, since the RESs are not always available, the plant may work only during certain hours in a day, reducing the operation hours. In this case, the CAPEX is relatively high, usually not at a competitive cost. Moreover, for alkaline electrolyzers, the fluctuating power input may lead to crossover gas and performance degradation [5]. Water electrolysis can produce not only H_2 but also O_2. Crossover gas is a mix of H_2 and O_2, which can easily explode. From [20], we know that crossover gas reaches relatively high concentrations in an alkaline electrolyzer when power generation is relatively low, sometimes even more than 1% in the experimental simulations, which is dangerous. Therefore, to keep the crossover gas concentration under control, it is necessary to set a minimum load restriction for alkaline electrolyzers. As for PEM electrolyzers, since they are able to operate with fluctuating power, there are no minimum load requirements for PEM electrolyzers. The electrolyzer must stop operating when the power falls below the operating range. During shutdown, RESs cannot be utilized, leading to a reduction in overall energy efficiency.

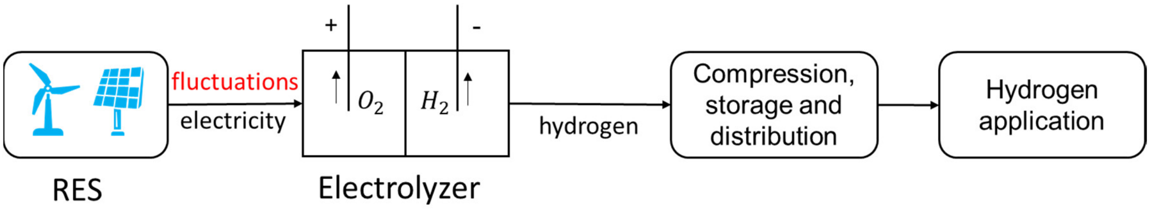


Figure 1. Off-grid hydrogen production system.

One potential solution is using grid electricity to complement the power supply to the electrolyzer. This situation is presented in Figure 2. In this case, the electrolyzer will use RES electricity whenever it is available and grid electricity when necessary. Although the electricity cost and emission cost of grid electricity are higher than that of RES electricity, this method can extend the operating hours of the electrolyzer, reaching a higher capacity factor and higher hydrogen production. Thus, the electrolyzer in this system is more productive than the only-RES case, reducing the CAPEX. Moreover, this method can also avoid crossover gas and slow electrolyzer degradation.

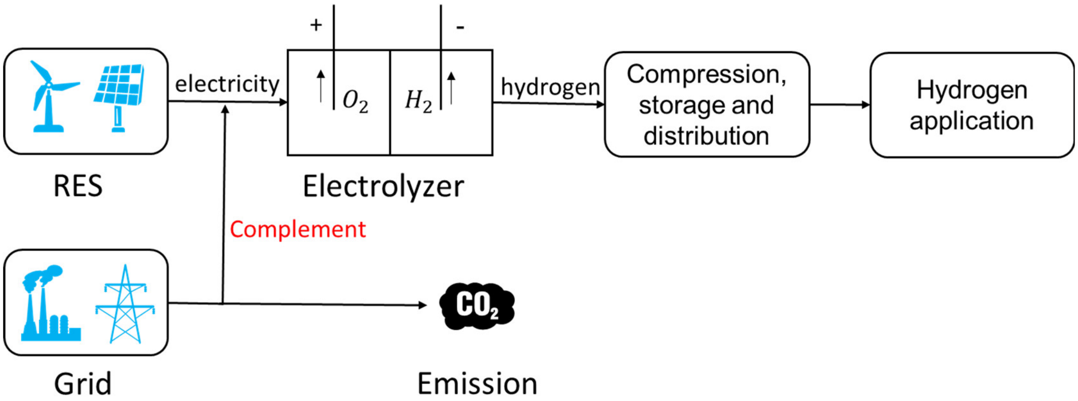


Figure 2. Grid-connected hydrogen production system.

Figure 3 describes an example of an alkaline electrolyzer working in the above two systems. Consider an off-grid photovoltaic hydrogen production plant that operates in the daytime when solar energy is available. Because of the minimum load restriction, part of the RES electricity cannot be utilized. When connecting to the grid, it is possible to use the RES electricity below the operating range and increase hydrogen production by injecting grid electricity, which will significantly influence reduction of the CAPEX per unit (“unitary CAPEX”). However, the average electricity cost and emission cost will increase due to the grid electricity used. There exists a trade-off between the unitary CAPEX and average electricity cost and emission cost.

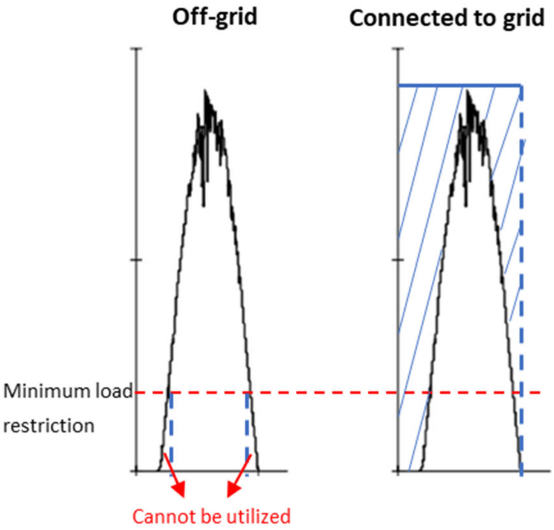


Figure 3. Example of an alkaline electrolyzer working connected to grid. The blue area on the right means the complementing electricity from power grid.

