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# Economic Analysis of Hydrogen Production from Variable Renewables

Yoshiaki Shibata*

## Summary

Hydrogen, contributing to energy saving, $CO_2$ emission reduction, improvement in energy security and development of related industry, is expected to be widely used. Nevertheless, how to produce and procure hydrogen is a challenging issue. In the short term, hydrogen resources will be domestic by-product hydrogen and steam reforming of fossil fuel. Import of hydrogen by means of energy carriers such as liquefied hydrogen and organic hydride (methylcyclohexane) is also being studied by the private sector in anticipation of the future when hydrogen demand will increase. One of the important activities to establish a world hydrogen supply network is the development of $CO_2$-free hydrogen import. However, relying on import inherently carries with it persisting issues such as hydrogen price volatility, uncertainty of stable supply and national wealth leakage. On the other hand, hydrogen production from domestic renewable energy has an advantage in that these issues can be avoided, though there are technological barriers such as the input power variability tolerance of the electrolyzer. Hydrogen production from surplus variable renewable electricity (surplus power type) is recently drawing much attention as a grid integration measure and, in Germany, many pilot projects are being carried out as “Power to Gas.” However, the low load factor of the surplus electricity causes higher cost for hydrogen production. Meanwhile, by using the stable part of variable renewable electricity defined as the bottom part of variable renewable power output that is less affected by variability and by which relatively stable power can be supplied (referred to as stable power type), the production cost can be reduced due to the higher capacity factor of the electrolyzer.

This study identified the surplus electricity in scenarios of variable renewable integration and revealed that the stable power type electrolysis, whose capacity factor is 40% to 70% point higher than the surplus power, is a considerably economic option.

Utilization of surplus electricity that is typically regarded as inexpensive is frequently proposed as a grid integration measure. Nevertheless, the extremely low capacity factor of the electrolyzer increases the hydrogen production cost. As the pricing of surplus electricity, highly depending on the grid integration measures option and the electricity market structure, is volatile, it is preferable to use the stable part of renewable power generation at the bottom power generation output, which can bring about much a higher capacity factor electrolyzer, even though the purchase price may be expensive. Even if the surplus electricity can be purchased for free, the capacity factor of the electrolyzer is no higher than several percent and the capital cost of the electrolyzer is

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* Senior Economist, New and Renewable Energy Group and Energy Demand, Supply and Forecast Analysis Group, The Institute of Energy Economics, Japan

required to be reduced to 1/3 to 1/4 in order to achieve the cost level of the stable power type that has a capacity factor of more than 90%.

However, there are many barriers to reduction in the cost of hydrogen production from variable renewables. It is indispensable to sufficiently reduce the power generation cost of variable renewables and, also, research and development on tolerance to variable electricity input to the electrolyzer, improvement in hydrogen production efficiency and reduction of capital cost should be continued. On top of that, recovery and utilization of the oxygen produced in the electrolysis process that is mostly released into the atmosphere may be a solution to reduce hydrogen production cost.

With regard to hydrogen production and use as a grid integration measure, an analysis comprehensively including the energy system that compares the hydrogen system with other measures such as energy storage, strengthening of interregional transmission lines and demand side measures is required. Meanwhile, if the establishment of a hydrogen economy is targeted in the long term, domestic $CO_2$-free hydrogen should also be addressed, not only relying on hydrogen import. Producing hydrogen from the stable part of variable renewable electricity is an issue to be positively addressed, instead of passively regarding the hydrogen system using surplus electricity from variable renewables as a grid integration measure.

## Introduction

Hydrogen, contributing to energy saving, $CO_2$ emission reduction, improvement in energy security and development of related industry, is expected to be widely used. Nevertheless, how to produce and procure hydrogen is a challenging issue. In the short term, hydrogen resources will be domestic by-product hydrogen and steam reforming of fossil fuel. Import of hydrogen is also being studied by the private sector in anticipation of the future when fuel cell electric vehicles (FCEV), hydrogen thermal power generation and pure hydrogen-driven fuel cell combined heat and power (CHP) will be widely deployed. The major candidates of resource for import hydrogen include $CO_2$-free hydrogen production from brown coal combined with CCS (Carbon Capture and Storage) in Australia, $CO_2$-free hydrogen production from associated gas combined with EOR (Enhanced Oil Recovery) or CCS in oil producing countries in the Middle East and $CO_2$-free hydrogen production by electrolyzer from wind power in the wind-rich Argentine Patagonia region. The hydrogen will be imported by means of energy carriers such as liquefied hydrogen and organic hydride (methylcyclohexane). One of the important activities to establish a world hydrogen supply network is the development of $CO_2$-free hydrogen import. However, relying on import inherently carries with it persisting issues such as hydrogen price volatility, uncertainty of stable supply and national wealth leakage.

On the other hand, hydrogen production from domestic renewable energy has an advantage in that it can avoid these issues, though the power production cost of renewables is expensive and significant reduction in hydrogen production cost is required through R&D. Hydrogen production from variable renewables is often regarded as a grid integration measure and the use of surplus electricity is presumed. Many pilot projects for hydrogen production from surplus electricity are being carried out in Germany as “Power to Gas” [1]. However, it is readily understood that using the surplus electricity (*surplus power type*) would raise the hydrogen production cost due to the low capacity factor of the electrolyzer. Meanwhile, by using the stable part of variable renewables defined as the bottom part of variable renewable power output that is less affected by variability and that can supply relatively stable power (referred to as *stable power type*. See 3.1 for details), the production cost can be reduced due to the higher capacity factor. Though pricing of the surplus electricity remains uncertain depending on a future framework for grid integration measures and power market reform, if the price of electricity input to the electrolyzer is set constant, it is evident that the hydrogen production cost of the stable power type would be less expensive than the surplus power type. However, it has not yet been revealed to what extent the cost can be reduced.

This study identifies the amount of the surplus electricity and the capacity factor of the electrolyzer in scenarios of variable renewables integration and compares the hydrogen production cost between the surplus power type and the stable power type. Then, the preferable mode of hydrogen production from variable renewables is discussed. This study excludes the case where the surplus electricity may be traded at negative price in the wholesale power market.

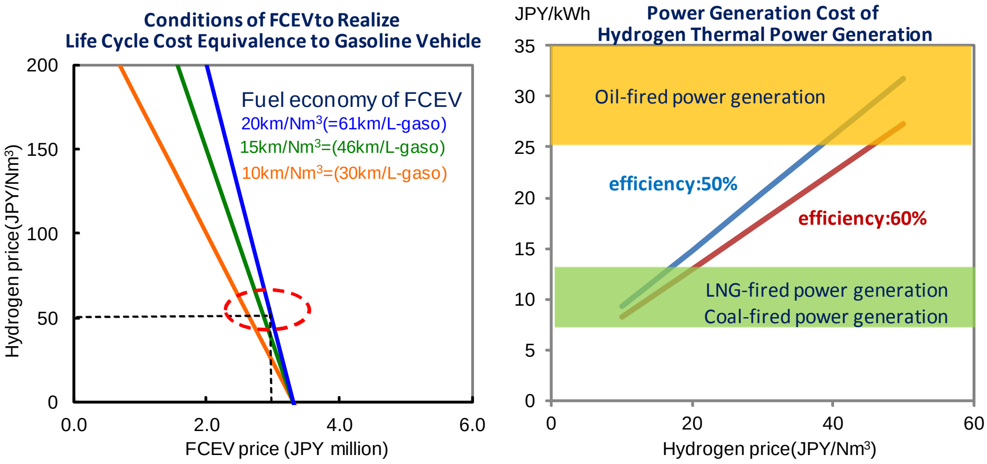
## 1. Economic Evaluation of Hydrogen Production by Electrolysis

### 1-1 Retail Price Level of Hydrogen

Apart from the by-product hydrogen that is consumed by oil refineries and the steel industries, the hydrogen distributed in the market is used in the light electric machinery, metallurgy, chemical and glass industries, of which approximately 200 million Nm$^3$ of hydrogen is compressed hydrogen [2]. The sales price of compressed hydrogen is about JPY40/Nm$^3$ [3]. Marketplace hydrogen, used as material, is not of reference for the price of hydrogen that is expected to be used as energy.

The required retail price level of hydrogen for energy use varies depending on the type of use. The price of hydrogen for FCEV that meets the running cost equivalent requirement would be from JPY100/Nm$^3$ to JPY150/Nm$^3$ when the gasoline price is JPY150/L, assuming that the fuel economy of FCEV is two to three times better than a gasoline vehicle. In terms of life cycle cost including car price and the lifetime fuel cost, the hydrogen price is required to be JPY50/Nm$^3$ when the FCEV price is JPY3 million (Fig. 1-1). In the case of hydrogen thermal power generation, the power generation cost lies between oil-fired and coal/natural gas-fired power generation, when the hydrogen price is JPY30/Nm$^3$ (Fig. 1-1). In the case of residential stationary pure hydrogen-driven fuel cell CHP, the price of hydrogen that meets the running cost equivalent requirement would be JPY60/Nm$^3$ if compared with the city gas retail price (JPY170/m$^3$=the average residential retail price of the major three gas companies in 2012), ignoring the capital cost and assuming that the power generation efficiency of natural gas-driven PEFC is 40% and that of hydrogen-driven PEFC is 50% (the efficiency of the reformer is 80%). These rough estimates provide information on the hydrogen price level required by end-users. The hydrogen production cost should be much lower than these retail prices as storage and distribution cost should be added.

