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국내 원유기반 수송용 연료 전과정 온실가스 배출량 및 에너지 사용량 분석

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2015년 2월

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Well-to-Wheel Analysis on Greenhouse Gas Emission and Energy Use with Petroleum-based Fuels in Korea

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This study aims at performing the first comprehensive well-to-wheel (WTW) analysis on greenhouse gas (GHG) emissions and energy uses of petroleum-based automotive fuels, i.e. gasoline and diesel, in Korea. Although Korean Renewable Fuel Standard is supposed to take effect in 2015, there are very few WTW results available in Korea.

In this study, all relevant processes in the whole fuel cycle are covered, which will provide Korea-specific results to policy makers and stakeholders in Korea. Input raw data were collected with the help of Korean petroleum industries and related association, as well as governmental institutions. Literature survey was carried out, especially for overseas processes in the crude oil recovery fields. The

GREET model, developed by the U.S. Argonne National Laboratory, was adopted as a tool for WTW calculation, and most of the data were replaced by using the Korean specific information. Additional analysis was also performed for the refining process which was the most energy-intensive in the fuel life cycle. A process-level allocation method was used in calculating the refining energy use of individual petroleum products, which could reflect the detailed refining processes.

As a result, the well-to-pump (WTP) GHG emissions of Korean gasoline and diesel are calculated as 12,047-12,677 g CO_2 eq./GJ_{Final_fuel} and 11,025-11,643 g CO_2 eq./GJ_{Final_fuel}, respectively. The main difference comes from the higher GHG emission in the refining process of gasoline than in diesel. As compared to other countries, the WTP results of Korean fuels are smaller than those of the U.S. and Europe mainly due to higher refining efficiency, while larger than that of Japan with a significant difference in GHG emissions regarding crude oil recovery. In the WTW results with all the Korean vehicle models in 2014 considered, similar weight of diesel models demonstrate overall lower WTW emissions than gasoline models, since the former has both the lower WTP GHG emissions and better fuel economy than the latter. There is relatively large uncertainty from the refining process, which should be further investigated to improve the accuracy of the results.

Keywords: Fuel cycle analysis, Well-to-wheel analysis, Automotive fuels, Petroleum-based fuels, Greenhouse gas emission

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1. Introduction

The greenhouse gas (GHG) concentration in the atmosphere has increased to the unprecedented level due to human activities (IPCC 2006), which causes the global climate change with accompanying environmental, economic, and social issues. Among the human activities, transportation sector accounts for a significant share and, in 2010, it represented 22 % of global CO_2 emissions (IEA 2013). Most of these emissions originate from the combustion of petroleum-based fuels for road transportation, mainly gasoline and diesel, and thus the governments, especially in developed countries, are enforcing regulations on automotive fuels to reduce the GHG emissions.

For example, Low Carbon Fuel Standards (LFCS) in California, U.S., which came into effect in 2011, regulates the GHG emissions of transportation fuels by giving credits or deficits to fuel providers according to carbon intensity of their fuels (CARB 2012). U.S. Renewable Fuel Standard (RFS), and EU Renewable Energy Directive (RED) set mandatory GHG reduction levels by increasing the share of renewable fuel usage in the transportation sector (U.S. EPA 2013; European Parliament and Council 2009). It should be noted that all these regulations concern the life-cycle GHG emissions of the fuel based on well-to-wheel (WTW) analysis, not merely the tailpipe emissions.

The WTW analysis quantifies energy consumptions and GHG emissions during the whole processes associated with the life cycle of automotive fuels. For example, the WTW analysis of a gasoline fuel covers crude oil recovery, refining, transportation, distribution, and final use in vehicles, thus providing a useful means to evaluate lifetime environmental impact of the fuel.

For a recent decade or so, several comprehensive WTW analyses of automotive fuels have been developed in the U.S., Canada, Europe, and Japan. Argonne National Laboratory (ANL) in the U.S. has developed a WTW model called GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), which is to estimate the life-cycle energy use, GHG emissions, and pollutant emissions of various fuel/vehicle systems in the U.S. (ANL 2012). Canadian consulting company, $(S\&T)^2$ consultants, has developed GHGenius model to analyze WTW energy use and GHG emissions of conventional and alternative transportation fuels in Canada ($(S\&T)^2$ consultants 2012). Edwards et al. have performed a WTW analysis on automotive fuels and powertrains in the European situation (Edwards et al. 2011a, b). Toyota Motor Corporation (TMC) estimated the WTW energy use and GHG emissions of fuels used in Japan (TMC 2004). It is noted that the results from these models have been used to make GHG-related government policies in those countries.

