# Is Power to Gas Feasible in Japan?

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## Summary

This study discussed the feasibility of Power to Gas in Japan. In Germany, as the challenging $CO_2$ emission reduction target and limited supply capacity of stable renewable energies requires large-scale variable renewable energies integration, Power to Gas is not passively regarded as one of the grid integration measures, but as an important technology that can decarbonize not only the power generation sector but also the heat demand sector and also the transport sector by integrating a large amount of variable renewables positively. It should be underlined that the fact that the existing natural gas network including pipeline and underground gas storage is available nationwide and enables working together with the power grid to absorb as much as variable renewables supports the feasibility of Power to Gas.

The gas produced in Power to Gas is for the most part hydrogen and synthesis natural gas (SNG). In Germany, hydrogen blending to the natural gas pipeline would be the most reasonable measure as far as the amount of surplus electricity is small, since the standard for natural gas calorific value is sufficiently tolerant so as to accept a small volume of hydrogen. In the longer term when mass integration of variable renewable is expected, SNG may be the option as the constraint of blending is significantly small.

On the other hand, in Japan, though depending on the grid integration measures taken, as the surplus electricity in 2030 is expected to be small, the need for Power to Gas is very limited. Even if Power to Gas is to be promoted in the long-term perspective, the poorly-developed natural gas pipeline network hinders working with the power grid and hydrogen or SNG blending is considerably difficult. The activities toward establishing the hydrogen economy have recently been accelerated in Japan and new infrastructure is required to realize the hydrogen economy. Hence, new infrastructure should be constructed either for hydrogen or SNG in Japan. To judge which is the most cost effective option requires detailed cost-benefit analysis. Meanwhile, in terms of production cost of gases, the renewable power generation cost should be reduced to JPY5/kWh for either hydrogen or SNG to equal the competing energy. SNG faces a challenge to effectively capture $CO_2$.

Power to Fuel to produce chemicals and fuels for vehicles can use the existing infrastructure for storage and delivery, which shows an advantage over Power to Gas. It is worth addressing the feasibility of Power to Fuel in Japan. If artificial photosynthesis that can integrate the electrolysis process and the reverse shift reaction is developed, the synthesis gas can be produced directly from water and carbon dioxide avoiding the power generation process, which may alleviate the grid connection constraint.


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Last not but least, reduction in the renewable power generation cost and capital cost of electrolysis and methanation is sine qua non to make Power to Gas and Power to Fuel feasible. In addition, as Power to Gas and Power to Fuel accompany energy system transformation through networking with the existing infrastructure and building new infrastructure, how to integrate Power to Gas/Power to Fuel should be discussed based on the energy system concept that Japan should build in the long-term perspective.

## Introduction

Power to Gas (PtG) is a technology to produce hydrogen or methane from renewable energies and a number of pilot projects are recently being carried out especially in Germany. This study illustrates the factors behind promotion of PtG in Germany. By comparing the factors between Germany and Japan, the feasibility of PtG in Japan is examined. In addition, the conditions in which PtG can be economically feasible in Japan are analyzed.

## 1. What is Power to Gas

### 1-1 Transportation and Storage of Renewable Energies by Hydrogen

The first PtG attempt in the world is allegedly the electrolysis hydrogen production from a wind turbine in 1895 by Poul la Cour, known as a Danish wind turbine pioneer. As the wind turbine was built away from the power grid so that the electricity generated by the wind turbine could not be transmitted, hydrogen was produced from the wind turbine, stored and used for lighting[1].

During the late 1980s and 1990s, a number of pilot projects of hydrogen production were demonstrated in Europe aiming at large-scale deployment of transportation and storage of renewable energies by hydrogen as an energy carrier. EQHHPP (Euro Quebec Hydro Hydrogen Pilot Project: 1986-1998) was a pilot project with the concept to transport hydrogen produced from abundant hydropower in Canada to Europe by sea. The plan was designed to produce 16,000 tons of hydrogen annually from 100MW hydropower. Though the hydrogen mass transportation that was originally targeted could not be achieved due to financing problems, the transportation mode was examined and a liquefied hydrogen storage tank test was carried out. In addition, hydrogen utilization technologies in automobile, airplane, ship and steel manufacturing were developed [1]. The German-Saudi Arabian collaborative HYSOLAR (1986-1995) project demonstrated hydrogen production from solar PV. The possibility of commercialization was explored by testing 350kW of solar PV and alkaline electrolysis [1]. SWB (Solar-Wasserstoff-Bayern: 1986-1998) carried out pilot projects of hydrogen production from solar PV with support from the Bayern state [1].

These PtG pilot projects contributed to technology development in hydrogen production, transportation and storage. However, practical application and commercial use could not be realized.

### 1-2 Absorption of Variability of Renewable Energies by the Whole Energy System

From around 2010, PtG is drawing attention anew in Germany. However, this time, PtG pilot projects are being carried out to aim at establishing a low carbon energy system by making use of the surplus electricity from variable renewables. The concept is to produce hydrogen and SNG (Synthetic Natural Gas/Substitute Natural Gas) from renewable energies and these gases are

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1 The flame of hydrogen is colorless. It is said that the flame is colored as the impure substance from burner is mixed with hydrogen.

supplied to FCEV (Fuel Cell Electric Vehicle) and NGV (Natural Gas Vehicle) or injected into a natural gas pipeline (Fig. 1-1). The hydrogen and SNG produced by PtG can be regarded as $CO_2$-free gases.

In general, the grid integration measures for variable renewables such as curtailment, strengthening transmission lines, energy storage or demand response, are frequently discussed, designed and introduced in the closed system that is the power grid[2]. On the other hand, PtG targets the whole energy system as stakeholders who deal with the variability of renewable energies, by including not only the power grid but also the natural gas pipeline network and transport sector.

The processes that produce liquid fuel such as methanol from gases produced from the PtG process are called Power to Fuel or Power to Liquids [2].

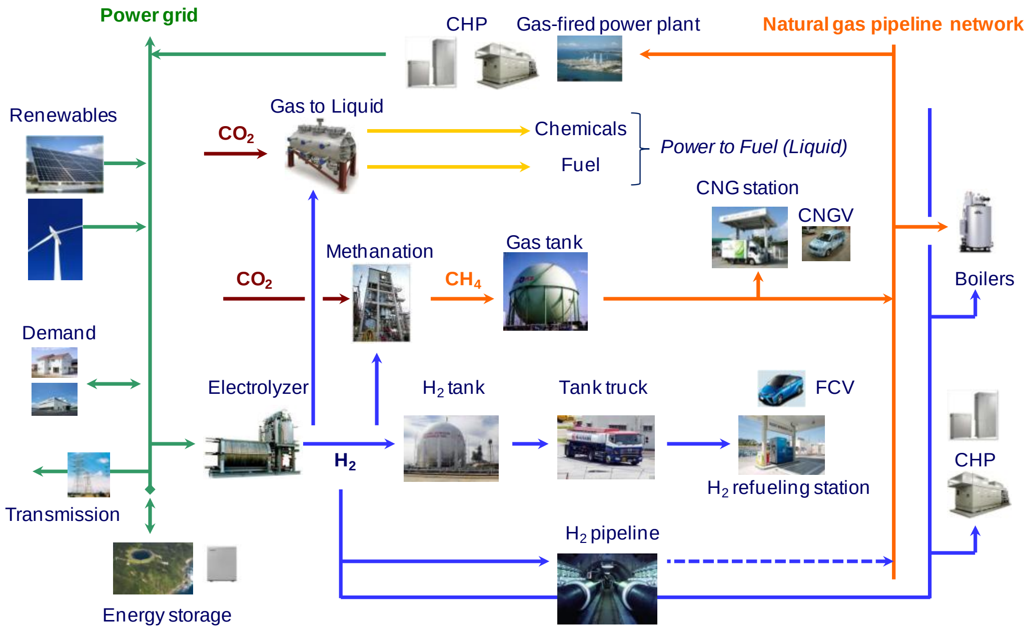



**Fig. 1-1 Concept of Power to Gas**

Note: Includes Power to Fuel.

## 1-3 Key Technologies of Power to Gas

The major technologies of PtG are shown below. These are matured technologies, although there are challenging issues such as improving the conversion efficiency and cost reduction.

### (1) Hydrogen production

Among major electrolysis technologies to produce hydrogen that are commercially available are alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis. Hydrogen is either supplied to fuel cells or can be blended into the existing natural gas pipeline networks with relatively low concentrations, up to around 10% hydrogen by volume to avoid calorific adjustment

[2] As energy storage systems that convert electricity to heat such as electric water heaters with tanks (either a heat pump or heater) and electric vehicles can indirectly reduce fossil fuel consumption, these are not theoretically in the closed power grid system.

of natural gas using equipments.

