MIZUHO

Life Cycle Greenhouse Gas Emissions Analysis Report of Hydrogen Supply Chain

Executive Summary

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Table of Contents

1. Goal of the study

1.1 Reasons for carrying out the study

With the launch of commercial fuel cell vehicles (FCVs), new propulsion options have emerged alongside conventional gasoline and hybrid vehicles. In addition, automotive fuels are becoming increasingly diversified. While hydrogen-powered FCVs present the advantage of not emitting greenhouse gases (GHGs) during driving, GHGs are emitted during hydrogen production pathways. Since the amount of GHG emissions produced varies with energy sources and hydrogen production pathways, this Well-to-Tank study was conducted to quantitatively clarify the GHG emissions characteristic of different hydrogen production pathways, and to consider future possibilities for reducing emissions.

1.2 Intended applications

This study was conducted to demonstrate to organizations involved in the production, supply, and use of hydrogen, and to FCV users the differences in GHG emissions between the various hydrogen production pathways. It also aims to promote the development of technologies for reducing GHG emissions, as well as the increased adoption of hydrogen production methods with lower GHG emissions.

1.3 Intended audiences

Organizations involved in the production, supply, and use of hydrogen, and FCV users

2. Scope of the study

2.1 Functional unit

This study evaluates the production pathways of hydrogen to be supplied to FCVs. The hydrogen evaluated herein needs to satisfy the quality requirements for refueling FCVs, and is assumed to be in conformance with the international standards of hydrogen fuel for FCVs (ISO 14687-2: 2012), as indicated in the table below.

Table 2.1 Standards of hydrogen fuel for FCVs, according to ISO 14687-2: 2012 (excerpt)

Characteristics	Standards
Hydrogen fuel index (Minimum mole fraction)	99.97 % -
Total hydrocarbons (Methane basis)	- 2 ppm
H_2O	- 5 ppm
O_2	- 5 ppm
He	- 300 ppm
Ar, N_2	- 100 ppm
CO_2	- 2 ppm
CO	- 0.2 ppm

Source: Tomioka [2013]

For this study, the amount of hydrogen required for the same FCV model to travel a certain distance within Japan was defined as a functional unit. Specifically, refueling the fuel tank of an FCV with 1 Nm^3 of hydrogen gas was defined as the reference flow.

2.2 System boundary

The system boundary for this study is shown in Figure 2.2. In this study, the energy used in all of the processes concerning hydrogen intended for use as automotive fuel, from mining and production to transport and storage of the feedstock, the production of hydrogen (conversion of the feedstock to hydrogen), and the transport and storage of hydrogen up to the time of FCV refueling was evaluated. However, the manufacturing, assembly, and disposal processes of the devices used in each process were considered to be outside of the system boundary.
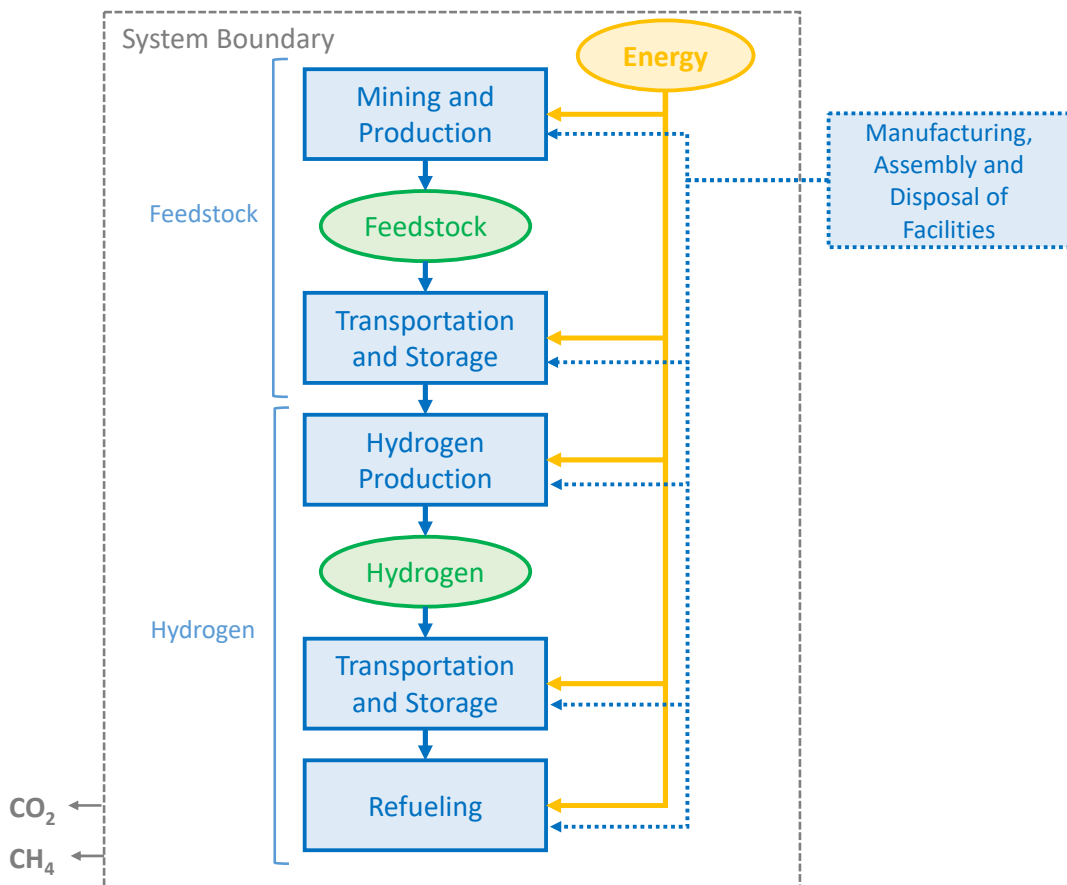
Figure 2.2 System boundary in this study

The process flow diagrams of the nine hydrogen production pathways evaluated in this study are shown in Figures 2.3 to 2.11.

Mining → Crude gas → Refining & liquefaction → LNG → Offshore transport (overseas) → City gas production

City gas → Desulfurization & reforming → Refining (PSA) → H_2 → Compression & storage → Refuelling →（FCV）
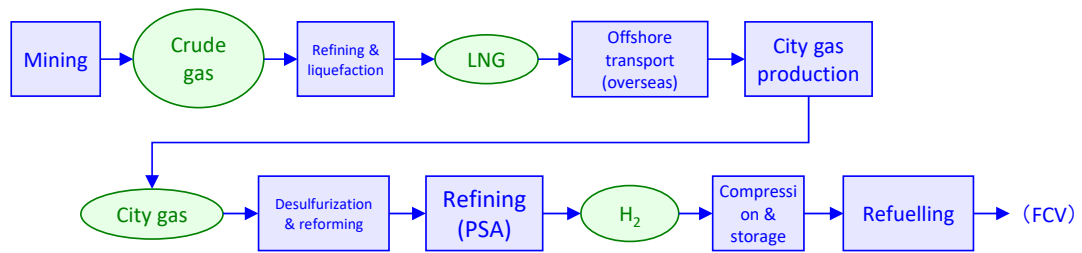
Figure 2.3 Hydrogen production pathway by onsite city gas reforming

Mining → Crude gas → Refining & liquefaction → LNG → Offshore transport (overseas) → Reforming

Refining (PSA) → H_2

Compression → Onshore transport (domestic) → CH_2 storage

Liquefaction → Onshore transport (domestic) → LH_2 storage

→ Refuelling →（FCV）
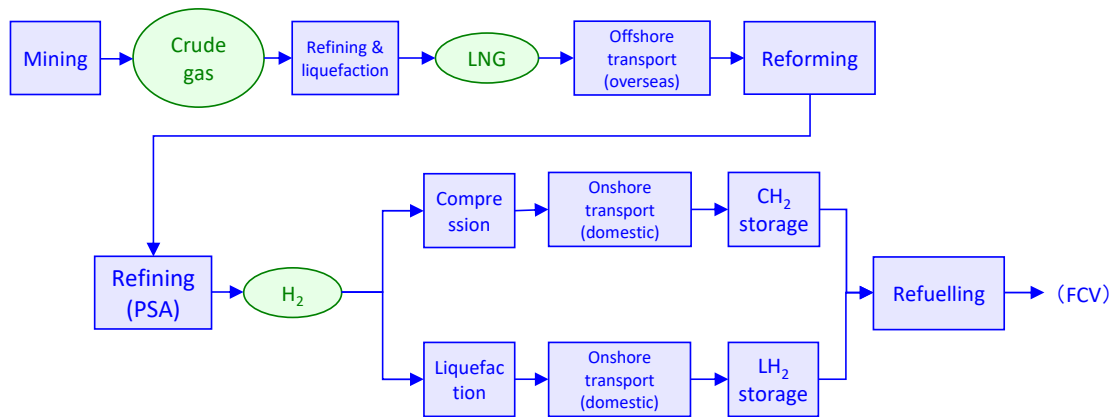
Figure 2.4 Hydrogen production pathway by offsite natural gas reforming and transport of compressed hydrogen (CH_2) or liquid hydrogen (LH_2)

