Chapter 15

Life Cycle Assessment of Hydrogen Supply Chain: A Case Study for Japanese Automotive Use

Yuki Kudoh and Akito Ozawa

Research Institute of Science for Safety and Sustainability, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

15.1 INTRODUCTION

Hydrogen is a flexible energy carrier having the following characteristics in its supply chain. From the hydrogen supply side, it can be produced from various primary and renewable energy resources. This includes hydrogen production from fossil fuels and biomass resources by chemical processes and from renewable electricity by electrolysis of water. From this point of view, hydrogen is expected to play an important role to diversify the energy supply. Another role expected from the supply side is its use as a buffer to stabilize the electricity from intermittent renewable energy, such as wind power and solar photovoltaics, in which the excess renewable power is stored in the form of hydrogen by electrolysis of water. From the hydrogen demand side, hydrogen can be consumed by diverse end-use applications, such as fuel cells, turbines, boilers, and engines to obtain electric, thermal, and kinetic energy across all energy sectors. Because hydrogen itself contains no carbon, another advantage of using hydrogen as energy is that no carbon dioxide (CO_2) is emitted from the energy conversion processes of hydrogen use technologies.

Japan has long focused on the potential of hydrogen energy use. In 1974, right after the 1973 oil crisis, Japan formulated the first national strategic program to promote the long-term research and development of potential energy technologies, including hydrogen energy, to secure and diversify the national energy supply (Kimura and Suzuki, 2006). Since the start of the World Energy Network (WE-NET) Program (Chiba et al., 1998) in 1993, the Japanese government has been continuously implementing national projects related to the

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hydrogen value chain and has accumulated plenty of technological know-how in hydrogen infrastructure operations, as well as hydrogen production, mass transport and storage, and utilization technologies. Hence, it is not too much to state that Japan is leading the world in the technologies surrounding hydrogen.

Given this background, hydrogen is regarded as one of the promising clean secondary energies for Japan that can contribute to diversifying the energy basket and reducing greenhouse gas (GHG) emissions. The Japanese government, industry, and academia are now working in tandem according to the Strategic Road Map for Hydrogen and Fuel Cells (Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, 2016), which specifies the efforts to be made for the components of the hydrogen supply chain and the timelines necessary to enable realization of a future hydrogen economy. The Japanese government also plans to showcase hydrogen technology during the Tokyo 2020 Olympic and Paralympic Games and pass on a hydrogen society as a legacy of the Tokyo 2020 Games (Tokyo Organising Committee of the Olympic and Paralympic Games, 2017).

Let us place the focus on the environmental benefits of using hydrogen as energy. As described earlier, no CO_2 is generated when obtaining energy from hydrogen. However, it should be emphasized again that hydrogen is an energy carrier, but not an energy source, as it must be produced from other primary and renewable energies. In addition, a supply chain is necessary to transport hydrogen from where it is produced to where it is used. The supply chain comprises hydrogen production, storage, and distribution processes and each process requires energy and material inputs for its operation. This means that hydrogen is responsible for a certain amount of CO_2 and other GHG emissions that are attributed to the energy and material inputs to the supply chain. Hence, if we are to understand the environmental benefits of hydrogen use technology over the conventional counterpart system, the emissions from the whole hydrogen supply chain should be included in the assessment. In this context, life cycle assessment (LCA) must be conducted to evaluate the emissions associated with hydrogen use technology and its counterpart.

LCA is a methodology to evaluate the environmental performance and potential impacts associated with a product system across its entire life cycle. Among various LCA studies that evaluated the environmental benefits of using hydrogen over conventional energy sources, the so-called well-to-wheel (WtW) studies, an LCA approach to evaluate the environmental advantages of alternative fuel vehicles (AFVs) over conventional internal combustion engine vehicles across the entire automotive fuel pathway, are conducted to calculate the life cycle emissions, including the hydrogen supply chains, in the United States (Argonne National Laboratory, 2016), Europe (JEC-Joint Research Centre-EUCAR-CONCAWE Collaboration, 2014), and Japan (Toyota Motor Corporation and Mizuho Information and Research Institute Inc., 2004; Japan Hydrogen and Fuel Cell Demonstration Project Steering Committee, 2011).

However, it should be noted that WtW studies are conducted under specific assumptions, such as the energy supply structure of a certain year, system boundary settings, and the LCA methodology and database used. This means that comparison of the calculated results is valid only within the same WtW study and the observation of the same hydrogen pathway or the WtW results in different studies may not make sense. The distinctive problem surrounding the Japanese WtW studies is that the Japanese energy supply figures have drastically changed due to the Fukushima nuclear accident that occurred after the 2011 Great East Japan Earthquake and Tsunami, but the previous WtW studies (Toyota Motor Corporation and Mizuho Information and Research Institute Inc., 2004; Japan Hydrogen and Fuel Cell Demonstration Project Steering Committee, 2011) were conducted under the energy supply structure of the first decade of the 2000s. As far as the authors can ascertain, the LCA of hydrogen pathways conducted by the Mizuho Information & Research Institute (Mizuho Information and Research Institute Inc., 2016) is the only study that has assessed the life cycle GHG profiles of various hydrogen supply chains under the current energy supply structure, but most of the data used for their calculations are not provided in their report due to confidentiality agreements with their contributors. LCA should be conducted with an equal footing and clear evidence to understand the energy and environmental profiles of the hydrogen supply chains, and to discuss the role of hydrogen in diversifying the energy supply and mitigating global warming.