$H_2O \rightarrow H_2 + 1/2O_2$ ΔH＝286kJ/mol (endothermic reaction)

(2) Methanation

Reaction of hydrogen and carbon dioxide at elevated temperature and pressure produces methane (SNG: synthetic natural gas). Being the feedstock for city gas, the synthetic natural gas can be blended into the natural gas pipeline network.

$CO_2 + 4H_2 \rightleftarrows CH_4 + 2H_2O$ ΔH＝-165kJ/mol: Sabatier reaction (exothermic reaction)

$CO_2 + H_2 \rightleftarrows CO + H_2O$ ΔH＝ 41kJ/mol: Reverse gas shift (endothermic reaction)

$CO + 3H_2 \rightleftarrows CH_4 + H_2O$ ΔH＝-206kJ/mol (exothermic reaction)

## 1-4 Power to Fuel Technology

Fuel can be produced by a combination of water electrolysis and GTL (Gas to Liquid). This process is called “Power to Fuel” or “Power to Liquids.” The typical processes are presented below.

(1) Fischer-Tropsch Process

Through the Fischer-Tropsch process, feeding in the synthesis gas (mixture of CO and $H_2$) produced from the reverse gas shift reaction, straight-chain hydrocarbon, olefin or alcohol are produced. These synthetic hydrocarbons are refined to be used for automobile fuel, plastic or gum.

$2H_2 + CO \rightleftarrows -(CH_2)- + H_2O$ ΔH＝-167kJ/mol (exothermic reaction)

(2) Methanol Synthesis

Methanol is produced from the synthesis gas. Methanol is used to produce formalin, MTBE (Methyl Tertiary Butyl Ether), gasoline, and MTO (Methanol to Olefin). Methanol is also supplied to Direct Methanol Fuel Cells (DMFC).

$2H_2 + CO \rightleftarrows CH_3OH$ ΔH＝-91kJ/mol (exothermic reaction)

## 1-5 Power to Gas as Energy Storage Technology

PtG has a characteristic as energy storage technology. Economics will be compared between PtG and major energy storage technologies, pumped hydro and battery. Equation (1) is a simplified expression to show the cost per unit of discharged electricity. With regard to PtG, hydrogen-fired power generation and fuel cells are assumed in the case of hydrogen, and natural gas-fired power generation is assumed in the case of SNG.

$$C = \frac{p_{EL}}{\eta} + \frac{S \times R}{\sum EL} \quad (1)$$

Here,

$C$: Cost per unit of discharged electricity (JPY/kWh)

$p_{EL}$: Electricity rate (JPY/kWh)

$\eta$: Roundtrip efficiency
$S$: Capital cost of energy storage (JPY/kWh)
$R$: Storage capacity (kWh)
$EL$: Discharged energy in a cycle (kWh)

The first term of the Equation (1) represents the electricity cost per unit of discharged electricity and the second term represents the capital cost levelized by the gross discharged electricity for lifetime operation. The higher the roundtrip efficiency is and the lower the capital cost is, the cost per unit of discharged electricity is reduced. Fig.1-2 compares the cost per unit of discharged electricity among battery, pumped hydro and PtG.

As the roundtrip efficiency of the battery is the highest and that of PtG is the lowest, the vertical axis intercept of battery lies in the lowest part. As the capital cost of battery is highest, the slope of the battery is steepest. As the roundtrip efficiency of battery ranges sufficiently high, from 85% to 90%, the electricity cost per unit of discharged electricity is small and also the capacity can be kept small for a shorter cycle period (hourly), leading to smallest cost per unit of discharged electricity. When storage with a longer cycle (daily) is required, battery needs huge capacity which leads to huge capital cost, and pumped hydro, though the roundtrip efficiency is lower (70%), shows the most cost effective technology. As the roundtrip efficiency of PtG is significantly low, 30%~50%[3] depending on the technology, the cost per unit of discharged electricity is expensive for a shorter cycle period, but can be less expensive for the longer cycle period (weekly to monthly or seasonally). However, the existing infrastructure should be used to reduce the capital cost (See 3-1).

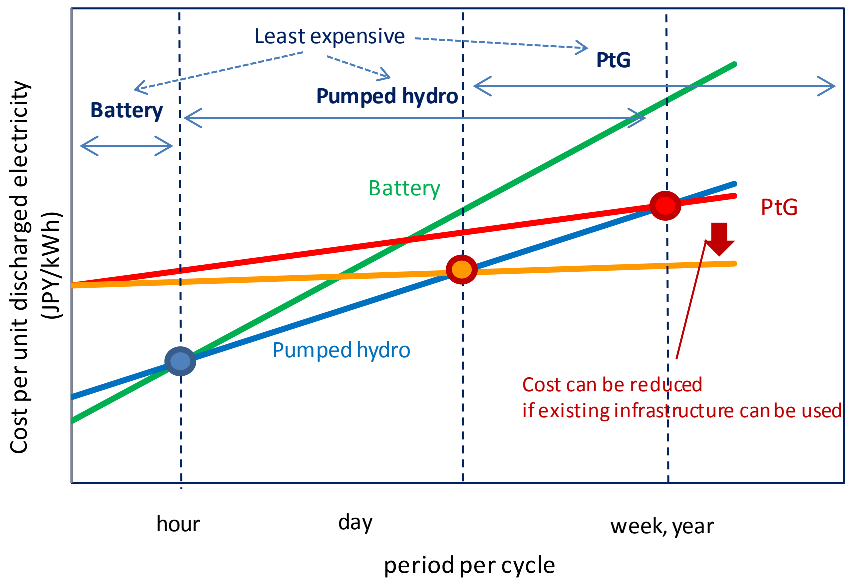



**Fig. 1-2 Compartmentalization of Energy Storage Technologies**

Note: The slope of PtG line is expressed as “0” in “ETOGAS smart energy conversion” [3]. However, this is the extreme case where the existing infrastructure can be fully used and new investment is not required.

# 2. Power to Gas Activities in Germany

## 2-1 Profile of Pilot Projects

There are presently more than 20 pilot projects in Germany including those under construction or at the planning stage (Fig.2-1). With regard to the categories of 30 pilot projects in Europe (Fig.2-2), the number of projects that blend the produced gas (either hydrogen or SNG) into the natural gas pipeline exceeds the number of projects that supply the produced gas for mobility use. Great difference is not observed in the type of produced gas (hydrogen or SNG). Many of the projects feed the variable electricity to PtG rather than the base load electricity.


**Fig. 2-1 Power to Gas Pilots Map in Germany**

Source: Strategieplattform Power to Gas, dena (http://www.powertogas.info/)

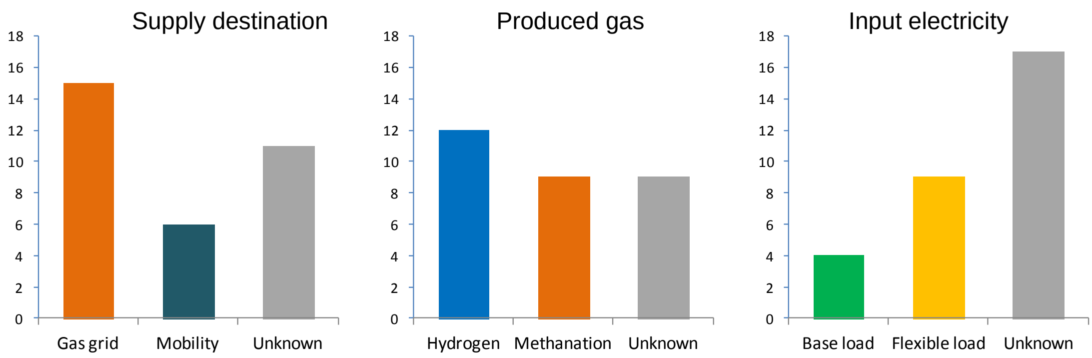



**Fig. 2-2 Profile of Power to Gas Pilots in Europe**

Source: Aggregated data from "Final Report, Systems Analyses Power to Gas, June 20 2013," DNV KEMA Energy & Sustainability.

Note: Vertical axis represents the number of pilot projects

For example, Audi's pilot project (EtoGas: Fig.2-3) produces SNG from hydrogen produced by renewables and $CO_2$ supplied from the biomass plant nearby. The SNG is delivered to the CNG stations through the existing natural gas pipeline. As more than 1,000 CNG stations are already available in Germany, choosing methanation can avoid the construction of the new infrastructure that is required in case of hydrogen for FCEV. The automobile is a gasoline-natural gas hybrid type (Audi A3 Sportback g-tron) and the cruising range is 400km by natural gas and 900km by gasoline.