3. Model

In this paper, we perform the optimization in a wholesale electricity market, which is closer to the real situation in Japan. The proposed model is general, so it can be applicable in other wholesale markets globally. However, it is important to note that some countries set fixed charge rates for electricity, in which case our research may not be suitable.

3.1. Optimization Model of the LCOH

The objective function of the optimal *LCOH* can be defined as follows:

$$\min C_{LCOH} = \min(C_{el} + C_{CAPEX} + C_{OPEX} + C_{em}) \tag{1}$$

where C_{LCOH} is the *LCOH*, C_{el} is the average electricity cost, C_{CAPEX} stands for the unitary CAPEX, C_{OPEX} represents the OPEX excluding the electricity cost per unit ("unitary OPEX"), and C_{em} means the average emission cost.

For the electricity cost, it includes the basic electricity cost, C_{RES} and C_{grid}, and the wheeling charge cost, C_{wh}. Here, we assume that only grid electricity requires a wheeling charge since the green hydrogen production plants are usually in the same place as the *RES*. Then, the average electricity cost C_{el} is as follows:

$$C_{el} = \frac{(C_{RES} + C_{grid} + C_{wh})}{P_{H2}} \tag{2}$$

where

$$C_{RES} = \sum_t E_{RES}^t \cdot Price_{RES}^t \tag{3}$$

$$C_{grid} = \sum_t E_{grid}^t \cdot Price_{grid}^t \tag{4}$$

$$C_{wh} = \sum_t E_{grid}^t \cdot Price_{wh} \tag{5}$$

$$P_{H2} = \eta \sum_t (E_{RES}^t + E_{grid}^t) \tag{6}$$

where C_{RES} and C_{grid} are the total electricity cost of *RES*s and grid power, C_{wh} is the total wheeling charge cost, and P_{H2} means hydrogen production. When the time period $T = 1$ year, P_{H2} will be the annual hydrogen production, $P_{H2annual}$. E_{RES}^t and E_{grid}^t stand for electricity used from RESs and the grid in time-step t. $Price_{RES}^{t}$ and $Price_{grid}^{t}$ represent RES and grid electricity prices in time-step t. $Price_{wh}$ is the wheeling charge price. η is the efficiency of hydrogen production.

To ensure the total load within the operating range, the above equations are subject to the following constraint:

$$E^{t}=(E_{RES}^{t}+E_{grid}^{t})\in[E_{\min},E_{\max}] \tag{7}$$

where E^{t} means the total electricity used in time-step t, and E_{min} and E_{max} represent the minimum and maximum load for the electrolyzers. For an alkaline electrolyzer, the minimum load restriction here is set to be 10% of the capacity [6]. In the case of a PEM electrolyzer, the minimum load is set as zero.

The unitary $CAPEX$ can be calculated as the quotient between the annualized $CAPEX$, C_{CAPEX}^{annual} and the annual production of hydrogen, $P_{H2annual}$, as follows:

$$C_{CAPEX}=\frac{C_{CAPEX}^{annual}}{P_{H2annual}} \tag{8}$$

The unitary $OPEX$ can be obtained as follows:

$$C_{OPEX}=OPEX_{fixed}+OPEX_{\mathrm{var}} \tag{9}$$

where $OPEX_{fixed}$ is the fixed cost, such as the maintenance cost and employee salaries, and $OPEX_{var}$ is the variable cost depending on total hydrogen production volume, for example, the water consumption cost.

We assumed that there is no CO_2 emission related to RES electricity. Thus, the average emission cost can be calculated as follows:

$$C_{em}=\frac{\lambda\cdot\mu_{tax}\cdot\sum_{t}E_{grid}^{t}}{P_{H2}} \tag{10}$$

where λ is the emission factor, which presents the CO_2 emission related to the grid electricity used, and μ_{tax} is the CO_2 tax.

Finally, the $LCOH$ can be obtained by adding the result of (2), (8), (9), and (10). Here, we suppose that hydrogen production will use RES electricity whenever it is available, and grid electricity when necessary. To minimize the $LCOH$ means to find an optimal operation strategy for the variable, E_{grid}^{t}. However, regarding the evaluation models, the P_{H2}, which can be calculated by E_{RES}^{t} and E_{grid}^{t}, is in the denominator of the equations. Thus, this optimization problem is nonlinear, which is hard to solve directly. Another limitation is that the electricity spot price cannot be available one year in advance. One simplified but reasonable strategy is to find the threshold price (TP) according to historical data to estimate whether the current electricity price is relatively high or low. This strategy only uses historical data and solves the nonlinear problem by determining E_{grid}^{t} alone. Although it may not obtain the global optimum of the original model due to the simplification, the solution still shows a high performance in a practical situation without any complex algorithms. The specific process of the operation strategy will be introduced in the next section.

