Domestic Low-carbon Hydrogen Production via Renewables and PPA in Japan

Tianhong Zhang*, Masahiro Mae, Ryuji Matsuhashi

The University of Tokyo
(Corresponding Author: tenkozhang@gmail.com)

ABSTRACT

This study explores strategies for domestic hydrogen production in Japan in the 2030s. To address the shortcomings of previous work, we proposed the integration of a Power Purchase Agreement (PPA) into the renewable energy system for hydrogen production. An in-depth sensitivity analysis was conducted, which examined the impact of key factors on production costs and CO_2 emissions, including the proportion of PPA power, the price of PPA power, and the criteria for low-carbon hydrogen classification. Coastal regions in Tohoku and Hokkaido were found to be among the most economically promising areas for domestic hydrogen production. The results indicate that integrating PPA power to complement renewables is a viable option, as it can enhance system resilience against weather uncertainties and power shortages, while potentially reducing overall production cost under certain conditions.

Keywords: low-carbon hydrogen production, economic assessment, PPA, optimization, linear programming

1. INTRODUCTION

Hydrogen is gaining increasing attention as an essential energy carrier for achieving carbon neutrality, as it can contribute to the decarbonization of Hard-to-Abate sectors, such as transportation and industry, where reducing CO_2 emissions is particularly challenging. From the perspective of improving Japan's extremely low energy self-sufficiency rate and providing significant benefits to the domestic economy, previous work [1] explored green hydrogen production in Japan using only renewables (namely solar and wind) with battery storage assistance. In this framework, the produced hydrogen qualifies as green hydrogen, meaning that no CO_2 emissions are associated with the production process. However, two major shortcomings exist:

(1) Water electrolyzers typically have a minimum operational load, meaning they cannot shut down entirely without risking efficiency losses or damage. At times, such as during the night when there is no sunlight or wind, renewable power supply may cease entirely. In these times, battery storage must be pre-charged to provide the necessary power for continuous operation. This requires the installation of large battery capacities that are utilized infrequently, significantly increasing system costs.

(2) Battery storage serves as the sole component to prevent system shutdown during periods without renewable power supply. This approach is acceptable in optimization models, where perfect foresight is assumed, meaning future weather events are assumed to be known with certainty. In practical implementation, however, weather forecasts are not always reliable, and medium- to long-term predictions remain difficult, potentially leading to power shortages.

In this study, we continue to explore strategies for domestic hydrogen production in Japan in the 2030s, focusing on optimal production sites, system sizing and operation. To address the shortcomings of previous work mentioned earlier, we propose the integration of a Power Purchase Agreement (PPA) into the energy system for hydrogen production. The proposed system, illustrated in Figure 1, is designed to further reduce hydrogen production costs and enhance resilience against weather uncertainties and power shortages.

Since the PPA power considered in this study is a mix of renewable, nuclear, and thermal power, a certain level of CO_2 emissions is inevitable during hydrogen production. To ensure that the produced hydrogen remains economically viable and qualifies as low-carbon

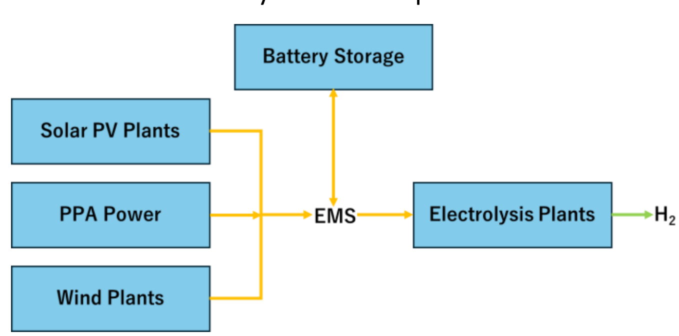

Fig. 1 Proposed energy system for low-carbon hydrogen production

hydrogen, we conducted an in-depth sensitivity analysis. This analysis examined the impact of key factors, including the proportion of PPA power, the price of PPA power, and the criteria for low-carbon hydrogen classification.

2. METHODS

2.1 Meteorological data, target area and period

In this study, ERA5 dataset [2] is utilized. ERA5 is the reanalysis data by ECMWF, which has a geographical resolution of 0.25°, and a time resolution of 1 hour. Meteorological data of ERA5 is processed into power generation data of Solar PV Plants and Wind Plants using the python library atlite [3].

The target area is the land area of the four major islands of Japan, namely Hokkaido, Honshu, Shikoku and Kyusyu. With the geographical resolution of ERA5, 791 cells are selected for calculation.

The target period is the year 2023. With the time resolution of ERA5, 8760 hours are calculated.

2.2 Optimization model and PPA settings

The optimization model used in this study is an improved version of the Linear Programming (LP) model employed in previous work [1][4]. This model minimizes the hydrogen production cost per unit while determining the optimal capacity (sizing) and operation for each technology in the system. The key economic and technical assumptions are also consistent with previous work and are primarily based on data from the energy data sheets published by the Danish Energy Agency (DEA) [5][6]. The exchange rate between Euro and Yen is set to be 130 Yen/Euro.