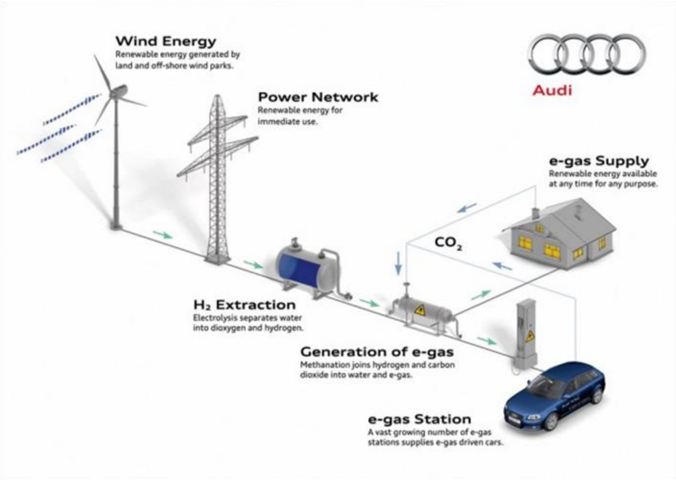



**Fig. 2-3 Audi e-gas Project**

Source: Audi

## 2-2 Background that Power to Gas is Needed

One of the factors for Germany to promote PtG is the challenging $CO_2$ emission reduction target (Fig.2-4) – 80% reduction in 2050 compared with 1990. To achieve this target, not only the power generation sector but the heat demand sector is also required to be low-carbon. In what follows, the reasons why PtG is necessary to decarbonize the power generation and heat demand sector will be described.

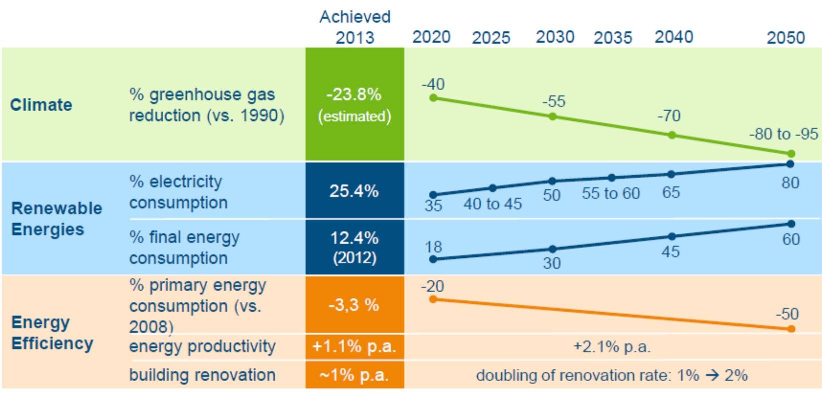



**Fig. 2-4 German's Long Term Energy Target**

Source: "Introduction to Energy Efficiency and Renewable Energies in the Building Sector in Germany," Jelka Schedlinsky, June 22nd, 2015

### (1) Decarbonization of Power Generation Sector: Inevitable dependency on VRE

As Germany decided to phase out nuclear power stations, and a large amount of renewable energies is required to meet the $CO_2$ emission target, the share of renewable energies in the power generation mix should increase from 25% in 2013 to 80% in 2050 (Fig.2-4). Among renewable energies, geothermal and hydro as stable power have limited resource potential. Biomass also cannot be heavily relied on as stable power due to limited agricultural and forest land, competition with the food and paper & pulp industry and also disruption of nature [4]. Competition over biomass with these industries may cause an increase in biomass fuel price. Import of less expensive biomass can raise a concern about supply constraint resulting from biomass demand increase in developing countries.

For these reasons, Germany cannot choose but to depend on variable renewables like solar photovoltaic and wind power. However, a large amount of variable renewables integration generates surplus (excess) electricity. The surplus electricity rate in 2013 was no more than 0.7% even though variable renewables' share accounts for as much as 14% in the power generation mix with 70GW of the total capacity of PV + wind (Fig.2-5). However, if the 80% target is to be attained, the surplus electricity rate will inevitably increase.

Though strengthening interregional transmission lines connecting the northern part and southern part is planned so as to absorb rather than curtail this surplus electricity majorly occurring in the northern part (Fig.2-6), it is not clear how completely the planned transmission lines can be built, due to opposition from the local residents along the lines.

Under these circumstances, PtG is positively studied as one of the grid integration measures along with energy storage technologies and demand side measures. However, it should be noted that the technology demonstration projects are not carried out indiscriminately, but rather promoted based on the fact that the conditions that support the feasibility of PtG are satisfied; existing infrastructure is available. This point will be described in the next chapter.

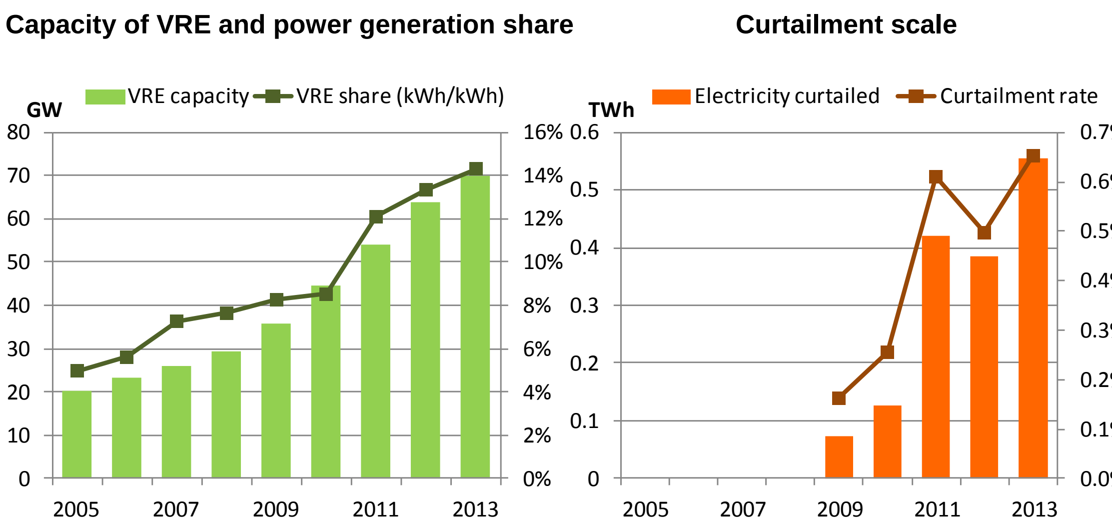



**Fig. 2-5 Curtailment of Variable Renewables in Germany**

Source: "Monitoringreport 2014," Bundesnetzagentur
Note: VRE is Variable Renewable Energies.
Note: Curtailment rate = curtailed electricity/(curtailed electricity＋absorbed electricity)

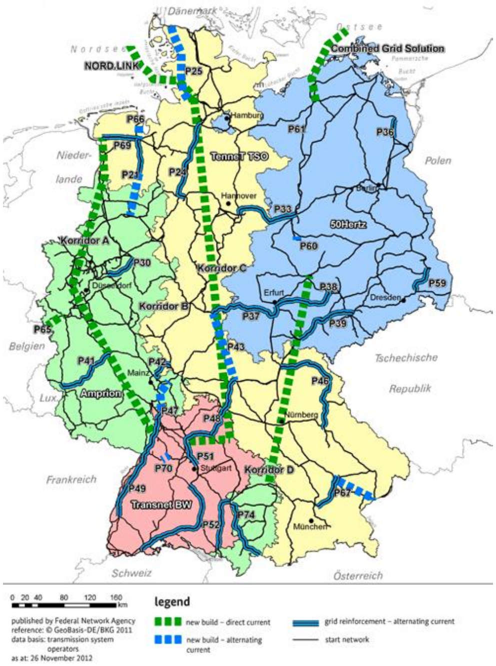



**Fig. 2-6 Transmission Line Construction Plan in Germany**

Source: "First Monitoring Report, "Energy of the future," Summary

## (2) Decarbonization of Heat Demand Sector

As the heat demand majorly represented by space heating approximately doubles electricity demand in Germany, the heat demand sector should also be decarbonized in order to meet the challenging $CO_2$ emission reduction target. Therefore, renewable energies have to replace oil and natural gas. Although one of the renewable energies expected in the heat demand sector is biomass, the use of biomass is constrained. For these reasons, Germany cannot help but depend on variable renewable and PtG plays an important role to decarbonize the heat demand sector by supplying variable renewables.

In particular, hydrogen and SNG produced by PtG will be blended into the existing natural gas pipelines and delivered to consumers for heat demand. One of the advantages of PtG in Germany is that wind power generation increases in winter when the heat demand increases (Fig.2-7), which can avoid excess investment in energy storage. When renewable power generation and heat demand do not coincide, storage is required. However, storage of hydrogen or SNG causes only a significantly small energy loss through boil-off. In the case of electricity conversion to heat, there are advantages in that the technology is matured and less expensive, though thermal loss is inherent with thermal storage.