3.2. Operation Strategy in the Wholesale Market

In this section, an operation strategy is proposed to determine the electricity bidding process for a hydrogen production plant to minimize the LCOH in the wholesale electricity market.

The details of the subsequent steps in determining the operation strategy of the water electrolysis plants are illustrated in Figure 4. In this paper, the time-step is set as 30 min, and the period T = 1 year. We can determine the threshold price by analyzing historical data. Firstly, we calculate the LCOH at different initial threshold prices using last year's electricity prices. Then, we plot a graph of the LCOH against the threshold price, and the threshold price is obtained by identifying the point on the figure with the lowest LCOH value. The threshold price is determined in a one-year version, considering the grid price fluctuations throughout the whole year. Next, by comparing the current grid electricity price with the threshold price, the operation state of an electrolyzer is determined from two scenarios. If $Price_{grid}^{t} \leq TP$, the electrolyzer is set as the maximum load to produce more hydrogen. Otherwise ($Price_{grid}^{t} > TP$), hydrogen production will return to the required minimum load. In this case, grid electricity is only used to make up the difference from the minimum load. So, if $E_{RES}^{t} \geq E_{min}$, there is no need to consume additional power from the grid. Thus, E_{grid}^{t} can be calculated as follows:

$$E_{grid}^{t} = \begin{cases} E_{\max} - E_{RES}^{t} & if\ price_{grid}^{t} \leq TP \\ E_{\min} - E_{RES}^{t} & if\ price_{grid}^{t} > TP \text{ and } E_{RES}^{t} < E_{\min} \\ 0 & if\ price_{grid}^{t} > TP \text{ and } E_{RES}^{t} \geq E_{\min} \end{cases} \tag{11}$$

where *TP* means the threshold price.

Finally, the LCOH can be calculated with E_{grid}^{t}. The procedure is applied for every time-step within the period. Moreover, the proposed method is capable of estimating negative electricity pricing by using the threshold price, although it does not yet exist in the current Japan electricity market.

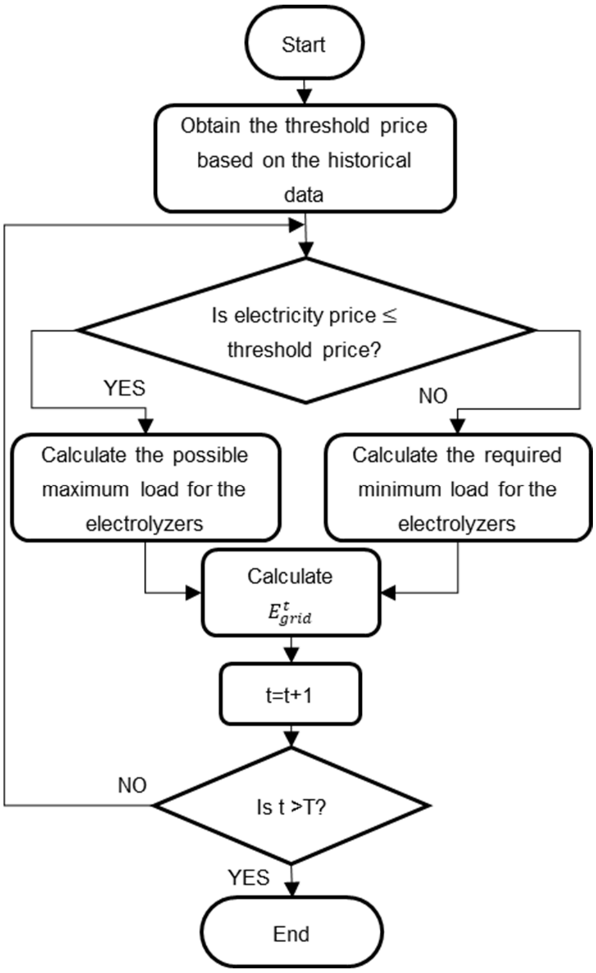


Figure 4. Flowchart for determining an operation strategy for water electrolysis plants in the wholesale electricity market.

This research allows variable H_2 production rates, but in some cases, a fixed H_2 production rate for downstream applications is required. That is to say, the load of electrolyzers should remain stable. In such situations, grid electricity can still complement the input power when RES electricity is insufficient. Conversely, when RES power exceeds the demand, the excess power can be integrated into the grid or stored in batteries.

4. Case Study

4.1. Data Source

The proposed model is general and can be applied to any area with significant RES potential. To illustrate the proposed model, we choose the Kyushu area to perform the case study due to the relatively high penetration rate of RESs, especially PV installation. The simulation data used in this paper come from previous literature and real data from the Japan electricity market. Tables 1 and 2 summarize the information on alkaline and PEM electrolyzers [6,15,18]. Average values are used to calculate the optimal LCOH, and the ranges presented are used to perform the sensitivity analysis.

Table 1. Hydrogen production with electrolyzers [6].

	Alkaline	**PEM**	**Units**
CAPEX	55,000–154,000	132,000–198,000	JPY/kWe
Efficiency	63–70	56–60	%
Load range	10–110	0–160	%

Table 2. Information on electrolyzers.