**Fig. 1-1　Price Level of Hydrogen**



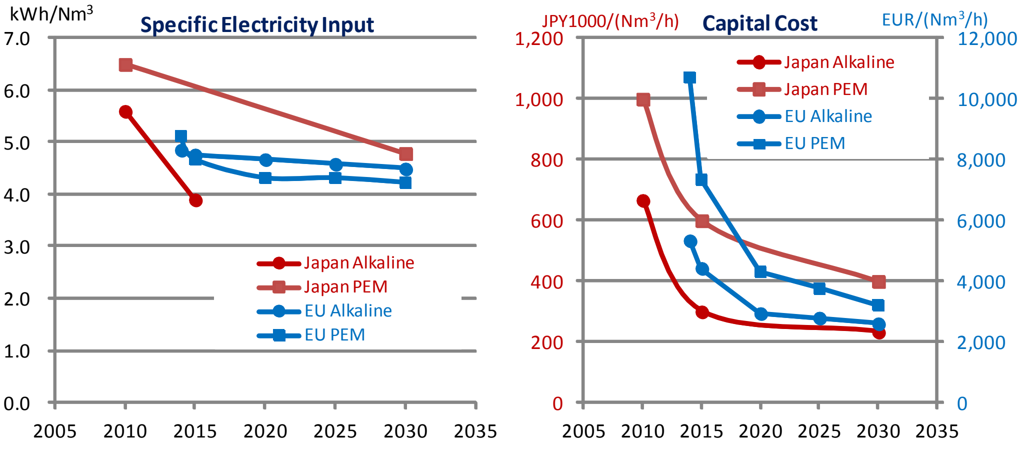
Note: The gasoline car price is JPY2 million, fuel economy is 15km/L, gasoline price is JPY150/L and lifetime is 13 years. The capacity factor of the hydrogen thermal power generation is 50%. The capital cost is JPY120,000/kW, the same as an LNG-fired power plant.

On the supply side, domestic by-product hydrogen can reportedly be supplied at JPY20/ $Nm^3$~JPY40/$Nm^3$ [2] and a feasibility study [4] analyzed that the $CO_2$-free hydrogen from brown coal can be imported from Australia to Japan at JPY30/$Nm^3$ (CIF). These price levels may be a target for hydrogen that will be newly produced domestically[1].

## 1-2　Cost of Hydrogen Production from Renewable Energy

Among major electrolysis technologies that are commercially available are alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis. The capital cost of alkaline

**Fig. 1-2　Outlook for Specific Electricity Input and Capital Cost of Electrolyzer**



Source: "NEDO Fuel Cell/Hydrogen Technology Development Roadmap, 2010" and "Development of Water Electrolysis in the European Union," EU Joint Undertaking, 2014

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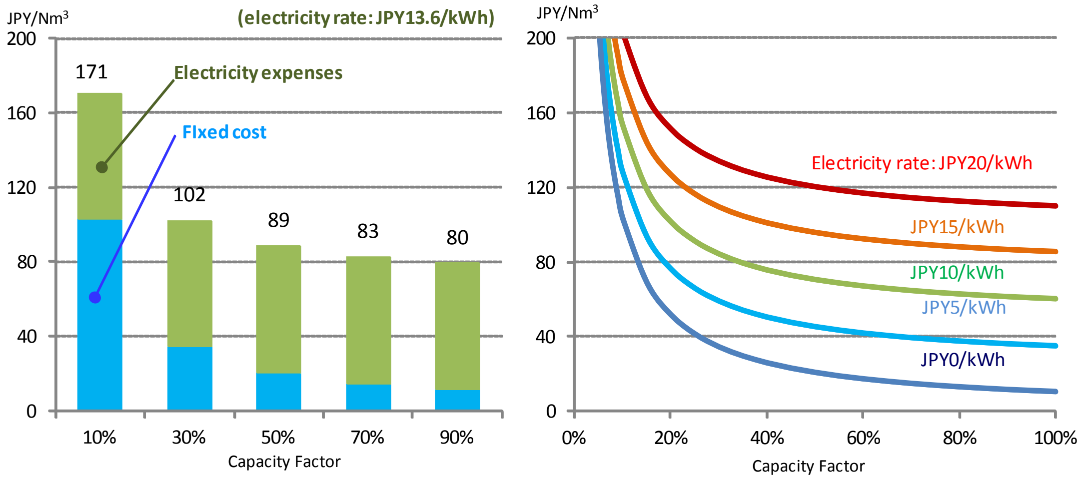
[1] DOE/USA targets \$0.2/$Nm^3$ in 2020 for the hydrogen production cost by electrolyzer (\$0.4/$Nm^3$ in 2011) [5].

electrolysis is less expensive than PEM electrolysis that needs platinum material. The conversion efficiency of PEM electrolysis is higher than the alkaline type [6]. Fig. 1-2 shows the outlook for specific electricity input and capital cost. The current specific electricity input is about 5kWh/Nm$^3$ and the EU targets 4.2 kWh/Nm$^3$ for the PEM type around 2030 [7]. The theoretical minimum specific electricity input at ambient temperature and pressure is 3.54 kWh/Nm$^3$, but the electricity input may be reduced below 3.54 kWh/Nm$^3$ if suitable heat is provided to the electrolyzer. The capital cost of the PEM type, which is presently 1 million JPY/(Nm$^3$/h), is targeted to be below JPY 400,000/(Nm$^3$/h) in 2030, and the current JPY600,000/(Nm$^3$/h) of the alkaline type is targeted to be JPY200,000/(Nm$^3$/h) in 2030.

Fig. 1-3 shows the hydrogen production cost from the current PEM electrolyzer with JPY1milllion/(Nm$^3$/h) of capital cost and 5kWh/Nm$^3$ of specific electricity input. Assuming that the electricity price is JPY13.6/kWh[8], electricity expenses only account for JPY68/Nm$^3$. The fixed cost decreases as the capacity factor rises. The production cost is JPY171/Nm$^3$ when the capacity factor is 10% and JPY80/Nm$^3$ when the capacity factor is 90%. If the electricity can be purchased at JPY5/kWh, the production cost is about JPY80/Nm$^3$ with the capacity factor at 20% and JPY40/Nm$^3$ at 80%. These production cost levels are considerably high as the cost for storage and distribution should be added.

In order to realize JPY30/Nm$^3$ addressed in 1.1, the electricity price is required to be less than JPY6/kWh~JPY8/kWh, taking into account improvement in the specific electricity input from the current 5kWh/Nm$^3$-$H_2$ to the theoretical minimum level, 3.54 kWh/Nm$^3$-$H_2$ (Table 1-1).

**Fig. 1-3　Production Cost of Hydrogen from Water Electrolysis**



Note: Specific electricity input is 5kWh/Nm$^3$-$H_2$, capital cost is JPY1 million/(Nm$^3$/h), OPEX is 4% of CAPEX, 20 year operation is assumed. The left side figure shows the cost at JPY13.6/kWh of electricity price (wind power generation cost).

**Table 1-1 Conditions to Achieve JPY30/Nm$^3$ of Hydrogen Production Cost**

| Specific electricity input | Electricity price | Capital cost | Capacity factor |
|---|---|---|---|
| 5kWh/Nm$^3$-H$_2$ | JPY5/kWh | JPY500,000/(Nm$^3$/h) | 95% |
| | | JPY200,000/(Nm$^3$/h) | 40% |
| 4kWh/Nm$^3$-H$_2$ | JPY5/kWh | JPY1000,000/(Nm$^3$/h) | 100% |
| | | JPY500,000/(Nm$^3$/h) | 50% |
| | | JPY200,000/(Nm$^3$/h) | 20% |
| | JPY7/kWh | JPY200,000/(Nm$^3$/h) | 85% |

Hydrogen production from variable renewables is often regarded as a grid integration measure and the use of surplus electricity is presumed. Only if the surplus electricity would be curtailed and could be purchased free of cost, JPY30/Nm$^3$ can be realized by a capacity factor of 35%, 18% and 8% for a capital cost of JPY 1milion/(Nm$^3$/h), JPY 500,000/(Nm$^3$/h) and JPY 200,000/(Nm$^3$/h), respectively. However, the pricing mechanism of the surplus electricity in Japan is unclear and heavily affected by the renewable energy promotion policies and the future power market structure. In principle, purchase of surplus electricity for free would only be feasible when the amount of surplus electricity is limited. Purchase of surplus electricity for free in a situation where a large amount of surplus electricity is produced hinders renewable energy investment per se because the renewable energy power producers would not be able to recover the investment cost. Therefore, reduction in the power generation cost of renewable energy is a crucial issue to reduce the hydrogen production cost. In addition, reducing the specific electricity input and the capital cost should also be tackled through research and development activities.

On the other hand, among the operational side measures to reduce the production cost is improvement of the capacity factor of the electrolyzer. For example, an increase in the capacity factor from 10% to 90% can yield JPY90/Nm$^3$ of cost reduction when the capital cost is JPY 1million/(Nm$^3$/h) and JPY18/Nm$^3$ when the capital cost is JPY 200,000/(Nm$^3$/h). Hereafter, how much surplus electricity is produced depending on the renewable energy integration level is figured out and measures to improve the electrolyzer capacity factor are discussed.

## 2. Surplus Electricity from Variable Renewables

The amount of surplus electricity largely depends on the level of renewable energy integration and what integration measures, like strengthening the interregional transmission line, energy storage technologies, curtailment and demand side measures, are implemented and to what extent. This chapter uses a power generation mix model to identify the hourly surplus electricity in the individual regions in Japan.

## 2-1 Analysis Framework

Data on electric load curve, power generation mix, power generation capacity of renewable energy, capacity factor and power generation pattern were prepared. The model simulates hourly power balance, including operation of pumped hydro and battery and power inter-exchange between regions. The surplus electricity from variable renewable is defined as the electricity that cannot be absorbed in the grid. The whole of Japan is divided into the nine regions of the nine utilities. Assumptions, data and scenarios are presented below.