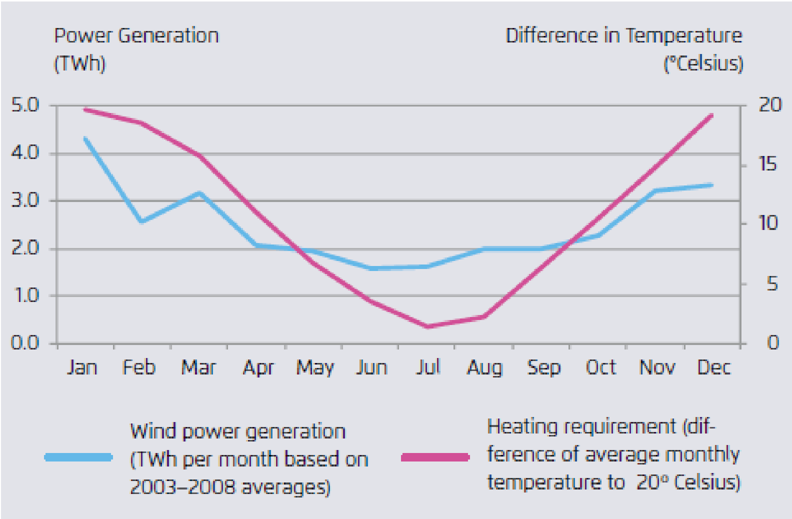



**Fig. 2-7 Monthly Heat Demand and Wind Power Generation Output**

Source: Agora, 12 Insights on Germany's Energiewende, 2013

## 3. Feasibility of Power to Gas in Japan

As describe above, the challenging $CO_2$ emission reduction and variable renewables target require PtG in Germany. It should however be noted that there are factors that can enhance the feasibility of PtG. By comparing these factors between Germany and Japan, the feasibility of PtG in Japan will be discussed in this chapter.

### 3-1 What Enhances the Feasibility of Power to Gas

(1) Natural Gas Pipeline Network

If the produced gas, either hydrogen or SNG, can be blended into the existing natural gas pipeline network, investment can be avoided and economic advantage is yielded (See 1-5). The natural gas pipeline network in Europe has been historically developed in order to establish domestic distribution and import natural gas from outside the European region. On the other hand, as Japan has been developing pipelines in connection with LNG receiving terminals, the pipeline network is still undeveloped (Fig.3-1). This difference between Germany and Japan can easily be highlighted by the density of the natural gas pipeline network; Japan is one-tenth of Germany (Fig.3-2).

As the natural gas pipeline network is well developed in Germany, the power grid and the natural gas network can link together geographically (Fig.3-3). This is one of the strong factors that raise the feasibility of PtG in spite of the fact that the renewable energy resource potential is unevenly distributed; the northern part is wind-rich and the southern part is solar-rich region (Fig.3-4). On the other hand, in Japan, the power grid and the natural gas pipeline network are not well developed in the solar or wind abundant regions, which is a strong barrier against developing PtG in Japan.

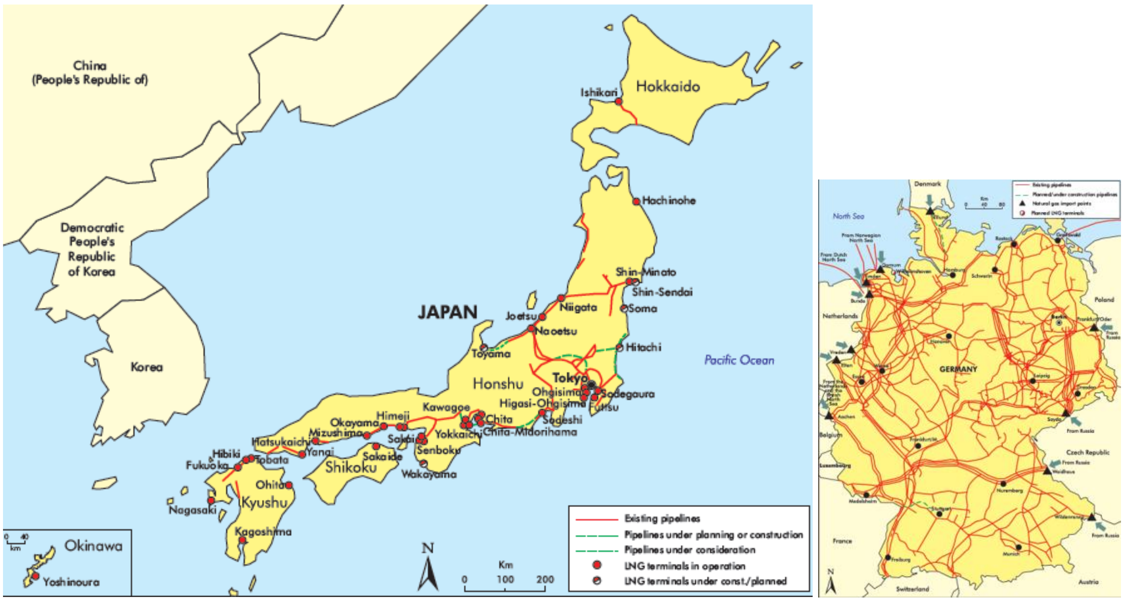



**Fig. 3-1 Japan-Germany Comparison of Natural Gas Pipeline Infrastructure**

Source: "Natural Gas Information 2015," IEA

Note: Only trunk lines are shown.

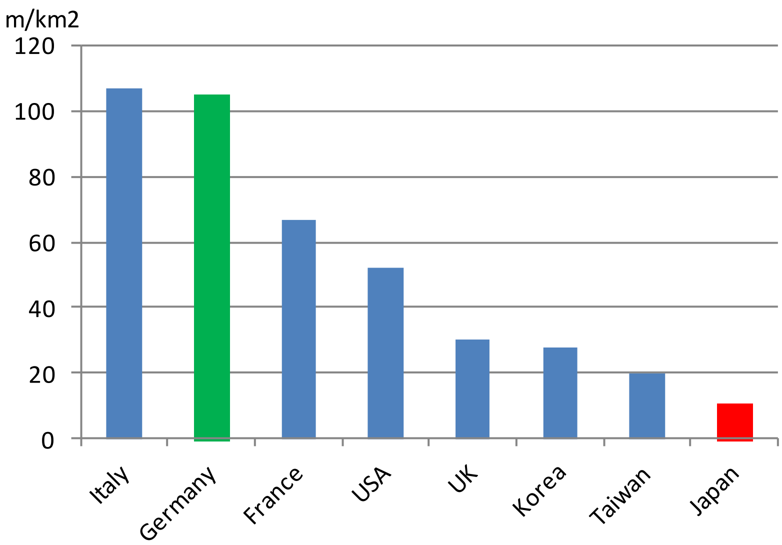



**Fig. 3-2 Density of Natural Gas Pipeline**

Source: "Current Status and Issues of Natural Gas Infrastructure in Japan," January, 2012, Agency for Natural Resources and Energy.

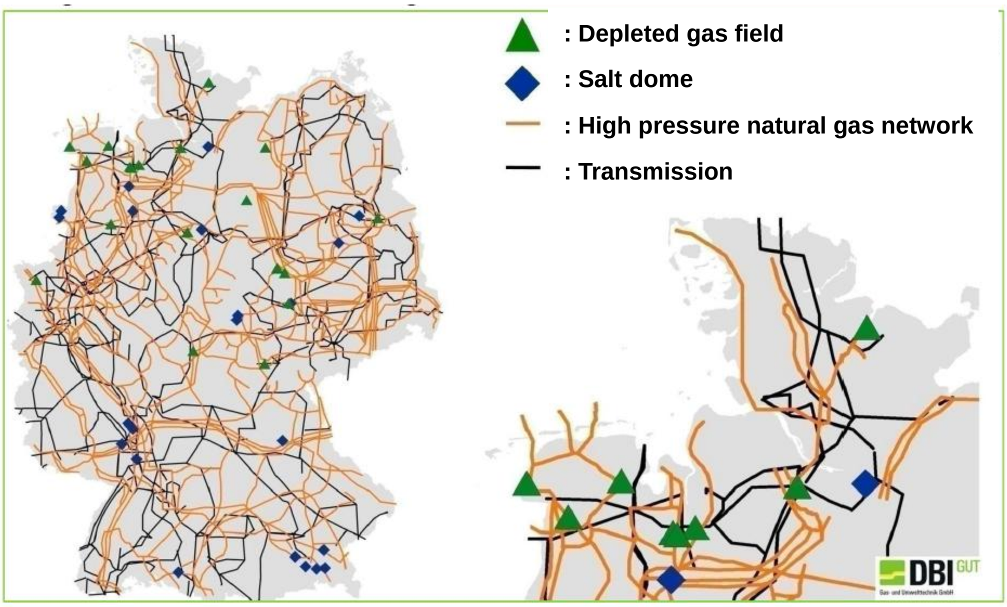



**Fig. 3-3 Natural Gas Pipeline and Transmission Line in Germany**

Source: Energiespeicherung in Erdgasnetzen, Power-to-Gas, DBI GUT

Note: Only pipelines over 60bar (6MPa) are shown and correspond with the right figure in Fig.3-1.