Chloralkali electrolysis (by-product) → H_2

Compression → Onshore transport (domestic) → CH_2 storage

Liquefaction → Onshore transport (domestic) → LH_2 storage

→ Refuelling →（FCV）
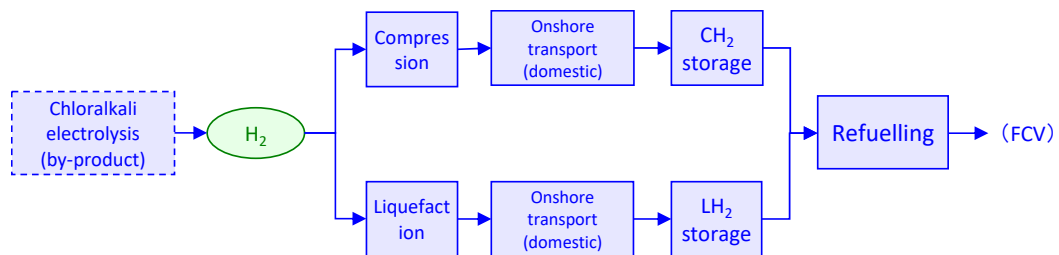
Figure 2.5 Hydrogen production pathway as by-product from Chloralkali electrolysis and CH_2 or LH_2 transport

Sewage treatent process → Sewage biogas → Siloxane removal → Membrane Separation → Methane gas

Reforming → Refining (PSA) → H_2 → CHG storage → Refuelling →（FCV）
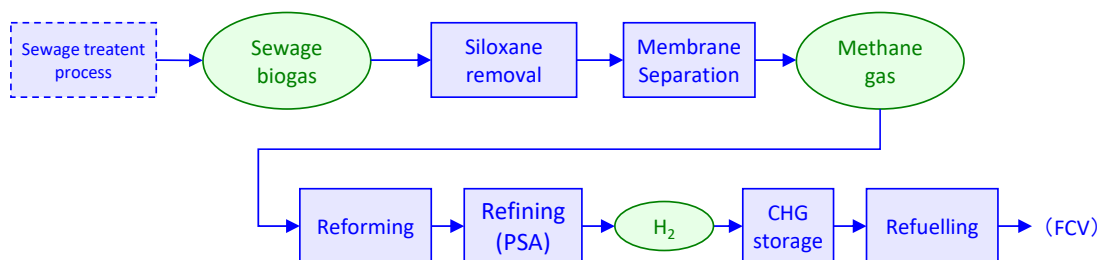
Figure 2.6 Hydrogen production pathway by onsite biogas reforming using sewage sludge
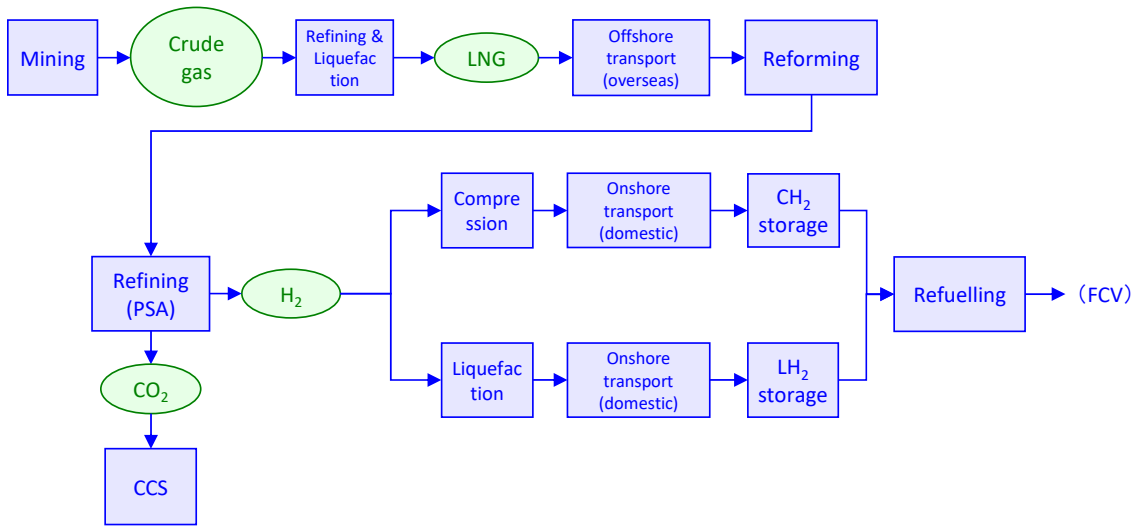
Figure 2.7 Hydrogen production pathway by offsite natural gas reforming with Carbon Capture and Storage (CCS), and CH_2 or LH_2 transport
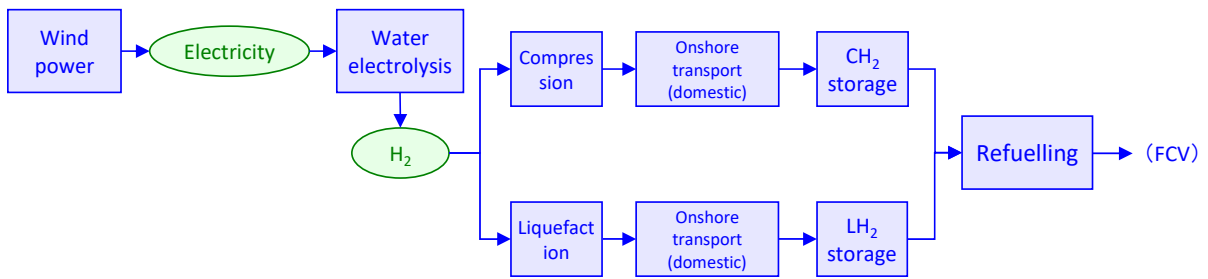
Figure 2.8 Hydrogen production pathway by offsite water electrolysis with wind power, and CH_2 or LH_2 transport
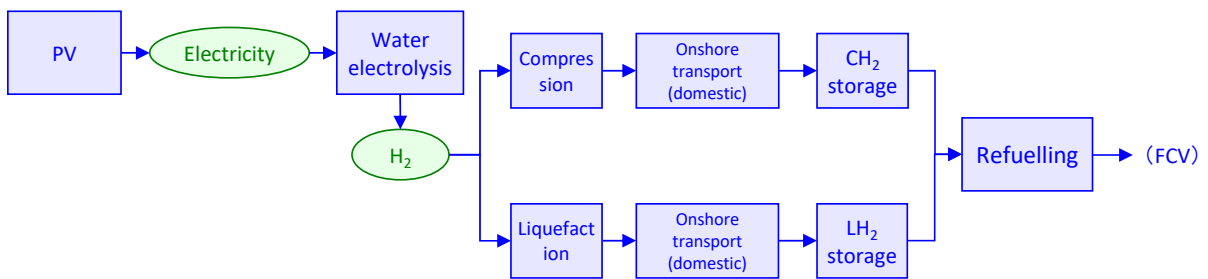
Figure 2.9 Hydrogen production pathway by offsite water electrolysis with photovoltaic power (PV), and LH_2 transport
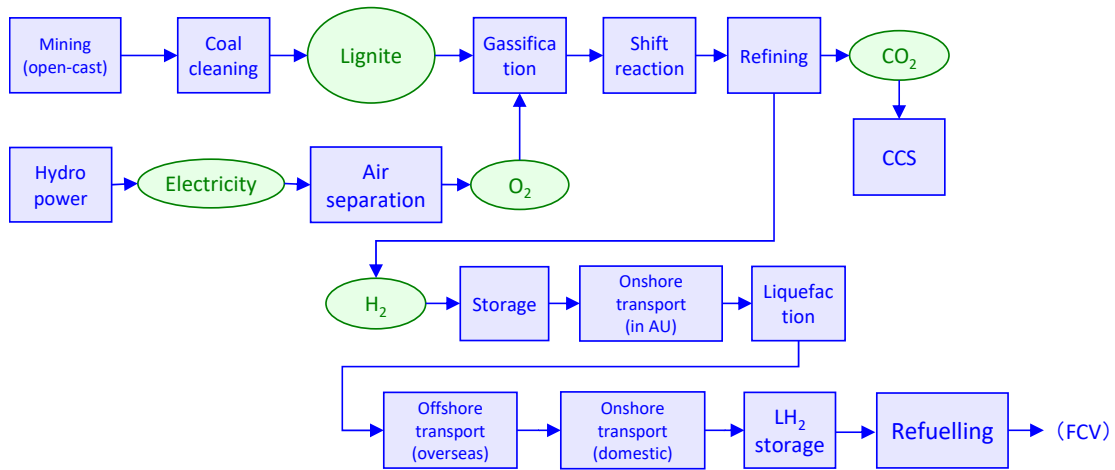
Figure 2.10 Hydrogen production pathway by overseas lignite reforming with CCS, and LH$_2$ transport
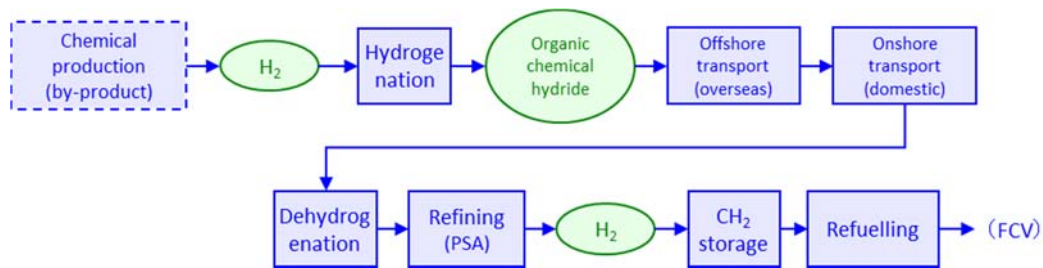
Figure 2.11 Hydrogen production pathway as by-product from the overseas chemical production process, and transport of organic chemical hydride (OCH)

2.3 Environmental burdens

The following were defined as environmental burdens in this study.