As a part of establishing a Japanese scenario for a future hydrogen economy, the authors have been conducting technology assessments of hydrogen to understand the role of hydrogen within the energy system and its socioeconomic effects. LCA studies were conducted to assess the environmental benefits of hydrogen use, to identify the environmental hotspots in the hydrogen supply chain, and to examine the opportunities to reduce GHG emissions across the whole supply chain. In addition to our previous results for calculating the life cycle GHG emissions from the hydrogen supply chain (Ozawa et al., 2017), case studies are being conducted for various hydrogen technologies, including the emissions from end-use applications. This chapter introduces the WtW GHG emissions results that were calculated for a Japanese fuel cell vehicle (FCV), and its conventional counterparts. First, it outlines the general procedure for calculating the GHG emissions by life cycle inventory (LCI) analysis. It then introduces the case study results for the life cycle GHG emissions that were calculated for the potential Japanese hydrogen supply chains as automotive fuel and concludes with the potential options for establishing a low-carbon hydrogen supply chain.

15.2 LIFE CYCLE INVENTORY ANALYSIS IN BRIEF

According to ISO 14040 (International Organization for Standardization (ISO), 2006), which standardizes the LCA methodology, the LCA framework comprises goal and scope definition, inventory analysis, impact assessment, and interpretation phases. In brief, the goal and scope of an LCA study are determined first. Secondly, in the inventory analysis, relevant inputs and outputs of a product system are collected and calculated throughout its life cycle. Then, in the impact assessment, the magnitude and significance of the potential environmental impacts of a product system are evaluated. Finally, the findings of either the inventory analysis or the impact assessment, or both, are combined, consistent with the defined goal and scope, in order to reach the conclusions and recommendations in the interpretation phase.

The most important thing when conducting an LCI analysis to calculate the environmental footprint is to collect all the data related to the life cycle of the target product system. As shown in Fig. 15.1, the data necessary for LCI analysis are the foreground and background data. Foreground data are the direct inputs, such as energy and materials, that are specific to the target product system, and are usually collected by those who are going to conduct the LCI analysis. Background data are not directly related to the product system but relate to all the indirect inputs that are induced by the direct inputs to the product system. Because it is difficult for those who are going to conduct LCI analysis to collect all the indirect input data, including the upstream processes data, the industry average data from LCA databases are often used as background data.

The life cycle GHG emissions, E, from a product system can be calculated by Eq. (15.1), where x_i are the foreground data of the input i to the product

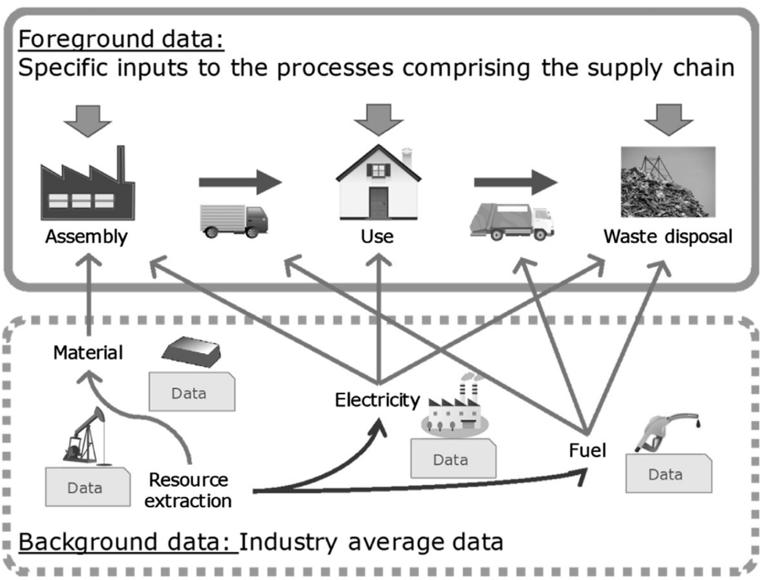

FIG. 15.1 Foreground and background data for LCI analysis.

system and e_i are the background embodied GHG emissions data of the input i from an LCA database.

$$E = \sum_i e_i x_i \tag{15.1}$$

15.3 CASE STUDY FOR JAPANESE WTW EMISSIONS

15.3.1 Overview

This case study calculated the GHG emissions from the entire hydrogen supply chain used for a FCV driven in Japan. A gasoline vehicle (GV) and gasoline hybrid vehicle (HV) were set as the conventional counterparts of the FCV, and the GHG emissions from both the gasoline supply chain and onboard gasoline combustion were calculated for the GV and HV. Fig. 15.2 outlines the target WtW pathways and their system boundary assumed in this study. In the WtW studies, the supply chain of automotive fuel from resource extraction to the vehicle tank is called well-to-tank (WtT), and the energy or environmental performance of vehicles themselves is called tank-to-wheel (TtW).

Among the potential hydrogen supply chains for Japanese FCVs, this study placed the focus upon renewable hydrogen (hydrogen produced by electrolysis using renewable power) and natural gas (NG) reforming hydrogen supply chains. Because the main target of our entire project was to investigate the potential of producing cheap, low-carbon hydrogen for a future Japanese hydrogen economy, it was assumed in this study that the renewable hydrogen was produced abroad and imported into Japan using hydrogen carriers. Thus, the renewable hydrogen supply chain comprised overseas and domestic stages. The overseas chain included renewable power generation, hydrogen production via water electrolysis by renewable power, production and storage of the hydrogen carrier, and ocean transport of the hydrogen carrier to Japan. The domestic chain involved the hydrogen carrier storage and distribution to a hydrogen station by tanker truck, restoration of hydrogen from hydrogen carrier, and hydrogen compression and fueling of a FCV. In the other study conducted as part of our project, the countries and regions that have enough potential to supply renewable electricity (wind and solar photovoltaic (PV) power generation) hydrogen production at a low cost to Japan were identified. Among them, electrolysis hydrogen from Australian wind and solar PV power, and from Norwegian wind power, were chosen for the assessment. The one-way ocean transport distance to Japan was set to 10,000 km from Australia and 20,000 km from Norway. Liquid hydrogen (LH) and methylcyclohexane (MCH) were assumed to be the hydrogen carriers of this case study, due to their fitness for long-term storage, long-range transport, and their relative ease of handling (Gupta et al., 2015). The NG reforming hydrogen supply chain comprised the overseas extraction and liquefaction of NG, ocean transport of liquefied natural gas