[Assumptions]

- The nationwide power generation share of the base load power generation (nuclear, hydro, biomass and geothermal) is 30%.
- The minimum requirement of the ramping capacity of the thermal power generation is constantly 2% of the electricity demand.
- Pumped hydro firstly operates to absorb as much variable renewable electricity as possible (however, surplus nuclear at the bottom period comes prior to the variable renewables).
- Secondly, the variable renewable power generation that cannot be absorbed by pumped hydro is transmitted to another region (interregional transmission lines are not strengthened. The current operational capacity [9] is maintained).
- The variable renewable power generation that spills over even after these integration measures is defined as the surplus electricity.
- This study does not include energy storage technologies.

[Data]

- Granularity: hourly
- Electric load curve (2012): collected from the homepages of the nine utilities.
- Hourly power generation of photovoltaic and wind power (2012): Estimated from the data of AMeDAS (Automated Meteorological Data Acquisition System) of the Japan Meteorological Agency) [10][11].
- Regional distribution of photovoltaic and wind power: Prefectural distribution as of March 2014 persists for the future.

[Scenarios]

- Combination of 10GW to 100GW of photovoltaic and10GW to 70GW of wind power

## 2-2 Simulation Results

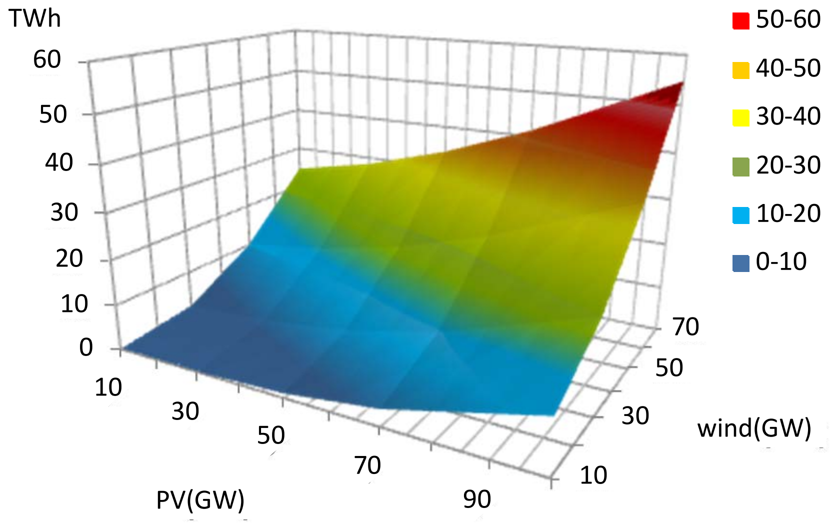
Fig. 2-1 shows the surplus electricity as a function of installed capacity of photovoltaic and wind power. The surplus electricity begins to be produced when the capacity combination exceeds 30GW of photovoltaic and 10GW of wind power. When 70GW of photovoltaic and 50GW of wind power are integrated, 23TWh of electricity spills over, which is equivalent to 13% of the total power generation from photovoltaic and wind power. If 100GW of photovoltaic and 70GW of wind power are integrated, 55TWh of electricity spills over, which is equivalent to 23% of the total power generation from photovoltaic and wind power. Beyond the integration level of 50GW of photovoltaic and 30GW of wind power, the incremental surplus electricity per incremental capacity of photovoltaic is 300 to 400kWh/kW, smaller than that of wind power that is 600 to 800kWh/kW. This is because the photovoltaic power generation largely coincides with the electric demand peak time.

Examples of how the individual power generation operates and how the surplus electricity appears are shown in Fig. 2-2 for the region of Hokkaido, Tohoku and Tokyo. The surplus electricity appears in Hokkaido and Tohoku when 50GW of photovoltaic and 30GW of wind power are integrated nationwide. The electricity transmitted to Tokyo is frequently observed in the bottom season. When 100GW of photovoltaic and 70GW of wind power are integrated, a large amount of surplus electricity is frequently produced through the year, even after the spillover electricity of Hokkaido and Tohoku is transmitted to Tokyo.

Very little surplus electricity is observed in Tokyo, Kansai and Chubu (Fig. 2-3 and Fig. 2-4), while Hokkaido, Tohoku and Kyushu see massive surplus electricity and as much as 40% to 60% of the total power generation from photovoltaic and wind power spills over from the grid when 100GW of photovoltaic and 70GW of wind power are integrated.

The load factor of the surplus electricity is shown in Fig. 2-5. The load factor is very low at small scale integration of variable renewables. Even when 100GW of photovoltaic and 70GW of wind power are integrated, the highest load factor (Hokkaido) is no higher than 17%. The load duration curves of variable renewables are presented in Fig. 2-6.

**Fig. 2-1　Surplus Electricity from Variable Renewables in Japan**

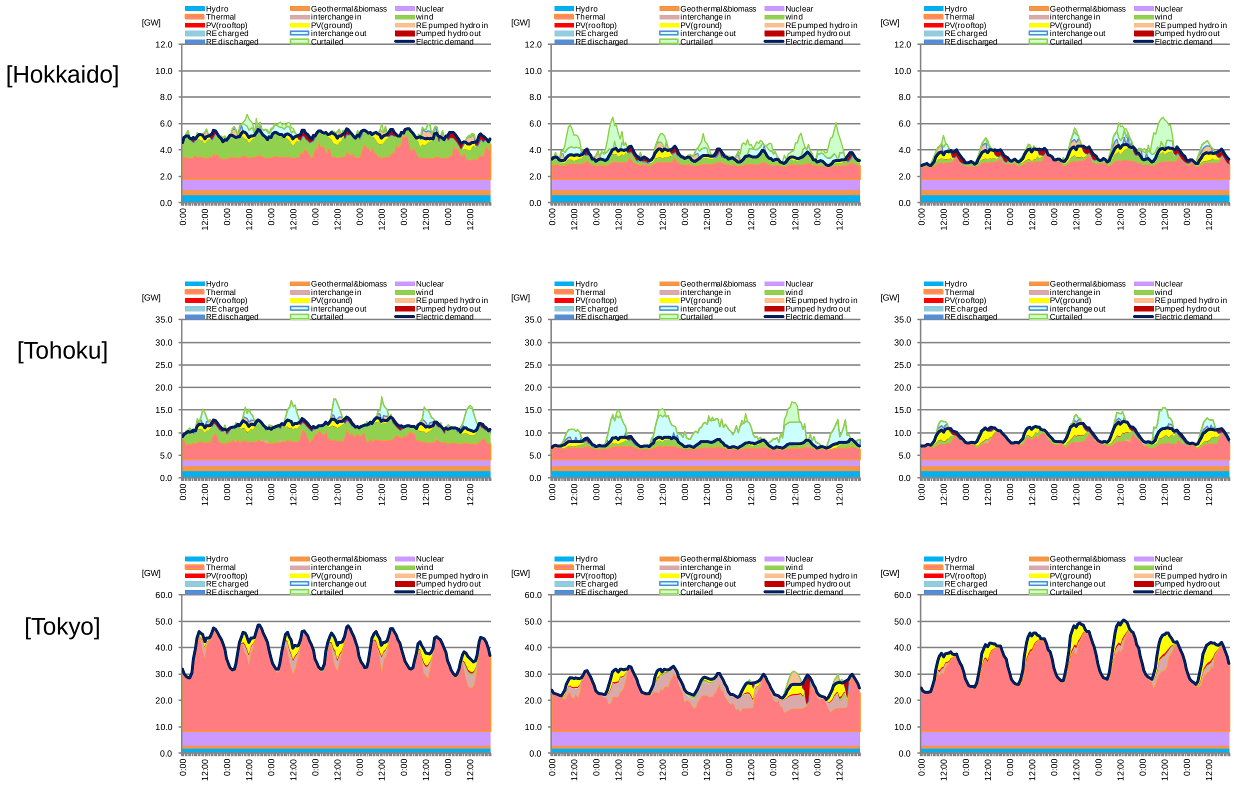


Note: The amount of surplus electricity varies depending on the combination of grid integration measures and power generation mix.