- Air emissions (CO$_2$, CH$_4$)

In line with the goal of this study, only the above environmental burdens were evaluated. All other air emissions and environmental burdens (e.g., resource and energy consumption) were excluded from this study.

2.4 Quantification of GHG emissions due to energy consumption and power generation

This study employed life cycle data that included not only emissions from the combustion process, but also from the upstream process (from the mining of raw materials to transport to the combustion site) for GHG emissions (CO$_2$ equivalents) per unit heating value (LHV) of fossil fuels.

In this study, GHG emissions due to power generation were obtained by calculating the average values for Japan, using data on the primary energy consumption in the power generation sector and the power supply (i.e., receiving-end generation after subtracting self-consumption and transmission losses from the total power generated) given in the "General Energy Statistics of Japan" (FY2013 results). GHG emissions during the upstream process for the fuels used to generate power were also included.

3. Life Cycle Inventory (LCI) Analysis

3.1 Data collection

For this study, input/output data was collected for the processes that comprise each of the nine hydrogen production pathways covered herein. While existing published literature values (secondary data) are used as a base, we also conducted interview surveys with relevant companies and industry associations to obtain primary data that is not available to the public.

The procedures described below were used to collect data for the nine hydrogen production pathways.

3.1.1 Onsite city gas reforming

(1) Production and liquefaction of crude gas

Data on GHG emissions during the production (mining and refining) and liquefaction of crude gas for ship transport of natural gas were obtained from Okamura *et al*. [2004].

(2) LNG transport by ship

To obtain fuel consumption during the ship transport of LNG, the fuel consumption intensity per t-km was calculated from the data on fuel consumption and LNG load for one-way transport, as well as the transport distance obtained from interviews to industry associations. Fuel consumption per transport volume of LNG was then calculated using data on the weighted-average transport distance, which reflected the import volume of LNG for city gas by region, as obtained from interviews to related companies.

(3) City gas production

Data on GHG emissions from the city gas production process was obtained from Okamura *et al*. [2004]. Although the cited document takes into account the reduction in GHG emissions due to LNG cold energy utilization, the data in this study was calculated so as to omit this effect, since the utilization of cold energy is not directly related to the fuel production process.

(4) City gas reforming

The values (improved case with a reforming efficiency of 80%) in NEDO [2003] were used for city gas consumption at onsite hydrogen stations.

Data on power consumption during reforming and hydrogen refining was obtained from PEC *et al*. [2011].

(5) Hydrogen compression and refueling for delivery

The FCV tank refueling pressure was set to 70 MPa for the calculation, which is the most common value. Data on power consumption during compression and utility pre-cooling were obtained from PEC *et al*. [2011].

3.1.2 Offsite natural gas reforming and transport

(1) Production and liquefaction of crude gas

Data on GHG emissions during the production (mining and refining) and liquefaction of crude gas to be used in offsite natural gas reforming were obtained from Okamura *et al*. [2004].

(2) LNG transport by ship

To obtain the fuel consumption during the ship transport of LNG, the fuel consumption intensity per t-km was calculated as in the case of onsite city gas reforming. Fuel consumption per transport volume of LNG was then calculated using data on the weighted-average transport distance, which reflected the average import volume of LNG by region, as obtained from interviews to related companies.

(3) Natural gas reforming

According to information obtained from interviews to related companies, the current efficiency of offsite natural gas reforming is nearly the same as for onsite city gas reforming, and future efficiency would be expected to be at around 80% even if technological improvements were taken into consideration. Therefore, the same values as those used for onsite city gas reforming were used in this study.

(4) CH_2 transport

Hydrogen produced by natural gas reforming is transported to refueling stations in a highly compressed, high-density gas form. Due to the deregulation of hydrogen transport, hydrogen trailers with a CH_2 pressure of 45 MPa are commercially available. However, due to a lack of specific data on the transport process, 19.6 MPa was used in the calculations, as in Toyota and MHIR [2004].

A 100-km round-trip distance was also used here, under the assumption that the primary destinations were located within the Kanto region.

(5) Hydrogen compression and refueling for delivery (CH_2 transport)

As in the case of onsite city gas reforming, the refueling pressure in FCV tanks was set to 70 MPa, and the data on the power consumption for compression and utility pre-cooling was obtained from PEC [2011].

(6) LH_2 transport by land

Hydrogen produced by natural gas reforming can be transported to refueling stations also in a high-density liquid form. Data on power consumption for liquefaction was obtained from IAE *et al.* [2009].

To avoid underestimates, the fuel efficiency of a lorry during LH_2 transport was set at 3.5 km/L-diesel in this study, based on the data obtained from interviews to related companies (3.5 to 4.0 km/L-diesel). As in the case of CH_2 transport, a 100-km round-trip distance was also used here, based on the assumption of transport within the Kanto region.

(7) Hydrogen compression and refueling for delivery (LH_2 transport)

This study assumes all FCVs to be equipped with a hydrogen gas storage tank. Therefore, it was assumed that LH_2 is gasified and pressurized to refuel FCVs at 70 MPa. Data on power consumption for compression was obtained from IAE *et al.* [2009]. Although specific data on power consumption for pre-cooling in refueling LH_2 was not available, according to information obtained from interviews to related companies, the power consumption for pre-cooling is nearly the same as that for CH_2. Therefore, the data in JPEC *et al.* [2011] was used in this report.

3.1.3 Offsite chloralkali electrolysis and transport

(1) Chloralkali electrolysis

Hydrogen produced by the Chloralkali electrolysis pathway is obtained as a by-product of sodium hydroxide production. In this study, it was assumed that by-product hydrogen that is not currently utilized effectively is put to use. Accordingly, the production process of sodium hydroxide, which is the main product, was considered to be outside of the system boundary.

(2) CH_2 transport

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(3) Hydrogen compression and filling for delivery (CH_2 transport)

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(4) LH_2 transport by land

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

(5) Hydrogen compression and refueling for delivery (LH_2 transport)

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

3.1.4 Onsite biogas reforming using sewage sludge

(1) Membrane separation

In this process, CO_2 is removed from biogas generated at a sewage treatment plant using a membrane separation device, and high-concentration methane gas is captured. The power consumption for membrane separation was set based on the information obtained from interviews to related companies.

This study assumes that hydrogen is produced using biogas generated as a by-product at sewage treatment plants. Accordingly, the process that generates biogas (the treatment process at the sewage plant) was considered to be outside of the system boundary.

(2) Other processes

The power consumption for the removal of siloxane (gas cooling and pressurization) was set based on the information obtained from interviews to related companies.

The introduced amount of methane gas and power consumption for the reforming and refining of methane gas, as well as the compression and refueling processes were set to be the same as in the pathway using onsite city gas reforming.

3.1.5 Offsite natural gas reforming with Carbon Capture and Storage (CCS), and transport

(1) Production and liquefaction of crude gas, LNG transport by ship, and natural gas reforming

Same setting as the pathway by offsite natural gas reforming.

(2) CCS

In the natural gas reforming pathway with CCS, CO_2 is separated and captured from the flue gas after reforming, and then compressed and transported to the storage site, after which it is injected deep underground. Since additional energy such as electricity and fuel is consumed during the CCS process, the actual reduction in CO_2 emissions due to CCS were obtained by subtracting the CO_2 emissions caused by the CCS process from the total amount of stored CO_2.

Based on the previous LCA study on the CCS process (Tang *et al.* [2013]), it was assumed that CO_2 emissions from the flue gas after reforming could be reduced by 80% through the CCS process.

(3) CH_2 transport

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(4) Hydrogen compression and refueling for delivery (CH_2 transport)

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(5) LH_2 transport by land

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

(6) Hydrogen compression and refueling for delivery (LH_2 transport)

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

3.1.6 Offsite water electrolysis with wind power and transport

(1) Wind power

In this study, GHG emissions generated during the life cycles of all of the devices that comprise the hydrogen production pathways (device manufacturing, assembly, disposal, etc.) were not included. Since wind power generation does not generate GHGs, it was assumed that no GHGs are emitted during the power generation process.

(2) Water electrolysis

The efficiency and power consumption of water electrolysis were set with reference to the data in Japan Automobile Research Institute (JARI) [2011].

(3) CH_2 transport

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(4) Hydrogen compression and refueling for delivery (CH_2 transport)

Same setting as the pathway by offsite natural gas reforming and CH_2 transport.

(5) LH_2 transport by land

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

(6) Hydrogen compression and refueling for delivery (LH₂ transport)

Same setting as the pathway by offsite natural gas reforming and LH₂ transport.

