Optimal Dispatching for Hybrid Hydrogen Production System Considering Hydrogen Demand#

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ABSTRACT

The penetration rate of renewable energy sources (RES) in hydrogen production systems has continued to increase in recent years. However, the intermittent nature of these sources presents significant operational challenges, especially for the electrolyzers. One possible solution is using grid electricity to complement the RES power supply with the battery to smooth the fluctuations. In this paper, an optimal dispatching scheme is proposed for hydrogen production plants integrating the battery. With the proposed dispatching scheme, a hydrogen production plant can reduce the total cost through participation in the wholesale electricity market while satisfying the hydrogen demand. Simulation based on actual data from Kyushu is conducted to evaluate the performance of the proposed optimal dispatching scheme. Compared with the normal operation method, the proposed scheme reduces the total cost by 12.6% for hydrogen production plants.

Keywords: hydrogen production, water electrolysis, renewable energy, optimal dispatching, battery.

NONMENCLATURE

Abbreviations	
JEPX	Japan Electric Power eXchange
RES	Renewable Energy Source
SOC	State of Charge
Symbols	
η_c/η_d	Charging/discharging efficiency
η_e	Electrolyzer efficiency
λ	Carbon intensity of grid electricity
μ_{tax}	CO_2 tax
c_b	Cost coefficient of battery
c_{P2H}	Cost coefficient of water electrolysis
C_b	Operation cost of battery
C_{em}	Emission cost
C_{grid}	Grid electricity cost
C_{op}	Operation cost
C_{P2H}	Operation cost of water electrolysis
C_{RES}	RES electricity cost
C_{total}	Total cost of hydrogen production
E_b^t	Energy in battery at time step *t*
$E_b^{\min}, E_b^{\max}$	Minimum and maximum energy in battery
E_{grid}^t	Grid electricity used at time step *t*
$E_{grid,b}^t$	Grid electricity used for charging the battery at time step *t*
$E_{grid,p}^t$	Grid electricity used for filling the gap at time step *t*
E_{in}^t	Charging energy at time step *t*
$E_{in}^{\max}$	Maximum charging rate
E_{out}^t	Discharging energy at time step *t*
$E_{out}^{\max}$	Maximum discharging rate
E_p^t	Required electricity for hydrogen production plant at time step *t*
E_{RES}^t	RES electricity used at time step *t*
$E_{RES,g}^t$	RES electricity provided at time step *t*
H^t	Hydrogen demand at time step *t*
t	Time step (1 hour)

1. INTRODUCTION

Hydrogen, as a versatile and clean energy carrier, has garnered significant attention in recent years due to its potential to address critical energy and environmental challenges [1]. However, due to the intermittent nature of renewable energy source (RES) generations and the high costs associated with electrolysis processes, green hydrogen production still faces several barriers. One of the potential solutions is integrating the power grid and battery to increase both long-term and short-term flexibility [2].

At present, many studies have considered different configurations of joint water electrolysis systems with external energy networks. In such work, research is commonly aimed at optimizing the costs or profits of the

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whole system or maximizing hydrogen production. For example, Ju et al. [3] construct a multi-time scale dispatching optimal model for a rural biomass waste energy system integrating a micro-energy grid to minimize the operation cost of the system and maximize eco-environment benefits. Wang et al. [4] optimize the electricity-gas-heat system with the objective of the minimum total operating cost considering the users' dissatisfaction. Maluenda et al. [5] introduce an optimal operation scheduling for a solar-battery-electrolyzer system to maximize profits by participating in the frequency regulation market and selling its energy surplus to the grid. Pavić et al. [6] propose an approach for a solar-battery-hydrogen plant to participate in three energy markets: electricity, natural gas, and hydrogen, aiming at reducing green hydrogen costs. However, fewer studies have focused on the cost of hydrogen production plants integrating the battery as the main subject of research. Ibáñez-Rioja et al. [7] optimize the component capacities and system control for an off-grid solar-battery-water electrolyzer plant to minimize the cost of green hydrogen production. However, this method will change the rated power of the electrolyzer, neglecting hydrogen demand. Therefore, there is still a lack of proper analysis for hydrogen production plants to minimize the production cost in the hybrid system considering hydrogen demand.