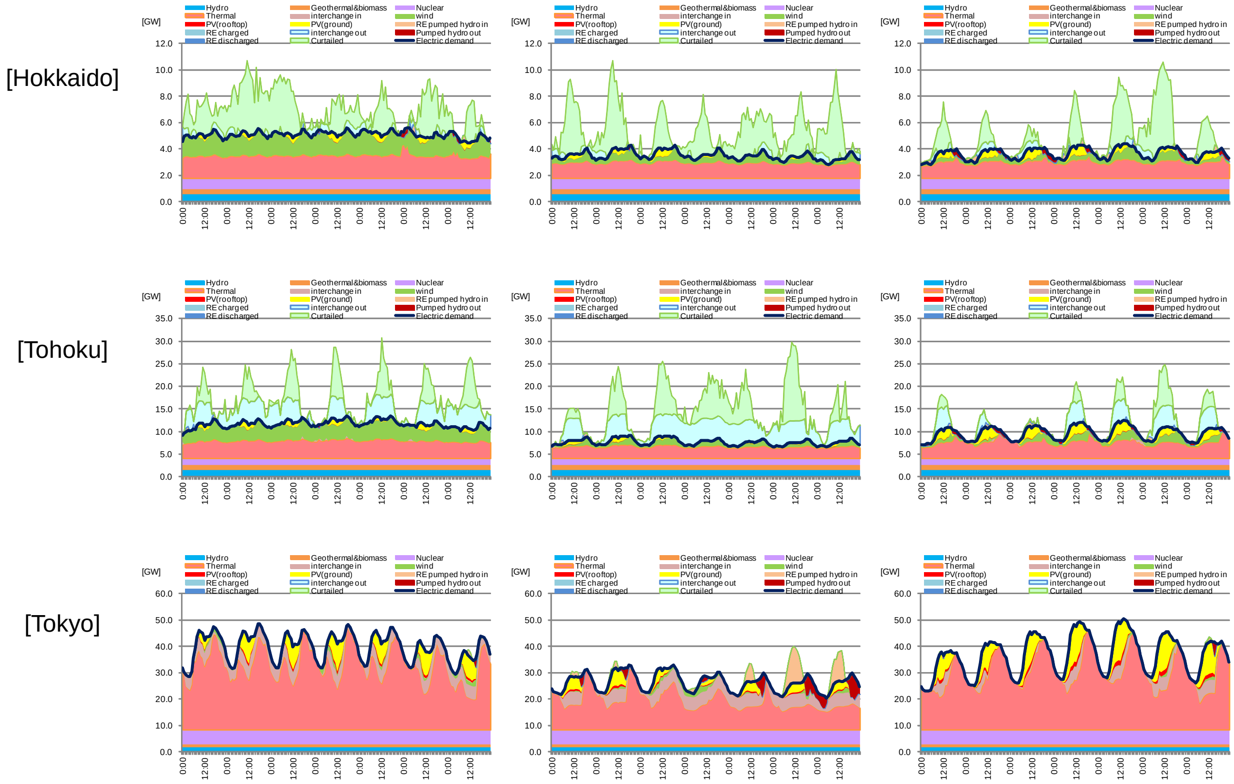
## Fig. 2-2　Samples of Simulation Results

[1/23-1/29]　　[4/30-5/6]　　[7/23-7/29]

<50GW of Photovoltaic + 30GW of Wind power>

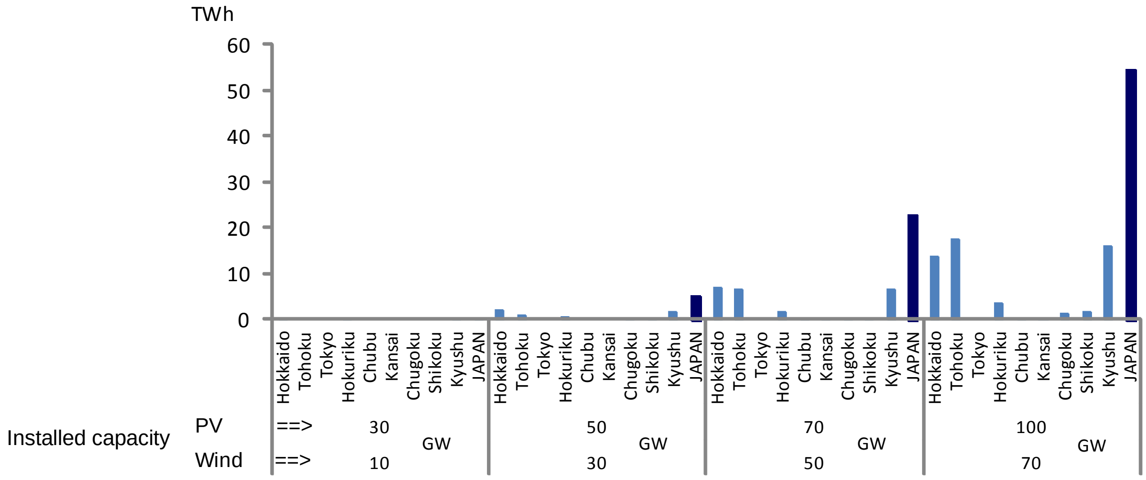


<100GW of Photovoltaic + 70GW of Wind power>

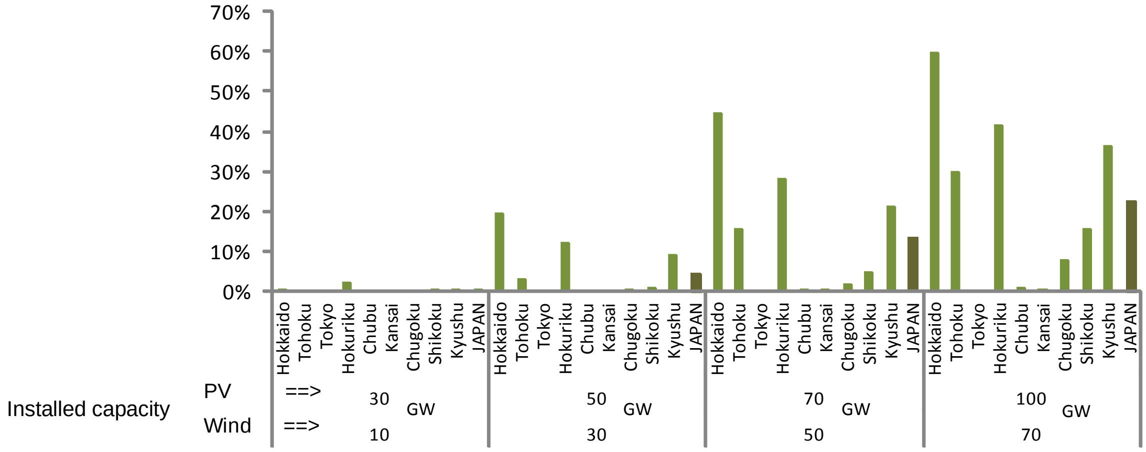


Note: “Curtailment” means the surplus electricity. “PV” and “Wind” mean the electricity generation absorbed in the grid.

## Fig. 2-3　Regional Surplus Electricity from Variable Renewables



## Fig. 2-4　Regional Ratio of Surplus Electricity from Variable Renewables



## Fig. 2-5　Load Factor of Surplus Electricity from Variable Renewables

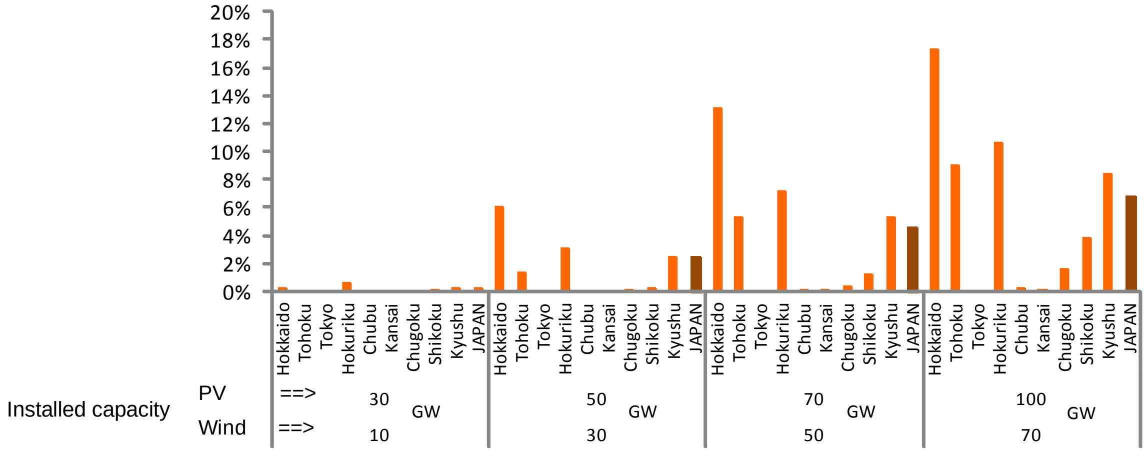
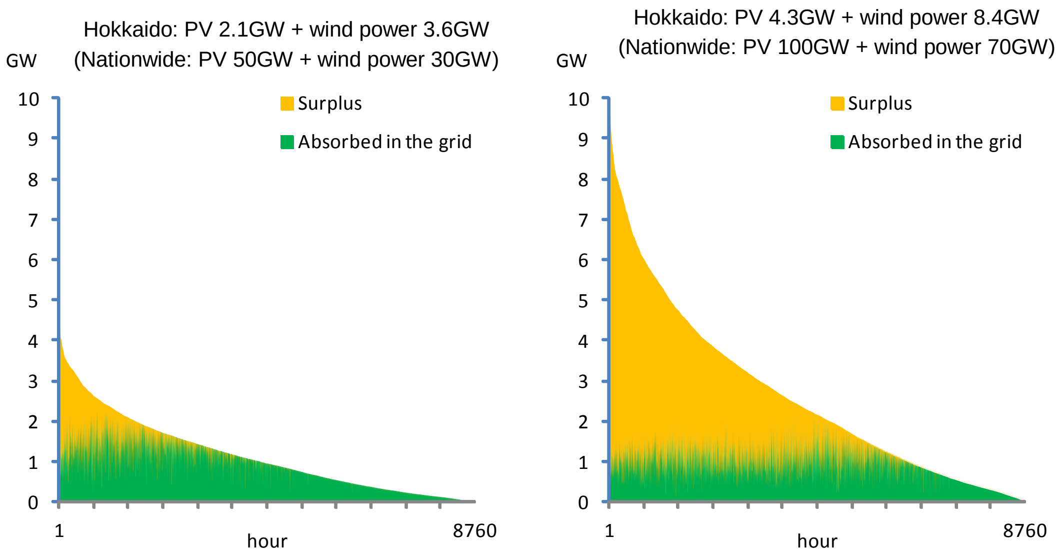


**Fig. 2-6 Load Duration Curve of Variable Renewables (Hokkaido)**



Note: Photovoltaic and wind power are added.

