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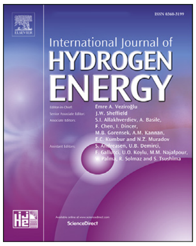

Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea

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ABSTRACT

This study provides methodologies, data collection and results of well-to-wheel greenhouse gas analysis of various H_2 production pathways for fuel-cell electric vehicle (FCEV) in Korea; naphtha cracking, steam methane reforming, electrolysis and coke oven gas purification. The well-to-wheel (WTW) greenhouse gas emissions of FCEV are calculated as 32,571 to 249,332 g-CO_2 eq./GJ or 50.7 to 388.0 g-CO_2 eq./km depending on the H_2 production pathway. The landfill gas (on-site) pathway has the lowest GHG emissions because the carbon credit owing to use landfill gas. The electrolysis with Korean grid mix (on-site) pathway has the highest GHG emissions due to its high emission factor of the power generation process. Furthermore, the results are compared with other powertrain vehicles in Korea such as internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV) and electric vehicle (EV). The averaged WTW result of FCEV is 35% of ICEV, is 47% of HEV, and is 63% of EV.

Introduction

Energy resource depletion and climate change have become global issues, mainly caused by the increased use of fossil fuels and accompanying greenhouse gas (GHG) emissions. One of the most responsible causes is the rapid growth in energy use in the transportation sector [1]. This has led to the development of non-conventional fuels and energy conversion systems for automotive applications, which require new judgment tools to better compare them with their conventional counterparts in terms of environmental friendliness or energy efficiency.

Life cycle analysis (LCA) is a method that estimates the energy use and GHG emissions associated with a product during all stages of its life. Specifically, as a part of LCA for automotive fuels, well-to-wheel (WTW) analysis has been given significant attention and can be divided into two groups of processes: well-to-tank (WTT) and tank-to-wheel (TTW) processes. WTT includes processes such as feedstock recovery, fuel production, fuel storage, distribution to fueling stations and refueling. TTW represents vehicle operation whereby fuel is consumed to power the vehicle. A number of research groups have performed WTW analysis, mostly in the U.S., Canada, and European Union (EU) [2–5].

In Korea, Jang et al., Choi et al., and Kim et al. performed WTW GHG emission analysis on major automotive fuels in Korea, i.e., gasoline, diesel, and compressed natural gas, as well as on newly introduced fuels, i.e., naphtha-based hydrogen and electricity [6–9].

In this study, we focus on the WTW GHG emissions analysis of production pathways of gaseous hydrogen (H_2) fuel for

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fuel-cell electric vehicles (FCEVs) considered in South Korea. According to the specific fulfillment plans of controlling fine dust, there is a plan to expand the number of supplied FCEVs in Korea from 100 in 2016 and to 10,000 in 2020 [10]. The H_2 production pathways, currently in use or expected to be used, are included in the scope of analysis in this paper. The most recent literatures on comparative evaluation of environmental impacts of hydrogen production methods are summarized in Table 1.

Many previous studies of life cycle analysis of H_2 production pathways have still focused on SMR, electrolysis, and coal gasification pathways and some researches covered the H_2 production pathways with biomass. Furthermore, most of recent researches are focused on the case of European countries and U.S.

The goal of this paper is to build a database to evaluate the environmental impact of FCEVs through the analysis of well-to-wheel greenhouse gas emissions for various H_2 production pathways in Korea. In particular, this is the first comprehensive study of WTW analysis on H_2 produced by naphtha cracking and comparison to other H_2 production technologies. In addition, the WTW results can be compared with other types of fuel and powertrain vehicles, such as internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs) and electric vehicles (EVs), and it is possible to evaluate which H_2 production paths are suitable for such application.

Method

WTW processes of various H_2 production pathways

The annual production of H_2 in Korea is 2.1 million tons, with 1.4 million tons of by-product H_2 [24]. More than 90% of by-product H_2 produced is consumed as a process fuel within the boundary of the corresponding production plant, and the remaining H_2 is shipped out for sale. Table 2 shows the average H_2 production rate of various technologies for sale in Korea [24]. Naphtha cracking is the main technology for H_2 production for sale in Korea. In particular, it is noted that the gross production rate from COG is 2.1 million m^3/hr from the Korean steel industries, although only 300 m^3/hr is available for sale.

Table 2 – Hydrogen production rate for sale in Korea [24].

H_2 production rate	For sale (m^3/hr)	Percentage (%)
Naphtha cracking	161,900	54.1
Electrolysis	67,500	22.6
Steam methane reforming	51,600	17.2
Coke oven gas purification	300	0.1
Propane dehydrogenation	14,000	4.7
Methanol reforming	4000	1.3
Total	299,300	100

Fig. 1 shows the well-to-wheel processes from feedstock recovery to FCEV operation in Korea. In this study, the WTW processes are classified by their feedstock (COG, naphtha, NG, landfill gas (LFG) or electricity) and the site of H_2 production (off-site or on-site). Finally, seven representative pathways for use in FCEVs are selected for the analysis, and the details are as below.

Off-site production corresponds to the situation whereby H_2 is produced at a location distant from where it is used, typically with a relatively large production capacity, and then distributed to a gas station for final usage. On the other hand, on-site H_2 production refers to the production at an H_2 gas station achieved by installing a H_2 generator directly at the station. The first to fourth rows in Fig. 1 show the pathways of the off-site production, and the remaining three rows represent the pathways of the on-site production.

The 'Upstream process' in Fig. 1 represents the processes that are associated with producing the feedstock for each H_2 production process. In the case of Elec. (off-, on-site), the first process is 'upstream for feedstock'. There are several types of resources for power generation, e.g., coal, NG, uranium, residual oil, and renewable energy. Therefore, the pathways producing each resource are grouped together as 'upstream for feedstock'. Detailed descriptions of these upstream processes are given in Section Upstream process.

Another dashed line box indicates the H_2 production process from each feedstock. In Section Hydrogen production,

Table 1 – The most recent literatures on comparative evaluation of environmental impacts of hydrogen production methods [11–23].

