Hydrogen technologies and developments in Japan

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Abstract

The successful development of hydrogen-energy technologies has several advantages and benefits. Hydrogen-energy development could prevent global warming as well as ensure energy security for countries without adequate energy resources. The successful development of hydrogen would provide energy for transportation and electric power. It is a unique energy carrier, as it can be produced from various energy sources such as wind, fossil fuels and biomass and, when it is combusted, it emits no CO2 emissions. The other advantage is the wide distribution of resources globally that can be used to produce hydrogen. In Japan, the Ministry of Economy, Trade and Industry (METI) published a ‘Strategic Roadmap for Hydrogen and Fuel Cells’ in 2014, with a revised update published in March 2016. The goal of the roadmap is to achieve a hydrogen society. The roadmap aims to resolve technical problems and secure economic efficiency. The roadmap has been organized into the following three phases: Phase 1—Installation of fuel cells; Phase 2—Hydrogen power plant/mass supply chain; Phase 3—CO2-free hydrogen. This paper reports on the current status of fuel cells and fuel-cell vehicles in Japan and gives a description and status of the R&D programmes along with the results of global energy model study towards 2050.

Keywords: hydrogen and fuel cell; energy system and policy; energy and environment; energy storage

Introduction

Japan has challenges in energy security and in the reduction of greenhouse gas (GHG) emissions. Almost 94% of the primary energy supply of Japan is dependent on fossil fuel produced abroad, 40% of which is petroleum; 90% of the petroleum is imported from the Middle East, which has geopolitical risks. The targets for the reduction of GHG are also challenging. The Japanese government has declared its goal to achieve a 26% reduction in GHG emissions in 2030 as compared to 2013.

In order to achieve this extensive energy saving, the aggressive introduction of renewable energy and a moderate adoption of nuclear energy are proposed. The mix of power sources in 2030 is proposed to be 56% fossil fuel, nuclear 22–20% and renewable energy 22–24%. The final energy demand in 2030 is expected to be reduced by 13%, which corresponds to a 35% increase in the efficiency of energy usage. Furthermore, Japan aims to reduce GHG emissions by 80% in 2050 with respect to current emission levels. This is considered unattainable without innovative technologies such as carbon capture and sequestration (CCS) and hydrogen.

In 2015, the primary energy supply of Japan consisted of oil (8113PJ, 41.1%), coal (5133PJ, 26.0%), natural gas (4806PJ, 24.4%), nuclear (~0PJ), hydro (710PJ, 3.6%) and new energy and geothermal (970PJ, 4.9%). Since the Great East Japan Earthquake in 2011, the primary energy self-sufficiency of Japan has been ~6% due to the shutdown of most of the nuclear power plants, which is the second lowest level among OECD countries [1]. In particular, 98% of fuels for
transportation are oil products, 87% of which are imported from the Middle East.

In order to reduce GHG emissions and limit climate change, there have been studies carried out on different energy technologies. Those technologies include nuclear energy, renewable energy and fossil fuels with CCS. The prospects for the development of a hydrogen system have also been discussed in Japan since the 1990s among policy makers and researchers.

1 Hydrogen prospects

The ultimate energy system adopted in a low-carbon society for Japan is considered to have primary energy consisting of nuclear energy, renewable energy and fossil energy with CCS. Renewable energy is a key option. As of 2017, the renewable-energy capacity in Japan was 39.1 GW for solar power, 3.4GW for power wind, 0.5 GW for geothermal, 48.1 GW for hydro and 3.2 GW for biomass. The introduction of solar and wind power has been accelerated by a Feed-in Tariff scheme since 2012, but has resulted in a surcharge on electricity charges. The cost of renewable power generation in Japan has been found to be higher than in other countries. For example, a non-residential photo voltaic power generation system is twice as expensive as one in Europe due to its high capital cost.

In order for Japan to achieve a low-carbon society, it will be necessary to import low-carbon energy from abroad. The source of low-carbon energy is considered to be fossil fuel plus CCS and renewable energy. Some of the prospective examples are low-carbon hydrogen obtained by the gasification of brown coal treated with CCS in Victoria, Australia, and hydrogen produced by the electrolysis of water using electricity from wind power in Patagonia, Argentina. Japan has almost no economically available fossil-fuel reserves domestically and large-scale CCS is expected to be less economical than abroad.

To evaluate the contribution of hydrogen needed to achieve a low-carbon society in Japan, the Institute of Applied Energy undertook several studies. The evaluation included research on the global hydrogen demand using a global and long-term inter-temporal optimization energy model, named GRAPE (Global Relationship to Protect the Environment) [2]. GRAPE is an integrated assessment model to evaluate the interaction between energy, economics, climate, land use and the influence of climate change. In this study, the energy module of the model was used. In GRAPE’s energy module, energy demands predicted from the future population and gross domestic product (GDP) were given. The global energy demand and supply structure was obtained as the optimum solution for linear programming by the minimization of energy-system costs under the given constraints. Countries were aggregated in 15 regions, as shown in Fig. 1.