Parameter	**Value**	**Units**	**Ref.**
Lifetime	25	years	[15]
Other capital cost	30.5%	of total CAPEX	[15]
Maintenance cost	3%	of total CAPEX	[15]
Labor cost	5%	of total CAPEX	[18]
Water consumption	10	l/kg H_2	[15]
Other OPEX	10%	of total CAPEX	[15,18]

The data of the grid were obtained from the Japan Electric Power eXchange (JEPX). In particular, the spot price in the Kyushu area from April 2020 to March 2021 (data FY2020), and from April 2021 to March 2022 (data FY2021). Moreover, the wheeling charge price in the Kyushu area is 2.43 JPY/kWh. The CO_2 tax considered is 289 JPY/t CO_2, which is the current value in Japan.

The RES data were obtained from the Kyushu Electric Power Transmission and Distribution Company. In particular, the data consists of information on wind power and solar power in the Kyushu area, which are shown in Figure 5. There is an assumption that the whole of the Kyushu area is a hydrogen production plant. Since the proposed model is general, there is no effect on the results.

The LCOH of hydrogen production adopting the proposed operation strategy is simulated in the following four cases:

Case 1: alkaline electrolyzer using solar power.
Case 2: alkaline electrolyzer using wind power.
Case 3: PEM electrolyzer using solar power.
Case 4: PEM electrolyzer using wind power.

There are three scenarios as follows:

Scenario 1: using only RES electricity.
Scenario 2: using both RES and grid electricity in a wholesale electricity market.
Scenario 3: using both RES and grid electricity under the average pricing scheme [15].

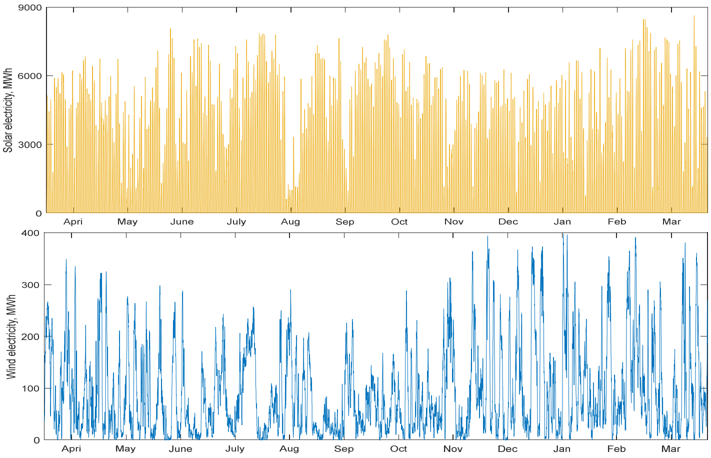
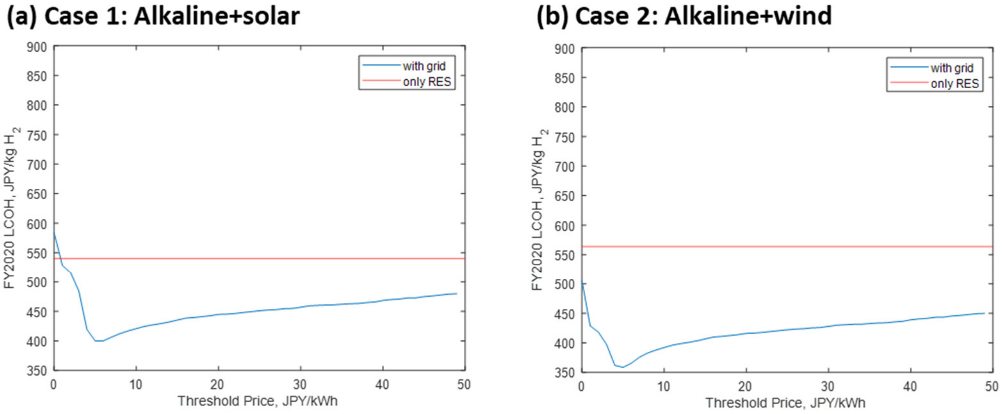


Figure 5. Solar and wind electricity in Kyushu over the period from April 2021 to March 2022.