In Korea, WTW analysis on automotive fuels has been paid little

attention to. Although Korean RFS on transportation fuels, i.e. gasoline and diesel, is supposed to take effect in July 2015, there are few WTW database on these petroleum-based fuels. Korea Environmental Industry & Technology Institute (KEITI) built national life cycle inventory of materials in Korean industry, which included life cycle GHG emissions of gasoline and diesel in Korea. However, the report does not reveal the data sources or the assumptions in the analysis, and thus there is significant uncertainty in the final results (KEITI 1998). Jung et al. performed an analysis on environmental impacts of petroleum refinery products (gasoline, diesel, and naphtha) in Korea, but it only covered refining process and used relatively outdated data from a few exemplary refineries (Jung et al. 2001).

The main goal of this study is to construct the first comprehensive WTW GHG database of petroleum-based automotive fuels, i.e. gasoline and diesel, in Korea. This study is supported by the Korean Ministry of Environment, and the results will provide the useful information for the future GHG policies. The main body of the paper is divided into three sections: In section 2, life cycle of petroleum-based fuels, methodology, and major assumptions, are introduced. In section 3, key parameters, data sources, and assumptions in each individual process are described. Lastly, the WTW GHG emissions results of gasoline and diesel are presented with sensitivity analysis on major parameters in section 4.

2. Well-to-Wheel Analysis Approach

Figure 2.1 shows the life cycle of petroleum-based automotive fuels in Korea. The whole life cycle is categorized into five processes: crude oil recovery, crude oil import, petroleum refining, petroleum product distribution, and vehicle operation. Here, the first four processes up to the petroleum product distribution to the gas station are collectively called "well-to-pump (WTP)", while the final vehicle operation process with the combustion of fuel in an internal combustion engine corresponds to "pump-to-wheel (PTW)".

Korea relies entirely on import to meet all of its crude oil demand. Middle East (Saudi Arabia, Kuwait, Iraq, etc.) is the largest source, accounting for over 80 % of the total import. Once the crude oil is recovered in these countries, it is shipped to Korea by ocean tankers and then transported to local petroleum refineries. There are four oil companies in Korea which produce all the automotive fuels and petrochemical for domestic demand, or they are exporting the excess. Gasoline and diesel are the major petroleum-based automotive fuels, which account for ~50 % and ~36 % of automotive fuel usage (2010) in Korea. It is noted that liquefied petroleum gas (LPG) and compressed natural gas (CNG) are the other major automotive fuels in Korea, but their WTW analyses are above the current scope and the readers are referred to the separate work

by the author (Choi 2014). Finally, gasoline and diesel are distributed either to the bulk storage or gas stations throughout the country, mainly by pipeline or tank lorry.

For the present WTW analysis, raw data were collected with the help of Korea Petroleum Association (KPA). KPA provided the data on crude oil import, petroleum refining, and domestic distribution by compiling industry data from Korean oil companies. For the rest of the processes, various literatures were referred to, and additional analyses were performed as appropriate. For the WTW calculation, GREET model (version 2012), developed by ANL, was adopted, and most of the data were replaced by using the Korean specific information.

When performing WTW analysis on a fuel, one should consider the GHG emissions from the use of "process fuel" in each process. Here, the process fuel refers to any type of energy resource that is expended to operate certain devices or facilities in the designated process. For example, during crude oil recovery, natural gas and electricity are needed as process fuels to operate steam injector and oil extractor. The process fuel also includes the fuels for transportation and distribution by ships or ground vehicles. Then, in order to fully account for the life-cycle impact of using such process fuels, they are also treated from the life cycle point of view, which is explained in the following paragraph. For the present study, major process fuels are residual oil, electricity, and natural gas,

whose life-cycle GHG emissions are also evaluated by using Korea-specific data.

Figure 2.2 shows the calculation procedure of the total GHG emissions in a single process. There are three parts of the emissions that are summed up: (1) emissions from combustion of process fuels, (2) life-cycle emissions regarding the process fuels up to the point where they are used, and (3) non-combustion emissions or the greenhouse gases exhausted in the outlet streams of the given process. The first part of the emissions can be evaluated by considering "energy use" and "GHG emission factor". Here, the energy use refers to the lower heating value of process fuel consumed in the process. The GHG emission factor is defined as the amount of GHG emitted when the specific amount of process fuel is combusted in certain combustion facility. Then, the total combustion-related emissions in the process are calculated by summing all the products of emission factors and energy uses for all the combustion facilities. In this study, emission factors from Intergovernmental Panel on Climate Change (IPCC) database (IPCC 2006) are adopted. The second part of the emissions is based on the life-cycle analysis of the process fuels concerned. In GREET software, life-cycle GHG emissions are analyzed for all the process fuels, at the same time with our final products, i.e. gasoline and diesel. The built-in iterative calculation method in Microsoft Excel program is used to resolve the

circular reference issue in evaluating this intrinsic equation problem. The last part of the GHG emissions is mainly associated with the venting or leaking of gaseous fuel or greenhouse gas included in the product streams of certain process. For example, during crude oil extraction, associated natural gas is vented to the atmosphere, and during hydrogen production in a refinery, carbon dioxide is included in the product gas of the steam methane reformer (SMR) (i.e. $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$).