A variety of primary energy resources are transformed into secondary energy carriers to meet the final energy demands. Primary energy resources are natural gas, crude oil, coal, biomass, hydropower, wind, solar energy and uranium. The final demand consists of electricity, transport and other demands (stationary non-electric demand). The study was conducted under the assumption that CO₂-free hydrogen can be produced in all regions and transported to other global regions. Hydrogen is produced from low-grade coal (lignite), natural gas, hydropower, wind power and solar photovoltaics. Once produced, it is liquefied at the port for interregional seaborne transport.

Several constraints were adopted in the present model study and include:

(i) a 50% reduction compared with 1990 levels for global CO₂ emissions in 2050 and 80% reduction for Japan;
(ii) nuclear power generation in Japan: no new construction; life of reactors assumed to be 40 years;
(iii) CCS capacity of Japan: 0.2 billion tons of CO₂/year by 2050.

The model results showed that the hydrogen demand of the world in 2050 is 972 Mtoe (3.8 trillion Nm³), with the bulk of the hydrogen used in the transport sector. In 2050, the USA, China, Western Europe and India regions (including Pakistan) account for approximately 80% of the global hydrogen demand (Fig. 2).

In Japan, the hydrogen demand in 2050 is estimated to be 53 Mtoe (0.22 trillion Nm³), with the major share of the hydrogen used in the power sector (Fig. 3).

Under the set of constraints cited above, hydrogen is widely utilized in the world as well as in Japan. Fig. 4 shows that the share of hydrogen will result in 13% of the total primary energy supply in Japan by 2050. This suggests that hydrogen will contribute to the aim of the Japanese government in achieving a low-carbon society and enhance energy security.

2 Japan’s policies for hydrogen before the Paris Agreement

Historically, in Japan, the use of hydrogen as a fuel was mainly limited to industrial applications. However, in the last few decades, hydrogen began to attract attention as a new energy source for fuel cells and fuel-cell vehicles (FCVs). “The Strategic Energy Plan” [3] approved by the Cabinet in 2014 states that it is essential for Japan to formulate a roadmap towards the realization of a ‘hydrogen society’. In line with the plan, the Ministry of Economy, Trade and Industry (METI) published ‘The Strategic Roadmap for Hydrogen and Fuel Cells’. It shows how Japan would utilize hydrogen, goals to be achieved in each step of production, the transport and storage of hydrogen and collaborative efforts among industry, academia and government for achieving these goals. The roadmap sets out clear time frames for achieving the different goals with an initiative for disseminating hydrogen energy. This roadmap was revised in 2016 [4]. Fig. 5 is a simplified overview of the roadmap.
Research and development for solving technical problems in each phase are being promoted mainly by New Energy and the Industrial Technology Development Organization (NEDO). For example, in Phase 1, research and development aimed at the cost reduction of stationary fuel cells and hydrogen-refuelling stations (HRSs) are carried out. More details will be shown later. In Phases 2 and 3, research and development of a hydrogen combustion gas turbine, large-scale hydrogen supply-system technology and power-to-gas technology will be undertaken.

3 Impacts of the Paris Agreement on the energy policies of Japan

After the ratification of the Paris Agreement, three sets of policies were developed by the government.
The Prime Minister's Office released 'The Global Warming Prevention Measures Plan' [5], stating: 'Based on the Paris Agreement, we have formulated a global warming prevention measures plan, paving the way to achieve the goal to reduce global GHG emissions 26% by 2030.'

Within a fair and effective international framework, in which all major countries participate, we will lead international society so that each major country reduces its emissions in accordance with its ability, and we have indicated our direction of aiming to achieve the long-term goal of reducing global GHG emissions 80% by 2050, while both implementing global warming prevention measures and sustaining economic growth.

To achieve the objectives, the Cabinet Office compiled the 'Energy & Environment Strategy for Technological Innovation' [6], in which hydrogen is listed as one of the innovative energy-storage technologies. METI published the 'Innovative Energy Strategy' [7] and declared that 'Establishing a strategy for creating hydrogen society towards the post-2030 era' is necessary.

4 Enhanced hydrogen policies

On 26 December 2017, 'The Ministerial Council on Renewable Energy, Hydrogen and Related Issues' decided on a 'Basic Hydrogen Strategy' [8]. The key points of the strategy are:

(i) Vision on 2050+ Action by 2030;
(ii) position hydrogen as a new carbon-free energy option aligned with renewable energy;
(iii) hydrogen cost targets: ¥100/Nm³ (present), ¥30/Nm³, ¥20/Nm³ (future).