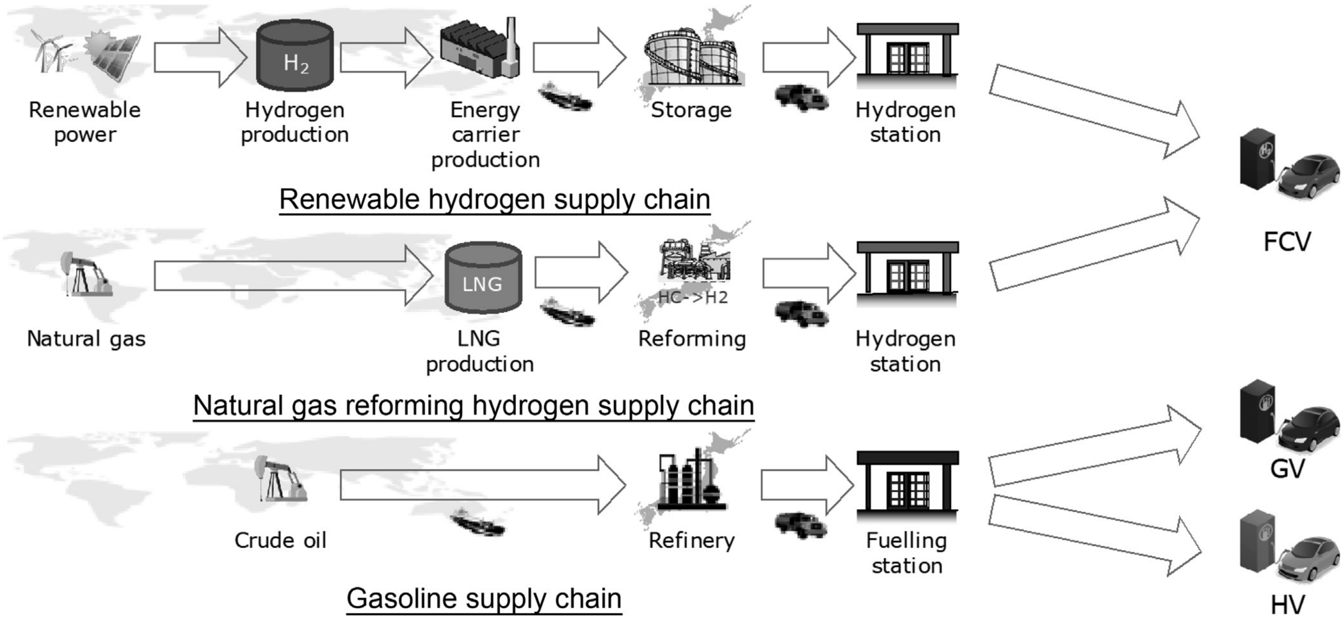

FIG. 15.2 Target WtW pathways and their system boundary outline.

(LNG), domestic hydrogen production by steam reforming of NG, which is obtained by regasification of LNG, compression, and distribution of hydrogen as compressed gaseous hydrogen (CH) to the hydrogen station by tanker truck, and hydrogen compression and fueling of a FCV. The gasoline supply chain comprised the overseas extraction of crude oil, ocean transport of crude oil, domestic refining of crude oil to gasoline, gasoline distribution, and fueling of a GV or HV.

All the foreground data were collected from previous WtW and LCI studies related to the target automotive fuel supply chains in this study. If more than two process options were found for a process comprising the supply chain, due to differences in equipment specifications, the minimum, average, and maximum values were calculated as the foreground input data. The Inventory Database for Environmental Analysis (IDEA) (National Institute of Advanced Industrial Science and Technology, 2015) developed by National Institute of Advanced Industrial Science and Technology was used as the background data.

IDEA is a Japanese LCA database that mainly uses national statistics and process data as its data source and aims to model the environmental footprints associated with all Japanese industries. Since the latest version 2.0 was released in May 2016, which covers all the items in the Japan Standard Commodity Classification, the environmental footprints of any product produced in Japan in the year 2014 are included in the IDEA. This study focused on the embodied GHG emissions of the products that were calculated as the sum of CO_2, CH_4, N_2O, HFCs, PHCs, and SF_6 converted to CO_2 equivalent using the global warming potential (GWP) over 100 years of the IPCC AR4 (Intergovernmental Panel on Climate Change (IPCC), 2007).

The embodied GHG emissions data provided in the IDEA are limited to Japanese industries. In order to approximate the overseas emissions (in this study, the GHG emissions associated with the inputs to Australian and Norwegian processes comprising the renewable hydrogen supply chain) using the IDEA, the following assumptions were made:

- The economic activity level of the target country or region was the same as in Japan. For example, if the same product was produced in Japan or Australia, all the inputs were the same in both countries.
- The inventory data for overseas transport of resources were set to zero. This meant that the approximated emissions of a product did not include those by resource overseas transport.
- All Japanese grid electricity inputs to the processes were substituted for the grid electricity in the target country or region.