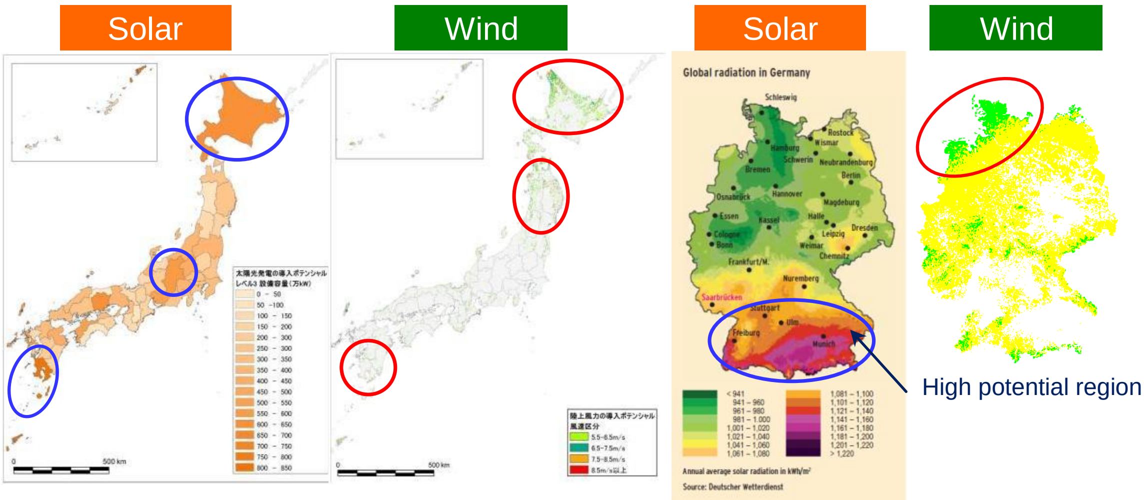



**Fig. 3-4 Distribution of Renewable Energies Potential**

Source: "Renewable Energy Introduction Potential," Ministry of Environment, 2010. Ministry of Environment, and "Renewable Energies Perspectives for a Sustainable Energy Future," BMU, 2011, Geoportal.de

### (2) Availability of Natural Gas Storage

Natural gas storage is required to inject the gas produced by PtG into the pipeline, as power generation output of renewable energies is variable. The PtG pilot project installed nearby the existing gas storage facility is observed (left figure of Fig.3-5), but a large volume storage facility is required when a large amount of gas is produced.

There are a number of underground natural gas storage facilities (right figure of Fig.3-5: salt dome and depleted gas field) and distributed widely in Germany (Fig.3-3), which makes it easy to receive SNG from PtG. On the other hand, Japan has fewer underground storage facilities (Table 3-1), and new storage facilities should be constructed to receive the gas from PtG.

**Table 3-1 Scale of Natural Gas Underground Storage**

| | Natural gas demand (billion $m^3$/year) | Number of underground storage facilities | Storage volume (Working gas) (billion $m^3$) |
|---|---|---|---|
| Germany | 88.4 | 51 | 22.8 |
| Italy | 86.0 | 10 | 12.7 |
| UK | 91.6 | 49 | 3.5 |
| Japan | 77.1 | 5 | 1.2 |

Source: "Current Status and Issues of Natural Gas Infrastructure in Japan," January, 2012, Agency for Natural Resources and Energy. "Natural Gas Information," IEA.


**Fig. 3-5 Natural Gas Holder (left) and Underground Storage (right) in Germany**

Source: KBB (left), "ETOGAS, smart energy conversion," ETOGAS GmbH, 2013 (right)

### (3) Tolerance to Hydrogen Blending into the Natural Gas Pipeline

In general, major challenges do not exist to blend SNG into the natural gas pipeline. Meanwhile, the calorific value adjustment in the gas-burning equipment is required when a large volume of hydrogen is blended as the volumetric calorific value of hydrogen is much smaller than natural gas. In particular, performance and durability of fuel cell are greatly affected by the natural gas composition.

The calorific value of the Japanese natural gas totally imported by LNG is homogeneous, while the calorific value of European natural gas is categorized into high calorie gas and low calorie gas; for example, the Russian natural gas is high calorie gas and the Dutch gas (Groningen) is low calorie gas. This is the reason why the European natural gas standard has a wider range than the Japanese natural gas (Fig.3-6). In addition, the natural gas composition and the calorific value vary according to region and time. European natural gas has wider tolerance against the calorific value, which means that hydrogen blending is accepted to some extent. Fig.3-6 shows the natural gas standards and natural gas calorific value change by blending hydrogen. Blending hydrogen by up to 10% to 15% does not exceed the natural gas standards in Europe. On the other hand, it is obvious that the Japanese standard is much less tolerant.

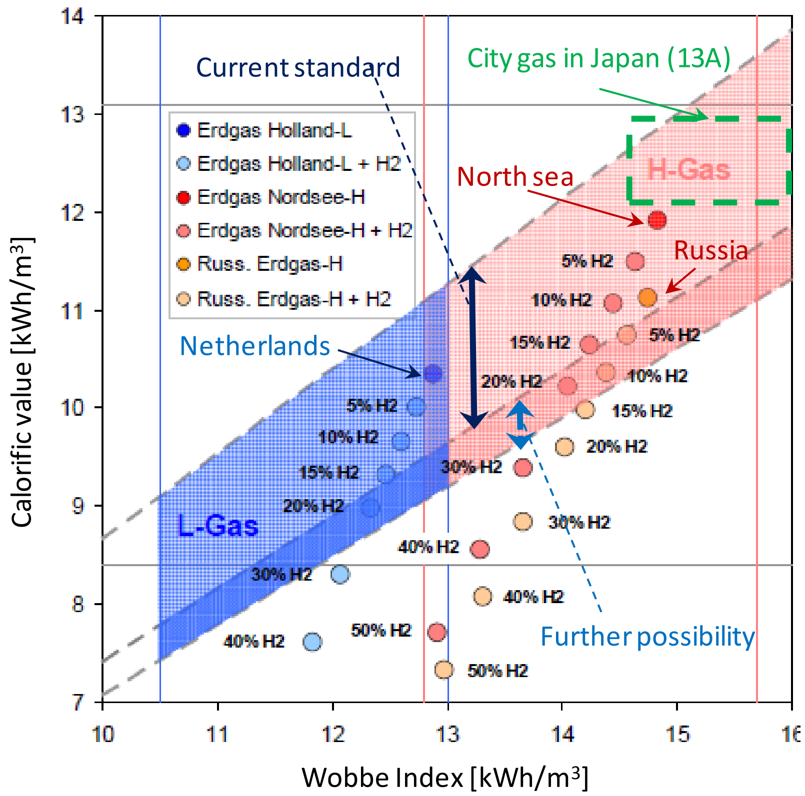



**Fig. 3-6 Natural Gas Standard in Germany and Impact of Hydrogen Blending**

Source: The author modified the figure in "DBI Gas- und Umwelttechnik GmbH, "Energiespeicherung in Erdgasnetzen Power-to-Gas," Fachtagung, Erdgas Umwelt Zukunft," 2. February 2011."

Note: "Further possibility" is proposed by DBI, and not yet realized.

## (4) Heat Demand

As described above, Germany has a greater share of heat demand in final energy consumption and is required to decarbonize the heat demand sector. The ratio of electricity demand to heat demand does not differ greatly between Germany, 2.4 and Japan, 1.5 (Fig.3-7). So, decarbonization in Japan is also of high importance.

On the other hand, the share of natural gas in the final energy consumption in Japan was 11% in 2013, much smaller than 25% in Germany, though the share is increasing every year (Fig.3-8). This is because a large part of heat demand is met by petroleum products such as kerosene. It can be said that there is not yet strong need to decarbonize natural gas in Japan compared with Germany. Rather, decarbonization of the heat demand sector and the transportation sector where currently petroleum products are supplied is required.