Resources	Biomass	Coal	Electricity	NG
Region	U.S [22] Portugal [13] Sweden [12] Germany [18]	U.S [22] Portugal [13] EU [11] Germany [18] China [17]	U.S [14,22] Portugal [13] Sweden [12] Germany [18] EU [15] China [16,17] Mexico [20] No regional classification [19]	U.S [14,21,22] Portugal [13] Sweden [12] Germany [18] EU [15] China [16,17] No regional classification [19]

Notes

- Some papers analyzed not only GHG emissions but also other environmental impact categories, e.g., acidification potential, human toxicity, ozone layer depletion, PM emissions, radiation, cost, system energy efficiency [11,12,15,19,22]
- Woody is included in the 'Biomass' category
- Hydrogen produced from 'Coal' resources used coal gasification technology
- Electricity is not a feedstock for hydrogen, but it is required resource for electrolysis process
- Some papers covered renewable electricity [12–15,18,22]

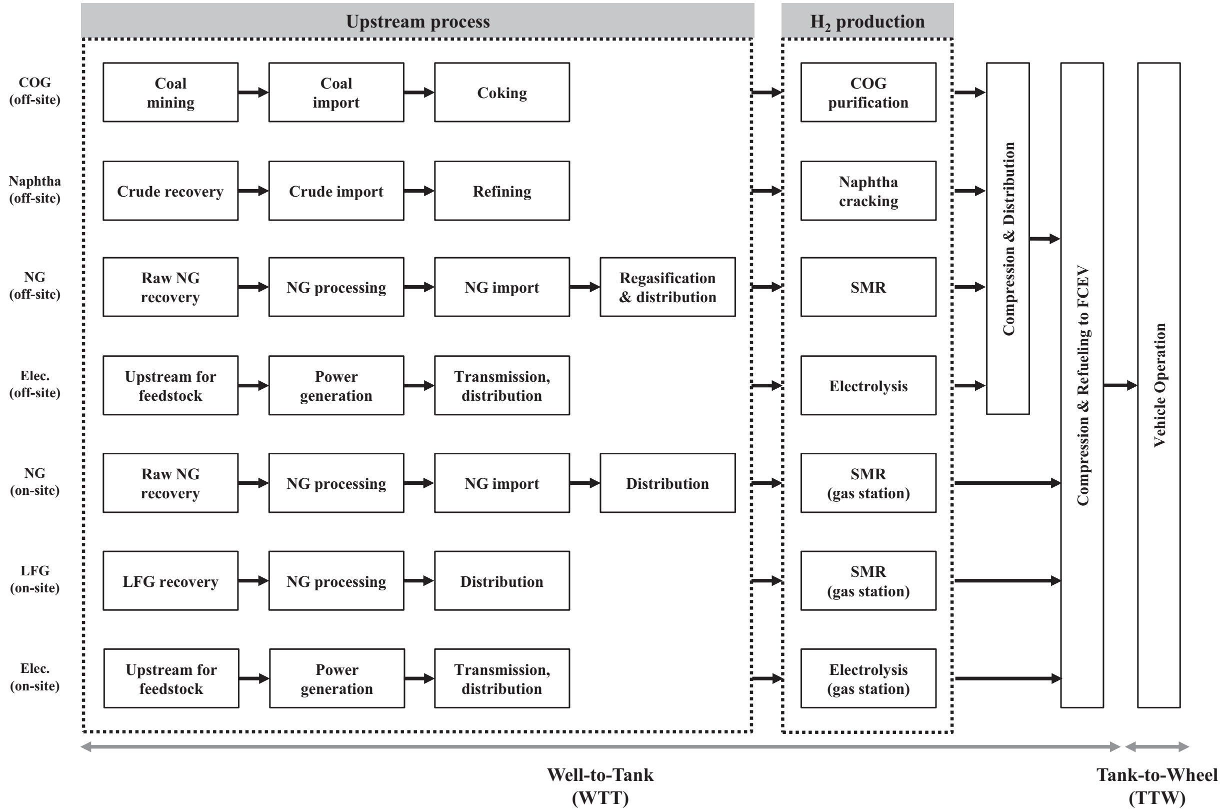

Fig. 1 – Well-to-Wheel processes of Hydrogen in Korea.

each technology is explained in detail. The two processes following the H_2 production process are the compression and distribution processes and the compression and refueling processes. As shown in Fig. 1, the off-site pathways require compression and distribution processes, but these processes are not needed in the on-site pathways. The compression, distribution and refueling processes are described in Section Distribution, Compression and Refueling. The processes from the upstream process to the refueling process correspond to the WTT process. The last column in Fig. 1 is the vehicle operation process, which is the TTW process.

Methods for evaluation

The GREET model [2] was adopted as a base calculation tool, but the detailed parameters and some of the calculation methods were modified for our own purposes. To apply the GREET program, the term efficiency (η) of each process is defined as follows:

$$\eta = \frac{\textit{Output Energy}}{\textit{Input Energy}} = \frac{\textit{Product energy}}{\textit{Feedstock energy} + \textit{Feed loss} + \textit{Process fuel energy}}$$

The input energy is equal to the sum of the feedstock energy, feed loss and process fuel energy. In the definition above, the feedstock energy has the same value as the product energy. Some feedstock is lost in the form of leakage and evaporation. These energy losses are represented as a feed loss.

Process fuel is the energy source required to supply heat or steam and convert the feedstock into the product. Output energy is the specific product energy from a process such as the H_2 energy from the SMR process and the naphtha energy from the refining process. In particular, in the COG purification and naphtha cracking processes, various products are produced together with H_2. In this case, it is assumed that each product consumes the energy of the process fuel according to the energy ratio of the product by following the energy-based allocation [25]. Through each process, the feedstock energy is converted into product energy and fed to the next process.

Raw data for calculating each process efficiency were collected through both domestic and foreign literature surveys and the support of related associations. If there are several applicable references for one parameter, the mean value is selected as a representative value, and the minimum and maximum values are used to produce the error bars. Meanwhile, if there is a domestic, official reference on a certain parameter, it is regarded as the representative value of that parameter, and the other values are selectively included in the error bars to consider the uncertainty of such representative data. The year 2015 was the base year of the data collection. The GHG emissions from process fuel combustion are calculated as the product of the amount of process fuel energy and the emission factor (EF). EFs for overseas production sites and some domestic plants were obtained from the IPCC [26] and the U.S. EPA [27]. We also obtained and applied Korean EFs to analyze the refining, power generation, and TTW processes.

The quantity of GHG emissions in this paper is presented in g-CO_2-eq./GJ. Here, the unit means the number of grams of CO_2-equivalent GHGs emitted to produce 1 GJ of product under a certain process. Additionally, in Section Results and Discussion, the WTW results are expressed in the unit of g-CO_2-eq./km, which means the amount of CO_2-equivalent GHGs emitted when a vehicle travels 1 km. We use global warming potentials of 25 and 298 to convert CH_4 and N_2O emissions into CO_2-equivalents, respectively, based on the 100-year time horizon [28].

Key parameters and assumptions

Upstream process

In Section Upstream process, the details of the GHG emissions from the upstream process will be described. Here, we classify the seven pathways into four types according to the type of feedstock and production process in four Subsections, COG purification – COG (off-site)–Electrolysis with Korean grid mix – Elec. (off-site), Elec. (on-site), which will present COG purification, naphtha cracking, SMR (with NG or LFG), and electrolysis with Korean grid mix, respectively.

COG purification – COG (off-site)

COG is a byproduct gas of the coking process, which transforms coal into coke to use in steel making processes. According to coal consumption statistics by sector in Korea, all the coal consumed in iron and steel production facilities in 2015 was imported bituminous coal [29]. Thus, the upstream process starts with coal mining and cleaning at overseas coal mines. After the coal import stage, COG is collected through the coking process at the steelworks [30]. Through the coking process, coal is separated into coke and COG. The process fuel energy consumed for H_2 production is estimated according to the energy-based allocation.