In this paper, an optimal dispatching scheme is proposed for the hybrid hydrogen production system. The proposed scheme allows hydrogen production plants integrating the battery to perform the following:

- schedule the bidding in the grid electricity market to reduce the hydrogen production cost.
- ensure that produced hydrogen meets the hydrogen demand.

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

- propose an optimal dispatching scheme for the hybrid hydrogen production system considering hydrogen demand.
- examine clearly the impact of the hydrogen demand, battery capacity, and rated power on the cost for hydrogen production plants.

The remainder of this paper is organized as follows. Section 2 introduces the configuration and operation mechanism of the hybrid hydrogen production system. Section 3 presents the system model employed and the optimal dispatching scheme. The simulation results are shown in Section 4 to validate the effectiveness of the proposed dispatching scheme. Finally, conclusions are drawn in Section 5.

2. HYBRID HYDROGEN PRODUCTION SYSTEM

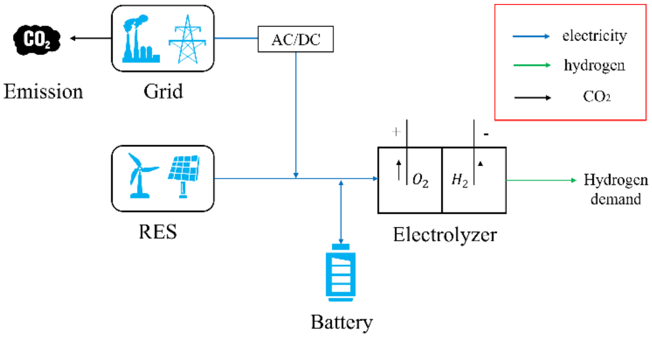

Fig. 1 Hybrid hydrogen production system.

The configuration of the hybrid hydrogen production system is illustrated in Fig. 1. The hydrogen production plant is powered in three ways: through RES generation, the battery, and the power grid. Among these, the RES generation has priority in satisfying the hydrogen demand to increase the proportion of green hydrogen. The battery helps to smooth the fluctuating power input for the electrolyzers. When there is insufficient clean energy available, the grid electricity will be purchased to complement the power supply.

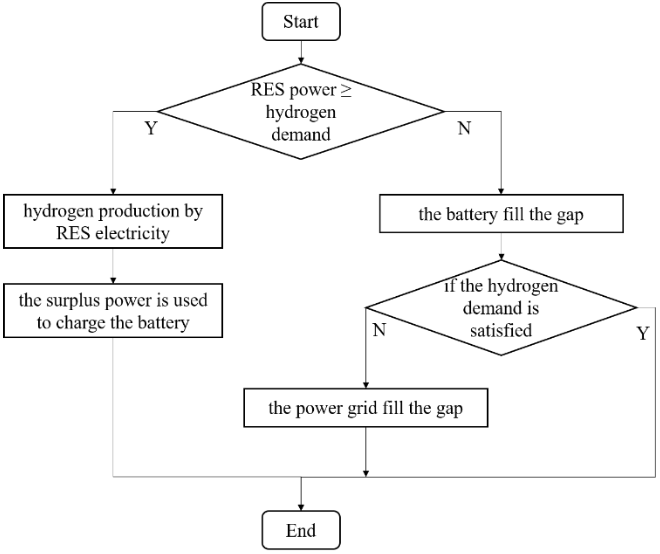

Fig. 2 The operation mechanism of hybrid system.

Fig. 2 shows that the hybrid hydrogen production system operation scheme is formulated according to the demand for hydrogen. The specific operation mechanism is as follows:

(1) If the RES generation is sufficient and can satisfy the hydrogen demand, the hydrogen production will use entire RES electricity to produce green hydrogen. The surplus power will charge the battery or be curtailed when the battery is full.

(2) On the contrary, if the hydrogen demand is not satisfied by the RES generation, the power gap will be filled by the battery.

(3) If the hydrogen demand is still not satisfied when the output of the battery is not enough, the remaining power gap will be filled by purchasing power from the grid.

3. MODEL EMPLOYED

3.1 Hybrid system model

In time step *t*, the hydrogen demand is H^t.