The PPA scheme in this study assumes a constant price and a fixed quantity of power procurement at all times. The carbon intensity of PPA power is set at 0.25 kg-CO_2/kWh, which aligns with Japan's governmental target for grid power carbon intensity in 2030 [7]. For the low-carbon classification criteria, three cases are considered: High (H), Medium (M), and Low (L). The base case value is 2.4 kg-CO_2/kg-H_2, with a higher value of 3.4 kg-CO_2/kg-H_2 and a lower value of 1.5 kg-CO_2/kg-H_2. Similarly, for PPA price, three cases are analyzed: Expensive (E), Medium (M), and Cheap (C). The base case price is 15 Yen/kWh, with 20 Yen/kWh as the higher price and 10 Yen/kWh as the lower price. Integrating the three low-carbon classification criteria with the three PPA price scenarios yields a total of nine cases, as summarized in Table 1.

Table. 1 Combinations of different low-carbon classification criteria and PPA price

Case name	Low-carbon classification criteria [kg-CO_2/kg-H_2]	PPA price [Yen/kWh]
H-E	3.4	20
H-M	3.4	15
H-C	3.4	10
M-E	2.4	20
M-M (Base)	2.4	15
M-C	2.4	10
L-E	1.5	20
L-M	1.5	15
L-C	1.5	10

To determine the optimal proportion of PPA power usage, seven cases with varying PPA proportions are examined: 0% (no PPA), 1%, 3%, 5%, 7%, 9%, and 11%, with the base case set at 5%. PPA proportions exceeding 11% are not considered, as the electrolysis efficiency of 50.6 kWh/kg-H_2 used in this study constrains the PPA proportion to remain below 11.86% to comply with the strictest low-carbon classification criteria of 1.5 kg-CO_2/kg-H_2.

3. RESULTS AND DISCUSSION

First, using the base case values for low-carbon classification criteria, PPA price, and PPA proportion, we calculated the cost of domestic low-carbon hydrogen production in Japan in the 2030s. Consistent with previous findings, the results indicate that coastal regions in Tohoku and Hokkaido are among the most economically promising areas for domestic hydrogen production.

Next, we conducted a detailed analysis of a specific cell located in Shimokita Peninsula, which achieved a low production cost below 30 Yen/Nm^3. The optimal system sizing and operation for this cell were examined and compared with the results from previous study.

A comprehensive sensitivity analysis was conducted on the same cell. First, to investigate the impact of low-carbon hydrogen classification criteria and PPA price, the nine cases listed in Table 1 were analyzed using the base case value for PPA proportion. The results show that integrating PPA power into the system can effectively reduce the required battery storage capacity. However, since PPA power is generally more expensive than renewables, its introduction did not always reduce the overall production cost. In some cases, however, the reduction in battery costs outweighed the higher cost of PPA power, resulting in a lower total cost.

Next, to determine the optimal PPA proportion, seven cases with varying PPA proportions were studied, using the base case values for low-carbon classification criteria and PPA price. We found that increasing the proportion of PPA power could reduce the overall production cost by raising the system's capacity factor. However, it should be noted that higher PPA usage also leads to increased CO_2 emissions in hydrogen production. If a carbon tax or other forms of CO_2 emission penalties were implemented, the results could differ.

4. CONCLUSION

This study explored domestic low-carbon hydrogen production in Japan using a combination of renewable energy and PPA power, focusing on optimal production sites, system sizing and operation. Coastal regions in Tohoku and Hokkaido are found to be among the most economically promising areas for domestic hydrogen production. The sensitivity analysis results indicate that integrating PPA power to complement renewables is a viable option, as it can enhance system resilience against weather uncertainties and power shortages, while potentially reducing overall production cost under certain conditions.

In the PPA scheme assumed in this study, a fixed amount of power had to be procured at all times. As for future work, we plan to examine more flexible PPA schemes that allow for procuring power based on actual demand and assess their impact on both production costs and CO_2 emissions.

ACKNOWLEDGEMENT

The authors would like to thank the anonymous reviewers for their time and patience.

REFERENCE

[1] Zhang, T., Mae, M., & Matsuhashi, R. (2025). Exploring Japan's domestic green hydrogen production strategy in the 2030s. Energy Proceedings, 54. https://doi.org/10.46855/energy-proceedings-11554

[2] ECMWF. (n.d.). *ECMWF Reanalysis v5 (ERA5)*. https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

[3] Hofmann, F., Hampp, J., Neumann, F., Brown, T., & Hörsch, J. (2021). atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series. *Journal of Open Source Software*, 6(62), 3294. https://doi.org/10.21105/joss.03294

[4] Berger, M., Radu, D., Detienne, G., Deschuyteneer, T., Richel, A., & Ernst, D. (2021). Remote Renewable Hubs for Carbon-Neutral Synthetic Fuel Production. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/fenrg.2021.671279

[5] Danish Energy Agency. (n.d.). *Technology data for renewable fuels*. Danish Energy Agency. https://ens.dk/en/our-services/technology-catalogues/technology-data-renewable-fuels

[6] Danish Energy Agency. (n.d.). *Technology data for energy storage.* Danish Energy Agency. https://ens.dk/en/our-services/technology-catalogues/technology-data-energy-storage

[7] METI. (2021). *Outlook for Energy Supply and Demand in Fiscal Year 2030 (Related Materials)*. https://www.meti.go.jp/press/2021/10/20211022005/20211022005-3.pdf