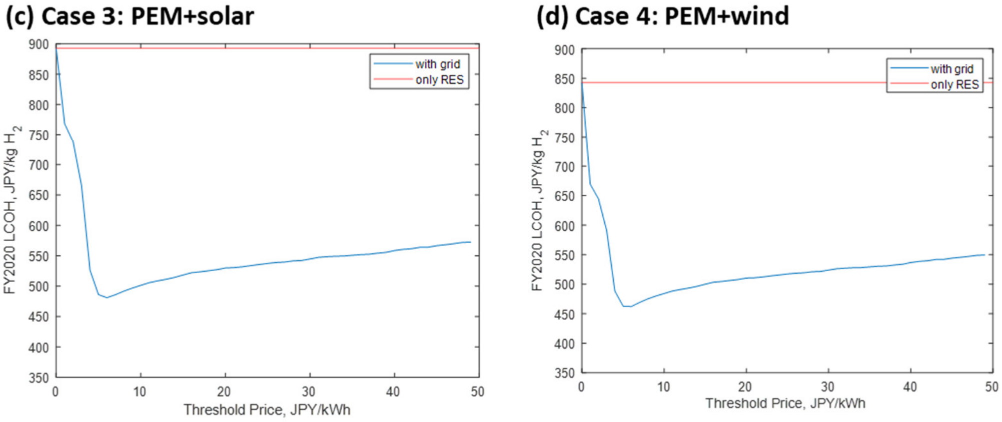
4.2. Optimization Results

Based on data FY2020, we have obtained the threshold prices for different cases. The results are presented in Figure 6, which show the relationship between the LCOH and threshold price. In this figure, "with grid" means using grid electricity to supplement the power supply, while "only RES" refers to using only RESs to produce hydrogen. It is worth noting that the LCOH has a minimum value when connected with the grid, where the threshold price is set as the reference for all cases. Figure 7 shows how the grid price fluctuates in relation to the threshold price in case 1. The threshold price can avoid using high-priced electricity.



(a) Case 1: Alkaline+solar

(b) Case 2: Alkaline+wind



(c) Case 3: PEM+solar

(d) Case 4: PEM+wind

Figure 6. The relationship between the LCOH and threshold price in FY2020.

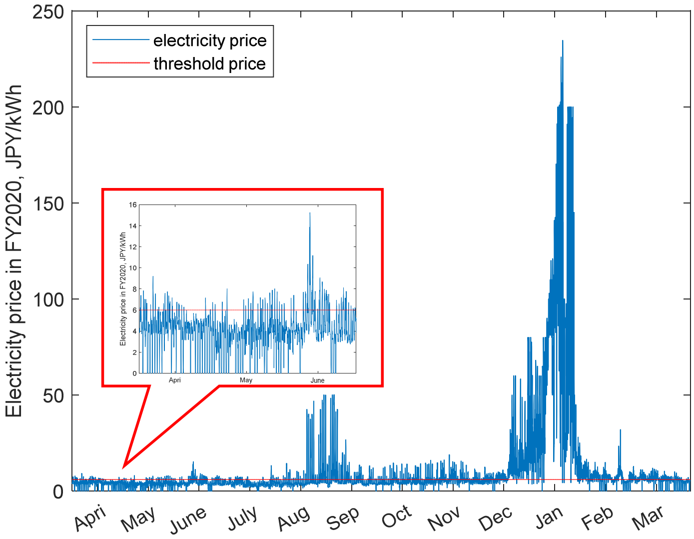


Figure 7. The electricity price and the threshold price in case 1.

Based on data FY2021 and the threshold prices, we can obtain the optimization results of the LCOH in FY2021 for each case. The results are presented in Table 3 and Figure 8. Among the three scenarios, the proposed method has the lowest LCOH, proving its effectiveness. In particular, when the electricity supply is supplemented with grid electricity in a wholesale electricity market, the LCOH decreases by 11% to 33% in the four cases, which is much lower than the only-RES scenario. This is because the hydrogen production increase impacts more than the rise of electricity and emission costs. However, the average price scenario shows poor performance in the alkaline cases, and the LCOH is even higher than the only-RES scenario. On the other hand, in the PEM cases, although the LCOH is still higher than scenario 2, it is lower than the only-RES scenario. This is because using the average electricity price means dynamic electricity prices cannot be taken advantage of, resulting in an increase in average electricity costs. For alkaline cases, the impact of this increase is higher than the impact of increased hydrogen production. However, for PEM cases, this impact is still lower than the increased hydrogen production due to the high CAPEX. For the same reason, the LCOH of the PEM electrolyzer is higher than that of the alkaline electrolyzer in all cases. PEM technology may seem economically uncompetitive when compared to alkaline technology. However, it can offer other benefits that are helpful for hydrogen production processes. PEM electrolysis allows for flexible operation without the restriction of a minimum load. Additionally, the high CAPEX of PEM technology makes it profitable to incorporate grid electricity to increase operation hours. This can be observed in Figure 8, where the LCOH reductions are relatively larger in PEM cases.

Table 3. The LCOH for the four cases.

Unit: JPY/kgH$_2$	Only RES	With Grid	Average Price
Case 1	541.9	480.5	563.8
Case 2	535.8	373.8	555.0
Case 3	894.4	623.5	685.2
Case 4	798.6	537.2	675.1

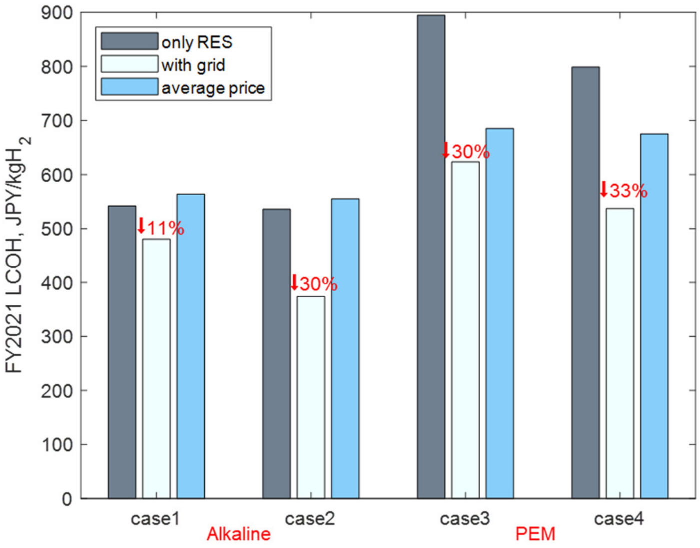


Figure 8. The optimal LCOH for the four cases. The red numbers are the decreases between "only RES" scenario and "with grid" scenario.