For hydrogen production plant, the electricity load, E_p^t, should fulfill the requirement.

$$E_p^t = \frac{H^t}{\eta_e} \tag{1}$$

where η_e is the electrolyzer efficiency.

For RES generation, the provided electricity $E_{RES,g}^t$ and the electricity used by hydrogen production plant E_{RES}^t are shown in (2).

$$E_{RES}^t = \begin{cases} E_{RES,g}^t & \text{if } E_{RES,g}^t < E_p^t \\ E_p^t & \text{if } E_{RES,g}^t \geq E_p^t \end{cases} \tag{2}$$

For battery, the energy stored can be formulated as:

$$E_b^t = E_b^{t-1} + E_{in}^t - E_{out}^t \tag{3}$$

$$E_b^t \in \left[E_b^{\min}, E_b^{\max}\right] \tag{4}$$

where E_b^t is the stored energy of battery at time step *t*. E_{in}^t and E_{out}^t represent the charging and discharging energy in time step *t*. $E_b^{\min}$ and $E_b^{\max}$ are the minimum and maximum energy of the battery.

Considering the charging process.

$$E_{in}^t = \begin{cases} \eta_c(E_{RES,g}^t - E_p^t) & \text{if } E_{RES,g}^t \geq E_p^t \\ 0 & \text{if } E_{RES,g}^t < E_p^t \end{cases} \tag{5}$$

$$E_{in}^t \in [0, E_{in}^{\max}] \tag{6}$$

where $E_{in}^{\max}$ is maximum charge rate. η_c is the charging efficiency.

Considering the discharging process.

$$E_{out}^t = \begin{cases} \eta_d(E_p^t - E_{RES,g}^t) & \text{if } E_{RES,g}^t < E_p^t \\ 0 & \text{if } E_{RES,g}^t \geq E_p^t \end{cases} \tag{7}$$

$$E_{out}^t \in [0, E_{out}^{\max}] \tag{8}$$

where $E_{out}^{\max}$ is maximum discharge rate. η_d is the discharging efficiency.

As a result, the operation model for battery is formulated as:

$$\begin{cases} E_{in}^t = \min\left(\eta_c(E_{RES,g}^t - E_p^t), E_b^{\max} - E_b^{t-1}, E_{in}^{\max}\right) & \text{if } E_{RES,g}^t \geq E_p^t \\ E_{out}^t = \min\left(\eta_d(E_p^t - E_{RES,g}^t), E_b^{t-1} - E_b^{\min}, E_{out}^{\max}\right) & \text{if } E_{RES,g}^t < E_p^t \\ E_{in}^t \cdot E_{out}^t = 0 & \end{cases} \tag{9}$$

For grid, the grid electricity purchased E_{grid}^t is:

$$E_{grid}^t = \begin{cases} E_p^t - E_{RES}^t - E_{out}^t & \text{if } E_p^t > E_{RES,g}^t + E_{out}^t \\ 0 & \text{if } E_p^t \leq E_{RES,g}^t + E_{out}^t \end{cases} \tag{10}$$

3.2 Optimal dispatching scheme

The proposed scheme allows to charging of the battery by grid electricity when the electricity price is relatively low. In this case, the grid electricity used in time step *t* is changed to:

$$E_{grid}^t = E_{grid,p}^t + E_{grid,b}^t \tag{11}$$

where $E_{grid,p}^t$ is the grid electricity used to fill the gap in time step *t*, which can be calculated by (10). $E_{grid,b}^t$ is the grid electricity used to charge the battery.

Since the battery cannot charge and discharge simultaneously, charging the battery with grid electricity only occurs when the battery is in "charge" or "idle" mode. Then, the charging process of the battery in (5) should be modified as:

$$E_{in}^t = \begin{cases} \eta_c(E_{grid,b}^t + E_{RES,g}^t - E_p^t) & \text{if } E_{RES,g}^t \geq E_p^t \\ \eta_c \cdot E_{grid,b}^t & \text{if } E_{RES,g}^t < E_p^t \text{ and } E_{out}^t = 0 \\ 0 & \text{if } E_{RES,g}^t < E_p^t \text{ and } E_{out}^t \neq 0 \end{cases} \tag{12}$$

The hydrogen production plant aims to minimize the total cost of producing hydrogen. Thus, the objective function is defined as:

$$\min C_{total} = \min\left(C_{grid} + C_{RES} + C_{op} + C_{em}\right) \tag{13}$$

where C_{total} is the total cost of producing hydrogen in demand. C_{grid} and C_{RES} are the electricity cost of grid and RES. C_{op} is other operation cost. C_{em} means the CO_2 emission cost. Time step *t* is 1 hour.