It should be noted here, that in the same manner as the other WtT and WtW studies (Argonne National Laboratory, 2016; JEC-Joint Research Centre-EUCAR-CONCAWE Collaboration, 2014; Toyota Motor Corporation and Mizuho Information and Research Institute Inc., 2004; Japan Hydrogen and Fuel Cell Demonstration Project Steering Committee, 2011; Mizuho

Information and Research Institute Inc., 2016), the GHG emissions calculated in this study only focused upon the embodied emissions related to energy and material input of the process inventory data. Hence, the emissions attributed to the life cycle of infrastructure components were out of the system boundary of this study, except for the renewable power in hydrogen producing countries (details explained in Section 15.3.2).

15.3.2 Renewable Power Generation in Hydrogen Producing Countries

It was assumed that the renewable power plants (wind and solar PV in Australia, and wind in Norway) were constructed solely to supply electricity for the hydrogen supply chain. This meant that the hydrogen supply chain was responsible for all the embodied emissions of the renewable power plants. Hence, in this study, all the emissions that could be attributed to the life cycle of renewable powers (materials production, construction, transport, and operation) were included in the system boundary. Table 15.1 shows the specifications assumed and the life cycle GHG emissions from the wind and solar PV power plants used in this case study, which were calculated using the input data by the Central Research Institute of Electric Power Industry (CRIEPI) (Central Research Institute of Electric Power Industry (CRIEPI), 2016) and the IDEA database.

15.3.3 Renewable Hydrogen Production by Water Electrolysis

It was assumed in this process that hydrogen was produced from renewable power by water electrolysis using either polymer electrolyte membranes or alkaline water. The electricity input to this process was calculated as

TABLE 15.1 **Specifications and the Life Cycle GHG Emissions From Wind and Solar PV Power Plants**

Parameters		Wind	Solar PV
Capacity (MW)		40	10
Load factor (%)		35	18
Auxiliary power ratio (%)		10	3
Amount of electricity generated (MWh/year)		122,640	14,532
Power plant life time (year)		30	30
Life cycle GHG emissions (g-CO_2eq./kWh)	Australia	15.3	66.4
	Norway	10.8	–

4.9 kWh/Nm^3-H_2 on average, with a range of 3.7–6.5 kWh/Nm^3-H_2. The pure water requirement was set to the theoretical value of 0.80 kg/Nm^3-H_2.

15.3.4 Hydrogen Energy Carriers

15.3.4.1 Liquid Hydrogen

Fig. 15.3 shows the renewable hydrogen supply chain using LH that was assumed in this study. Assumptions given for each process comprising the supply chain were described as follows:

- LH production

The LH could be produced by adiabatic expansion of gaseous hydrogen. The amount of electricity required for this process was 0.91 kWh/Nm^3-H_2 on average, with a range of 0.55–1.3 kWh/Nm^3-H_2.

- LH storage at loading port

The LH was stored in stationary insulation tanks at a loading port. It was assumed that the boil-off hydrogen gas during this stage was liquefied back to LH. The electricity input for this stage was set to 0.055 kWh/Nm^3-H_2.

- LH ocean transport by tanker

A LH tanker with 160,000 m^3 tank capacity and 16 knots cruising speed (Mizuno et al., 2017) was assumed for LH transport to Japan. Because LH tankers are still under development, there are no available data for calculating emissions for LH ocean transport. Thus, the GHG emissions were estimated using the data for LNG tankers in the IDEA under the assumption that GHG emissions of a LH tanker per transport volume of LH expressed in ton-kilometer units were equal to those of a LNG tanker per ton-kilometer of LNG. The emissions from both laden and ballast voyages were included in the calculations. It was also assumed that the average boil-off rate of LH released to the atmosphere during the voyage is 0.30% per day, with a range of 0.20%–0.40% per day.

- LH storage at discharging port

It was assumed that the LH was transferred from the tanker to stationary tanks at a domestic discharging port. The boiled-off hydrogen gas from this stage was liquefied back to LH and stored in stationary tanks. The electricity input for this stage was set to 0.055 kWh/Nm^3-H_2.

- Domestic LH distribution by tanker truck

A LH tanker truck with a 23-kL tank capacity and 3.5 km/L-diesel fuel economy was assumed for domestic distribution from the LH storage terminal at the discharging port to a hydrogen station. The one-way distribution distance was set to 50 km. The emissions from both laden and empty trips were included to the calculation.

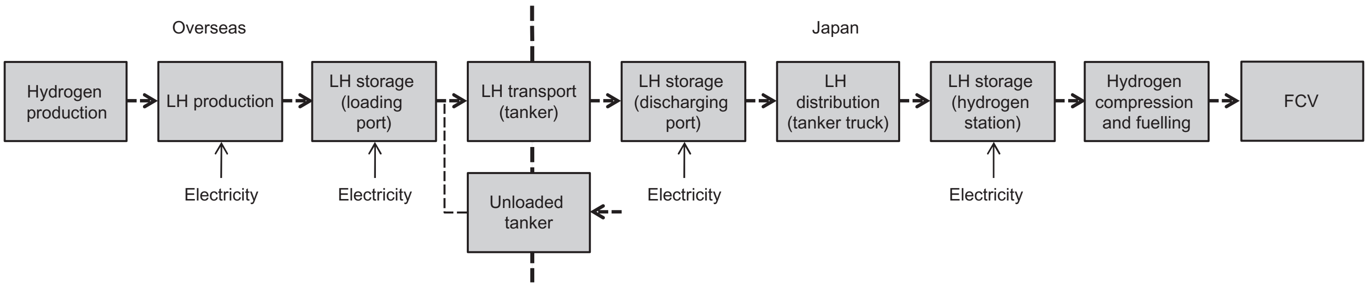

FIG. 15.3 Renewable hydrogen supply chain using LH.

- LH storage at hydrogen station

The LH was transferred from the tanker truck to a stationary tank at a hydrogen station. The electricity input for this stage was set to 0.055 kWh/Nm^3-H_2.