Hydrogen productivity and emission cost are presented in Table 4 and Figure 9. Here, hydrogen productivity means the amount of hydrogen production per year and per unit capacity of the electrolyzers. We can observe that, for all cases, hydrogen productivity connecting to the grid increases by 86% to 140% compared with the only-RES electricity scenario. It may be reasonable for a hydrogen plant to choose to inject grid power to increase hydrogen production and gain more profits. However, the CO_2 emissions related to hydrogen production will increase. Figure 10 presents the specific hydrogen productivity and emissions for scenario 2. When compared to scenario 1, the production from RES electricity in alkaline cases increases, while that in PEM cases remains the same. This is because more RES electricity can be utilized by injecting grid power to meet the minimum load restriction for alkaline electrolyzers. Figure 10 also shows the CO_2 emission levels for the four cases. The emission levels are affected by both the grid electricity proportion and electrolyzer efficiency. More CO_2 emissions are produced when the grid electricity proportion is high. For the same grid electricity proportion, high efficiency leads to more hydrogen production, reducing CO_2 emission levels. For instance, the lowest emission level is seen in case 2. This is because, compared to case 1, case 2 uses less grid electricity at the same efficiency, producing less CO_2 emissions. On the other hand, although the grid electricity proportion in case 3 is lower than in case 2, the higher efficiency of case 2 reduces CO_2 emission levels. The same reason applies to case 4. Moreover, compared to directly using coal (20 $kgCO_2/kgH_2$) or natural gas (8.5 $kgCO_2/kgH_2$) [6], CO_2 emissions when either using alkaline or PEM electrolysis are always lower than those produced by fossil-fueled hydrogen production. Therefore, complementing green hydrogen production with grid power can reduce the LCOH, increase hydrogen productivity, and keep CO_2 emissions within an acceptable range.

Table 4. Hydrogen productivity for the four cases.

Production	Only RES	With Grid	Units
Case 1	21.5	51.6	kgH_2/year/kWe
Case 2	21.8	48.2	kgH_2/year/kWe
Case 3	19.7	36.7	kgH_2/year/kWe
Case 4	22.1	44.2	kgH_2/year/kWe

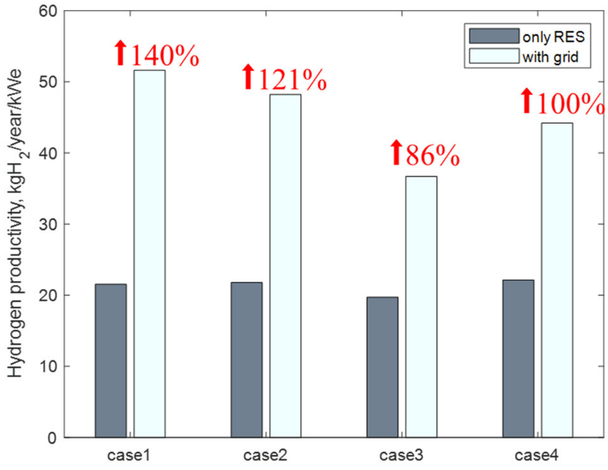


Figure 9. Hydrogen productivity for the four cases.

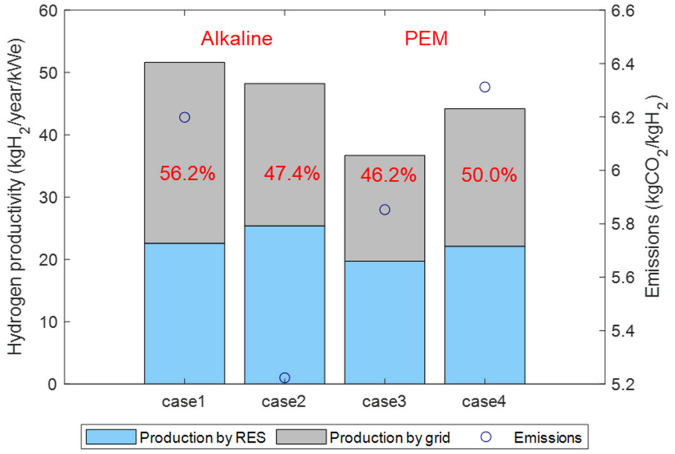


Figure 10. Hydrogen productivity and emissions for scenario 2.