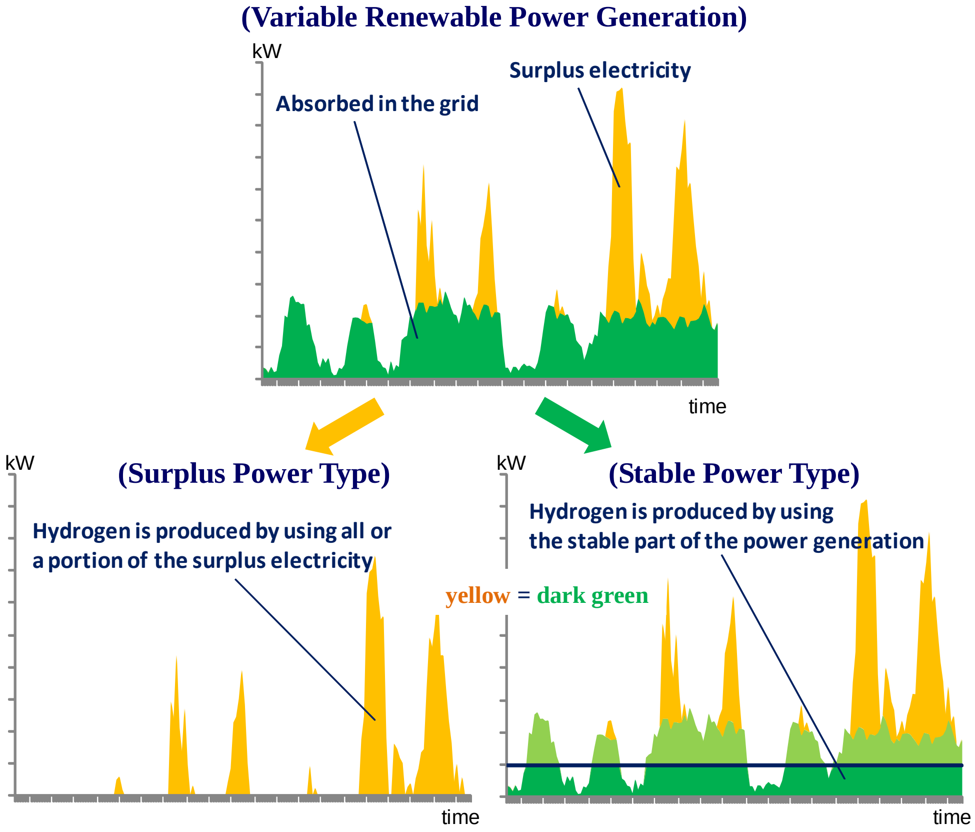
## 3. Economic Analysis of Hydrogen Production from Variable Renewables

Following the results of Chapter 2, cost analysis on hydrogen production will be carried out below focusing on Hokkaido, Tohoku and Kyushu where a larger amount of surplus electricity is produced than in other regions. Though it makes sense that smaller scale electrolyzers are installed in conjunction with renewable energy power plants, this study assumes concentrated installation of electrolyzers at a single site in the individual region for the sake of simplicity in discussion.

### 3-1 Concept of Surplus Power Type and Stable Power Type

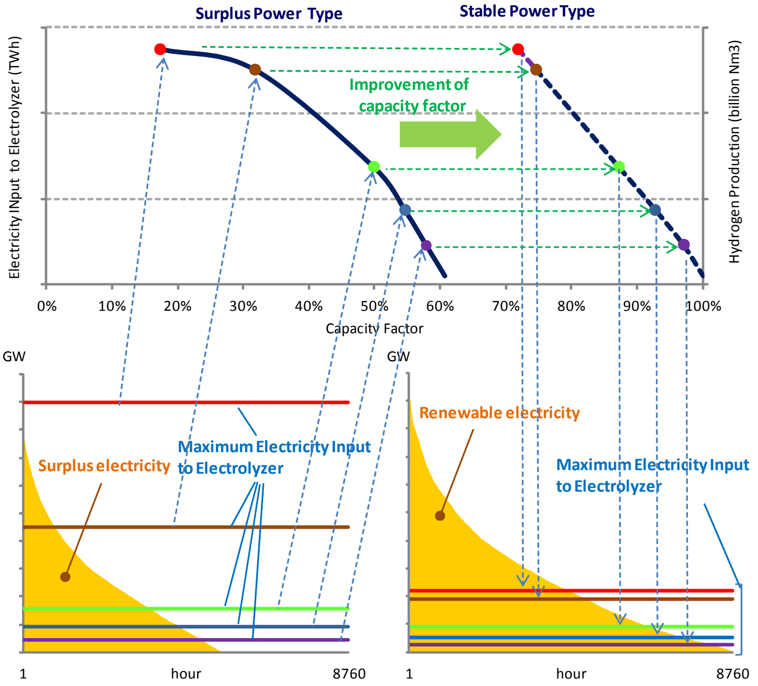
According to the analysis of Chapter 2, a small load factor of surplus electricity from variable renewables lowers the capacity factor of the electrolyzer and raises the cost of hydrogen production. In what follows, hydrogen production cost is compared between a case where the surplus electricity from variable renewables is used (*surplus power type*) and a case where the stable electricity situated at the bottom part of the variable renewables power output curve is used (*stable power type*). Fig. 3-1 compares these two concepts. The surplus power type uses the whole or a part of the electricity from the variable renewables that could not be absorbed in the grid. On the other hand, the stable power type uses the stable part of the variable renewables defined as the bottom part of variable renewable power output that is less affected by variability and that can supply relatively stable power. The electricity input to an electrolyzer is identical with that of surplus power type, assuming that partial load efficiency of the electrolyzer does not change from the rated efficiency (the yellow area is identical to the dark green area in Fig. 3-1). The capacity factor of the stable power type is obviously higher than the surplus power type (Fig. 3-2). However, the advantage of the stable power type is affected by the capacity factor of the surplus power type that depends on how much surplus electricity is used.

**Fig. 3-1　Hydrogen Production Concepts from Variable Renewables**



Note: Variable renewable is the summation of photovoltaic and wind power.
Note: The same amount of electricity is supplied to the electrolyzer in both types.

**Fig. 3-2　Improvement in Capacity Factor of Electrolyzer by Stable Power Type**

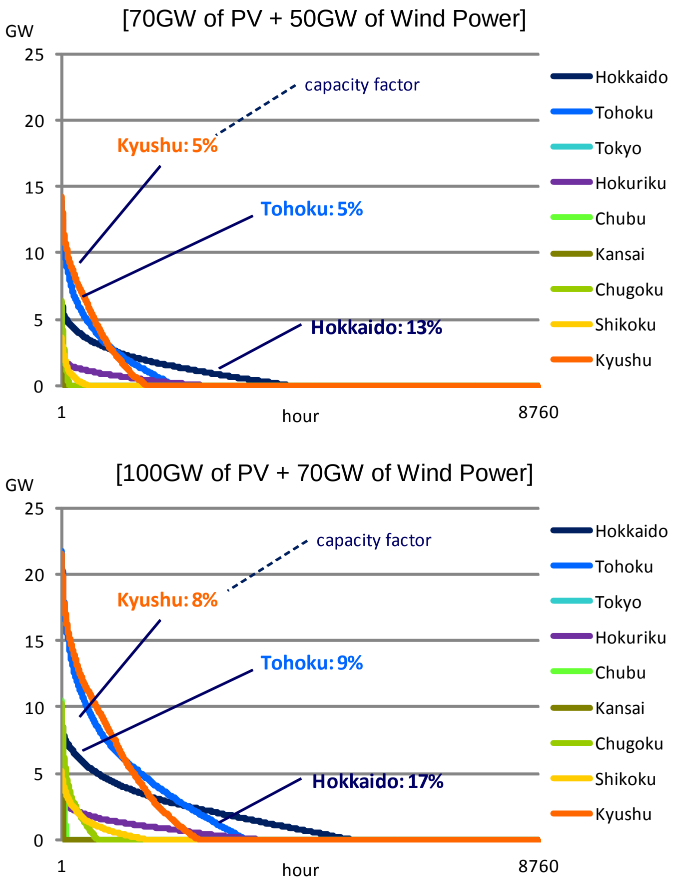


## 3-2　In the Case of Surplus Power Type

Ignoring the technological barriers such as input power variability tolerance, if all of the surplus electricity when 100GW of photovoltaic and 70GW of wind power are integrated (55TWh) is used, 11 billion $Nm^3$ of hydrogen will be produced (at the specific electricity input 5kWh/ $Nm^3$-$H_2$). This scale almost equals the domestic by-product hydrogen supply capacity, 11 to 17 billion $Nm^3$ [12] and can meet the hydrogen demand by 11 million FCEVs.

In spite of the large share of the surplus electricity in the power generation from the variable renewables (30% to 60% in Hokkaido, Tohoku and Kyushu), the load factor of the surplus electricity is no more than 17%, 9% and 8% in Hokkaido, Tohoku and Kyushu, respectively (bottom Fig. 3-3). When 70GW of photovoltaic and 50GW of wind power are integrated, the load factors of the surplus electricity are 13%, 5% and 5%, respectively (upper Fig. 3-3).

**Fig. 3-3　Regional Load Duration Curve of Surplus Electricity from Variable Renewables**



Given an amount of hydrogen produced, the electricity required and operation cost areconstant, then a major factor to determine the hydrogen production cost is capacity factor that affects the fixed cost. If all of the surplus electricity is used, the capacity factor of the electrolyzer coincides with the load factor of the surplus electricity and raises the production cost. In the case of 100GW of photovoltaic and 70GW of wind power, the hydrogen production cost is at least JPY130/$Nm^3$, JPY180/Nm$^3$ and JPY200/Nm$^3$ in Hokkaido, Tohoku and Kyushu, respectively (note that the average price of the surplus electricity is affected by the share of photovoltaic and wind power).