3.1.7 Offsite water electrolysis with photovoltaic power and transport

(1) Photovoltaic power

As in the case of wind power, since photovoltaic power (PV) generation does not emit GHGs, it was assumed that no GHGs are emitted during the power generation process.

(2) Water electrolysis

Same setting as offsite water electrolysis with wind power.

(3) CH₂ transport

Same setting as the pathway by offsite natural gas reforming and CH₂ transport.

(4) Hydrogen compression and refueling for delivery (CH₂ transport)

Same setting as the pathway by offsite natural gas reforming and CH₂ transport.

(5) LH₂ transport by land

Same setting as the pathway by offsite natural gas reforming and LH₂ transport.

(6) Hydrogen compression and refueling for delivery (LH₂ transport)

Same setting as the pathway by offsite natural gas reforming and LH₂ transport.

3.1.8 Overseas lignite reforming with CCS, and LH₂ transport

Lignite, a kind of low-grade coal, accounts for roughly 20% of all recoverable coal resources, worldwide. It is used in limited areas near mining districts, since it is prone to spontaneous combustion and its high water content makes it inefficient to a long-distance transport. To use lignite as energy in other areas, one solution under consideration is the combination of gasification and refining of lignite to produce hydrogen. This method would make it possible to transport the energy contained in lignite safely and efficiently, allowing the resource to be used effectively.

In this study, GHG emissions were calculated based on data from KHI [2012-1] and data obtained from interviews to related companies for the pathway in which brown coal is gasified to produce hydrogen in Australia, CCS is implemented, and the produced hydrogen is transported to Japan as LH₂.

(1) Mining and cleaning of lignite

Data on energy consumption in the mining and cleaning process of lignite was obtained from interviews to related companies. It was assumed that electricity is supplied entirely by local hydro-electric generation.

(2) Lignite gasification, reforming, CCS, and liquefaction

Based on the data in KHI [2012-1] and information from interviews to related companies, the annual hydrogen production volume, as well as lignite, fuel (natural gas), and power consumption at lignite gasification, reforming and liquefaction plants were estimated.

CO_2 generated by the gasification of lignite and the combustion of natural gas is separated and captured from the flue gas at a capture rate of 95%. The residual gas after separating CO_2 is then combusted, together with natural gas in a boiler and CO_2 is captured from the gas at a capture rate of 90%.

The electricity consumed at lignite gasification, reforming and liquefaction plants was assumed to be supplied by local hydro-electric generation.

(3) LH_2 transport (by land in Australia) and ship loading

LH_2 produced at a lignite gasification, reforming and liquefaction plant is transported by lorries to a port-side loading base and transferred to LH_2 carrier ships. Fuel and power consumption by LH_2 lorries and at the loading base were estimated, based on the data in KHI [2012-1] and information from related companies. The electricity consumed at the loading base was assumed to be supplied by local hydro-electric generation.

(4) LH_2 transport (by ship) and unloading

Ship transport of LH_2 is considered to be a means of transporting large volumes of hydrogen. Since LH_2 has a cryogenic temperature of -253 degrees centigrade under normal pressure, it is necessary to develop dedicated carrier ships equipped with low-temperature insulated tanks. This study refers to the data in KHI [2012-1] and KHI [2012-2], as well as that obtained from interviews to related companies.

Boil-off gas (BOG) is generated at a rate of 0.2% per day during transport by ship using LH_2 carriers. Since BOG is consumed as fuel by carriers, the net transported volume of LH_2 was calculated by subtracting the BOG generated during transport from the loaded volume.

It was assumed that the electricity consumed at unloading bases is supplied by the electricity grid in Japan.

(5) LH_2 transport (by land in Japan)

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

(6) Hydrogen compression and refueling for delivery

Same setting as the pathway by offsite natural gas reforming and LH_2 transport.

3.1.9 By-product hydrogen from the overseas chemical production process, and transport of organic chemical hydride

(1) Chemical production

This study assumed that by-product hydrogen that is not currently utilized effectively at overseas chemical plants is put to use. Accordingly, the production process for chemicals, which is the main product, was considered to be outside of the system boundary.

(2) Transport of organic chemical hydride (by ship)

Organic chemical hydride is used as a storage medium in hydrogen transport, where hydrogen is chemically fixed to an aromatic organic compound such as toluene through hydrogenation. Hydrogen is then transported as a liquid chemical, such as methylcyclohexane at normal temperature and pressure, and separated from methylcyclohexane through dehydrogenation onsite.

In this study, a toluene/methylcyclohexane combination, which is expected to be the closest to that in practical use, is assumed for hydrogen offshore transport. Data on energy consumption for hydrogenation was obtained from interviews to related companies.

The use of chemical tankers was assumed for transport by ship, and the fuel efficiency (0.19 g-C heavy oil/km-GJ hydrogen) obtained from interviews to related companies was used.

(3) Transport of organic chemical hydride (by land)

In this study, with regard to the pathway with transport of organic chemical hydride, it was assumed that organic chemical hydride is transported directly to hydrogen stations and dehydrogenated at the hydrogen stations.

Tank lorries commonly used for transporting petrochemical products are used for the domestic transport of organic chemical hydride. In this report, fuel efficiency of tank lorries was set based on information obtained from interviews to related companies.

Energy consumed during dehydrogenation and refining was based on data obtained from interviews to related companies. Since a part of the hydrogen that has undergone the dehydrogenation and refining process is captured as the flue gas by the PSA process and self-consumed as the heat energy necessary for dehydrogenation, the GHG emissions of the hydrogen production and transport (by ship or land) processes were evaluated so as to take such self-consumption into account.

(4) Hydrogen compression and refueling for delivery

Same setting as the pathway using by offsite natural gas reforming and CH_2 transport.

3.2 Data calculation

The method described in 2.4 was consistently used to calculate the GHG emissions from each unit process. In particular, the energy input into each unit process was converted into a GHG emission from that unit process by multiplying the input amount of fossil fuel, etc. by the GHG emission per MJ of the fuel type, while for electrical power the input amount was multiplied by the GHG emission per kWh.

3.3 Sensitivity analysis for refining the system boundary

This study omitted the following processes from evaluation.
- All processes that comprise the life cycles of devices used in a hydrogen production pathway.

A sensitivity analysis was carried out to verify whether the omitted processes are significant, in light of the goal of this study. The results of this sensitivity analysis are presented in 5.2.1.

3.4 Allocation principles and procedures

3.4.1 Documentation and justification of allocation procedures

In this study, environmental burdens were not allocated in all processes.

Regarding by-product hydrogen, this study assumed that excess hydrogen that is not utilized effectively is put to use as FCV fuel, and there is no allocation of the environmental burdens caused by the production process of the main product.

However, as the demand for hydrogen grows in the future, the case may arise in which hydrogen that is already being utilized effectively in another application is diverted to energy use. A sensitivity analysis was therefore carried out for cases where burdens are allocated according to the following three approaches (see 5.2.2 for the sensitivity analysis results).

(i) Fossil fuel is used as an alternative fuel in place of extracting by-product hydrogen as a product (i.e., when by-product hydrogen is being used as energy)

(ii) Burdens are allocated between the main product and the by-product hydrogen according to physical quantity (kg)

(iii) Burdens are allocated between the main product and the by-product hydrogen according to economic value (yen)

3.4.2 Application of allocation procedures

The allocation procedures described in 3.4.1 were uniformly applied to the following three inputs and outputs.

- The hydrogen production pathway as by-product from Chloralkali electrolysis and CH_2 or LH_2 transport
- The hydrogen production pathway as by-product from the overseas chemical production process, and transport of OCH

4. Life Cycle Impact Assessment (LCIA)

4.1 LCIA procedures, calculations and results

In this study, LCIA was implemented according to the following procedures.
  (i) Selection of impact categories, category indicators, and characterization models
  (ii) Assignment of LCI results to the selected impact categories (classification)
  (iii) Calculation of category indicator results (characterization)
The steps indicated below, which follow characterization were not implemented.
  (iv) Normalization
  (v) Grouping
  (vi) Weighting
The category indicator results were calculated by multiplying the LCI results assigned to the selected impact category by a characterization factor (relating to the impact category). The results are summarized in 5.1.2.

4.2 Selection of impact categories and category indicators

LCIA was implemented for the following impact category and category indicator, which have been selected in light of the reasons for carrying out this study (see 1.1).

Impact category:	Climate change
Category indicator:	Infrared radiative forcing (W/m^2)

4.3 Selection of characterization models, characterization factors, and methods used

The following characterization model and characterization factor were used for the impact category selected in 4.2.

Impact category:	Climate change
Characterization model:	The 100-year baseline model of the Intergovernmental Panel on Climate Change
Characterization factor:	Global warming potential (GWP)
Category indicator result:	Σ (GHG emissions [kg] $\times$ global warming potential [kg-CO_2e/kg])

The above characterization model was selected in this study due to its frequent use in previous LCA studies.

4.4 Limitations of the LCIA results relative to the defined goal and scope of the LCA

The LCIA results in this study are based on the LCA results calculated for the defined system boundary, and do not include all of the environmental burdens (i.e., that affect climate change) generated through the life cycle of each hydrogen production pathway studied in this study.