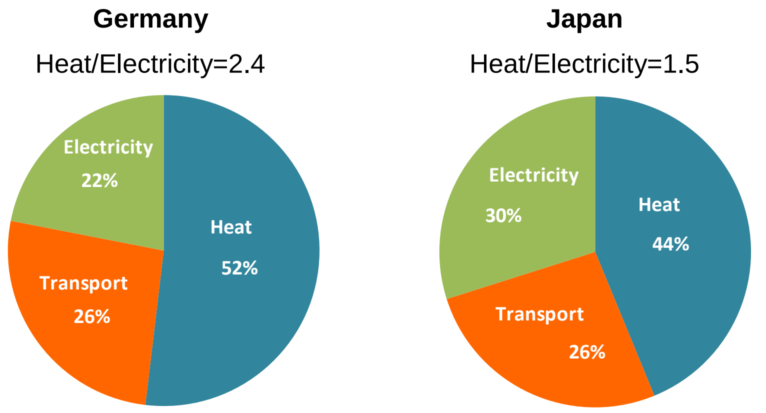



**Fig. 3-7 Breakdown of Final Energy Consumption by Type of Use (2013)**

Source: Estimated from IEA Energy Balance 2015. Non-energy use is excluded.

Note: Electricity used for space heating and water heating is included in electricity demand, not in heat demand.

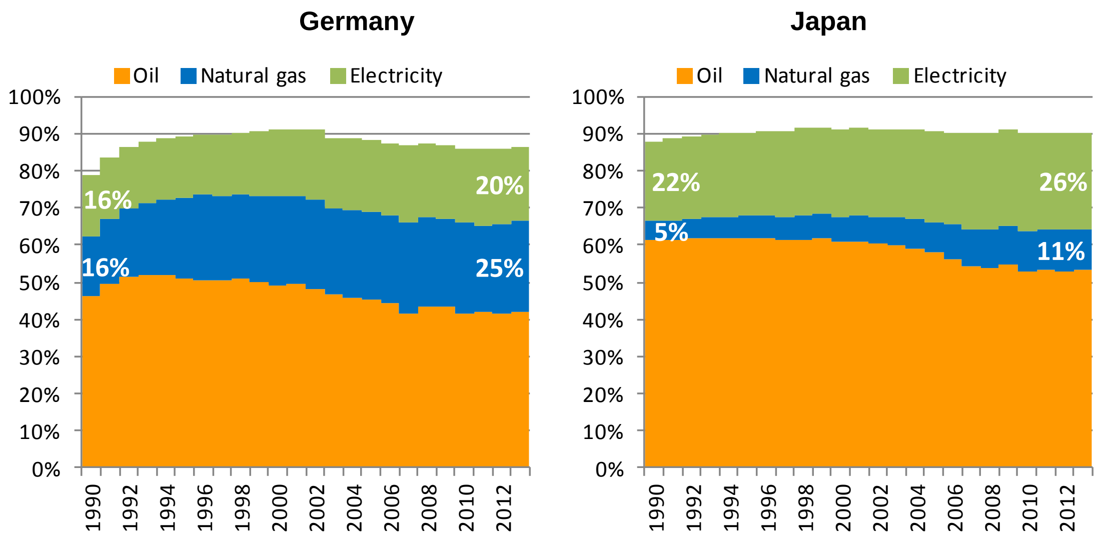



**Fig. 3-8 Breakdown of Final Energy Consumption by Type of Energy (historical trend)**

### (5) Qualitative Evaluation of the Feasibility of PtG in Japan

The necessity of PtG shown for Germany that targets challenging decarbonization is not found in Japan currently. In addition, the factors that are able to enhance the feasibility of PtG, which are observed in Germany, are not prepared in Japan. For these reasons, PtG is presumably not feasible in Japan presently. However, it would be worth evaluating the possibility of PtG in the long term when energy self-sufficiency should be improved and $CO_2$ emission reduction target would be strengthened. Chapter 1 showed PtG has a variety of forms, such as hydrogen, SNG and Power to Fuel as well. Which form would show feasibility in the long term will be analyzed below in terms of economics. Before that, the accelerated activities taken recently in Japan toward establishment of a hydrogen economy will be presented in the next section.

## 3-2 Hydrogen Trend in Japan

The Council for a Strategy for Hydrogen and Fuel Cells established by METI (Ministry of Economy, Trade and Industry, Japan) drew up the “Strategic Roadmap for Hydrogen and Fuel Cells”

[5] in June 2014. This roadmap indicates a rough timeline for promotion of utilization of hydrogen (Fig.3-9). Focusing on the hydrogen source, the domestic by-product hydrogen and fossil fuel reforming hydrogen are to be supplied to FCEV until around 2030. Natural gas and LPG will be supplied to the stationary fuel cell through existing infrastructure for the time being. As this hydrogen is associated with inevitable $CO_2$ emission, start of $CO_2$-free hydrogen import from the mid-2020s and its commercialization from around 2030 are targeted. Hydrogen production from renewable energies is positioned in the long term and will not be implemented on a full scale until around 2040, though demonstration projects will be continuously carried out. Methanation is excluded from the roadmap. Hydrogen production from domestic renewable energies has been downplayed in the roadmap.

However, the Council for a Strategy for Hydrogen and Fuel Cells has brought up hydrogen production from renewable energies as a new agenda for discussion in June 2015. As renewable energies have been rapidly introduced since the implementation of FIT in July 2012, hydrogen production can be regarded as one of the grid integration measures and its full-scale implementation may be brought ahead of 2040. Along with hydrogen production from renewable energies, the council demonstrates the need for accelerated activities toward commercialization of pure-hydrogen fuel cells, which also requires the development of hydrogen backup boilers necessary for stationary fuel cells and hydrogen odorant for safety reasons.

As described above, hydrogen production from domestic renewable energies is drawing much attention recently and is becoming an important issue. In the following section, how PtG should be promoted in Japan in terms of economics will be discussed.

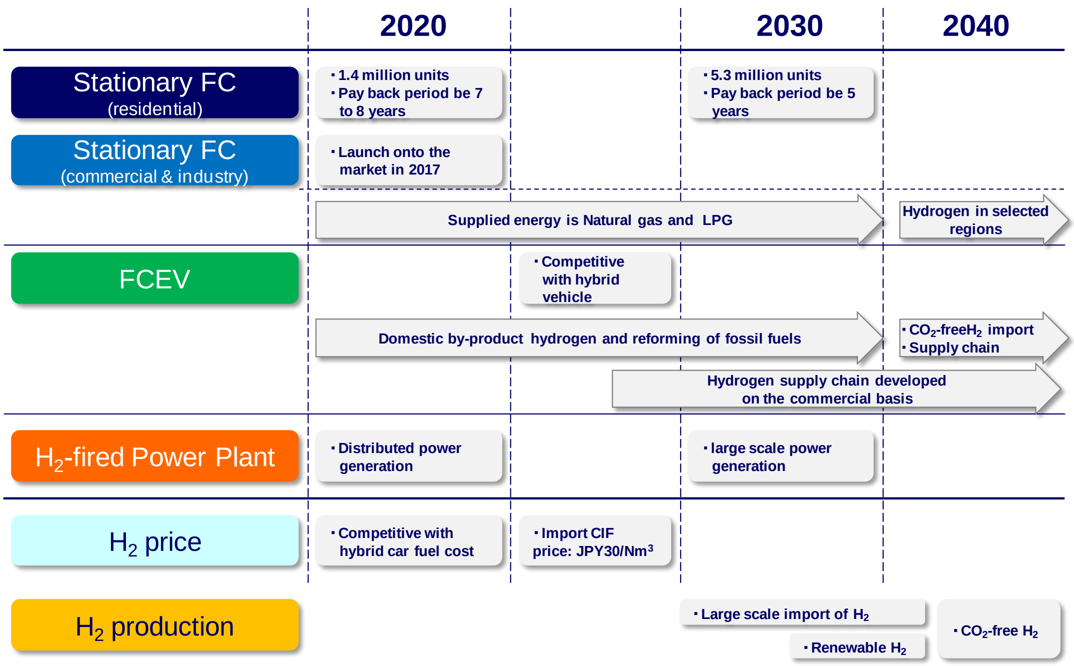



**Fig. 3-9 Outline of Roadmap for Hydrogen and Fuel Cell in Japan**

Source: Drawn based on the "Strategic Road Map for Hydrogen and Fuel Cells."

## 3-3 Simplified Economic Evaluation of Power to Gas

This section demonstrates the conditions that allow PtG to be feasible in terms of production cost.