There are technological issues to be addressed to supply the total of the surplus electricity that varies frequently and largely [6][7]. In addition, a lower capacity factor of the electrolyzer does not make sense. It is practical and feasible that less frequent surplus electricity with large power output is to be curtailed and the rest of the surplus electricity is supplied to the electrolyzer. Only if all of the surplus electricity is used, the hydrogen production cost is significantly high as described above.

### 3-3 If Curtailed Surplus Electricity can be Purchased for Free

The Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities stipulates a “30-day rule” for curtailment of renewable energy (as of December 2014) and the utilities are allowed to request renewable energy power producers to curtail their power output without any compensation up to 30 days a year. If electrolyzers can procure the electricity that would have been curtailed at free cost, the hydrogen production cost can be reduced. However, the load factor of the surplus electricity caught by the “30-day rule” is presumed to be low. Table 3-1 shows the amount and the load factor of surplus electricity caught by the “30 day rule” and also the load factor of the stable power type to which the same amount of electricity is supplied. The load factor of the free surplus electricity is not much higher than several percent in every region, while that of the stable power type exceeds 90%. Fig. 3-4 compares hydrogen production cost between the free surplus power type and the stable power type. The fixed cost determines the production cost of the free surplus power type as there are no electricity expenses. The extremely low capacity factor raises the production cost substantially if the capital cost is expensive; the production cost is higher than JPY200/Nm$^3$ when the capital cost is JPY1million/(Nm$^3$/h). On the other hand, the production cost of the stable power type is JPY70~80/Nm$^3$ in spite of the electricity expenses added, as a much higher capacity factor, exceeding 90%, can curb the fixed cost. In order for the free surplus power type to realize the same level of production cost as the stable power type, the capital cost should be reduced to as low as JPY50,000~250,000/(Nm$^3$/h) in the case of 50GW of photovoltaic and 30GW of wind power. In the case of 100GW of photovoltaic and 70GW of wind power, even though the capacity factor of the free surplus power type is raised due to an increase in the surplus electricity, the capital cost is required to be reduced to JPY300,000~400,000/(Nm$^3$/h).

As analyzed above, the disadvantage of the low capacity factor of the free surplus power type offsets the benefit from free electricity procurement and substantial reduction in the capital cost is required so that the hydrogen production cost of the free surplus power type can rival that of the stable power type.

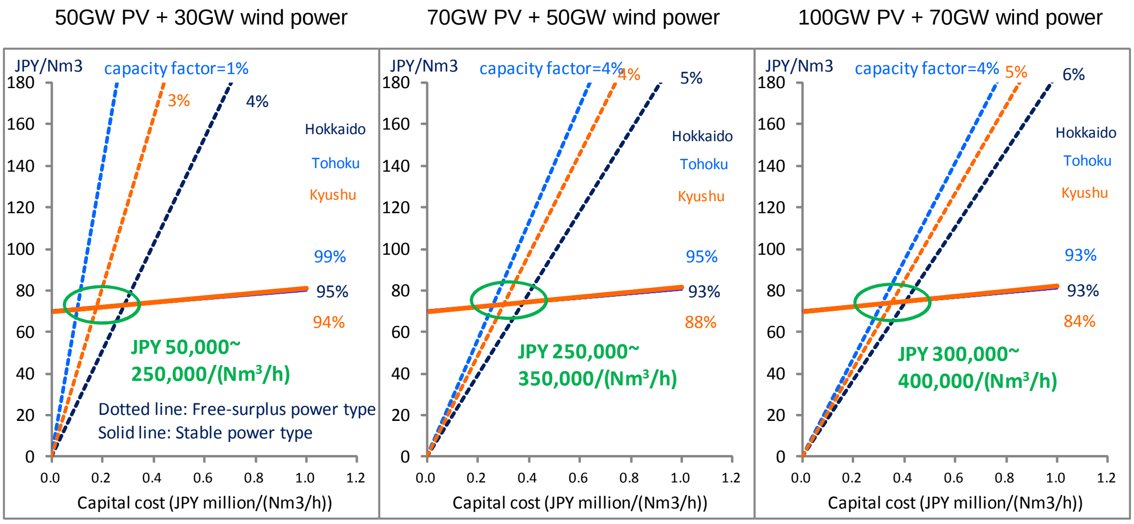
From another viewpoint, purchase of surplus electricity for free is in principle feasible only when the amount of surplus electricity is limited. Purchase of surplus electricity for free in a situation where a large amount of surplus electricity is produced hinders renewable energy investment per se because the renewable energy power producers could not recover the investment cost. The rule of curtailment without compensation might be, per contra, abolished to promote massive integration of renewable energy and the curtailed electricity could be compensated. A study of economic analysis of hydrogen production from surplus electricity in ERCOT (Electric Reliability Council of Texas) [13] gives an example that surplus electricity can be purchased for free when the electricity from wind power is priced negative in the wholesale market due to massive wind power generation in the bottom demand period. However, this does not happen many times in a year. In addition, the fact that the curtailed electricity is compensated in Germany indicates that free procurement of surplus electricity is limited.

**Table 3-1 Comparison of Capacity Factor of Free Surplus Power Type and Stable Power Type**

| | | | Hokkaido | Tohoku | Kyushu |
|---|---|---|---|---|---|
| PV 50GW+wind power 30GWW | Surplus type | Electricity (TWh) | 1.3 | 0.9 | 1.9 |
| | | Load factor | 4% | 1% | 3% |
| | | Ratio of the surplus | *65%* | *100%* | *100%* |
| | Stable type | Load factor | 95% | 99% | 94% |
| PV 70GW+wind power 50GWW | Surplus type | Electricity (TWh) | 2.9 | 4.5 | 5.3 |
| | | Load factor | 5% | 4% | 4% |
| | | Ratio of the surplus | *40%* | *68%* | *79%* |
| | Stable type | Load factor | 93% | 95% | 88% |
| PV 100GW+wind power 70GWW | Surplus type | Electricity (TWh) | 4.4 | 8.5 | 9.3 |
| | | Load factor | 6% | 4% | 5% |
| | | Ratio of the surplus | *32%* | *48%* | *58%* |
| | Stable type | Load factor | 93% | 93% | 84% |

Note: The amount of free surplus electricity is figured out based on the “30-day rule.”

**Fig. 3-4 Comparison of Hydrogen Production Cost between Free Surplus Power Type and Stable Power Type**



Note: The price of electricity input to the stable power type is assumed to be 14JPY/kWh (wind power). In fact, the surplus electricity, being composed of photovoltaic and wind power, is more expensive than this level.

## 3-4 Impact of Capacity Factor Improvement by Stable Power Type

The impact of capacity factor improvement by the stable power type on the hydrogen production cost is analyzed below under an assumption that the purchasing electricity price is identical for the surplus power type and the stable power type, since pricing of the surplus electricity is not clear as discussed above. Table 3-2 shows the capacity factor of the surplus power type and the stable power type in Hokkaido, Tohoku and Kyushu. Both types produce the same amount of hydrogen. In the case of nationwide integration of 100GW of photovoltaic and 70GW of wind power, the capacity factor of the surplus power type is 17% in Hokkaido, but the stable type can improve to 72%. If surplus electricity below the annual average power output is used, the capacity factor of the surplus power type is improved to 50%, but much lower than 87% of the stable power type.

**Table 3-2 Capacity Factor of Electrolyzer by Scenario**

[Hokkaido]

Electricity input to electrolyzer (TWh)

| | | | Using total surplus electricity | | | | | Using surplus electricity less than average output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | PV(GW) | | | | | PV(GW) | | | | |
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 |
| Wind (GW) | 10 | 1.2 | 0.0 | 0.0 | 0.1 | 0.3 | 1.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| | 30 | 3.6 | 1.2 | 1.5 | 2.0 | 2.7 | 4.0 | 0.2 | 0.3 | 0.4 | 0.7 | 1.2 |
| | 50 | 6.0 | 5.2 | 5.7 | 6.4 | 7.3 | 8.7 | 1.6 | 2.0 | 2.4 | 2.9 | 3.8 |
| | 70 | 8.4 | 9.9 | 10.6 | 11.4 | 12.3 | 13.7 | 4.0 | 4.5 | 5.2 | 5.9 | 6.8 |

Capacity factor

Surplus type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 |
| Wind (GW) | 10 | 1.2 | 0% | 0% | 1% | 2% | 4% | 0% | 1% | 2% | 6% | 12% |
| | 30 | 3.6 | 5% | 5% | 6% | 8% | 10% | 17% | 19% | 23% | 27% | 31% |
| | 50 | 6.0 | 11% | 11% | 12% | 13% | 15% | 32% | 34% | 38% | 41% | 44% |
| | 70 | 8.4 | 15% | 15% | 16% | 16% | 17% | 40% | 43% | 45% | 48% | 50% |

Stable type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 | 0.4 | 1.3 | 2.1 | 3.0 | 4.3 |
| Wind (GW) | 10 | 1.2 | 100% | 100% | 100% | 97% | 87% | 100% | 100% | 100% | 100% | 99% |
| | 30 | 3.6 | 95% | 94% | 92% | 89% | 84% | 100% | 100% | 99% | 98% | 96% |
| | 50 | 6.0 | 81% | 82% | 81% | 80% | 77% | 96% | 96% | 95% | 93% | 91% |
| | 70 | 8.4 | 71% | 73% | 73% | 73% | 72% | 92% | 91% | 90% | 89% | 87% |

