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 decarbonized various sectors. However, the economic competitiveness of hydrogen production by water electrolysis strongly depends on the availability of renewable energy sources (RESs). Thus, it is necessary to overcome the challenges related to the intermittent nature of RESs. This paper presents a comprehensive technoeconomic 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. Simulation results demonstrate that the proposed strategy can reduce the LCOH and increase hydrogen productivity, without significantly increasing CO_2 emissions.

Key words : Hydrogen production, Water electrolysis, Renewable energy, CO_2 emission, Levelized cost of hydrogen(LCOH).

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.

Regarding water electrolysis technologies for hydrogen production, we focus on the alkaline technology and proton membrane electrolysis (PEM) technology in this study. Alkaline electrolysis is the most mature and commercial technology with over 100 years of history [6]. 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

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electrolysis [11]. Few authors explicitly model the impacts of fluctuating power supply. Thus, how to model the influences of fluctuations in electrolyzers remains a challenge.

This paper aims to analyze the techno-economic benefits of complementing green hydrogen production with grid electricity. An evaluation model for levelized cost of hydrogen (LCOH) is proposed, including the CO_2 penalty, under a wholesale electricity market. Different capital expenditures (CAPEX) and different operating expenses (OPEX) are evaluated in the proposed model. An optimal operation strategy is developed to solve this nonlinear evaluation model.

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.

The remainder of this paper is organized as follows: Section 2 introduces the grid-connected system for producing hydrogen. Section 3 presents the LCOH model employed and the optimal operation strategy to minimize the LCOH. 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 via water electrolysis

Green hydrogen production by water electrolysis requires 100% RES electricity, such as wind power or solar power, which can be achieved with an off-grid production plant. 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 [12], 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 can operate with fluctuating power, there are no minimum load requirements. 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.

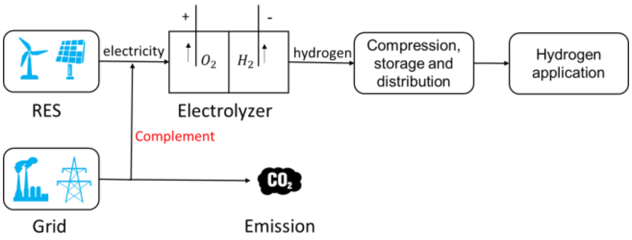

Fig.1 Grid-connected hydrogen production system.

One potential solution is using grid electricity to complement the power supply to the electrolyzer. This situation is presented in **Fig.1**. 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. Thus, there exists a trade-off between the unitary CAPEX and average electricity cost and emission cost.

3. Model

In this paper, we perform the optimization in a wholesale electricity market, which is closer to the real situation in Japan.

3.1 Evaluation model for LCOH

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

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

where C_{LCOH} is the LCOH, C_{el} is the average electricity cost, C_{CAPEX} stands for the CAPEX per unit ("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 and the wheeling charge cost. 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 and grid. C_{wl} is the total wheeling charge cost. P_{H2} means the amount of hydrogen production. 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*. $Price_{wl}$ 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*. 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:

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

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). 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. That is to say, we can only use the historical data to analyze the techno-economic performance.

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.

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. Finally, the LCOH can be calculated with E_{grid}^t. The procedure is applied for every time-step within the period.

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 [6,13,14].

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 [13].

4.2 Optimization results

Based on data FY2020, we have obtained the threshold prices for different cases. Then, 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 **Fig.2**. 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.

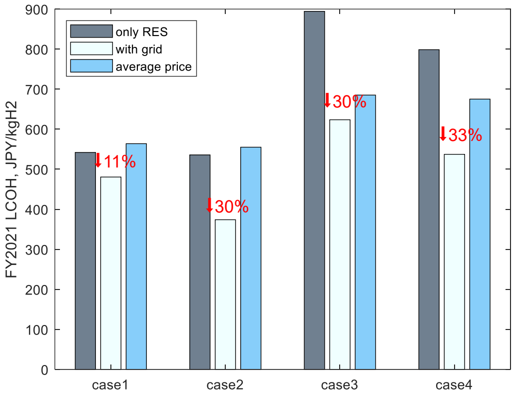

Fig.2 Optimal LCOH for 4 cases.

Hydrogen productivity and emission cost are presented in **Fig.3**. 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. **Fig.4** 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. **Fig.4** 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. Moreover, compared to directly using coal (20 kg CO_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.

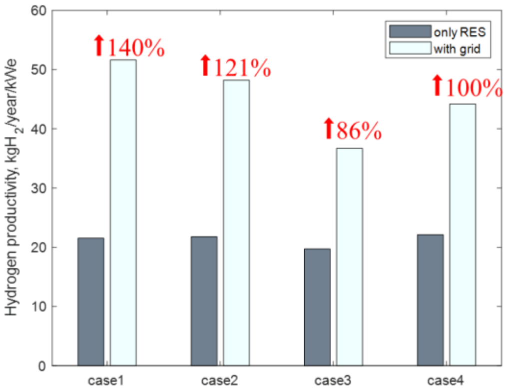

Fig.3 Hydrogen productivity for the four cases.