4.5 Relationship of LCIA results to the defined goal and scope

The category indicator result relating to climate change was selected as the LCIA result in order to be consistent with the reasons for carrying out this study, which is to quantitatively clarify the GHG emissions of different hydrogen production pathways.

4.6   Relationship of the LCIA results to the LCI results

The assignment of the LCI results to the selected impact categories in calculating the LCIA results is shown in Table 4.1. The characterization factors for each of the impact categories used in this study are shown in Table 4.2.

Table 4.1 Assignment of LCI results to selected impact categories (classification)

Impact category	Environmental burdens
Climate Change	CO_2
	CH_4

Table 4.2 Characterization factors for climate change

Environmental burdens	GWP [kg-CO_2e/kg]
CO_2	1
CH_4	28

Source: IPCC [2014]

5. Life cycle interpretation

5.1 Results

5.1.1 Life cycle inventory analysis results

The proportions of the environmental burdens (CO_2, CH_4) covered in this study, at each life cycle stage of the hydrogen production pathways are shown in Figure 5.1.

The CO_2 emissions at each life cycle stage differ between the hydrogen production pathways. For the production pathways where hydrogen is produced from fossil fuels, the proportion incurred by the hydrogen production process (either onsite or offsite) is comparatively high, at 50 to 70%, but can be reduced to 20 to 30% by implementing CCS. Meanwhile, for the hydrogen production pathways based on by-product hydrogen, the majority of CO_2 emissions are caused by hydrogen compression and liquefaction for delivery, domestic transport, and the compression and refueling process. For the hydrogen production pathways using renewable energy (wind or solar power), the proportion of emissions incurred by the compression and refueling process is the highest.

Compared to CO_2, the tendency for a high proportion of CH_4 emissions occurs in the upstream process of feedstock. This is because the CH_4 emissions considered in this study are incurred only by the mining process for fossil fuels.
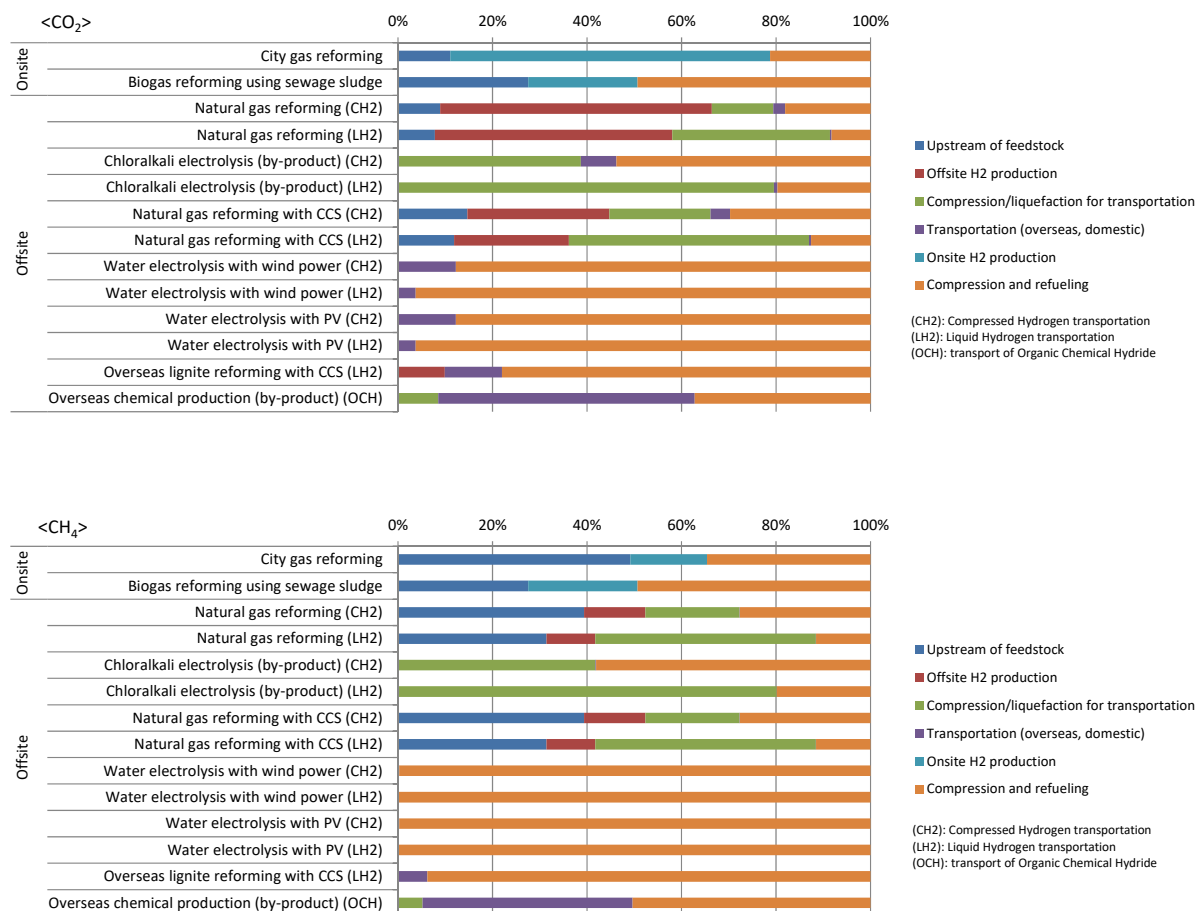

Figure 5.1 Proportions of CO_2 and CH_4 emissions at each life cycle stage of the hydrogen production pathways

5.1.2   Life cycle impact assessment results

The results of the life cycle impact assessment in this study are shown in Figures 5.2 and 5.3.

GHG emissions over the entire life cycle cover between 0.16 and 1.86 kg-CO_2e/Nm^3-H_2, depending on the hydrogen production pathways.

Since those pathways that produce hydrogen from fossil fuels (onsite city gas reforming and offsite natural gas reforming) generate feedstock-derived GHGs during the production of hydrogen, the proportion of GHG emissions during the production stage is high. Although GHG emissions are reduced at the production stage in the pathways where CCS is implemented (offsite natural gas reforming with CCS and hydrogen production by overseas lignite reforming with CCS), since the effect of GHG emission reduction using CCS is not -100% (an efficiency of -80% is assumed for offsite natural gas reforming with CCS), and there are other GHG emissions that cannot be captured by CCS (e.g., emissions due to electrical power used in the production process and emissions during mining of the feedstock), GHG emissions from the production stage do not reach zero.

On the other hand, with hydrogen production pathways that use by-product hydrogen or renewable energy, since GHG emissions during the production stage are zero, emissions are caused only at the transport, storage, and refueling stages (as an exception, in the hydrogen producing pathway by biogas reforming using sewage sludge, GHG emissions are caused by the power consumed when reforming by-product methane into hydrogen).

For offsite hydrogen production pathways, three methods of transporting hydrogen, namely CH_2 transport, LH_2 transport, and transport of OCH, are assumed in this study. Energy consumption and GHG emissions are normally higher for LH_2 transport than for CH_2 transport, in general. However, since the hydrogen production pathways that use renewable energy are assumed to use renewable energy sources to provide power for the liquefaction process, the result is that LH_2 transport, with its superior transport efficiency, has fewer emissions.

When considering the different sources of GHGs, for every hydrogen production pathway aside from onsite city gas reforming and offsite natural gas reforming (without CCS), the highest proportion of GHG emissions is due to the consumption of electrical power. In particular, for Chloralkali electrolysis and the production pathways in which hydrogen is derived from renewable energy, GHG emissions caused by the consumption of electrical power account for over 90% of the total, which indicates that the emission intensity of grid electricity has a significant effect on the GHG emissions of the entire hydrogen production pathways (with the production pathways where hydrogen is derived from renewable energy, there are no GHG emissions due to the electrical power used for hydrogen production, compression and liquefaction for delivery; accordingly, only the GHG emissions caused by electricity consumed by compression and refueling at hydrogen stations are evaluated).