[Tohoku]

Electricity input to electrolyzer (TWh)

| | | | Using total surplus electricity | | | | | Using surplus electricity less than average output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | PV(GW) | | | | | PV(GW) | | | | |
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 |
| Wind (GW) | 10 | 3.1 | 0.0 | 0.0 | 0.0 | 0.2 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| | 30 | 9.3 | 0.2 | 0.4 | 0.9 | 1.7 | 4.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.6 |
| | 50 | 15.4 | 3.3 | 4.1 | 5.1 | 6.6 | 9.6 | 0.5 | 0.7 | 0.9 | 1.4 | 2.5 |
| | 70 | 21.6 | 9.7 | 10.9 | 12.3 | 14.2 | 17.6 | 2.2 | 2.7 | 3.3 | 4.2 | 5.9 |

Capacity factor

Surplus type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 |
| Wind (GW) | 10 | 3.1 | - | - | 0% | 1% | 2% | - | - | 0% | 2% | 8% |
| | 30 | 9.3 | 1% | 1% | 1% | 2% | 4% | 2% | 4% | 6% | 10% | 16% |
| | 50 | 15.4 | 4% | 5% | 5% | 5% | 6% | 14% | 16% | 18% | 22% | 26% |
| | 70 | 21.6 | 7% | 8% | 8% | 9% | 9% | 23% | 25% | 27% | 30% | 34% |

Stable type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 | 1.5 | 4.4 | 7.4 | 10.4 | 14.8 |
| Wind (GW) | 10 | 3.1 | 100% | 100% | 100% | 99% | 92% | 100% | 100% | 100% | 100% | 100% |
| | 30 | 9.3 | 100% | 99% | 99% | 97% | 92% | 100% | 100% | 100% | 100% | 99% |
| | 50 | 15.4 | 96% | 95% | 94% | 92% | 87% | 100% | 99% | 99% | 99% | 98% |
| | 70 | 21.6 | 89% | 89% | 88% | 86% | 83% | 99% | 98% | 98% | 97% | 95% |

[Kyushu]

Electricity input to electrolyzer (TWh)

| | | | Using total surplus electricity | | | | | Using surplus electricity less than average output | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | PV(GW) | | | | | PV(GW) | | | | |
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 |
| Wind (GW) | 10 | 1.3 | 0.0 | 0.1 | 0.8 | 3.0 | 8.5 | 0.0 | 0.0 | 0.0 | 0.3 | 1.3 |
| | 30 | 3.8 | 0.0 | 0.4 | 1.9 | 4.6 | 10.7 | 0.0 | 0.0 | 0.1 | 0.6 | 2.0 |
| | 50 | 6.4 | 0.2 | 1.2 | 3.4 | 6.7 | 13.3 | 0.0 | 0.1 | 0.4 | 1.1 | 2.8 |
| | 70 | 8.9 | 1.0 | 2.6 | 5.4 | 9.2 | 16.1 | 0.1 | 0.3 | 0.9 | 1.9 | 4.1 |

Capacity factor

Surplus type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 |
| Wind (GW) | 10 | 1.3 | - | 0% | 1% | 3% | 6% | - | 1% | 4% | 9% | 16% |
| | 30 | 3.8 | 0% | 1% | 3% | 4% | 7% | 0% | 2% | 6% | 12% | 18% |
| | 50 | 6.4 | 1% | 2% | 4% | 5% | 8% | 3% | 7% | 11% | 16% | 21% |
| | 70 | 8.9 | 2% | 3% | 5% | 6% | 8% | 7% | 12% | 17% | 21% | 25% |

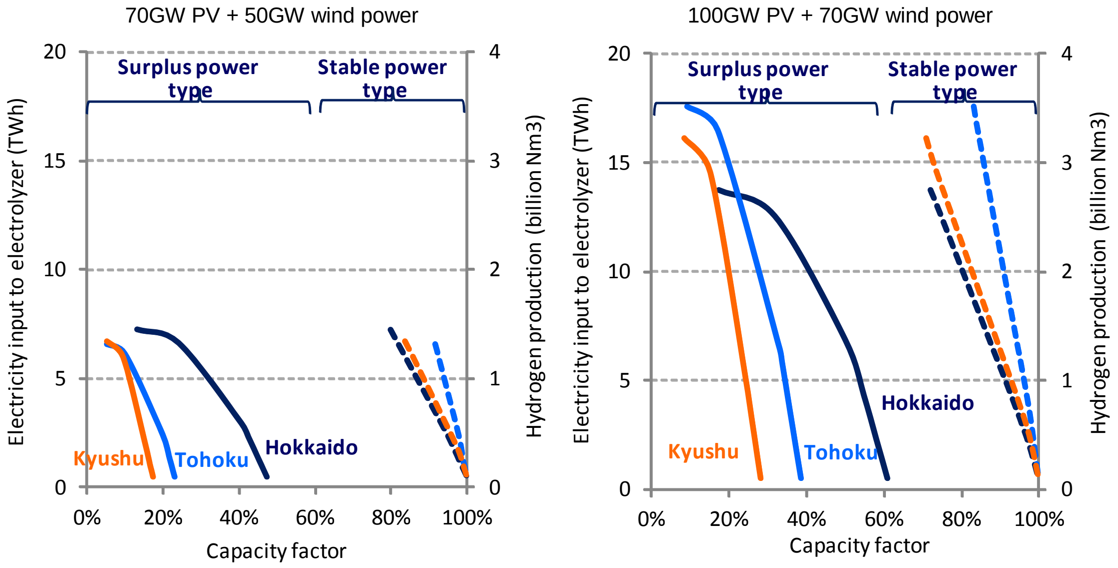
Stable type

| | | | PV(GW) | | | | | PV(GW) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nationwide | | 10 | 30 | 50 | 70 | 100 | 10 | 30 | 50 | 70 | 100 |
| | | region | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 | 2.5 | 7.6 | 12.6 | 17.6 | 25.2 |
| Wind (GW) | 10 | 1.3 | 100% | 100% | 92% | 69% | 50% | 100% | 100% | 100% | 99% | 85% |
| | 30 | 3.8 | 100% | 100% | 94% | 81% | 62% | 100% | 100% | 100% | 99% | 94% |
| | 50 | 6.4 | 100% | 99% | 93% | 84% | 68% | 100% | 100% | 100% | 99% | 95% |
| | 70 | 8.9 | 99% | 97% | 92% | 84% | 71% | 100% | 100% | 100% | 98% | 95% |

Fig. 3-5 compares the relation between the electricity input to the electrolyzer and the capacity factor for the surplus power type and the stable power type. If 5TWh is input to the electrolyzer (1 billion $Nm^3$ of hydrogen is produced), in the case of 70GW of photovoltaic and 50GW of wind power, the capacity factor of the stable power type is much higher than the surplus power type: 87% and 35% respectively in Hokkaido, 96% and 16% in Tohoku, and 89% and 11% in Kyushu. In the case of 100GW of photovoltaic and 70GW of wind power, the difference between the two types diminishes due to an increase in the surplus electricity, but the stable power type is still 40% to 70% point higher than the surplus power type.

Fig. 3-6, focusing only on the fixed cost, shows that the stable power type can reduce the cost substantially in comparison with the surplus power type. In the case of nationwide integration of 70GW of photovoltaic and 50GW of wind power, the hydrogen production cost can be reduced by JPY18/$Nm^3$, from JPY29/$Nm^3$ to JPY12/$Nm^3$ in Hokkaido when the capital cost is JPY 1million/($Nm^3$/h). The cost reduction is JPY54/$Nm^3$ in Tohoku and JPY82/$Nm^3$ in Kyushu. In the case of nationwide integration of 100GW of photovoltaic and 70GW of wind power, the cost reductions are JPY8/$Nm^3$, JPY20/$Nm^3$ and JPY32/$Nm^3$ in Hokkaido, Tohoku and Kyushu, respectively.