4.3. Sensitivity Analyses

It is necessary to illustrate the effectiveness of the threshold price used in this paper, as it is calculated using historical data. Meanwhile, as electrolysis technology continues to develop, the CAPEX and efficiency are expected to change in order to reach commercial maturity. In addition, the CO_2 tax will be increased by the Japanese government to further emphasize the importance of carbon neutrality. Therefore, in order to analyze how these changes will affect the LCOH, sensitivity analyses are applied to the above variations. For simplicity, these sensitivity analyses are only presented for case 1, but similar qualitative results can be obtained in the other cases.

The threshold price sensitivity is shown in Figure 11. Here, “CAPEX”, “other OPEX”, “electricity cost”, and “emission cost” are computed as expressed in (8), (9), (2), and (10), respectively. We can observe that each component of the LCOH is strongly affected by the threshold price. When the threshold price is relatively low, there is a decrease in the LCOH as shown. This situation occurs because the reductions in the CAPEX and other OPEX are higher than the increases in electricity cost and emission cost with the cheap electricity prices. On the other hand, when the threshold price is relatively high, the increase in electricity cost is much higher than the reductions in the CAPEX and other OPEX, resulting in an increase in the LCOH. In addition, the reference threshold price based on last year’s data is the threshold price used in previous analyses. It can be observed that the LCOH related to the reference threshold price is approaching the lowest point of the LCOH. That is to say, we can decrease the LCOH to close to the minimum value. Therefore, the operation strategy we used can actually obtain an approximate optimal result, proving its effectiveness. However, there still exists a little gap between the calculated LCOH and the minimum LCOH. To obtain a more precise threshold price, it is necessary to analyze the annual fluctuating trend of the threshold price and predict the electricity price for the coming year. By forecasting electricity prices, the threshold price can be calculated using both past and future data, resulting in a lower LCOH. This approach will be included in our future work.

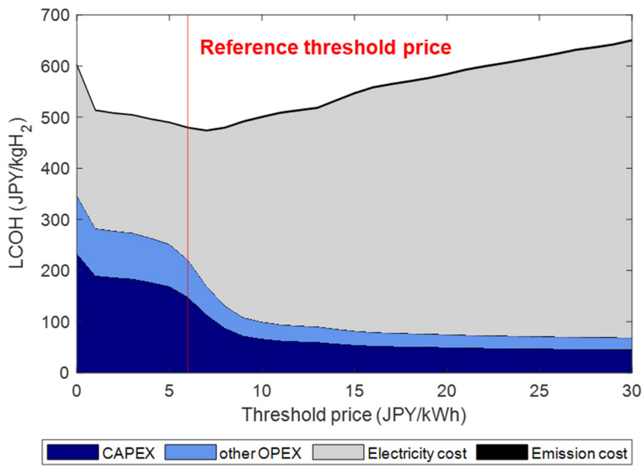


Figure 11. Sensitivity analysis for the threshold price: alkaline technology using solar power.

The result of the sensitivity analysis for the CAPEX is shown in Figure 12. It can be observed that as the CAPEX increases, the LCOH also increases proportionally. However, when the CAPEX is relatively high, the impact on the LCOH becomes less significant. This is due to the fact that cheap grid electricity can offset the effects of a high CAPEX to a certain extent. Based on the sensitivity analysis for electrolyzer efficiency presented in Figure 13, the LCOH will decrease when the electrolyzer efficiency increases. This is because the higher efficiency means more hydrogen production with the same energy input, leading to a lower LCOH. However, it is necessary to note that diminishing returns occur when the efficiency is relatively high. In general, both the CAPEX and the efficiency of the electrolyzer have a significant impact on the LCOH. To reduce hydrogen production costs in the future, it may be more effective to concentrate on improving electrolyzer technologies, such as reducing capital costs and enhancing electrolysis efficiency.

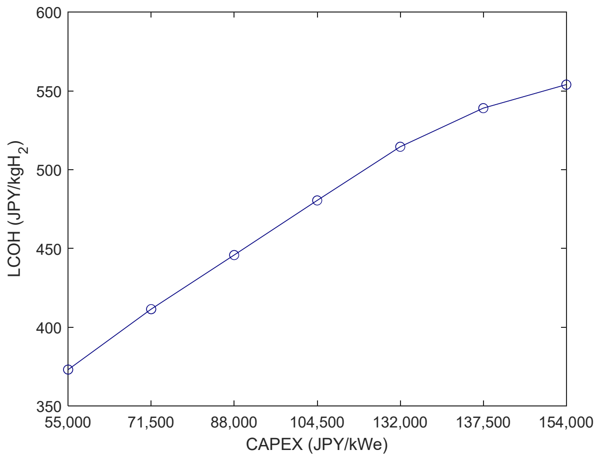


Figure 12. Sensitivity analysis for the CAPEX: alkaline technology using solar power.