### (1) Production Cost (Hydrogen and SNG)

Table 3-2 shows major specifications of an electrolyzer and a methanation plant [6]. Though the capital cost of an electrolyzer currently exceeds JPY 1 million/($Nm^3$-$H_2$/h), it is assumed to decrease to JPY 430,000/($Nm^3$-$H_2$/h) expecting further technology development. The capital cost of methanation equipment is assumed to be JPY 2.3 million/($Nm^3$-$H_2$/h). The unit electricity input to the electrolyzer is assumed to be raised to 4.7 kWh/$Nm^3$-$H_2$ from current 5 kWh/$Nm^3$-$H_2$. The unit electricity input to the methanation plant is assumed to be 16.4 kWh/$Nm^3$-$CH_4$. A case of 50% reduction in the capital cost is also set.

**Table 3-2 Major Assumptions**

| | Technology | Unit electricity input | Capital cost |
|---|---|---|---|
| $H_2$ | Electrolysis | 4.74 kWh/$Nm^3$-$H_2$ | 0.430~0.220 JPY million/($Nm^3$-$H_2$/h) |
| SNG | Methanation | 16.35 kWh/$Nm^3$-$CH_4$ | 2.34~1.17 JPY million/($Nm^3$-$CH_4$/h) |

Source: Based on ”THE ROLE OF POWER-TO-GAS IN ACHIEVING GERMANY’S CLIMATE POLICY TARGETS WITH A SPECIAL FOCUS ON CONCEPTS FOR ROAD BASED MOBILITY.”
Assumptions: The capital cost of the electrolyzer is €700/kWel (€3,300/($Nm^3$-$H_2$/h)) and that of methanation is €1,100/kWel (€18,000/($Nm^3$-$CH_4$/h)). The conversion efficiency is 75% for electrolysis and 61% for methanation. The calorific value (HHV) is 12,790kJ/$Nm^3$ for hydrogen and 35,900kJ/$Nm^3$ for methane. The exchange rate is 1€=JPY130. The operation time is 20 years. The annual operation & maintenance cost is 4% of the capital cost.
Note: The specifications are not the present ones, but a future outlook.

The estimated production cost of hydrogen and SNG based on these assumptions is presented in Fig.3-10. As competing energies, the estimated import CIF price of hydrogen (JPY30/$Nm^3$-$H_2$) [7], LNG import CIF price and natural gas retail price (city gas) are also indicated in the figure.

Hydrogen from PtG can compete with import hydrogen only if the capacity factor of the electrolyzer is sufficiently high and also power production cost of renewable energy is less than JPY7/kWh. If the power production cost of renewable energy reduces to JPY5/kWh, hydrogen can be competitive even if the capacity factor of the electrolyzer is 40% to 70%.

In order for SNG from PtG to equal import LNG (JPY 50/$Nm^3$-$CH_4$: methane calorific value equivalent), the capital cost of methanation should be reduced by 50%, the capacity factor should be around 100% and the power production cost of renewable energy should be JPY3/kWh. These conditions are considerably severe. If compared with city gas with JPY90~140/$Nm^3$-$CH_4$ (methane calorific value equivalent) of the retail price, the requirement is alleviated and the power production cost of renewable energy should be JPY7/kWh when the capacity factor of the methanation plant is 100% and the power production cost of renewable energy should be JPY5/kWh when the capacity factor of the methanation plant is 40%.

These results show that in order for hydrogen and SNG to be competitive, raising the capacity factor of production plants is a crucial issue, along with reduction in the power generation cost of renewable energies and capital cost of PtG plants. In the following part, measures to raise the capacity factor of production plants will be examined under the assumption that the surplus electricity will be used.

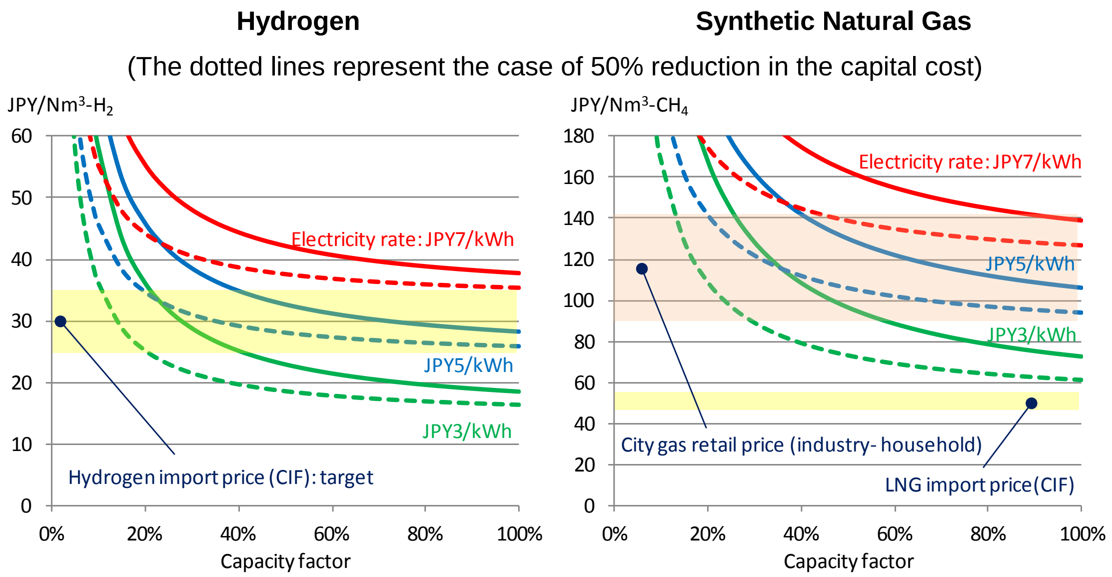



**Fig. 3-10 Production Cost of $H_2$ and SNG by PtG**

Note: LNG import price and city gas retail price (2012~2013) is $CH_4$-calorific value equivalent.
Note: Hydrogen import price (CIF) is referred to [7]. The price is indicated with some ranges. The hydrogen is produced from brown coal in Australia and exported to Japan. The carbon dioxide emitted during hydrogen production is processed by CCS.
Note: Requirements for SNG become severe if the wheeling price is subtracted from the retail price of city gas.

## (2) How to Raise Capacity Factor of PtG Plants

As most PtG assumes using surplus electricity from renewable energies, how much surplus electricity is produced in Japan will be analyzed first. The left figure in Fig.3-11 shows the results from analysis to identify the amount of surplus electricity according to the grid integration measures taken. The analysis was carried out by the power generation mix model [8] assuming the power generation mix in 2030 described in the “Long Term Energy Outlook” (Ministry of Economy, Trade and Industry). When 64GW of solar PV and 10GW of wind power are connected to the grid, 22TWh of surplus electricity (surplus rate is 24%) will be produced if no grid integration measures are taken[3]. If the existing pumped hydro can be used to the maximum extent, the surplus electricity will be reduced to 12TWh (surplus rate is 14%). If the existing interregional transmission lines can be additionally used to the maximum extent, the surplus electricity will be reduced to 4TWh (surplus rate is 4%).

The German cumulative installed capacity of variable renewables in 2013 was 70GW (36GW of solar PV and 34GW of wind power) that is equivalent to the Japanese 2030 target. Though the difference in share of solar PV and wind power between Germany and Japan does not allow precise comparison, the reason why the curtailment rate in Germany is only 0.7% (Fig.2-5), much lower

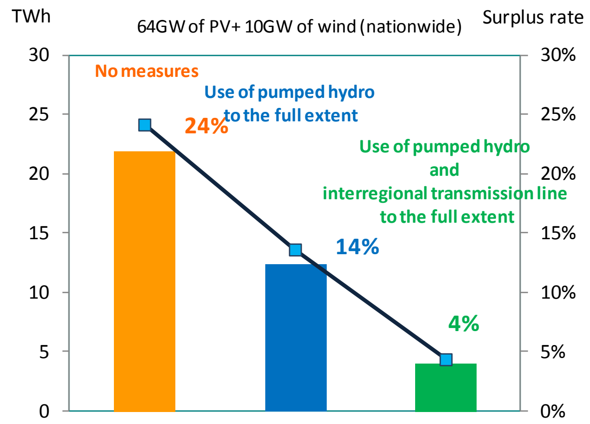
[3] Curtailment is executed. The surplus electricity is defined as the curtailed electricity.

than Japan, is that Germany can make use of international transmission lines. The amount of surplus electricity largely depends on which and how strongly the grid integration measures are taken.

Hydrogen production from surplus electricity is expected to be 0.8 to 4.6 billion $Nm^3$ in 2030 in Japan, which is equivalent to the amount consumed by 0.8 to 4.6 million FCEV. However, it was revealed in the existing study [8] that the load factor of surplus electricity is significantly low, even if larger-scale renewable energies are integrated and a larger amount of surplus electricity is expected. In a case where the existing pumped hydro and interregional transmission lines can be used to the maximum extent, as shown in the right figure in Fig.3-11, even in the regions where a large amount of surplus electricity is produced, the load factor of surplus electricity is no more than 8% to 17% when 100GW of solar PV and 70GW of wind power is integrated nationwide.