For electricity cost, we consider the wheeling charge and renewable charge to more accurately represent the situation in Japan. We assume that only the grid electricity incurs a wheeling charge, as green hydrogen production plants are typically located in the same area as the RES.

$$C_{grid} = \sum_t E_{grid}^t\left(P_{grid}^t + P_{wh} + P_{re}\right) \tag{14}$$

$$C_{RES} = \sum_t E_{RES}^t(P_{RES}^t + P_{re}) \tag{15}$$

where P_{grid}^t and P_{RES}^t are electricity price of grid and RES in time step *t*. P_{wh} is the wheeling charge price. P_{re} is the renewable charge price.

Operation cost C_{op} can be obtained by:

$$C_{op} = C_b + C_{P2H} \tag{16}$$

$$C_b = c_b \sum_t \left(E_{in}^t + E_{out}^{in}\right) \tag{17}$$

$$C_{P2H} = c_{P2H} \sum_t \left(E_{grid}^t + E_{RES}^t\right) \tag{18}$$

where C_b is the operation cost of battery. C_{P2H} is the operation cost of water electrolysis. c_b and c_{P2H} are the cost coefficient of battery and water electrolysis.

As for emission cost, we assume that there is no CO_2 emission associated with RES electricity, and the carbon intensity of grid electricity remains constant during the period. The emission cost can be obtained as:

$$C_{em} = \lambda \cdot \mu_{\text{tax}} \cdot \sum_t E_{grid}^t \tag{19}$$

where λ means the carbon intensity of grid electricity. μ_{tax} is the CO_2 tax.

Finally, the total cost for hydrogen production plants integrating the battery can be calculated as the sum of (14), (15), (16), and (19). This optimal dispatching scheme determines tomorrow's schedule based on the day-ahead market, so the optimization period is one day.

4. CASE STUDY

4.1 Data source

To verify the effectiveness of the proposed dispatching scheme, we performed a simulation based on actual data in Kyushu, Japan.

In particular, the electricity price data were obtained from Japan Electric Power eXchange (JEPX), including RES electricity price and electricity spot price in Kyushu from April 2021 to March 2022. RES generation data, including photovoltaic and wind power from April 2021 to March 2022, were obtained from Kyushu Electric Power Transmission and Distribution Company. We assume that a 9 MW photovoltaic power plant and a 4 MW wind turbine generate electricity equivalent to the scaled-down generation of the entire Kyushu region. Moreover, the wheeling charge price is 2.43 JPY/kWh, and the renewable charge price in 2021 is 3.36 JPY/kWh. The capacity of the battery is 2.0 MWh, and the rated charge/discharge power is 1.0 MW.

There are some other parameters that come from previous literature, as shown in Table 1.

Table 1. Simulation parameters

Parameter	Value	Unit	Ref.
λ	0.22	Kg CO_2/kWh	[8]
μ_{tax}	289	JPY/t CO_2	[9]
c_b	0.473	JPY/kWh	[10]
c_{P2H}	0.459	JPY/kWh	[11]
η_e	85	%	[4]
η_c/η_d	95	%	[5]
$[E_b^{\min}, E_b^{\max}]$	[20,95]	% of capacity	[12]

The total cost of producing hydrogen in demand for hydrogen production plant integrating the battery is simulated in two cases:

- Case 1: using the proposed optimal dispatching scheme to determine next day's schedule (3.2).
- Case 2: operating in normal condition (3.1).

The hydrogen demand in each hour is first set as 30 kg, and we will conduct the sensitivity analysis on it. The simulation is repeated for one year (2021.4-2022.3).