15.3.4.2 Methylcyclohexane

MCH ($CH_3C_6H_{11}$) is produced by the hydrogenation of toluene (TOL: $CH_3C_6H_5$) and releases hydrogen via catalytic dehydrogenation. Fig. 15.4 shows the renewable hydrogen supply chain using MCH that is assumed in this case study. After hydrogenation of TOL at the hydrogen supply site, MCH is transported by tanker and dehydrogenated at the demand site to yield H_2 and the original TOL, which is then returned to the supply site and reused. The dehydrogenation of MCH to TOL requires a large endothermic heat of reaction (205 kJ/mol-MCH or 68.3 kJ/mol-H_2). A variety of catalysts have been investigated for their ability to facilitate an efficient dehydrogenation of MCH. The assumptions given for each process comprising the supply chain are described as follows:

- MCH production

The MCH was produced by the chemical reaction between TOL and hydrogen. The reaction yield of hydrogenation to TOL and the hydrogen consumption rate were set to 99.8% and 97.9%, respectively. The electricity input for this process was 41 kWh/t-MCH on average, with a range of 7.5–93 kWh/t-MCH.

- MCH storage at loading port

The MCH was stored in corn roof tanks at a loading port. The electricity input for this stage was set to 0.92 kWh/t-MCH on average, with a range of 0.83–1.0 kWh/t-MCH.

- MCH ocean transport by tanker

An oil product tanker was assumed to be used for ocean transport of the MCH to Japan. The GHG emissions were calculated using the emissions data for the oil product tankers in the IDEA.

- MCH storage at discharging port

It was assumed that the MCH was transferred from the tanker to corn roof tanks at a domestic discharging port. The electricity input for this stage was assumed to be the same as that required for storage at the loading port.

- Domestic MCH/TOL distribution by tanker truck

A tanker truck with 20 kL tank capacity and 2.3 km/L-diesel fuel economy was assumed for domestic distribution of MCH to a hydrogen station and TOL return from the station. The one-way distribution distance was set to 50 km.

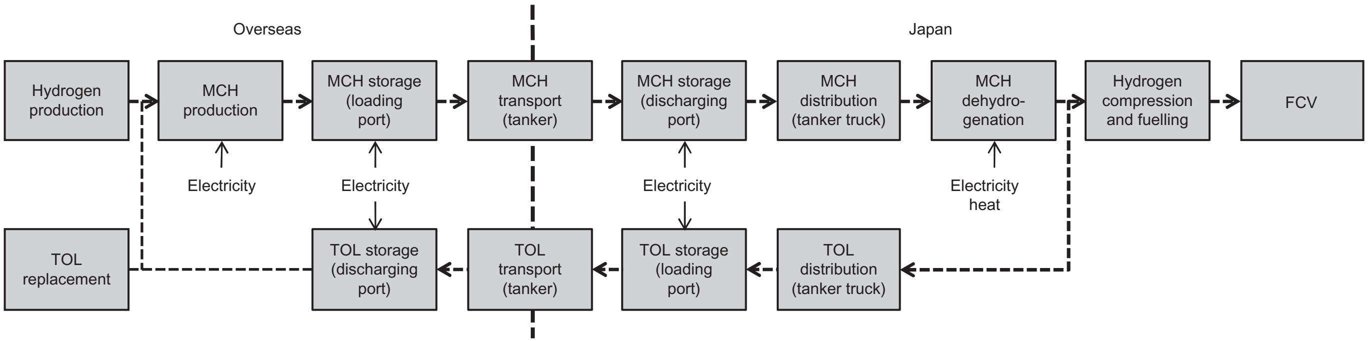

FIG. 15.4 Renewable hydrogen supply chain using MCH.

The emissions from both MCH- and TOL-laden trucks were included in the calculations.

- Dehydrogenation of MCH at hydrogen station

The MCH was converted to hydrogen and TOL by the dehydrogenation reaction at the hydrogen station. The conversion rate, selectivity, and hydrogen yield of the reaction were set to 95.0%, 99.9% and 90.0%, respectively. The electricity input for this stage was set to 0.31 kWh/t-MCH on average, with a range of 0.24–0.35 kWh/t-MCH.

- TOL storage at loading port

After the TOL was transferred from the hydrogen station to a loading port by tanker truck, TOL was stored in corn roof tanks. The electricity input for this stage was set to 0.92 kWh/t-TOL on average, with a range of 0.83–1.0 kWh/t-TOL.

- TOL ocean transport by tanker

An oil product tanker was assumed to be used for ocean transport of the TOL from Japan to the hydrogen producing countries. The GHG emissions were calculated using the emissions data for the oil product tankers in the IDEA.

- TOL storage at discharging port

It was assumed that the TOL was transferred from the tanker to corn roof tanks at an overseas discharging port. The electricity input for this stage was assumed to be the same as that required for storage at the loading port.

- TOL replacement

In the liquid organic hydride cycle of TOL and MCH, it was assumed that TOL from the supply chain could be used in the same manner as virgin TOL, so that the GHG emissions to produce the required amount of TOL were not included in the calculations. However, due to the chemical reactions, such as demethylation, isomerization, cycloreversion, and dimerization, that occur during the iterations of hydrogenation and dehydrogenation reactions, it was assumed that 3% of the initial TOL-loading should be replaced every year. The GHG emissions attributed to produce this amount of TOL were included in the calculations.