Therefore, 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 or methanation plant. Also, it may be an option to use the stable part of variable renewable power generation at the bottom power generation output[4], which can bring about much a higher capacity factor electrolyzer.

**Scale of surplus electricity (Nationwide)**




**Surplus rate and load factor (Hokkaido, Tohoku, Kyushu)**

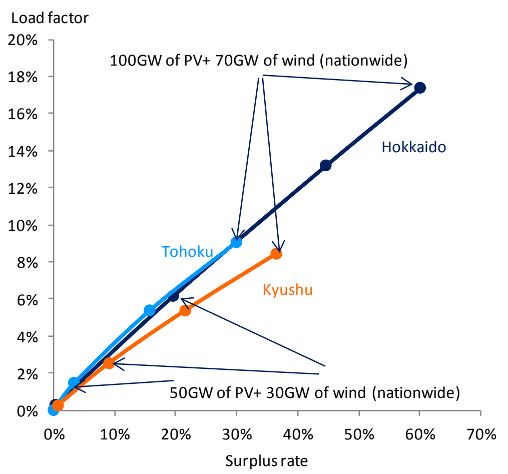



**Fig. 3-11 Surplus Electricity Scale in Japan**

Note: The left figure is analyzed based on the power generation mix in the “Long Term Energy Outlook (METI).” “To the full extent” means use of the existing infrastructure (pumped hydro/interregional transmission lines) by deregulating the rules for operation as far as the physical conditions allow, not constructing new infrastructure.

Note: Surplus rate = Surplus electricity/(Surplus electricity＋Absorbed electricity). VRE is variable renewables (solar PV and wind).

Note: The right figure shows the case where the pumped hydro and interregional transmission lines can be used to the full extent, but the capacity is not strengthened.

## 3-4 Concept of Power to Gas in Japan and Technological Challenges

(1) Concept of Power to Gas: Hydrogen or SNG

[4] It should be noted that if the stable part of the variable renewable power generation is used for hydrogen production and the rest is fed into the power grid, the other grid integration measures are required.

If blending the gas into the natural gas pipeline, hydrogen production that goes through fewer conversion processes than methanation is much cost effective when the amount of surplus electricity is small. Nevertheless, as Japan is less tolerant against calorific value variation in natural gas than Germany (Fig.3-6), the acceptable hydrogen volume is limited. In the long term, large-scale surplus electricity may be expected and SNG would show more advantage due to less constraint of blending into the natural gas pipeline.

In terms of production cost, according to the results from simplified analysis (3-3), SNG cannot compete with LNG, unless the price of LNG increases. However, if the $CO_2$ emission reduction target is set higher, competitiveness of SNG as being $CO_2$-free may be improved against LNG.

On the other hand, when SNG is compared with city gas, though reduction in the power generation cost of renewable energies (to JPY 5~7/kWh) is an indispensable requisite, SNG might compete with the (retail price of) city gas. But, the competing condition becomes severe if the cost of storage and transportation of SNG is taken into account. Although it would surely be rash to draw a conclusion here as the cost of storage and transportation greatly depends on the delivery distance and amount, it is noted that SNG competitiveness weakens if the SNG cannot be produced in the vicinity of natural gas consumers. Otherwise, it is required that the SNG production site be close to the existing natural gas pipeline or existing gas storage facilities like observed in Germany. As shown in 3-1, new infrastructure should be constructed in Japan to receive the SNG because the density of the existing pipeline network is significantly low.

With regard to hydrogen, the production cost was compared with the import price (CIF) target of $CO_2$-free hydrogen [7], as a hydrogen market price for energy use does not yet exist[5]. A condition similar to that for SNG to compete with the city gas retail price (the renewable energy power generation cost should be JPY5~7/kWh) is required. However, it is obvious that investment in storage and transportation of hydrogen and fuel cells is needed.

Therefore, hydrogen and SNG are in the same situation in that new infrastructure is needed. Establishing new infrastructure cost-effectively requires large-scale consumers. If hydrogen is to be supplied, designing a hydrogen city composed from FCEVs, hydrogen refueling stations, factories, commercial complexes and households should be examined.

### (2) Feasibility of Power to Fuel

To keep new infrastructure construction to the minimum, Power to Fuel (Power to Liquids) can be a candidate. Power to Fuel produces methanol from synthesis gas produced from hydrogen from electrolysis and carbon dioxide. The methanol can be used for chemicals and fuels and can be transported by the existing tank trucks, which avoids new investment.

### (3) Technological Challenges

[5] At present, hydrogen is sold at JPY90~100/ $Nm^3$ to FCEV at hydrogen refueling stations in Japan. This retail price is strategically set so as to compete with the gasoline fuel price taking into account the fuel economy of FCEV and gasoline vehicle. The hydrogen price for industrial use is JPY40/$Nm^3$ (Current Survey of Production, Statistics of Ministry of Economy, Trade and Industry, Japan).

In order to raise the economics of PtG, continuous efforts are needed to reduce the renewable energy power generation cost, to reduce the capital cost for the electrolyzer and methanation plant and to improve the conversion efficiency of production of hydrogen and SNG. Hydrogen production by electrolysis is technologically mature but methanation is facing a challenge of how to capture $CO_2$. Concentrated $CO_2$ emission sources are needed for efficient production of SNG. Coal-fired power plants and large-scale factories can be candidates, but renewable power plants should be located near these facilities.

With regard to Power to Fuel, the technology to produce fuels from synthesis gas (mix of CO and $H_2$) is matured, but cost reduction of hydrogen production is required. And also, how to capture $CO_2$ is a major challenge.

If artificial photosynthesis[6] that can integrate the electrolysis process and the reverse shift reaction are developed, the synthesis gas can be produced directly from water and carbon dioxide and the ultimate low carbon energy system might be constructed.

## 4. Concluding Remarks

This study discussed the feasibility of Power to Gas in Japan. In Germany, as the challenging $CO_2$ emission reduction target and limited supply capacity of stable renewable energies requires large-scale variable renewable energies integration, Power to Gas is not passively regarded as one of the grid integration measures, but as an important technology that can decarbonize not only the power generation sector but also the heat demand sector and also the transport sector by integrating a large amount of variable renewables positively. It should be underlined that the fact that the existing natural gas network including pipeline and underground gas storage are available nationwide, enabling working together with the power grid to absorb as much as variable renewables, supports the feasibility of Power to Gas.

The gas produced in Power to Gas is mostly hydrogen and synthesis natural gas (SNG). In Germany, hydrogen blending into the natural gas pipeline would be the most reasonable measure as far as the amount of surplus electricity is small, since the standard for natural gas calorific value is tolerant enough to accept a small volume of hydrogen. In the longer term when mass integration of variable renewable is expected, SNG may be the option as the constraint of blending is significantly small.

On the other hand, in Japan, though depending on the grid integration measures taken, as the surplus electricity in 2030 is expected to be small, need for Power to Gas is very limited. Even if Power to Gas is to be promoted from a long-term perspective, the poorly-developed natural gas pipeline network hinders working with the power grid, and hydrogen or SNG blending is considerably difficult. The activities toward establishing the hydrogen economy have recently been accelerated in Japan and new infrastructure is required to realize the hydrogen economy. Hence,

[6] Most of the current artificial photosynthesis produces formic acid, though the eventual target is methanol. The highest conversion efficiency is 1.5%.

new infrastructure should be constructed either for hydrogen or SNG in Japan. To judge which is the most cost effective option requires detailed cost-benefit analysis. Meanwhile, in terms of production cost of gases, the renewable power generation cost should be reduced to JPY5/kWh for either hydrogen or SNG to equal the competing energy. SNG faces a challenge to effectively capture $CO_2$.

Power to Fuel to produce chemicals and fuels for vehicle can use the existing infrastructure for storage and delivery, which shows advantages over Power to Gas. It is worth addressing the feasibility of Power to Fuel in Japan. If artificial photosynthesis that can integrate the electrolysis process and the reverse shift reaction are developed, the synthesis gas can be produced directly from water and carbon dioxide avoiding power generation process, which may alleviate the grid connection constraint.

Last not but least, reduction in the renewable power generation cost and capital cost of electrolysis and methanation is sine qua non to make Power to Gas and Power to Fuel feasible. In addition, as Power to Gas and Power to Fuel accompany energy system transformation through networking with the existing infrastructure and building new infrastructure, how to integrate Power to Gas/Power to Fuel should be discussed based on the energy system concept that Japan should build from a long-term perspective.

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