Fig. 3 Hydrogen demand (Japan)

The strategic hydrogen cost target of ¥30/Nm³ of ca.2030 was set on the basis that, by that time, the commercial scale supply chain of hydrogen should be established and

Fig. 4 Total primary energy supply (Japan)
One of the challenges in hydrogen technology is the realization of the cost reduction of hydrogen. In the ‘Basic Hydrogen Strategy’, three measures to achieve the cost reduction were shown, namely the acquisition of inexpensive resources, the establishment of large-scale hydrogen supply chains and the establishment of the mass usage of hydrogen as the fuel for FCVs, power generation and industrial use. Based on this strategy, research, development and demonstration projects were deployed. Ongoing projects are shown in Fig. 7. The New Energy and Industry Development Organization (NEDO) is the main player in the development of the technologies shown in Fig. 7 and

300,000 tons of hydrogen should be transported to Japan annually. Fig. 6 shows the scenario for the ‘Basic Hydrogen Strategy’.

**5 Development of hydrogen technology**

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is entirely funded by METI. The development of fuel cells for residential use (Ene-farm) is not included here, as Ene-farm was commercialized in 2009.

5.1 Technology development for Phase 1

5.1.1 Fuel cells

Target prices for Ene-farm are ¥800 000/unit for proton-exchange membrane fuel cell (PEFC) type by 2019 and ¥1 000 000/unit for solid-oxide fuel cell (SOFC) type by 2020. There are expected to be 1.4 million units in 2020 and 5.3 million units in 2030.

Fuel cells for business and industry use were launched as a SOFC cogeneration system in 2017. Some examples of the fuel cells (FCs) are shown in Fig. 8.

5.1.2 FCVs and HRSs

The Japanese car manufacturers Toyota and HONDA commercialized FCVs named MIRAI and Clarity in 2014 and 2015, respectively, at a sales price of ~7 million yen...
According to ‘The Basic Hydrogen Strategy’, car stocks are expected to increase from 40,000 in 2020 to 800,000 by 2030.

At present, 92 HRSs are in operation and nine HRSs are in preparation, as shown in Fig. 10. The typical HRS with a supply capacity of 300 Nm³/h is also shown in Fig. 10.

The goal of the roadmap is to ensure 160 HRSs in 2020, 320 HRSs by 2025.

The application of FC technology for mobility use is being conducted for FC buses and FC forklifts. The FC bus is scheduled to number up to 100 units in ~2020 and 1,200 units by ~2030. The FC forklift is expected to number 500 units by ~2020 and 10,000 units by ~2030.

5.2 Technology development for Phase 2
5.2.1 Establishing an inexpensive, stable supply system
The large-quantity hydrogen supply system consists of five steps, namely the production of the hydrogen and conversion into the hydrogen carrier, seaborne transport of the hydrogen carriers, storage of the hydrogen carrier, takeout of the hydrogen and use of the hydrogen, which are shown in Fig. 11 [9].

Hydrogen is expected to be produced from low-grade coal (lignite), associated gas and other processes. Liquefied hydrogen, methylcyclohexane/toluene and ammonia are being extensively developed as hydrogen carriers. Biomass is not considered to be an inexpensive resource of hydrogen. But further discussion is expected in the future.

5.2.2 Hydrogen power generation
Technologies for hydrogen gas turbine power generation are being developed in anticipation of the consumption of large quantities of hydrogen. The technologies are divided into two: the co-combustion of natural gas and hydrogen; and hydrogen firing power generation. NEDO is leading the development of these two technologies. Use of the direct combustion of ammonia is also being extensively studied.
in the Strategic Innovation Promotion Program, which is managed by the Cabinet Office [9].

5.3 Technology development for Phase 3

Production of CO₂-free hydrogen from renewable-energy sources is one of the ultimate targets of the ‘Strategic Roadmap for Hydrogen and Fuel Cells’. A system of a water electrolysis-hydrogen tank is considered by experts to have high potential for application with large-scale and prolonged energy storage (Fig. 12). This is due to the system having small losses over time and high expandability in comparison with other competing storage battery technologies. Power-to-gas is also a promising technology as a countermeasure against problems related to power-system interconnection during the introduction and future expansion of renewable energy in Japan.

5.4 Draft budget for hydrogen and fuel cells in FY2018

The latest METI draft budget for hydrogen and fuel cells is shown in Fig. 13. A key part of the budget allocation is for the dissemination of stationary fuel cells, FCVs, the establishment of a hydrogen supply chain, the research and development of fuel cells and the production, transport and storage of hydrogen [10].

6 Conclusion

The energy model study has shown that hydrogen has the potential to contribute to the realization of a low-carbon society and that the share of hydrogen will result in 13% of the total primary energy supply in Japan by 2050 under the severe environmental constraints. The Japanese government has launched various policies. These policies have been
encouraging corporations and academia and have resulted in the dissemination of residential FC units, FCVs and HRSs. These achievements are also expected to contribute to the construction of a mass supply chain of hydrogen in Japan by 2030. It is expected that, beyond 2030, towards 2050, Japan should realize a hydrogen society, and achieve energy security and mitigation of the emission of GHGs.

Since establishing an H₂ system is a key aim for Japan’s future technology portfolio, continuous research and development and the exploration of business models are also considered to be important.

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