15.3.5 Supply Chain for Hydrogen Produced by NG Reforming

Fig. 15.5 shows the supply chain for hydrogen produced domestically by NG reforming assumed in this case study. The embodied GHG emissions of LNG imported to Japan provided in the IDEA were used for the upstream emissions of this supply chain. The assumptions for the rest of the supply chain were set as follows:

- Hydrogen production via steam reforming of NG

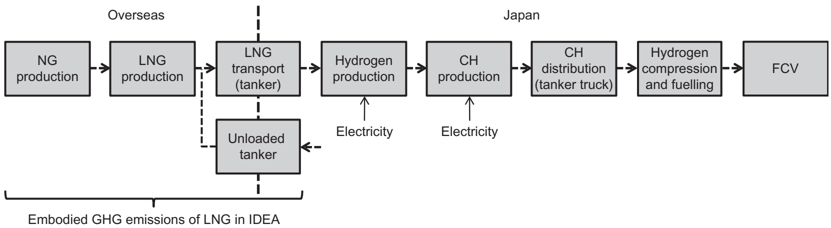

FIG. 15.5 Supply chain for hydrogen produced by NG reforming.

The gaseous hydrogen was assumed to be produced in Japan by reforming NG derived from imported LNG. The average NG input was calculated as 15.1 MJ-LHV/Nm^3-H_2, with a range of 14.8–15.3 MJ-LHV/Nm^3-H_2, while the average electricity input was calculated as 0.440 kWh/Nm^3-H_2, with a range of 0.0998–0.780 kWh/Nm^3-H_2. The process water requirement was set to 0.00196 m^3/Nm^3-H_2.

- Compressed hydrogen (CH) production

The hydrogen produced was assumed to be compressed to 20 MPa and loaded into a gas tanker truck for distribution. The electricity input for CH production was set to 0.272 kWh/Nm^3-H_2 on average, with a range of 0.119–0.440 kWh/Nm^3-H_2.

- Domestic CH distribution by tanker truck

A tanker truck was assumed for domestic distribution of CH to a hydrogen station. The average tank capacity of the truck was calculated as 2330 Nm^3-H_2, with a range of 2200–2460 Nm^3-H_2, while the average fuel economy was calculated as 2.75 km/L-diesel, with a range of 2.5–3.0 km/L-diesel. The one-way distribution distance was set to 50 km. The emissions from both laden and empty trips were included in the calculations.

15.3.6 Hydrogen Fueling of FCVs

At the hydrogen station, hydrogen was compressed to 70 MPa and pumped into the FCV tank. The electricity required for compressing and fueling hydrogen was set to 0.282 kWh/Nm^3-H_2 and 0.0928 kWh/Nm^3-H_2, respectively.

15.3.7 Supply Chain for Gasoline

Fig. 15.6 shows the supply chain for gasoline. The embodied GHG emissions of gasoline that was produced by domestic refining of imported crude oil were used for the upstream emissions of the supply chain. The assumptions for the rest of the supply chain were set as follows:

- Domestic gasoline distribution by tanker truck

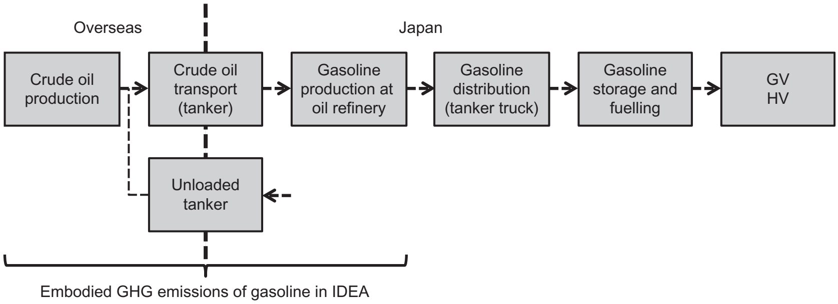

FIG. 15.6 Supply chain for gasoline.

The gasoline from oil refining was distributed and stored at a fueling station using a tanker truck with 20 kL tank capacity and 2.34 km/L-diesel fuel economy. The one-way distribution distance was set to 50 km. The emissions from both laden and empty trips were included in the calculations.

- Gasoline fueling of internal combustion engine vehicles

At the fueling station, the stored gasoline was pumped into the fuel tank of GVs and HVs. The electricity input for gasoline fueling was set to 0.0140 kWh/MJ-gasoline.

15.3.8 TtW Performance of the Target Vehicles

Table 15.2 shows the TtW energy performance of the FCV, GV, and HV used in this study that was assumed for the Japanese JC08 mode type-approval test cycle (Fig. 15.7) in the Toyota MIRAI's LCA report (Toyota Motor Corporation, 2015).

TABLE 15.2 Specifications and Life Cycle GHG Emissions From Wind and Solar PV Power Plants

Vehicle Type	TtW Fuel Economy	TtW Energy Consumption
FCV	152.17 km/kg-H_2	0.79 MJ-LHV/km
GV	11.4 km/L-gasoline	2.9 MJ-LHV/km
HV	23.2 km/L-gasoline	1.4 MJ-LHV/km

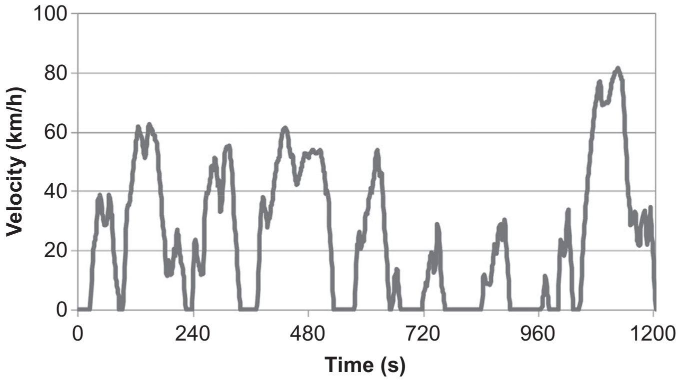

FIG. 15.7 Japanese JC08 mode test cycle. The cycle time, cycle distance, and average velocity of the cycle are 1204 s, 8.17 km, and 24.4 km/h, respectively.