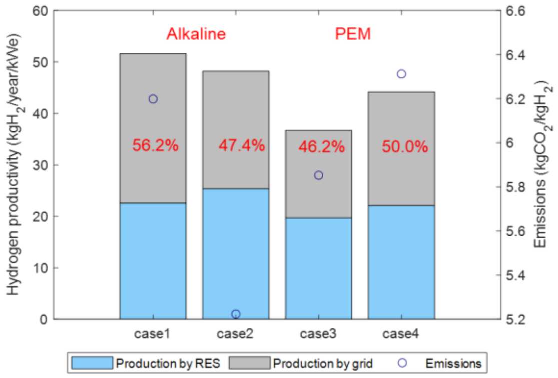

Fig.4 Hydrogen productivity and emissions for scenario 2.

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 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 **Fig.5**. 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 obtain an approximate optimal result, proving its effectiveness.

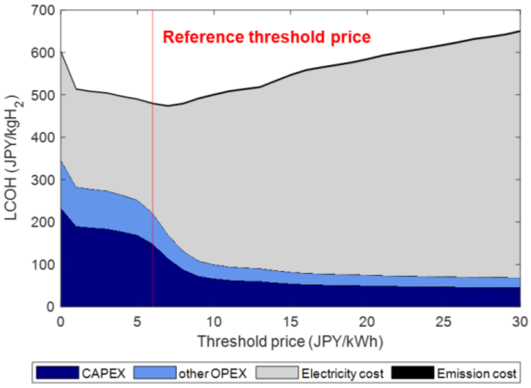

Fig.5 Sensitivity analysis for the threshold price.

The result of the sensitivity analysis for the CAPEX is shown in **Fig.6**. 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 because 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 **Fig.7**, 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.

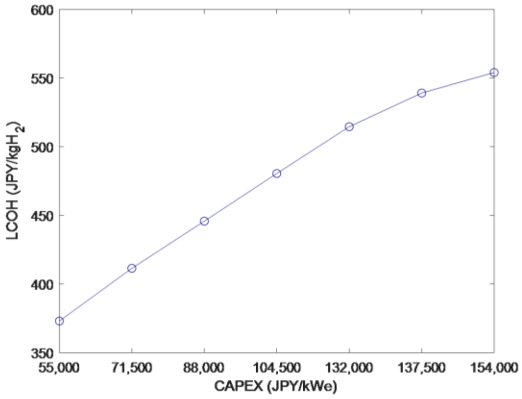

Fig.6 Sensitivity analysis for the CAPEX.

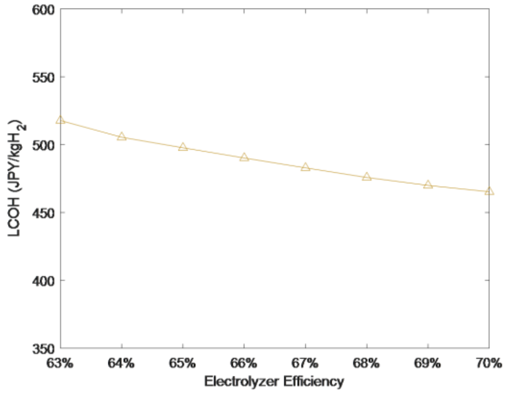

Fig.7 Sensitivity analysis for the efficiency

In **Fig.8**, 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. 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 **Fig.9**. 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.

5. Conclusion

This paper analyzes 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.

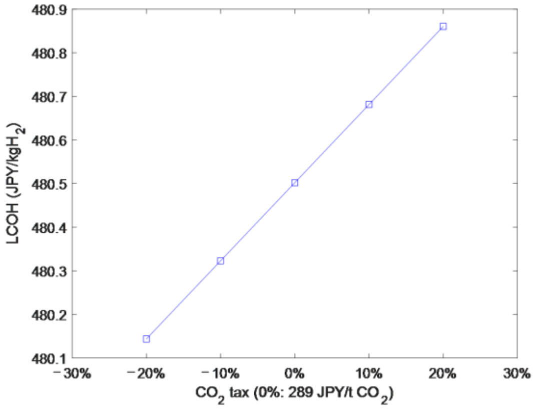

Fig.8 Sensitivity analysis for the CO_2 tax.

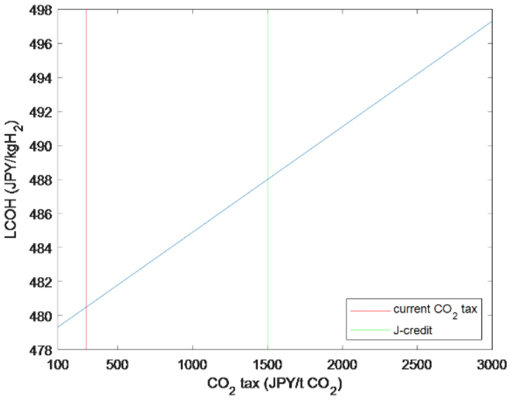

Fig.9 Sensitivity analysis for the CO_2 price in J-credit.

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