From the above, "energy consumption at the production stage and direct emissions from the feedstock" for the production pathways in which hydrogen is derived from fossil fuels, "energy consumption at the transport, storage, and refueling stages" for production pathways that make use of by-product hydrogen, and "energy consumption at the refueling stage" for production pathways in which hydrogen is derived from renewable energy are specified as important parameters. In addition, "power consumption over the entire life cycle" for every hydrogen production pathway (in particular, production pathways that derive hydrogen from renewable energy) is also specified as an important parameter.
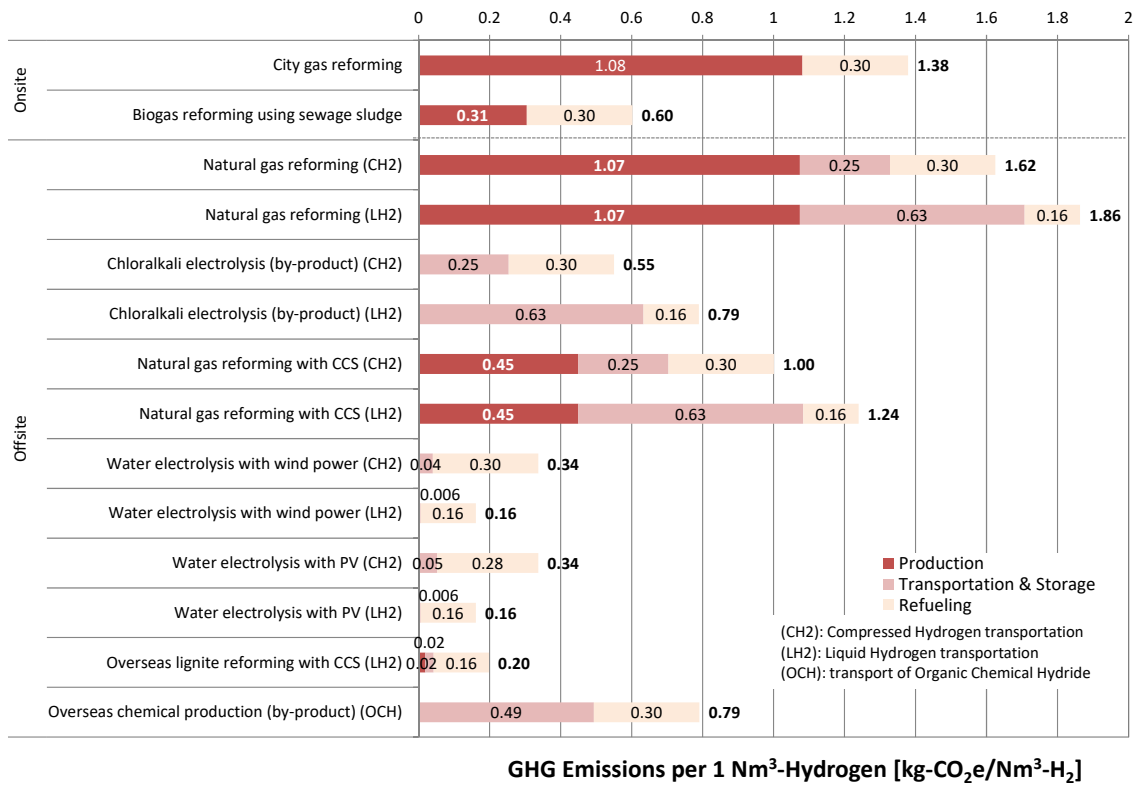
Figure 5.2 Life cycle impact assessment results (by process)
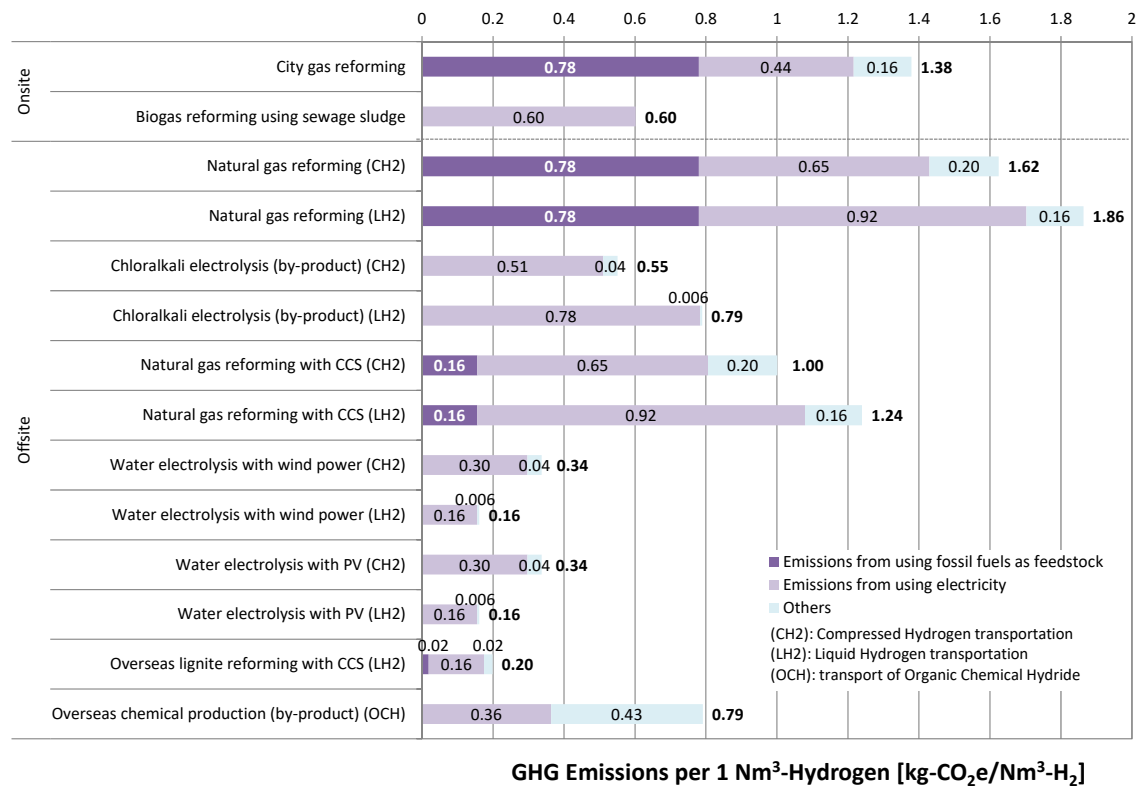

Figure 5.3 Life cycle impact assessment results (by emission source)

5.2   Assumptions and limitations associated with the interpretation of results

5.2.1   Results of sensitivity analysis for refining the system boundary

The degree of influence of the processes omitted in this study on the evaluation results was analyzed, as follows.

While processes related to the life cycle of all of the devices that comprise each of the hydrogen production pathways were not evaluated in this study, the influence resulting from inclusion of the devices related to the feedstock production process in the evaluation was analyzed. Since devices used in the production of hydrogen and the transport, storage, and refueling processes have not yet become commercialized, data relating to the life cycles of such devices could not be obtained. For this reason, a sensitivity analysis regarding the influence of those processes was not carried out.

In this analysis, GHG emissions data for the mining and transport processes of fossil fuels, and for the facility construction process for renewable energy was obtained by referring to Imamura et al. [2010].

From the results of this sensitivity analysis, it was found that for the hydrogen production pathways using city gas or natural gas as a feedstock, the influence of GHG emissions attributable to facility construction in the feedstock production process on the total amount of emissions for the entire hydrogen production pathway is minimal, at 0.1 to 0.3% (see Table 5.1). Based on this result, it is considered that the omission of GHG emissions due to facility construction in the feedstock production process of those hydrogen production pathways that do not use renewable energy exerts little influence on this study.

On the other hand, for those hydrogen production pathways that use renewable energy (wind, PV or hydro-electric power generation), including the GHG emissions due to construction of power generating facilities was found to increase the emissions of the entire hydrogen production pathway by approximately 13 to 110%, thereby demonstrating that the proportion of the total emissions accountable to facility construction is substantially high. As for the hydrogen production pathway of overseas lignite reforming with CCS, emissions due to both the lignite production process and the hydro-electric power generation process are considered as emissions attributable to facility construction; however, the proportion of emissions attributable to facility construction in the lignite production process is small (out of an increase of 13.3%, the lignite production process accounts for 3.9%).

Table 5.1 Contribution of GHG emissions due to facility construction for each hydrogen production pathway

(kg-CO$_2$e/Nm^3-H$_2$)	Onsite	Offsite			
	City gas reforming	Natural gas reforming (CH$_2$)	Natural gas reforming (LH$_2$)	Natural gas reforming with CCS (CH$_2$)	Natural gas reforming with CCS (LH$_2$)
Production	1.08	1.07	1.07	0.45	0.45
Transportation	0.00	0.25	0.63	0.25	0.63
Refueling	0.30	0.30	0.16	0.30	0.16
Subtotal	1.38	1.62	1.86	1.00	1.24
Construction of Facilities	0.003	0.003	0.003	0.003	0.003
Total	1.38	1.63	1.87	1.00	1.24
Increace	0.2%	0.2%	0.1%	0.3%	0.2%

(kg-CO$_2$e/Nm^3-H$_2$)	Offsite				
	Water electrolysis with wind power (CH2)	Water electrolysis with wind power (LH2)	Water electrolysis with PV (CH2)	Water electrolysis with PV (LH2)	Overseas lignite reforming with CCS (LH2)
Production	0.00	0.00	0.00	0.00	0.02
Transportation	0.04	0.01	0.05	0.01	0.02
Refueling	0.30	0.16	0.28	0.16	0.16
Subtotal	0.34	0.16	0.34	0.16	0.20
Construction of Facilities	0.10	0.11	0.15	0.18	0.026
Total	0.44	0.28	0.49	0.34	0.22
Increace	29.2%	70.6%	45.4%	109.9%	13.3%

5.2.2 Results of sensitivity analysis to confirm the influence of the allocation procedures

The following analysis was carried out to confirm the influence of the allocation procedures described in 3.4 on the results of this study.