Naphtha cracking – naphtha (off-site)

Because naphtha is a petroleum-based fuel, the upstream process begins with a crude recovery process. All the crude oil used in Korea is extracted from the wells of overseas production areas and imported to domestic refineries by oil tankers. Then, naphtha is produced alongside petroleum products, such as gasoline, diesel, and residual oil, during the refining process. The production energy of the refining process is allocated to each product through the refinery-level allocation. The naphtha production efficiency is 95.1%. For details, the readers can refer to our previous work on the WTW analysis of petroleum-based fuels [7].

SMR – NG (off-site), NG (on-site), LFG (on-site)

There are two major sources of NG used in Korea. One source is imported NG, the life cycle of which starts from recovering raw natural gas at overseas production sites. In the process of NG processing, the raw natural gas is cleaned and treated to produce dry NG. Then, NG is liquefied in the form of liquefied natural gas (LNG), imported into Korea using LNG carriers, regasified and distributed to various domestic factories, power plants, and gas stations in Korea. The readers can refer to our previous work to obtain more details about the WTW analysis of NG in Korea [8].

The other source of natural gas is LFG. In 2011, an on-site H_2 station was built in the World Cup Park in Seoul using LFG. The LFG is generated by decomposing waste buried in the ground. This gas mainly consists of CH_4, CO_2, and small amounts of N_2, O_2, and H_2S [31]. The upstream process starts with the LFG collection process. Next, the impurities are removed, and methane, the primary component of natural gas, is extracted. During the NG processing process, 2% of fuel leaks to the atmosphere and the amount of CH_4 emission due to this leakage is 400.0 g-CH_4/GJ [2].

It is noted that there is a carbon credit associated with using LFG to produce NG. Typically, the LFG should be extracted and burned from the landfill, and GHG emissions are generated during this flaring process. However, once NG is produced using landfill gas, GHG emissions from flaring are not emitted, and thus, this amount of GHG emissions during the flaring process is considered as a credit and is deducted from the total amount of GHGs for the LFG (on-site) pathway [32]. GHG emissions by flaring were calculated using the EPA emission factor [27], and the calculated value is 68,138 g-CO_2 eq./GJ. The emission factor of CO_2 is calculated based on the carbon balance, which is calculated assuming that the entire carbon contained in the fuel, excluding the carbon emitted as CH_4, VOC and CO, is discharged to CO_2. The sensitive analysis with three cases where EF of CO, VOC, CH_4 is 0, 10% increase, and 10% decrease is shown in Table 3. Even if we omit the emissions from CO, VOC, and CH_4 ("0 case" in the table), which is an extreme case, the effect on GHGs by flaring is less than 1%.

Electrolysis with Korean grid mix – Elec. (off-site), Elec. (on-site)

The upstream process for electrolysis with Korean grid mix begins with the feedstock recovery process, followed by production of the sources of electricity, their transportation to the power plants, and the electric power generation process. The domestic electric power generation mix for 2015 is shown in Table 4. Detailed data about domestic power generation were collected by referring to the report from KEPCO [33], which includes power generation efficiency, EFs, and transmission and distribution losses. The transmission and distribution loss is 3.6% on a yearly average. Based on these data, we calculated the GHG emissions, 52.7 g-CO_2-eq./kWh during the upstream process for power generation and 525.5 g-CO_2-eq./kWh during the power generation process. Detailed research data can be found by referring to our companion paper regarding the WTW analysis of electric vehicles in Korea [6].

Summary – GHG emissions during upstream process

The GHG emissions from individual pathways with detailed processes are listed in Table 5.

Table 3 – Sensitivity analysis for the emission factors by flaring.

Emission factors [g/GJ fuel burned]	CO	VOC	CH_4	N_2O	CO_2	GHGs by flaring [g-CO_2-eq./GJ]	Sensitivity
reference case (EPA)	39.31	22.43	29.94	1.043	54,895	68,138	–
0 case	0	0	0	1.043	55,109	67,487	−0.96%
10% increase	43.24	24.68	32.93	1.043	54,874	68,073	−0.10%
10% decrease	35.38	20.19	26.95	1.043	54,917	68,203	+0.10%

Table 4 – Power generation mix in Korea, U.S. and EU [4,22,33].

Fuel	Korea Mix (%)	U.S. Mix (%)	EU mix (%)
Coal	40.1	44.0	31.0
Uranium	31.4	21.0	33.0
NG	23.0	21.0	20.8
Renewable	4.1	13.0	11.7
Petroleum based fuel	1.4	1.0	3.5
Total	100	100	100
GHG emissions during power generation [g-CO_2 eq./kWh]	525.5	660	508

Hydrogen production

In Section Hydrogen production, the H_2 production processes in the seven pathways are described in four subsections, COG purification – COG (off-site)–Electrolysis with Korean grid mix – Elec. (off-site), Elec. (on-site), where each production process uses each of the four types of feedstocks discussed in Section Upstream process.

COG purification – COG (off-site)

According to Table 6, the main component of the COG produced in the coking process is H_2. Most of the generated COG is used as a process fuel in various steelwork processes, and some COG is purified to obtain H_2. The remaining carbon in the COG after the purification process is used as a process fuel in steel mills [34].

Pressure swing absorption (PSA) is a H_2 production technology that separates and extracts H_2 from the COG and obtains high-purity H_2 in Korean steel industry. In the present study, the efficiency of the PSA process is 91.9%, and all the process fuel for driving PSA units, such as compressors, separators and coolers, is electricity [34].

Naphtha cracking – naphtha (off-site)

In petrochemical plants, naphtha is decomposed into several products and the main products of the naphtha cracking process are ethylene and propylene; H_2 only accounts for ~1 wt% of the total product. Assuming energy-based allocation, the H_2 production efficiency is 88.0%, and considering the confidence interval, the efficiency is set to 86.9–89.1%. We presented the details on the efficiency of the naphtha cracking process in the previous work [9], and important details for the efficiency and the reference data are also reproduced in Appendix.

Table 5 – GHG emissions during upstream processes.

Production Technology	Parameters	CO_2 [g-CO_2/GJ]	CH_4 [g-CH_4/GJ]	N_2O [g-N_2O/GJ]	Total [g-CO_2 eq./GJ]
COG purification	Coal mining	688	128.75	0.002	3907
	Coal import	1667	1.48	0.007	1706
	Coking	14,379	21.11	0.001	14,907
Naphtha cracking	Crude recovery	1902	68.99	0.008	3629
	Crude import	1311	1.13	0.005	1341
	Refining	7144	1.61	0.109	7217
SMR (import NG)	Raw natural gas recovery	1276	78.75	0.012	3248
	NG processing	2572	35.28	0.009	3457
	Liquefaction	4642	26.17	0.084	5322
	NG import	766	27.78	0.004	1462
	Regasification & distribution	442	9.71	0.001	685
SMR (LFG)	NG processing	10,792	441.89	0.091	21,867
	Emission credits	−66,845	−36.46	−1.270	−68,134
Electrolysis with Korean grid mix	Upstream (based on generation mix)	8604	240.65	0.067	14,640
	Power generation	145,979	0.09	0.006	145,983

The unit/GJ means per 1 GJ of product under a certain process.