15.4 RESULTS AND DISCUSSION

15.4.1 WtT GHG Emissions for Hydrogen Carriers

15.4.1.1 Liquid Hydrogen

For the renewable hydrogen supply chain using LH as the hydrogen carrier, it was assumed by default that all the electricity inputs to overseas processes were supplied with the grid electricity of the hydrogen producing country, except for the hydrogen production process by water electrolysis using renewable electricity. As shown in Table 15.3, the technological opportunity of implementing a low-carbon electricity case was assumed to reduce the supply chain emissions by utilizing the same renewable electricity as the water electrolysis to all the overseas processes.

Fig. 15.8 shows the average WtT GHG emissions of imported renewable hydrogen using LH. Because a large amount of the electricity required in the LH production process was used to cool the hydrogen below its critical point of 33 K, the emissions from this process in the Australian default cases became

TABLE 15.3 Configuration of Default and Low-Carbon Electricity Cases for Hydrogen Supply Chain Using LH

Case	Description
Default case	Electricity for hydrogen production by water electrolysis was supplied with renewable electricity, while the electricity used in the other overseas processes was supplied with the grid electricity of the hydrogen producing countries
Low-carbon electricity case	Electricity used in all the overseas processes was supplied with the same renewable electricity as the water electrolysis

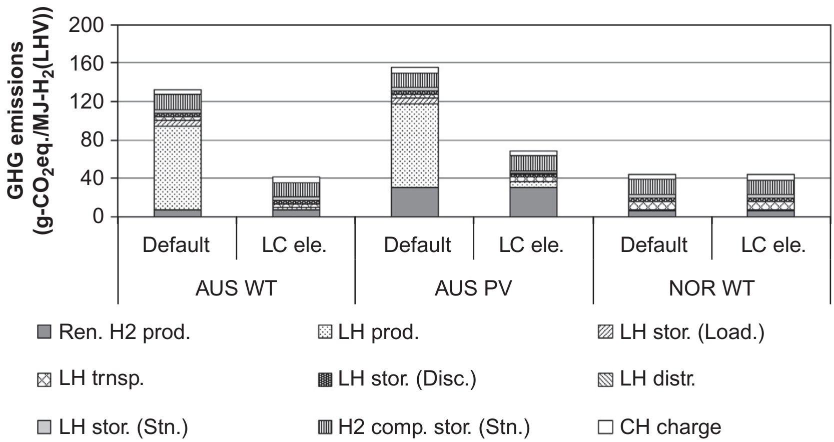

FIG. 15.8 WtT GHG emissions from imported renewable hydrogen using LH.

dominant (66% and 56% of the total for the wind and solar PV supply chains, respectively) due to the high GHG emissions intensity of grid electricity, which depends strongly on coal-fired power generation. By implementing a low-carbon electricity case in the Australian supply chains, the total GHG emissions would be reduced by 69% and 56% for wind power and solar PV cases, respectively. On the other hand, the main source of electricity in Norway is hydropower, and there was only a slight difference between the GHG emissions of wind power and grid electricity. Thus, the reduction effect of the Norwegian low-carbon electricity case only accounted for 1% of the default case emissions.

15.4.1.2 Methylcyclohexane

As described earlier, a large amount of heat is required to release hydrogen from MCH in the hydrogen supply chain, when using MCH as the hydrogen carrier. It was assumed by default that the heat required for dehydrogenation was supplied by combustion of city gas. As one of the options to reduce GHG emissions from this supply chain, a waste heat case that used waste heat instead of city gas combustion was configured as shown in Table 15.4.

TABLE 15.4 Configuration of Default and Waste Heat Cases for Hydrogen Supply Chain Using MCH

Case	Description
Default case	Heat required for dehydrogenation at hydrogen station was supplied by combustion of city gas
Waste heat case	Heat required for dehydrogenation at hydrogen station was supplied by waste heat from nearby plants or facilities

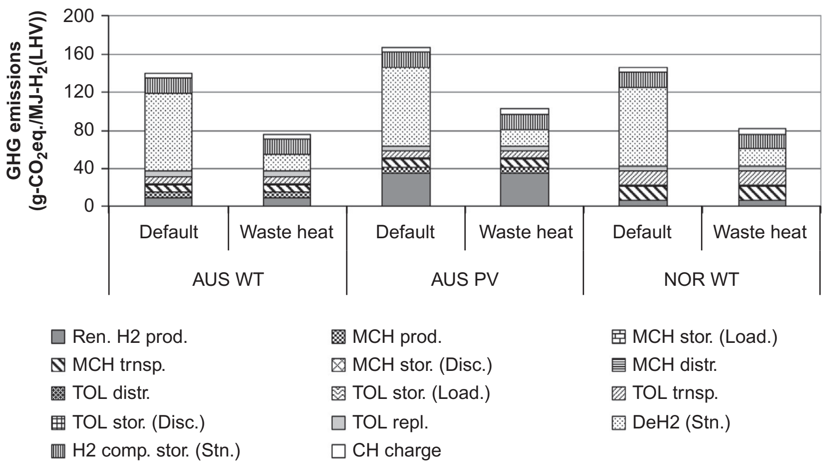

FIG. 15.9 WtT GHG emissions from imported renewable hydrogen using MCH.

Fig. 15.9 shows the average WtW GHG emissions of imported hydrogen using MCH. It can be confirmed that the emissions from dehydrogenation at the hydrogen station were dominant, which accounted for 47%–59% of the total. If the dehydrogenation process at the hydrogen station was designed to take advantage of waste heat utilization, it was expected that the emissions could be reduced by 46%, 39%, and 44% from the default case for Australian wind power, Australian solar PV, and the Norwegian wind power cases, respectively.