(1) Analyzed pathways

The following two pathways that use by-product hydrogen were selected.
- The hydrogen production pathway as by-product from Chloralkali electrolysis, and CH$_2$ or LH$_2$ transport
- The hydrogen production pathway as by-product from the overseas chemical production, and process, and transport of OCH

(2) Allocation procedures

Calculations were performed according to the following three procedures.
(i) Fossil fuel is used as an alternative fuel instead of extracting by-product hydrogen as a product (i.e., when by-product hydrogen is being used for energy)
(ii) Burdens are allocated between the main product and by-product hydrogen according to physical quantity (kg)
(iii) Burdens are allocated between the main product and by-product hydrogen according to economic value (yen)

(3)   Data employed

Assuming the use of coal (imported coal for general use), heavy oil, and city gas as the alternative fuels, GHG emissions were calculated for the combustion of the amounts of these fuels having a heat value equivalent to the by-product hydrogen.

Data of Chloralkali process recorded in the LCA system, "MiLCA ver.1.1," provided by the Japan Environmental Management Association for Industry (JEMAI), was used for calculating the GHG emissions in the production process for the main product.

When allocating burdens according to physical quantity, the GHG emissions resulting from the production process for the main product were allocated based on quantitative relationships in chemical reactions.

In addition, when allocating burdens according to economic value, the prices of the main product and the by-product were set as indicated below, and the mass ratio is also considered for the allocation of GHG emissions. The prices of sodium hydroxide, chlorine, and the chemical were set based on export price records for 2015, according to the Trade Statistics of Japan, by the Ministry of Finance. The current typical retail price of hydrogen at a hydrogen station of 1,100 yen/kg was used as the price of hydrogen.

(4)   Results of sensitivity analysis

The results of performing allocation according to the above procedures are shown below.

When alternative fuel use is considered, there is a substantial increase in GHG emissions for every hydrogen production pathway. Compared to the emissions before allocation, the GHG emissions of the entire pathway increase by 2.4 to 3.0-fold when coal is used, 2.2 to 2.7-fold when heavy oil is used, and 2.0 to 2.4-fold when city gas is used as the alternative fuel.

When burdens are allocated according to mass, there is an increase of approximately 1.2-fold for every hydrogen production pathway.

Furthermore, when burdens are allocated according to economic value, while there is an increase of approximately 1.3 to 1.4-fold for the hydrogen production pathway from Chloralkali electrolysis, there is a substantive increase in GHG emissions of approximately 3.7-fold for the production pathway where hydrogen is derived from chemical production. This increase in the hydrogen production pathway from Chloralkali electrolysis is due to the production of large amounts of chlorine as a co-product and the higher price of chlorine, so that most (roughly 90%) of the GHG emissions are allocated to chlorine. On the other hand, the production pathway where hydrogen is derived from chemical production produces no co-products and the price of the chemical is low, so that about 60% of the emissions are allocated to hydrogen.
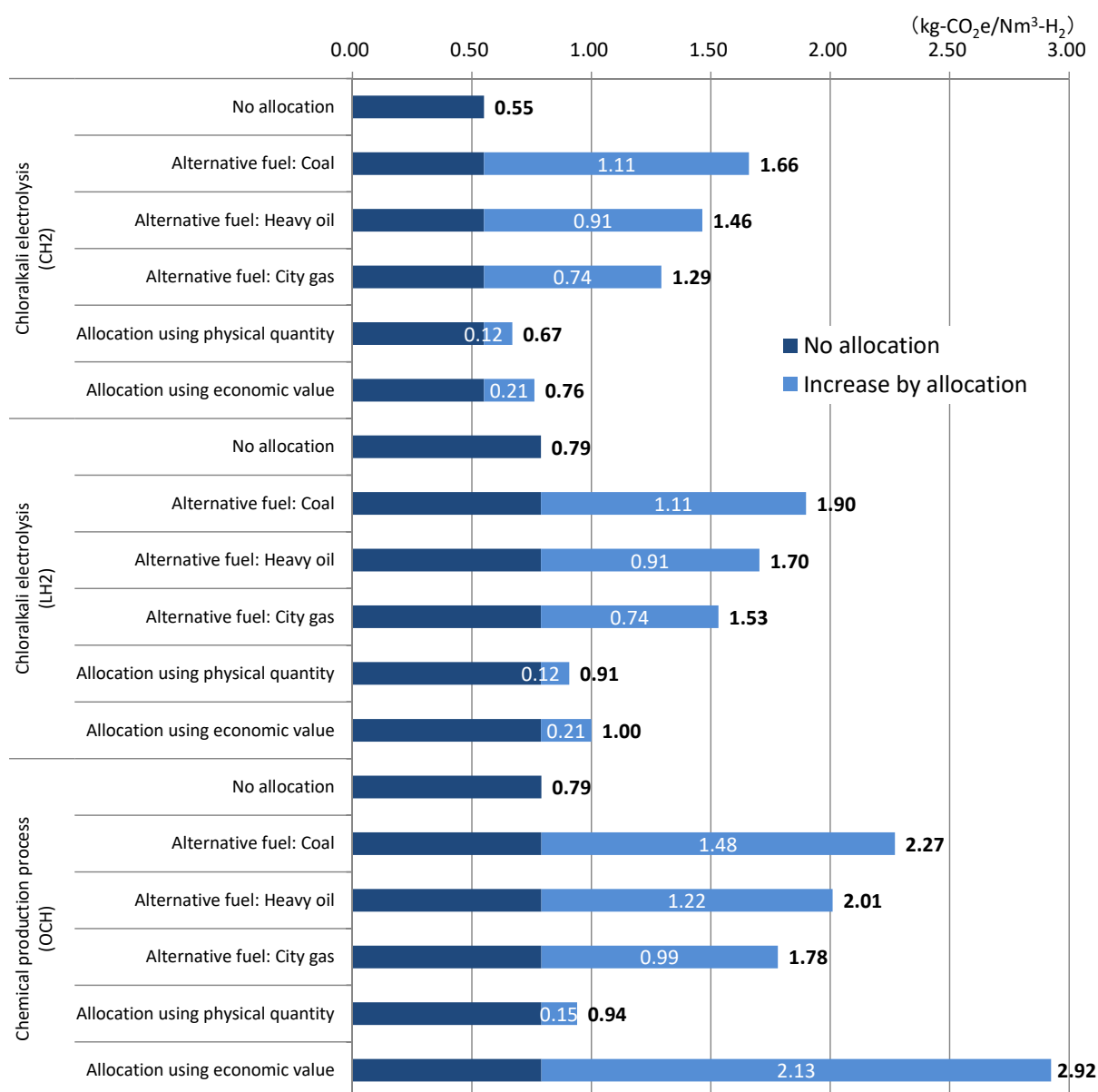
Figure 5.4 Results of sensitivity analysis for the allocation procedures

5.2.3 Results of uncertainty analysis

In this study, "power consumption over the entire life cycle," that is specified as an important factor in 5.1, was analyzed with regard to uncertainty in the emission intensity of domestic grid electricity in the future.

As the lowest emission intensity case, the 2030 target value of 370 g-CO_2/kWh stated in the "Action Plan for the Electricity Industry for Achieving a Low-Carbon Society" announced in 2015 by the Federation of Electric Power Companies of Japan (FEPC) was used. On the other hand, as the highest case, the calculation was performed for a hypothetical emission intensity for grid electricity of 900 g-CO_2/kWh, based on an emission factor of 864 g-CO_2/kWh (Source: Ministry of the Environment [2012]) for coal fired power generation, which is currently the power source with the highest GHG emissions.

The analysis results are shown in Figure 5.5. The influence on the overall GHG emissions of a hydrogen production pathway due to uncertainty in the electric power intensity becomes more prominent as the proportion

of the GHG emissions attributable to electrical power increases. Since LH$_2$ transport has a higher power consumption than CHG transport, it is indicated that the difference between the GHG emissions of LH$_2$ transport and CHG transport may increase even further if the emission intensity of grid electricity increases.
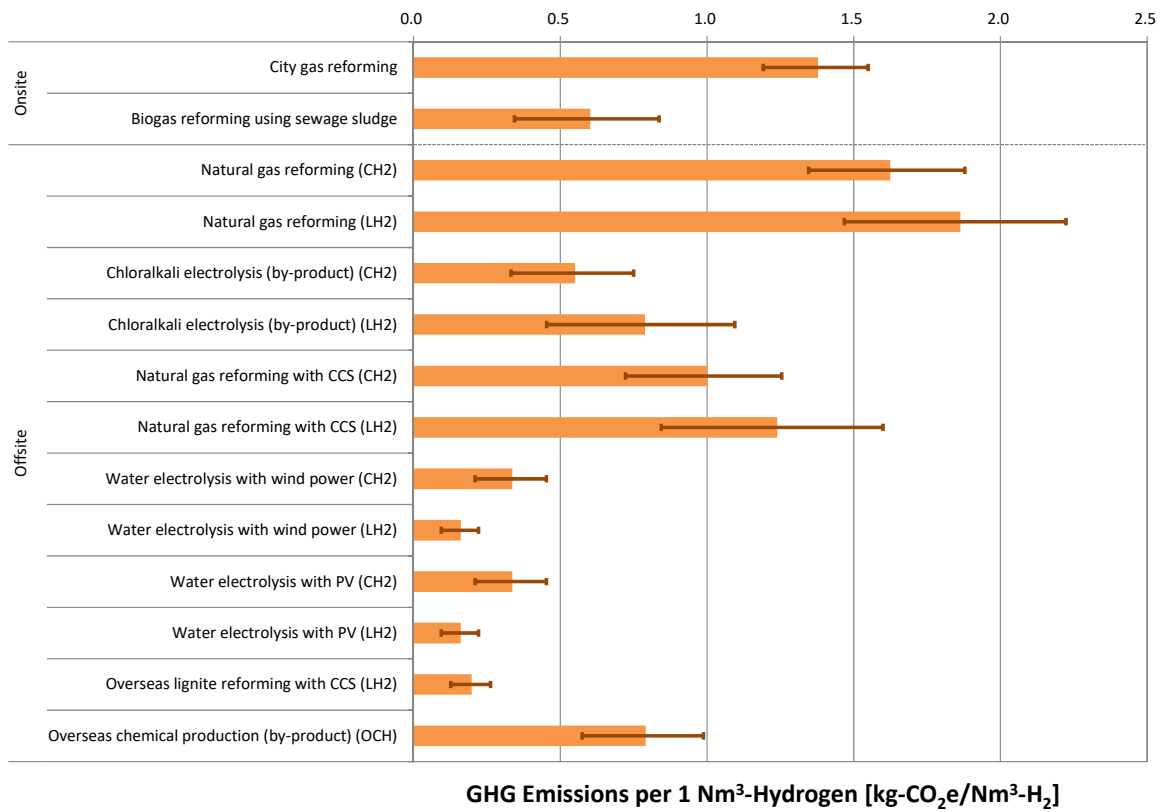