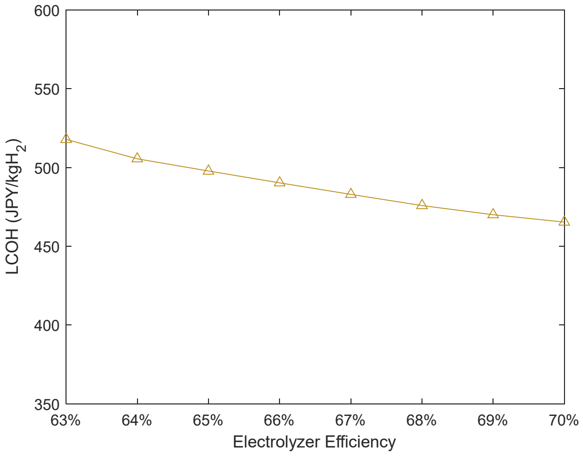
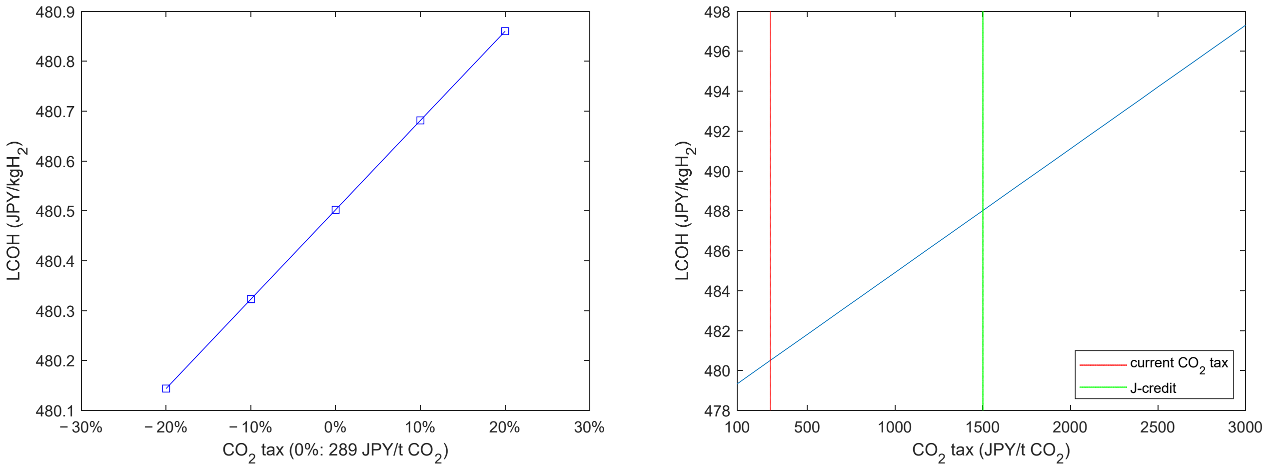


Figure 13. Sensitivity analysis for electrolyzer efficiency: alkaline technology using solar power.

In Figure 14a, the results of the sensitivity analysis for the CO_2 tax are presented. It can be observed that an increase in the CO_2 tax will slightly raise the LCOH. This is because the tax penalty imposed on CO_2 emissions is currently low in Japan, at only 289 JPY/t CO_2. The low CO_2 tax also has a minimal effect on determining the threshold price, making the relationship between the CO_2 tax and LCOH almost linear. The Japanese government is planning to increase the CO_2 tax, which means that in the future, the cost of CO_2 emissions will have a more significant impact on the LCOH. To further analyze the influence of CO_2 emission costs, we chose the CO_2 reduction credit offered by the J-credit Institution, which equals 1500 JPY/t CO_2, for the sensitivity analysis. The results are illustrated in Figure 14b. After the CO_2 price increases compared to the current CO_2 tax, we observe a larger impact on the LCOH. In other words, environmental factors will have a more significant impact on the economy with higher CO_2 prices. Therefore, the increase in CO_2 price can emphasize the importance of the environment.



(**a**) (**b**)

Figure 14. Sensitivity analysis for the CO_2 tax: (**a**) current CO_2 tax; (**b**) CO_2 price in J-credit.

5. Conclusions

The objective of this paper is to analyze the techno-economic benefits of complementing green hydrogen production with grid electricity. A model is proposed to evaluate the LCOH, including CO_2 emissions, to minimize the LCOH in the wholesale electricity market. The proposed model considers the influence of power fluctuations from RESs on water electrolysis, especially the minimum load restriction of alkaline electrolyzers to avoid crossover gas. Moreover, an optimal operation strategy is developed to solve the above nonlinear optimization problem. By injecting grid electricity, the LCOH decreases by 11% to 33%, compared to using an only-RES supply. Hydrogen productivity increases by 86% to 140%, while CO_2 emission levels are maintained within an acceptable range. In addition, electrolyzer efficiency and the CAPEX have larger impact magnitudes on the LCOH, while the impact of the CO_2 tax is relatively small compared to other factors.

Regarding future work, our main objective is to enhance the algorithm and achieve better results. The threshold price used in this paper is based on historical data. Although it is a simple approach, it may not lead to the lowest LCOH. Therefore, to estimate the threshold price more accurately, it is necessary to include the prediction of electricity prices. By forecasting electricity prices, the threshold price can be calculated using recent and future data, resulting in a more precise outcome. In addition, in the off-grid system scenario, akaline electrolyzers are not suitable for real conditions, as they cannot frequently start and stop, leading to safety issues. Therefore, the inclusion of a battery may be necessary in this case. Moreover, to study the entire hydrogen supply chain, it may be useful to include some elements such as the compression, storage, and distribution of hydrogen to demand locations. The inclusion of these elements may alter some of the results obtained here.

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