Table 6 – Dry basis composition of COG [30].

components	H_2	CH_4	CO	CO_2	C_2H_4	N_2	O_2	Total
% vol.	56–58	25–26	7–8	2.4–3	2.2–5.2	1.5	0.2–0.5	100

SMR – NG (off-site), NG (on-site), LFG (on-site)

When H_2 is produced through the SMR process, NG is used as both a feedstock and a process fuel. NG, which is supplied as a feedstock, reacts with steam to produce mainly H_2 and CO_2, and small amounts of CO, H_2O and CH_4 either are produced or remain. In the following chemical reaction, most of the carbon contained in NG as feedstock is discharged as CO_2. Thus, this CO_2 product should be accounted for in the total GHG emissions from the SMR process.

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

The hydrogen production efficiency of the SMR process is affected by the size of the plant, steam credit, etc. The efficiency of large-scale off-site processes is generally higher than that of smaller scale on-site counterparts. None of the H_2 stations currently using SMR in Korea export steam. Thus, it is assumed that there is no steam credit in the SMR process in determining the efficiency applied in this paper.

The efficiency of the SMR process was collected by mainly referring to GREET and NREL reports [2,35]. In addition, an efficiency of 54.8% was determined based on empirical data from a domestic on-site gas station [36]. Based on the collected data, the efficiency of the off-site method is 71.5–73.8%, and the efficiency of the on-site method is 54.8–70.0%.

In Korea, the H_2 production process using LFG is only used for the on-site type of gas station. The H_2 production efficiency of the SMR process when installing a reformer at the on-site gas station is assumed the same for both cases of using NG or LFG. However, the process fuel for this SMR process is coming from the landfill gas. Thus, not only the feedstock but also the process fuel has carbon credit during the life cycle of NG; from LFG to NG.

Electrolysis with Korean grid mix – Elec. (off-site), Elec. (on-site)

The H_2 production efficiency of a commercial device depends on the H_2 production scale, temperature and pressure conditions, etc. The efficiency was obtained from the GREET model, JEC and NREL reports [2,4,22]. Based on the collected efficiency data, the off-site production efficiency of the electrolysis process ranges 65.0–80.0%, and the on-site production efficiency is 56.0–71.5%.

Summary – GHG emissions during hydrogen production process

In Table 7, the GHG emissions from the H_2 production process of the seven pathways are shown in detail. For Elec. (off-site) and Elec. (on-site), it is obvious from Section Electrolysis with Korean grid mix – Elec. (off-site), Elec. (on-site) that no greenhouse gas is emitted during the electrolysis process.

Distribution, compression and refueling

H_2 distribution (off-site only)

The distribution process is the process of transporting the H_2 produced in the plant to the gas stations in each region, which is only applicable for off-site-produced H_2. Typically, the off-site-type of H_2 is first transported via pipelines to the gas distribution company near the plant. Considering the domestic situation in 2017, the average transportation distance is very short, ~3 km [9]. The H_2 is then delivered by the distribution company to the local gas stations. Korean distribution companies are currently using tube trailers as the means of transporting H_2, and the transport volume is approximately 320 kg-H_2/vehicle. It is noted that H_2 is a gaseous fuel with a very low energy density per volume, and since it is transported in the form of compressed gas, the amounts of GHGs emitted during the transportation process are larger than other typical liquid fuels for automobiles. For example, the mass of gasoline transported by a typical large oil tanker truck is 25,000 kg/vehicle, which corresponds to an approximately 26.4-times higher energy per truck than that of a H_2 tube trailer.

The average distance from the distribution companies to the local gas stations was calculated by considering the domestic H_2 production and the current availability of H_2 gas stations nationwide. As of 2017, there are 10H_2 gas stations in operation in Korea, and there are additional 14 gas stations under construction and soon to be installed [37]. Of the 24 gas stations, 20 stations use tube trailers as the transportation modality. Only one gas station uses pipelines to receive H_2 from a distribution company, and the transportation distance is 3.5 km. The remaining 3 stations are all of the on-site type, i.e., NG (on-site), LFG (on-site), or Elec. (on-site), and thus, the distribution process is not considered.

After collecting the distances of the shortest paths between each of the 20 charging stations and the distribution company

Table 7 – GHG emissions during H_2 production processes.

Pathways	CO_2 [g-CO_2/GJ]	CH_4 [g-CH_4/GJ]	N_2O [g-N_2O/GJ]	Total [g-CO_2 eq./GJ]
COG (off-site)	13,603	21.22	0.006	14,136
Naphtha (off-site)	7217	1.608	0.109	7290
NG (off-site)	78,606	51.63	0.010	79,899
NG (on-site)	103,762	120.6	0.659	106,974
LFG (on-site)	53,635	334.3	−0.971	61,704
Grid Elec. (off-site)	0	0	0	0
Grid Elec. (on-site)	0	0	0	0

The unit/GJ means per 1 GJ of product under a certain process.

supplying the H_2 to the designated gas station, we calculated the weighted average transportation distance using the H_2 filling capacity of each gas station. The H_2 filling capacity refers to the amount of H_2 that the gas station can provide in one day. As a result, the average transportation distance between the distribution companies and the local gas stations using the tube trailer as the transportation modality is 63.7 km.

As mentioned above, off-site H_2 gas stations in Korea all use H_2 produced by naphtha cracking. Due to a lack of further practical information, for the analysis of the COG (off-site), NG (off-site), and Elec. (off-site) pathways, it is assumed that the only transportation modality is the tube trailer, and the distribution distance is 63.7 km. Table 8 shows the H_2 filling capacity and average distribution distance for the seven pathways.

H_2 compression and refueling

We can categorize the compression and refueling process into three representative cases for the seven production pathways analyzed in this study. The main differences among these cases are the number of compressions, the compression ratio, and the compression efficiency. The three cases are as follows.

(Case 1) Off-site production, transported to the gas station using a tube trailer from a distribution company
(Case 2) Off-site production, transported to the gas station using a pipeline from a distribution company
(Case 3) On-site production, produced and compressed at the gas station

There may be small differences in practice in the compression and refueling process for the individual pathways; however, we simplified the process as below, and these assumptions would cause approximately 3% error in the final WTW GHG result. First, it is assumed that the pressure of the H_2 after being produced at the plant or the gas station is 10 bar. When H_2 is distributed through the pipeline, the inlet pressure is 20 bar and the outlet pressure is 10 bar. The transport pressure is 200 bar when H_2 is distributed through the tube trailer. It is also assumed that the H_2 tank pressure of the FCEV is 700 bar, and thus H_2 is compressed to 820 bar for charging FCEVs at the gas station. The compressors used by the H_2 plant and distribution company are NG compressors, while the compressors used at the gas station are electric compressors [9]. The specifications of the compressors used in this process are shown in Table 9.