**Fig. 3-5 Electrolyzer Input Electricity and Capacity Factor**

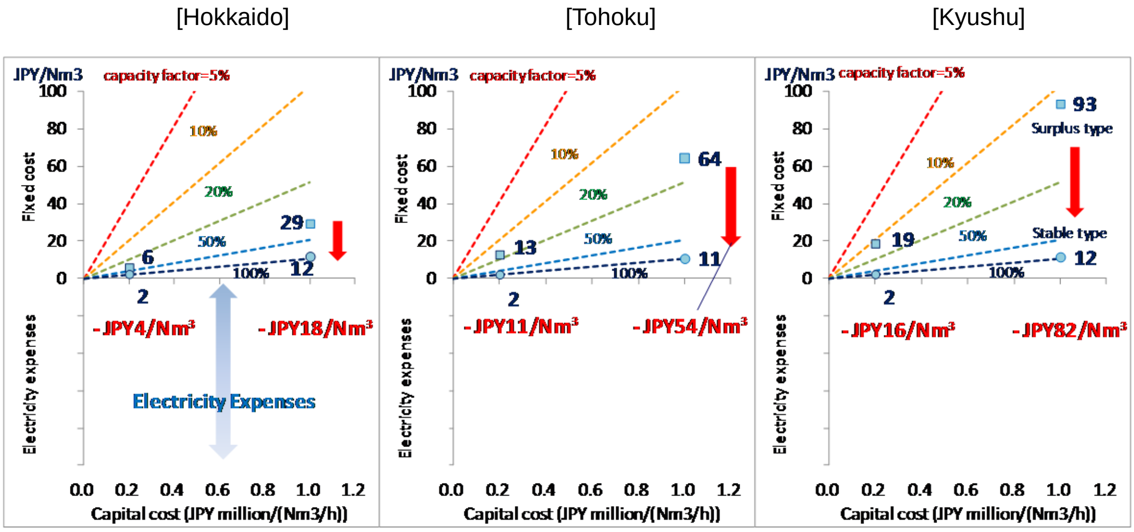


Capacity Factor of Electrolyzer in Case of 5TWh of Electricity Input

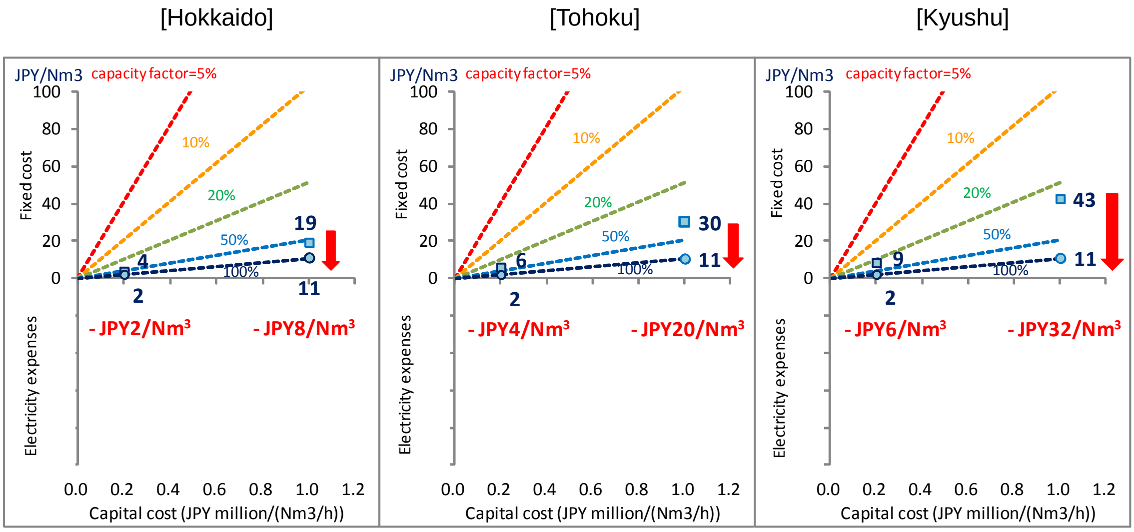
| | PV 70GW + Wind 50GW | | | PV 100GW + Wind 70GW | | |
|---|---|---|---|---|---|---|
| | Hokkaido | Tohoku | Kyushu | Hokkaido | Tohoku | Kyushu |
| Surplus power type | 35% | 16% | 11% | 53% | 34% | 24% |
| Stable power type | 87% | 96% | 89% | 91% | 96% | 93% |

Note: The specific electricity input is 5kWh/$Nm^3$-$H_2$.

**Fig. 3-6 Hydrogen Production Cost Reduction Impact by Stable Power Type**



<70GW PV + 50GW wind power>



<100GW PV + 70GW wind power>

Note: 5TWh electricity input (1 billion Nm$^3$ of hydrogen is produced).

Note: The electricity expenses are not expressed in order to highlight the variation of fixed cost as a function of capacity factor. The Electricity price is common for the two types.

## 3-5 Advantages and Disadvantages of Stable Power Type

The analyses above lead to a conclusion that the stable power type has great potential to reduce the cost of hydrogen production from variable renewables compared to the surplus power type. In terms of grid integration measures, the surplus power type has a benefit that it is able to reduce surplus electricity substantially. Meanwhile, the stable power type can also reduce surplus electricity to some extent, because variable renewable power generation that the grid has to absorb decreases due to input of the stable part of variable renewables to the electrolyzer. Out of the surplus electricity of 5.3TWh in the case of 50GW of photovoltaic and 30GW of wind power, 1.2TWh can be reduced by the stable power type. In the case of 100GW of photovoltaic and 70GW of wind power, about half of the surplus electricity of 55TWh can be reduced (Table 3-3).

On the other hand, in terms of disadvantages, the hydrogen production efficiency of the stable power type may be lower than the surplus power type, as the electrolyzer is in general designed so that the partial load efficiency is higher than the rated efficiency [7] and the stable power type operates at the partial load less frequently than the surplus power type.

**Table 3-3 Reduction of Surplus Electricity by Stable Power Type**

| | PV 50GW + wind 30GW | | | PV 70GW + wind 50GW | | | PV 100GW + wind 70GW | | |
|---|---|---|---|---|---|---|---|---|---|
| (TWh) | Surplus electricity | Surplus electricity after the stable part is used | Decrease in surplus electricity | Surplus electricity | Surplus electricity after the stable part is used | Decrease in surplus electricity | Surplus electricity | Surplus electricity after the stable part is used | Decrease in surplus electricity |
| Hokkaido | 2.0 | 1.4 | 0.6 | 7.3 | 3.2 | 4.1 | 13.7 | 4.3 | 9.4 |
| Tohoku | 0.9 | 0.8 | 0.1 | 6.6 | 5.0 | 1.5 | 17.6 | 10.7 | 6.9 |
| Tokyo | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Hokuriku | 0.5 | 0.4 | 0.1 | 1.7 | 1.1 | 0.6 | 3.6 | 1.8 | 1.8 |
| Chubu | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.0 |
| Kansai | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| Chugoku | 0.0 | 0.0 | 0.0 | 0.3 | 0.2 | 0.0 | 1.6 | 1.3 | 0.3 |
| Shikoku | 0.1 | 0.1 | 0.0 | 0.4 | 0.4 | 0.0 | 1.8 | 1.3 | 0.5 |
| Kyushu | 1.9 | 1.5 | 0.4 | 6.7 | 4.2 | 2.6 | 16.1 | 8.1 | 8.0 |
| JAPAN | 5.3 | 4.1 | 1.2 | 23.0 | 14.1 | 8.9 | 54.8 | 27.8 | 27.0 |

This study implicates that a concept using the stable part of variable renewables to produce hydrogen and transmitting the rest to the grid is worth being discussed deeply, if the primary objective is to reduce the cost of hydrogen production from variable renewables. For example, the National Renewable Energy Laboratory (NREL) analyzes the cost effectiveness of the electrolysis system combined with wind turbines, including revenue from sale of the electricity from wind power [14][15]. This system called “co-production” of power and hydrogen uses electricity from wind turbines and also from the grid to raise the capacity factor of the electrolyzer, and the wind power generation above the rated input to the electrolyzer is sold to the grid.

Though it is often forgotten, the electrolysis process also produces 0.5Nm$^3$ of oxygen along with 1Nm$^3$ of hydrogen. Nevertheless, oxygen is often released into the atmosphere. If oxygen can be used or sold, the hydrogen production cost may be reduced (according to the statistics, “Current Survey of Production,” oxygen is sold at 9JPY/Nm$^3$ in Japan).

## 3-6 Hydrogen and Grid Integration Measures

If economic analysis of hydrogen production and use as a grid integration measure, which this study excluded, is to be carried out, the hydrogen system should be compared with other measures such as energy storage, strengthening of interregional transmission lines and demand side measures. It is indisputable that the analysis should cover the overall hydrogen system including electrolyzer, storage, carrier and utilization technologies. The study on the optimal power generation mix considering hydrogen storage of variable renewable power generation done by Komiyama [16] indicates that it is not until the hydrogen system cost is substantially reduced and also stringent $CO_2$

emission constraints are imposed that the hydrogen system would be introduced as a grid integration measure for variable renewables.

## 4. Concluding Remarks

This study identified the surplus electricity from variable renewables for scenarios of variable renewable integration and compared the cost of hydrogen production by electrolysis between the surplus power type and the stable power type.

Taking the case of integration of 70GW of photovoltaic and 50GW of wind power for example, though more than 20TWh of surplus electricity is produced, the load factor of the surplus electricity is no higher than 5% to 15% even in the regions where a large amount of surplus electricity is produced. From viewpoint of reduction in hydrogen production cost, this study revealed that the stable power type whose capacity factor is 40% to 70% point higher than the surplus power type will be a much more economic concept.

Utilization of the surplus electricity that is typically regarded as inexpensive is frequently proposed as a grid integration measure. Nevertheless, the extremely low capacity factor of the electrolyzer increases the hydrogen production cost. As the pricing of surplus electricity highly depending on the grid integration measures option and the electricity market structure is volatile, it is preferable to use the stable part of renewable power generation that is located at the bottom power generation output, which can bring about much a higher capacity factor of electrolyzer, even though the purchase price may be expensive. Even if the surplus electricity can be purchased for free, the capacity factor of the electrolyzer is no higher than several percent and the capital cost of the electrolyzer is required to be reduced to 1/3 to 1/4 in order to achieve the cost level of the stable power type that has a capacity factor of more than 90%.

However, there are many barriers to reduction in the cost of hydrogen production from variable renewables. It is indispensable to sufficiently reduce the power generation cost of variable renewables and, also, research and development on tolerance to variable electricity input to the electrolyzer, improvement in hydrogen production efficiency and reduction of capital cost should be continued. On top of that, recovery and utilization of the oxygen produced in the electrolysis process that is mostly released into the atmosphere may be a solution to reduce hydrogen production cost.

If the establishment of a hydrogen economy is targeted in the long term, domestic $CO_2$-free hydrogen should also be addressed, not only relying on hydrogen import. Producing hydrogen from the stable part of variable renewable electricity is an issue to be positively addressed, instead of passively regarding the hydrogen system using surplus electricity from variable renewable electricity as a grid integration measure.

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