4.2 Simulation results

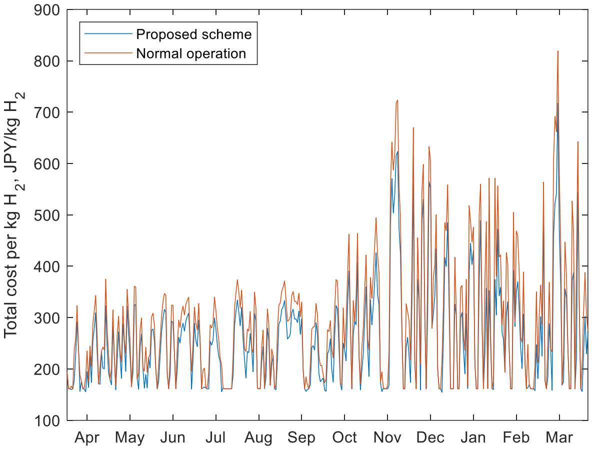

Fig. 3 Hydrogen production costs for 2 cases.

Since the amount of hydrogen produced is constant each hour, we use the total cost per kilogram of hydrogen to evaluate the performance of the proposed dispatching scheme. The results are illustrated in Fig.3. During the simulation period, the hydrogen production cost in the proposed scheme is always lower than in the normal operation. This is because using grid electricity to charge the battery in advance when the grid electricity price is relatively low can avoid using high-priced grid electricity when necessary. Moreover, the average cost of the year is given in Table 2. Compared to the normal operation, the average cost can be reduced by 12.6% with the proposed optimal dispatching scheme. Therefore, the proposed scheme shows better performance and has the potential to reduce the hydrogen production cost for water electrolysis plants integrating the battery.

Table 2. Average cost of the year for 2 cases.

(JPY/kg H_2)	Case 1	Case 2	Cost reduction
Average cost	257.2	294.2	12.6%

The detailed simulation results on November 14, 2021, are shown in Fig.4. The state of charge (SOC) of the battery is limited within the required range from 20% to 95%. It can be seen that the battery was charged at 10:00 in both cases due to the sufficient RES electricity supply.

In the proposed scheme, the battery was charged an additional three times by grid electricity when the price was relatively low and was discharged when the price was relatively high. Thus, the cost of purchasing grid electricity decreased by storing cheap electricity.

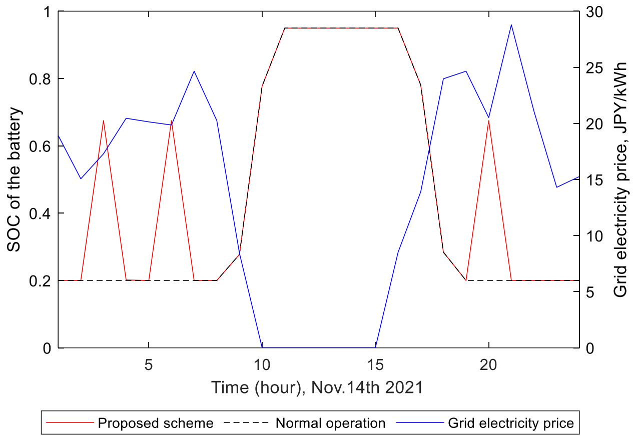

Fig. 4 Grid electricity used for charging the battery in relation to the price of grid electricity.

4.3 Sensitivity analysis

The impact of changes in hydrogen demand, battery capacity, and rated charge/discharge power of the battery is being analyzed through sensitivity analysis.

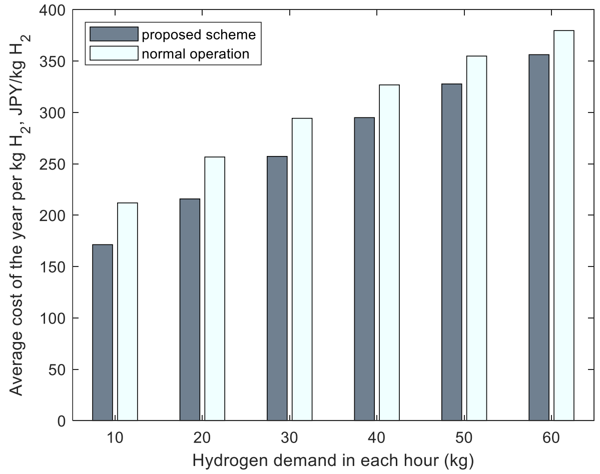

Fig. 5 Sensitivity analysis for hydrogen demand.