15.4.2 Variation of Hydrogen WtT GHG Emissions

Fig. 15.10 shows the variation in hydrogen WtT GHG emissions due to combinations of hydrogen sources and carriers. The bar chart shows the calculated average (same as Figs. 15.8 and 15.9) and the error bars representing the potential emissions range (minimum and maximum values) due to differences in the process inventory data included in the supply chain. It can be confirmed that the WtT GHG emissions from any of the renewable hydrogen pathways assumed in this study could be lower than those from NG reforming hydrogen, if the low-carbon electricity and waste heat cases were implemented for a renewable hydrogen supply chain using LH and MCH, respectively.

15.4.3 WtW GHG Emissions of the Target Vehicles

Fig. 15.11 illustrates the WtW GHG emissions of the FCV using hydrogen supplied with different supply chains, and of the HV and GV. It can be confirmed that the GHG emissions from the FCV were smaller than from the GV. However, it should be noted that the environmental advantage of the FCV over the HV in terms of WtW GHG emissions depends upon the selection of a

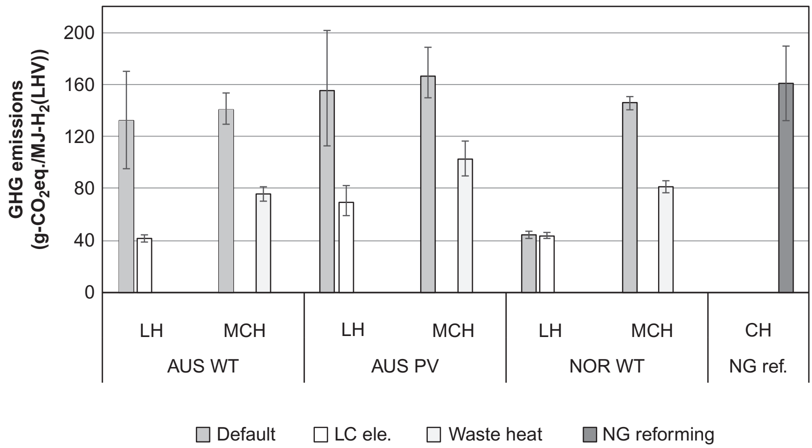

FIG. 15.10 WtT GHG emissions variation of hydrogen.

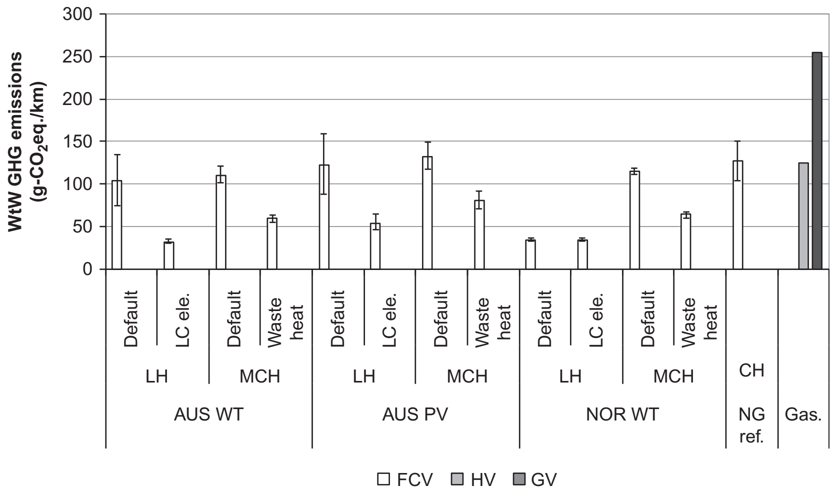

FIG. 15.11 WtW GHG emissions variation of the target vehicles.

low-carbon hydrogen supply chain and the TtW performance of both vehicles. Given the TtW performance of the vehicles shown in Table 15.2 and the calculated WtT GHG emissions from gasoline, it was calculated that the WtT GHG emissions from hydrogen should be lower than 158 g-CO_2eq./MJ, if the FCV was to have a GHG advantage over the HV.

15.5 CONCLUSIONS

In order to understand the role of hydrogen in mitigating GHG emissions in the automobile sector, a Japanese WtW analysis was conducted to evaluate the

GHG emissions profile of a FCV supplied with imported renewable hydrogen and domestically-produced NG reforming hydrogen and compared with the WtW emissions of a HV and GV as conventional counterparts. A LCI analysis was conducted using the energy and material input data to the processes comprising the automotive fuel pathways as the foreground data, and the Japanese LCA database IDEA as the background data.

The results indicate that in terms of GHG emissions the FCV had the advantage over the GV, but whether the FCV could prevail over the HV depends upon the choice of low-carbon hydrogen supply chain and TtW performance. It was identified that the main GHG hotspots of the renewable hydrogen pathways were hydrogen liquefaction for the LH supply chain and dehydrogenation for the MCH supply chain. Thus, innovations in technology development and process design are indispensable for the renewable hydrogen supply chain from overseas, if hydrogen is intended to contribute to GHG mitigation as one of the promising automotive fuels. Another important technological opportunity for the FCV to compete with the GHG profile of the HV is to improve energy consumption performance of the FCV.

In the context of using hydrogen as a secondary energy in the energy system, there are other technological options to produce hydrogen from other resources and transport hydrogen using other hydrogen carriers. In Japan, for example, another potentially feasible option is to produce hydrogen from brown coal with the combination of carbon capture and storage technologies (The Australian, 2016). Using ammonia as a hydrogen carrier or energy is another potential technology to reduce GHG emissions (Ammonia Energy, 2017). Conducting LCI studies of these hydrogen supply chains should prove useful in providing technological opportunities to reduce the environmental footprints from the life cycle perspective.

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