In Case 1, the overall efficiency is 84.3%, and the process fuels are 81.2% NG and 18.8% electricity. The overall efficiency of Case 2 is 86.5%, and process fuels are 31.6% NG and 68.4% electricity. Finally, in Case 3, the overall efficiency of Case 3 is 90.3% with 100% electricity as process fuel. Table 10 shows the GHG emissions from the compression and refueling process in three cases.

Results and discussion

For the seven pathways in Fig. 1, the WTW greenhouse gas emission (white bar) results per GJ of H_2 are shown in Fig. 2. Note that there are no TTW GHG emissions in the hydrogen fuel pathways for FCEV. Error bars are used to reflect the influences of the uncertainty of each variable used in the analysis or the range of the values of multiple references. The representative U.S. and EU results with H_2 production pathways similar to this study, are selected and compared. The following summarizes the major points for the individual pathways.

- COG (off-site): The upstream process, including the coal mining and coking processes, represents the largest portion of the WTW greenhouse gas emissions. The carbon component of the COG is ultimately used as the process fuel for steel mill processes, and is not released in the form of GHGs during the H_2 production process. All the GHGs emitted during H_2 production are due to the consumption of process fuels.
- Naphtha (off-site): The H_2 production efficiency is the highest among the technologies considered, and thus, the

Table 9 – H_2 compressor specification [2,38].

NG compressor		Electric compressor	
Inlet pressure (bar)	10	Inlet pressure (bar)	5–200
Outlet pressure (bar)	20–200	Outlet pressure (bar)	820
Compression ratio per stage	1: 2.1	Compression ratio per stage	1: 2.8
Adiabatic efficiency (%)	80	Adiabatic efficiency (%)	65
NG engine efficiency (%)	35	Electric motor efficiency (%)	92

Table 8 – Current status of H_2 filling stations in 2017 and distribution distance from distribution company to gas station [37].

Pathways	Transportation method	Number of gas stations	H_2 filling capacity		Distance (km)
			(kg_{H_2}/day)	(%)	
Naphtha (off-site)	tube trailer	20	5975	87.3	63.7
	pipeline	1	500	7.3	3.5
COG (off-site)	tube trailer	0	0	0	63.7
NG (off-site)	tube trailer	0	0	0	63.7
Elec. (off-site)	tube trailer	0	0	0	63.7
NG (on-site)	–	1	65	1.0	–
LFG (on-site)	–	1	65	1.0	–
Grid Elec. (on-site)	–	1	235	3.4	–

Table 10 – GHG emissions during compression & refueling processes.

Case	CO_2 [g-CO_2/GJ]	CH_4 [g-CH_4/GJ]	N_2O [g-N_2O/GJ]	Total [g-CO_2 eq./GJ]
Case 1	14,562	43.64	0.165	15,702
Case 2	19,464	37.17	0.061	20,411
Case 3	16,490	25.72	0.008	17,136

The unit/GJ means per 1 GJ of product under a certain process.

amount of GHG emitted during the H_2 production process is small. All the carbon component contained in the feedstock, naphtha, is converted to other petrochemicals and is not emitted as greenhouse gases. Overall, the total WTW GHG emissions of this pathway are the second lowest.

- NG (off-site) and NG (on-site): In addition to the GHG emissions from the use of process fuels, there are large amounts of CO_2 emissions in the product gas, which originate from the carbon contained in the feedstock NG. This accounts for more than 81% of GHG emissions during the off-site H_2 production process, and it represents 62% of GHGs emitted during the on-site H_2 production process. On the LFG (on-site) pathways also considers the GHGs arising for the same reasons. It is also noted that the off-site production efficiency is better than the on-site efficiency, which results in lower GHG emissions during H_2 production process at the large-scale, off-site plant. The GHGs from the NG (on-site) pathway are 6% lower than the U.S. case and 10% higher than the EU case. The different NG production routes in each region and the variation of the SMR efficiency cause these differences of the results.
- LFG (on-site): The upstream process of the LFG pathway has a negative GHG emission amount, which corresponds to the emission credit described in Section SMR – NG (off-site), NG (on-site), LFG (on-site). In addition, the emission credit for the process fuel, NG from the LFG, during the H_2 production process can be compensated for the low on-site efficiency. Thus, the total WTW GHG emissions of this pathway are the lowest.
- Elec. (off-site) and Elec. (on-site): There are no GHG emissions during the H_2 production because the process fuel is 100% electricity. It is noted that the generation mix used in this study is the Korean mainland mix, where thermal power generation, i.e., coal and NG, accounts for 63% of total generation mix. As a result, the total amount of WTW GHG emissions per unit H_2 production is the highest in electrolysis with Korean grid mix pathway. Some studies report that H_2 production using electrolysis is considered promising when it is combined with renewable sources, e.g. wind or photovoltaic power generation [22,39]. In these cases, there are no GHGs during upstream process and the total WTW GHG emissions of electrolysis pathways will decrease to only ~20,000 g-CO_2 eq./GJ.

  In Fig. 2, we include the results of Elec. (on-site) pathways in U.S. and EU. Difference in the results of electrolysis originates from different generation mix in those countries. As shown in Table 4, GHG emissions during power generation for Korea, U.S. and EU are 525.5, 660, and 508 g-CO_2-eq./kWh, respectively. Coal accounts for 44% in the U.S. mix and 31% in the EU mix. Meanwhile, carbon neutral sources (nuclear and renewable) account for 44.7% in the EU mix [4,22].
- Among the WTW processes, the GHG emissions from H_2 distribution, compression and refueling are rather high. For example, greenhouse gas emissions from these processes account for 51.9% of the WTW GHG emissions in the Naphtha (off-site) pathway. For reference, the corresponding processes of the WTW results for gasoline vehicles account for only ~2%, which is mainly attributed to the characteristics of the liquid fuel [7].

As shown in Fig. 2, it is well expected that the average WTW greenhouse gas emissions of FCEVs will vary significantly depending on the H_2 production pathway or a combination of them. As of 2017, there are only 24H_2 refueling stations, which are either in operation or scheduled to be

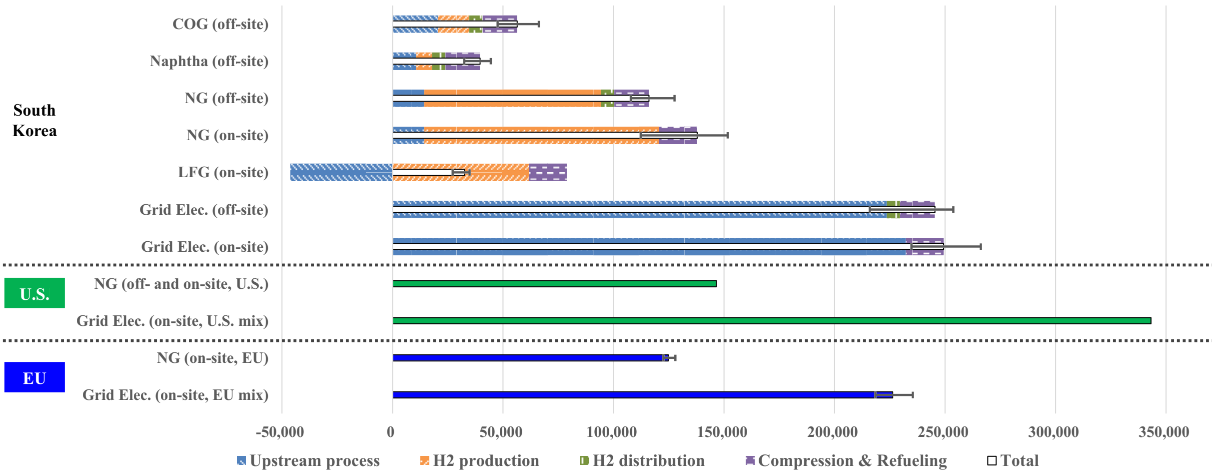

Fig. 2 – Well-to-Wheel GHG emissions per GJ of hydrogen [g-CO_2 eq./GJ].