In Fig. 5, the relationship between hydrogen demand and average cost is illustrated. The proposed scheme demonstrates its superiority compared to normal operation. Moreover, as the hydrogen demand per hour increases from 10 kg to 60 kg, the average cost in both the proposed scheme and normal operation also increases. This is due to the fact that meeting high hydrogen demand requires complementing with grid electricity, especially when RES electricity with low prices is insufficient. Additionally, the cost reduction decreases as hydrogen demand increases, as indicated in Table 3. This is because the proposed scheme's ability to regulate power is limited by the battery capacity when hydrogen demand rises. Further analysis of the battery capacity is conducted through sensitivity testing.

Table 3. Cost reduction in different hydrogen demands.

Hydrogen demand	10kg	20kg	30kg	40kg	50kg	60kg
Cost reduction	19.2%	15.9%	12.6%	9.8%	7.6%	6.2%

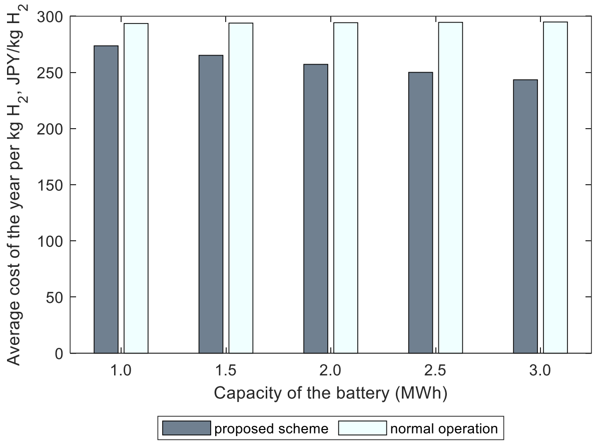

Fig. 6 Sensitivity analysis for battery capacity.

Fig.6 shows the relation between battery capacity and the average cost. The cost of hydrogen production in the proposed scheme decreases as the battery capacity increases. This is because the proposed scheme is able to fully utilize the battery capacity, leading to cost reduction. In contrast, the cost in normal operation remains the same due to low battery utilization. Furthermore, the results of sensitivity analysis on the rated power of the battery are presented in Fig.7. It is evident that the rated power has little influence on hydrogen production cost in both cases. This is due to the fact that the effect of power is limited by capacity. Therefore, to achieve better performance, it's important to focus on the battery capacity rather than the rated power.

5. CONCLUSION

In this paper, an optimal dispatching scheme is designed for a hydrogen production plant integrating the battery in the wholesale electricity market. The proposed method optimized the battery charging and grid electricity scheduling to minimize the total cost for the hydrogen production plant. The average hydrogen production cost decreased by 12.6% with the proposed scheme compared to that with normal operation. Moreover, the results of sensitivity analyses indicate that hydrogen demand and battery capacity have larger imp-

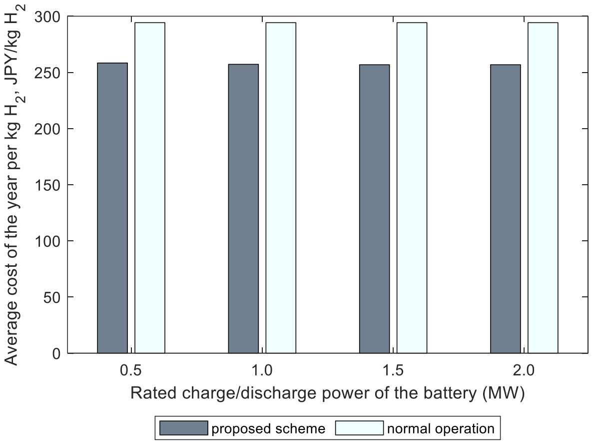

Fig. 7 Sensitivity analysis for battery power.

act magnitudes on the hydrogen production cost, while the impact of the rated power of the battery is relatively small compared to other factors.

As for future works, since the proposed scheme is for the day-ahead market, we should also consider the real-time market due to deviation caused by the great output uncertainties of photovoltaic and wind turbines. The day-ahead optimization results need to be adjusted in real-time in the actual system operation.

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