Figure 5.5 Results of uncertainty analysis relating to the emission intensity of grid electricity

6. Summary

This study was conducted to quantitatively evaluate the GHG emissions of different hydrogen production pathways, and to consider future possibilities for reducing the emissions. The reference flow was set as the refueling of an FCV fuel tank with 1 Nm^3 of hydrogen.

GHG emissions over the entire life cycles of the hydrogen production pathways were resulted in between 0.16 to 1.86 kg-CO_2e/Nm^3-H_2. Production pathways that produce hydrogen from fossil fuels have a tendency to have the highest GHG emissions, followed by hydrogen production pathways as by-product. A tendency for production pathways that produce hydrogen from renewable energy (solar or wind power generation) to have the lowest GHG emissions was observed.

When looking at a breakdown of the GHG emissions, it was confirmed that the parameters associated with significant impact for overall GHG emissions in the respective pathways are: "energy consumption at the production stage and direct emissions from the feedstock" for hydrogen production pathways that are fossil fuel-used; "energy consumption at the transport, storage, and refueling stages" for hydrogen production pathways as by-product; and, "energy consumption at the refueling stage" for production pathways where hydrogen is produced from renewable energy. It was also established that "power consumption over the entire life cycle" is an important parameter for every hydrogen production pathway, with this being especially prominent for production pathways that produce hydrogen from renewable energy. These results indicate that reductions in energy consumption by improving efficiency for the devices used in the respective processes, implementing CCS for fossil fuel-used pathways, and reducing GHG emission intensity for grid electricity are important to reduce total GHG emissions for each hydrogen production pathway.

Although processes that form the life cycle of devices comprising the respective hydrogen production pathways lie outside of the system boundary of this study, a sensitivity analysis was conducted to refine this system boundary. As a result, it was demonstrated that GHG emissions due to facility construction for the feedstock production process are extremely low for production pathways that produce hydrogen from fossil fuels, and hardly contribute to the total emissions of these pathways. On the other hand, for hydrogen production pathways using renewable energy, it was demonstrated that the GHG emissions due to the construction of power generating facilities increase the total emissions of the entire hydrogen production pathway by approximately 13 to 110%. This study did not include emissions due to the construction of facilities for the production of hydrogen or due to the transport, storage, and refueling processes, as the relevant data could not be obtained. Accordingly, including such emissions remain a challenge for future study.

This study assumes that excess by-product hydrogen that is not utilized effectively is put to use as FCV fuel, and environmental burdens are not allocated, in principle. However, a sensitivity analysis to apply different allocation procedures was carried out by taking into consideration the case in which by-product hydrogen that is already being utilized effectively is diverted for use as FCV fuel, and results indicated that GHG emissions increase by 2 to 3-fold when alternative fuels are considered. When burdens are allocated according to mass, there is an emissions increase of roughly 1.2-fold, and when burdens are allocated according to economic value, there is an increase of roughly 1.3 to 3.7-fold. In this manner, although wide variation was found regarding the extent of the increase in emissions depending on the selected allocation procedures, GHG emissions were found to increase in every case where allocation was adapted. From these results, it needs to be noted that using by-product hydrogen in the future as a fuel for FCVs will be accompanied by the risk to increase GHG emissions.

The results of this study should provide useful implications to organizations involved in the production, supply, and use of hydrogen, as well as FCV users, when developing technologies aimed at reducing the environmental burdens and selecting hydrogen with the lowest environmental burdens. However, the results given in this report are produced under certain preconditions for only the environmental aspect of climate change, and

therefore do not demonstrate the superiority of particular hydrogen production pathways, when all environmental aspects and other preconditions are considered.

In the future, it will be necessary to conduct as many studies as possible to examine environmental aspects and preconditions aside from those covered, in order to refine this study and make it possible to provide organizations involved in the production, supply, and use of hydrogen, as well as FCV users with more accurate information.
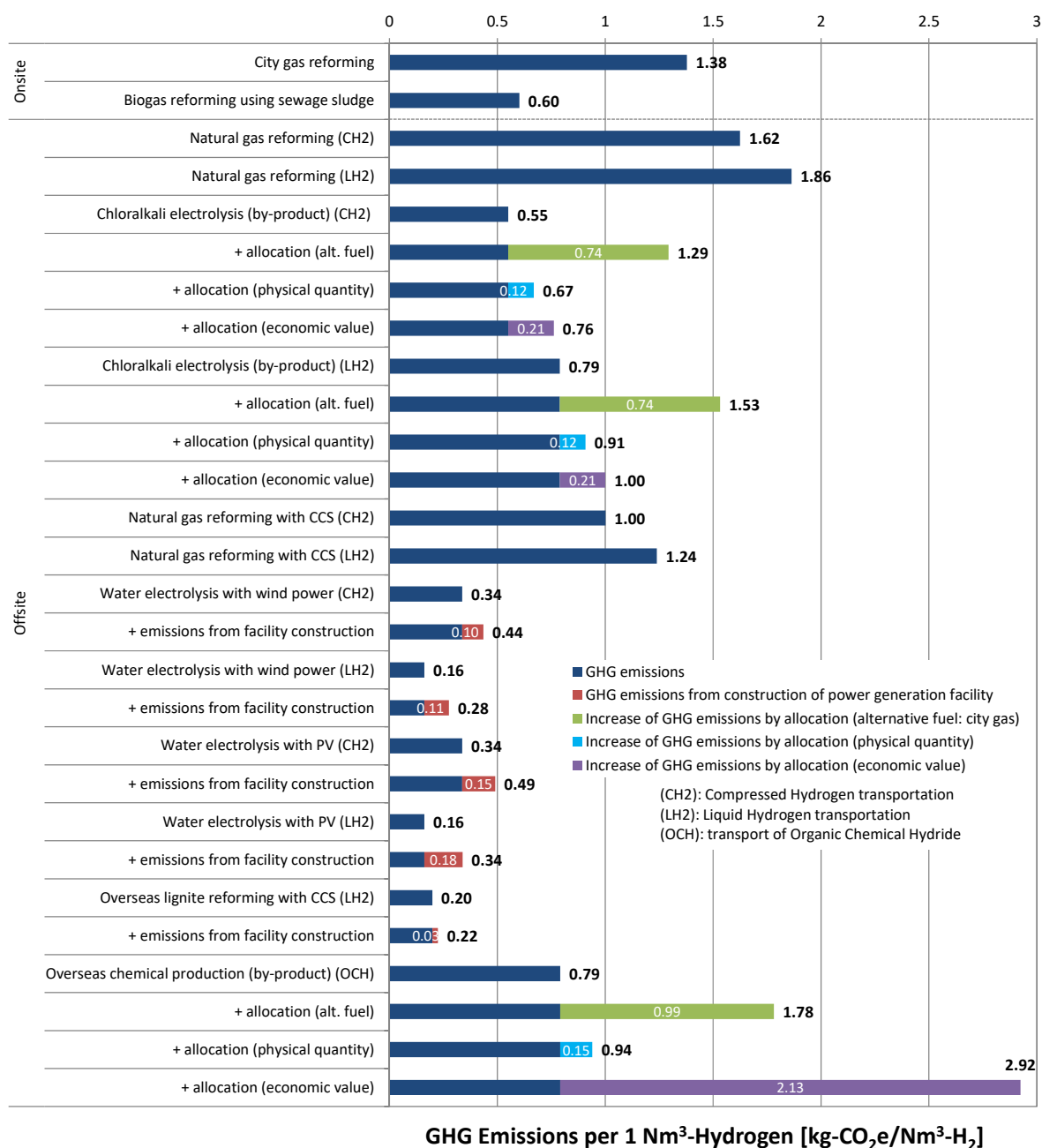

GHG Emissions per 1 Nm³-Hydrogen [kg-CO₂e/Nm³-H₂]

Figure 6.1 List of evaluation results

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