installed soon. To compare with other fuels and vehicle technologies, we consider the status of H_2 production pathways for FCEVs, although this number of charging stations might not be sufficient to represent the average pathway for the WTW analysis of FCEVs in the future. Most of the gas stations are located near petrochemical complexes, and most of them use H_2 produced through the naphtha cracking process. The resulting H_2 production mix used for the analysis is presented in Table 11.

Fig. 3 shows the WTW GHG emissions by incorporating vehicle technologies, including the results for the seven individual H_2 pathways and the representative average FCEV (FCEV – Korea Avg.), as well as the results for ICEV, HEV, and EV. Again, the Korea Avg. for FCEVs is a weight average of the WTW emissions from the seven pathways and the H_2 production mix in Table 9. WTW results for ICEV, HEV, and EV are obtained from the references [6–8], which are our previous researches on the WTW analysis of the automotive fuels in Korea.

Table 11 – H_2 production mix for FCEVs in Korea [37].

Pathways	Production mix (%)
COG (off-site)	0.0
Naphtha (off-site)	94.6
NG (off-site)	0.0
NG (on-site)	1.0
LFG (on-site)	1.0
Grid Elec. (off-site)	0.0
Grid Elec. (on-site)	3.4
Total	100.0

The fuel economy of the ICEV (gasoline), HEV and EV used in this calculation is the weighted average based on the sales volume of all passenger cars sold in Korea in 2015 [40]. For the ICEV (CNG), the fuel economy of a 2015 Honda Civic Natural gas vehicle was used because CNG passenger cars are not currently sold in Korea. The fuel economy of the FCEV is 77.1 km/kg-H_2, which is for the only FCEV sold in Korea currently: the Hyundai Tucson FCEV. Table 12 shows the fuel economy for each vehicle type. The unit of km/$L_{eq.}$ means gasoline equivalent fuel economy.

In Fig. 3, 'Upstream process (feedstock)' represents the processes including the raw material recovery, the production of feedstock, and the transport of feedstock to the fuel production site. This stage is the same as the 'Upstream process' in Fig. 2. 'Fuel production' refers to the processes from the production of the vehicle fuel to the charging of the vehicle fuel tank at the fuel station. In the case of EVs, the 'Fuel production' stage includes the electric power generation, transmission, distribution, and charging processes. Finally, 'Vehicle operation' represents GHGs emitted during the vehicle operation

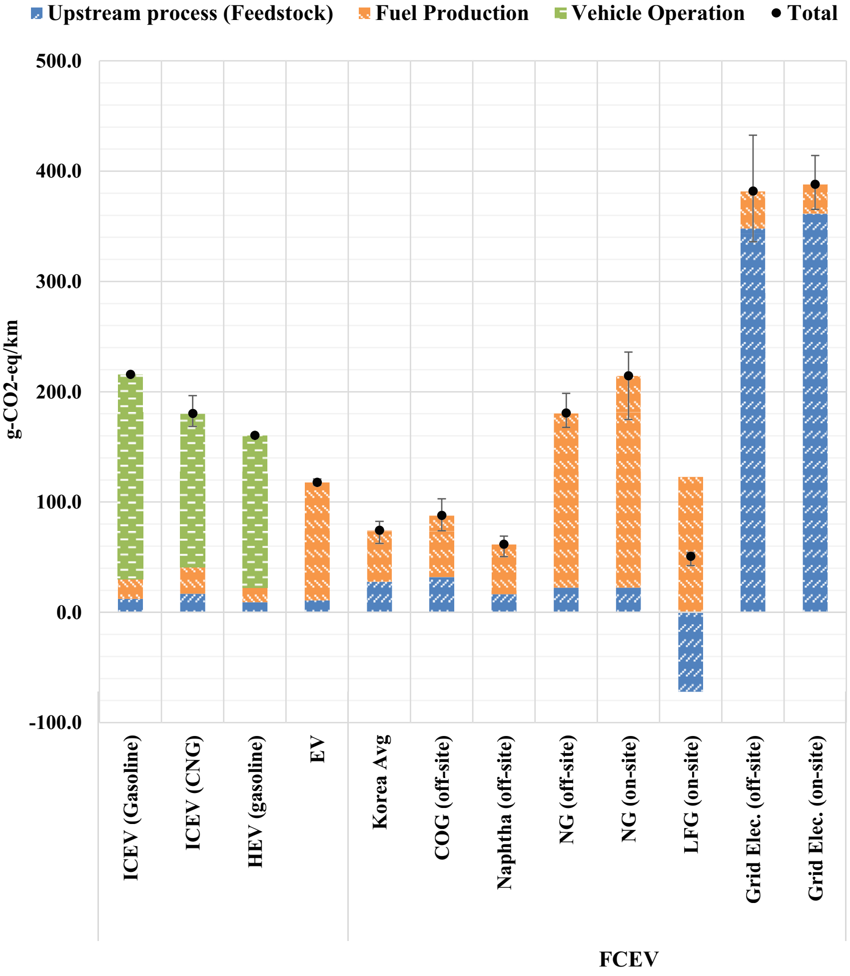

Fig. 3 – Well-to-Wheel GHG emissions per km of driving distance [g-CO2 eq./km].

Table 12 – Fuel economy for each vehicle type in 2015 [40].

Vehicle Types	Fuel economy [km/Leq.]
ICEV (gasoline)	12.4
ICEV (CNG)	12.8
HEV	16.7
EV	41.2 (4.9 km/kWh)
FCEV	19.5 (77.1 km/kg-H_2)

phase, where EVs and FCEVs do not generate GHGs. The major discussion points are summarized below.

- During the WTW processes for ICEVs, HEVs and EVs, the highest portion of the greenhouse gas emissions is emitted during the conversion of fuel chemical energy into mechanical energy or electrical energy through the combustion of fuel. This corresponds to the vehicle operation phase for ICEVs and HEVs with internal combustion engine operation and the fuel production phase for EVs with fossil-fueled power plant operation.
- The WTW GHG emissions of FCEVs with NCC (off-site) and COG (off-site) are the second and third lowest of all options. This is mainly because the carbon components contained in the feedstock are not carried into the vehicle fuel, whereas the other fuel pathways have such a burden in emitting feedstock-born GHG during either fuel production, e.g., H_2 production in the SMR process, or vehicle operation by combustion of gasoline-fueled ICEVs.
- We compared an ICEV (gasoline) and FCEV-Naphtha (off-site), which start from the same feedstock, crude oil, and undergo the same refining process. During the WTT process, the ICEV (gasoline) emits less GHGs than the FCEV-Naphtha (off-site). Because the Naphtha (off-site) pathway also considers the naphtha cracking process and amounts of GHGs emitted during the distribution and compression processes are much larger. However, the WTW results of the FCEV are lower than those of the ICEV because the GHG emissions of the vehicle operation process are added to the ICEV, and the FCEV-Naphtha (off-site) does not have corresponding GHG emissions.
- In the NG (off-site) and NG (on-site) pathways for the FCEV, CO_2 emitted during the NG reforming process was included in the fuel production phase, resulting in large total GHG emissions. Considering that the CO_2 originates from the carbon-containing molecules in NG, the CO_2 emissions from the combustion in an ICEV with NG and those from the chemical reaction of the SMR process correspond to each other, despite somewhat different minor species. The amount of CO_2 emissions from each process can vary depending on the efficiency of the SMR and the fuel economy of the powertrains. For example, the ICEV (CNG) and NG (on-site) in Fig. 3 go through the exact same processes until the NG arrives at the gas station. After that, CNG is charged to the ICEV and burned or converted to H_2 via SMR for FCEV. The low efficiency of the SMR process at the on-site gas station can be compensated for by the high fuel economy of the FCEV. Thus, the difference in the WTW results between the ICEV (CNG) and the NG (on-site) is approximately 35.4 g-CO_2-eq./km.
- The WTW results of the Elec. (off-site) and Elec. (on-site) pathways are the highest among all fuels and vehicle technologies considered in Fig. 3. Comparing the GHGs during the upstream process of Elec. (on-site) and the WTW results of the EV, the former is 3.5 times higher than latter. In other words, the amount of electricity required to drive the FCEV by 1 km using the H_2 produced with electrolysis at the on-site gas station is 3.5 times the amount of electricity required to drive the EV by 1 km. This is because of the additional energy conversion process that converts electricity to H_2, and the difference in fuel economy.
- The *Korea Avg.* value of the FCEV using the aforementioned H_2 production mix is 62.5–82.6 g-CO_2-eq./km since the Naphtha (off-site) pathways with the low WTW GHG emissions account for 94.6% of the total mix.

Conclusions

This paper provides the first estimates of the Well-To-Wheel greenhouse gas emissions from hydrogen fuel pathways as a transportation fuel in Korea, of which the results could be extended to similarly situated countries, such as Japan. The H_2 production pathways include all the commercially available options in Korea, or more or less, around the world. Furthermore, this is the first study of WTW analysis on H_2 generated in the naphtha cracking process and comparison to other H_2 production technologies.

The WTW GHG results are calculated as 32,571 to 249,332 g-CO_2 eq./GJ or 50.7 to 388.0 g-CO_2 eq./km depending on the H_2 production pathway. The LFG (on-site) pathway has the lowest GHG emissions and the Elec. (on-site) pathway has the highest GHG emissions. The naphtha (off-site) pathway has the second lowest GHG emissions. In addition, the WTW results are compared with other powertrain vehicles in Korea such as internal combustion engine vehicles, electric vehicles and hybrid electric vehicles. The overall environmental impacts of an FCEV on GHGs were estimated with WTW analysis in this study. Policy makers and stakeholders can use these WTW results when planning the production and supplementing of FCEVs.

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Appendix A. Detailed information on how to determine the efficiency of the naphtha cracking process

This is the first paper to compare H_2 produced through the naphtha cracking process with H_2 produced through other production technologies. The efficiency of the naphtha cracking process has been described in detail in our previous paper [9]. However, since the paper was written in Korean, key points and updates are summarized once again in this Appendix.

In Section Methods for evaluation, the efficiency of each process is defined as follow.

$$\eta = \frac{\mathit{Product\ energy}}{\mathit{Feedstock\ energy} + \mathit{Feed\ loss} + \mathit{Process\ fuel\ energy}}$$

First, energy-based allocation is assumed for the feed loss and process fuel energy. In other words, the total energy of the process fuel consumed and the total feed loss occurring during the naphtha cracking process are allocated to each product according to the energy ratio of the product. Based on these assumptions, all the products of the naphtha cracking process will have the same production efficiency. In the following description, to calculate the production efficiency of the naphtha cracking process, analysis was performed by obtaining the production efficiency of ethylene as the main product of the process. The averaged ethylene production rate of a domestic naphtha cracking plant is 3863.1 GJ/h [41].

The following data are needed to obtain the efficiency of the naphtha cracking process: the amount of feed loss, input process energy per unit product energy, and shares of process fuel used. Most process fuels consumed in the naphtha cracking process are intermediates, with additional electrical energy [42].

The total usage of process fuel energy in the naphtha cracking process is obtained from a report by KOSHA [41] and the paper by Ren et al. [42]. The share of process fuel was determined through the following assumptions. First, only 5.3% of the process fuel is electric energy that is externally applied, and all the energy is generated internally in the process [42]. Second, self-produced steam in the process is used for the naphtha cracking process. The energy of the steam was replaced by the energy of the spent fuel for steam production. Third, the intermediate products, used as process fuels, are in the form of naphtha when they are input into the process and are in the form of NG, H_2, and LPG when they are consumed. Fourth, the share of the intermediate product is 80% NG and H_2, and the remainder is supplemented with LPG [41]. In addition, the ratio of NG and H_2 was determined by the ratio between the NG and H_2 of the end product of the naphtha cracking process [43]. The error range bounds are given by the cases where all 80% is NG and where the 80% is all hydrogen.

Next, we find the feed loss. According to Ren et al. [42], 1.13 GJ of naphtha is injected when producing 1 GJ of ethylene. Applying an ethylene production rate of 3863.1 GJ/h, the amount of naphtha input per hour is 4365.3 GJ/h. Of this input naphtha energy, 3863.1 GJ/h is the energy used as feedstock, and 453.1 GJ/h is the energy of the intermediate used as process fuel. Thus, the remaining 49.1 GJ/h is the feed loss in the naphtha cracking process, and all the corresponding naphtha is emitted in the form of CO_2.

The efficiency of the naphtha cracking process obtained from the above data is as follows. Of the 478.5 GJ corresponding to the process fuel energy, 453.1 GJ is intermediate and 25.4 GJ is electrical energy.

$$\eta = \frac{\mathit{Product\ energy}}{\mathit{Feedstock\ energy} + \mathit{Feed\ loss} + \mathit{Process\ fuel\ energy}} = \frac{3863.1}{3863.1 + 49.1 + 478.5} = 88.0\%$$

Nomenclature

COG	coke oven gas
Elec	Electricity
EV	electric vehicle
FCEV	fuel-cell electric vehicle
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HEV	hybrid electric vehicle
ICEV	internal combustion engine vehicle
LCA	life cycle analysis
LFG	landfill gas
LPG	liquefied natural gas
PSA	pressure swing adsorption
SMR	steam methane reforming
TTW	tank-to-wheel
WTT	well-to-tank
WTW	well-to-wheel

REFERENCES

[1] IEA. Energy and climate change, world energy outlook special report. Paris, France: OECD, IEA; 2015.

[2] ANL. GREET1 (greenhouse gases, regulated emissions, and energy use in transportation) transportation fuel cycle analysis model version 2012 rev2. Argonne National Laboratory; 2012.

[3] (S&T)^2 consultants, Inc.. GHGenius. 4.03. 2013.

[4] Edwards R, Larivé JF, Rickeard DJ, Weindorf W. Well-to-wheels analysis of future automotive fuels and powertrains in the European context. In: Well-to-tank report version 4.0. Joint Research Centre of the European Commission; 2013.

[5] (S&T)2 Consultants, Inc.. Transportation fuel life cycle assessment: validation and uncertainty of well-to-wheel GHG estimates. Coordinating Research Council, Inc.. In: CRC report No. E-102. Alpharetta, GA: Coordinating Research Council; 2013.

[6] Choi W, Song HH. Well-to-wheel greenhouse gas emissions of battery electric vehicles in countries dependent on the import of fuels through maritime transportation: a South Korean case study. Appl Energy 2018;230:135–47.

[7] Jang JJ, Song HH. Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel. Int J Life Cycle Assess 2015;20(8):1102–16.

[8] Choi W, Song HH. Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea. Int J Life Cycle Assess 2014;19(4):850–60.

[9] Kim M, Yoo E, Song HH. Well-to-Wheel greenhouse gas emissions analysis of hydrogen fuel cell vehicle - hydrogen produced by naphtha cracking. Kor Soc Automot Eng 2017;25(2):158.

[10] Ministry of Environment, Repulic of Korea. Specific fulfillment plans of controlling fine dust. 2016 [Press release].

[11] Bicer Y, Dincer I. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. Int J Hydrogen Energy 2017;42(6):3767–77.

[12] Larsson M, Mohseni F, Wallmark C, Grönkvist S, Alvfors P. Energy system analysis of the implications of hydrogen fuel cell vehicles in the Swedish road transport system. Int J Hydrogen Energy 2015;40(35):11722–9.

[13] Pereira SR, Coelho MC. Life cycle analysis of hydrogen–a well-to-wheels analysis for Portugal. Int J Hydrogen Energy 2013;38(5):2029–38.

[14] Wang M. Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts. J Power Sources 2002;112(1):307–21.

[15] Miotti M, Hofer J, Bauer C. Integrated environmental and economic assessment of current and future fuel cell vehicles. Int J Life Cycle Assess 2017;22(1):94–110.

[16] Wang D, Zamel N, Jiao K, Zhou Y, Yu S, Du Q, et al. Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. Energy 2013;59:402–12.

[17] Shen W, Han W, Chock D, Chai Q, Zhang A. Well-to-wheels life-cycle analysis of alternative fuels and vehicle technologies in China. Energy Pol 2012;49:296–307.

[18] Wulf C, Kaltschmitt M. Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations. Int J Hydrogen Energy 2012;37(21):16711–21.

[19] Suleman F, Dincer I, Agelin-Chaab M. Environmental impact assessment and comparison of some hydrogen production options. Int J Hydrogen Energy 2015;40(21):6976–87.

[20] Giraldi MR, François J-L, Martin-del-Campo C. Life cycle assessment of hydrogen production from a high temperature electrolysis process coupled to a high temperature gas nuclear reactor. Int J Hydrogen Energy 2015;40(10):4019–33.

[21] Tong F, Jaramillo P, Azevedo IsM. Comparison of life cycle greenhouse gases from natural gas pathways for light-duty vehicles. Energy Fuels 2015;29(9):6008–18.

[22] Ramsden T, Ruth M, Diakov V, Laffen M, Timbario T. Hydrogen pathways: updated cost, well-to-wheels energy use, and emissions for the current technology status of ten hydrogen production, delivery, and distribution scenarios. Golden, CO: National Renewable Energy Laboratory (NREL); 2013.

[23] Ahmadi P, Kjeang E. Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. Int J Hydrogen Energy 2015;40(38):12905–17.

[24] Ministry of Trade, Industry and energy, Republic of Korea, NEW & Renewable Energy White Paper. 2016.

[25] Wang M, Lee H, Molburg J. Allocation of energy use in petroleum refineries to petroleum products. Int J Life Cycle Assess 2004;9(1):34–44.

[26] IPCC. IPCC guidelines for national greenhouse gas inventories. 2006. p. 2006.

[27] U.S. EPA. Compilation of air pollutant emission factors. 1995.

[28] Solomon S. Climate change 2007-the physical science basis: working group I contribution to the fourth assessment report of the IPCC, vol. 4. Cambridge University Press; 2007.

[29] Korea Energy Economics Institute. Yearbook of energy statistics. 2016.

[30] Chin KG. Energy use and heat treatment technology of steel industry. In: KOSCO symposium; 2015. Suncheon, Korea.

[31] Larney C, Heil M, Ha G-A. Case studies from the climate technology partnership: landfill gas projects in South Korea and lessons learned. Golden, CO: National Renewable Energy Laboratory (NREL); 2006.

[32] Mintz M, Han J, Wang M, Saricks C. Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model. Argonne National Laboratory (ANL); 2010.

[33] Korea Electric Power Corporation. Statistics of electric power in Korea (2015). 2016.

[34] Joseck F, Wang M, Wu Y. Potential energy and greenhouse gas emission effects of hydrogen production from coke oven gas in US steel mills. Int J Hydrogen Energy 2008;33(4):1445–54.

[35] Spath PL, Mann MK. Life cycle assessment of hydrogen production via natural gas steam reforming. Golden, CO (US): National Renewable Energy Lab.; 2000.

[36] Lee Y, Han J, Lee J, Kim Y, Cho Y, Kim S, et al. Analysis of experimental results on hydrogen generator for HCNG. Trans Kor Hydrogen New Energy Soc 2015;26(2):89–95.

[37] Ministry of Environment, Republic of Korea. , Increase trend of hydrogen car supply municipalities. 2017.

[38] Jung H. Technology of FCEV charging station. In: Hydrogen Industry development smposium; 2017.

[39] McDowall W, Eames M. Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature. Energy Pol 2006;34(11):1236–50.

[40] Korea Energy Agency. Vehicle fuel economy and CO2 emissions : data and analyses. 2016. p. 2016.

[41] Korea occupational Safety and Health Agency. Petrochemical process technology assessment Handbook - naphtha cracking process. 2007. p. 1–13.

[42] Ren T, Patel M, Blok K. Olefins from conventional and heavy feedstocks: energy use in steam cracking and alternative processes. Energy 2006;31(4):425–51.

[43] Korea Petrochemical Industry Association. Introduction of petrochemical industry. 2015.