In this study, the scope of the GHG emissions covers carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The total amount of GHG emissions is expressed in CO_2-equivalent-grams by using global warming potentials (GWPs). The GWPs of CO_2, CH_4, and N_2O used are 1, 25, and 298, respectively (IPCC 2006).

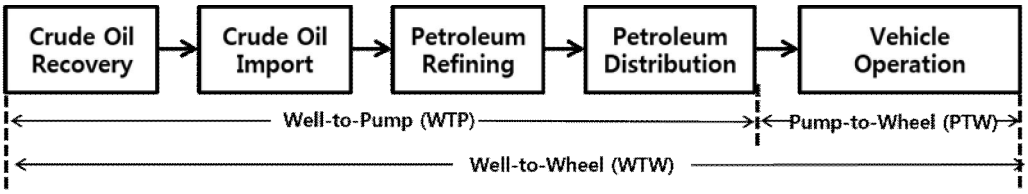


Figure 2.1 Life cycle of petroleum-based fuels in Korea

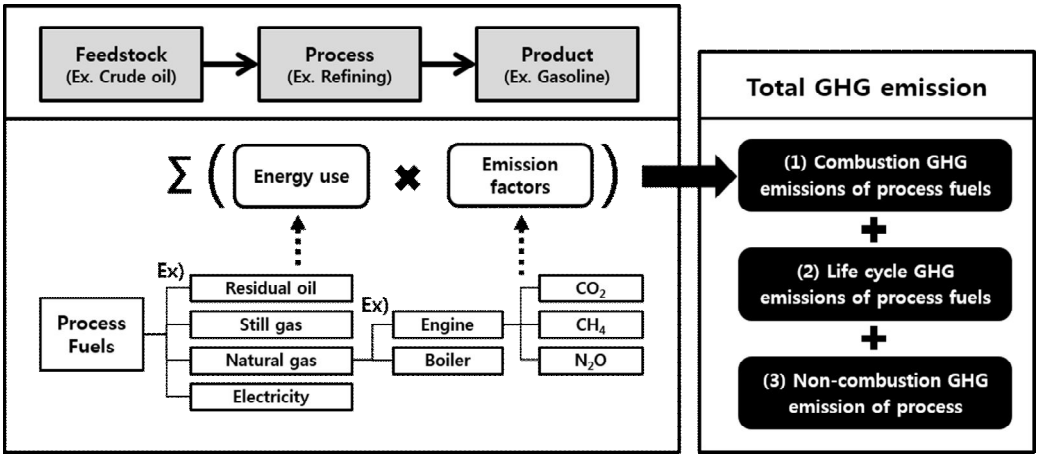


Figure 2.2 Calculation procedure of total GHG emissions of a process

3. Key Parameters & Assumptions

This section introduces data and assumptions used for determining key parameters in each individual process. The sources of raw data will be provided, although not all of the raw values are presented due to the restrictions by the data providers.

In the following sub-sections, the GHG emissions from each process are presented either in terms of "g CO_2 eq./$GJ_{Process}$" or "g CO_2 eq./GJ_{Final_fuel}". The first (g CO_2 eq./$GJ_{Process}$) is defined as CO_2-equivalent grams of GHGs emitted to produce 1 GJ of product at the end of the designated process. The second (g CO_2 eq./GJ_{Final_fuel}) is defined as CO_2-equivalent grams of GHGs emitted to produce 1 GJ of final fuel (gasoline or diesel) product at the end of the WTP process. If there is loss of fuel by leakage or evaporation during certain process, the GHG emissions, given in these two units, will be different values. Similarly, the energy use in a process is expressed either in terms of "kJ/$GJ_{Process}$" or "kJ/GJ_{Final_fuel}".

3.1. Crude oil recovery

Crude oil recovery process in Fig. 2.1 represents the whole process in oil fields to produce crude oil product before being exported to Korea, which includes injection, extraction, processing, and storage. In this process, recovery energy, flaring and venting emissions are the key parameters

discussed in the following subsections.

3.1.1. Recovery energy

Recovery energy includes the energy of process fuels used in injection, extraction, processing, and transportation of the crude oil in production fields. In this study, we referred to five references, and the following paragraphs explain each data source as well as how they are integrated in our analysis.

Firstly, GHGenius model provides the scaling factors for the recovery energy in different oil fields around the world by using the U.S. case as a reference value. For instance, the scaling factor of crude oil from Saudi Arabia is 0.91, which implies that the energy required for the recovery process of the crude oil in Saudi Arabia is 0.91 times lower than in the U.S. ((S&T)[2] Consultants 2012). By combining this regional scaling factors and the share of crude oil import in Korea from KPA, the average scaling factor of the crude oil imported into Korea is calculated as 0.98. Based on the reference recovery energy of the U.S. in GHGenius model, we get 51,762 $kJ/GJ_{Process}$ as the average recovery energy of the crude oil imported into Korea.

Secondly, GREET model provides the average recovery energy of crude oil in the U.S., which contains crude oil both from domestic and foreign sources. We first derived recovery energy of crude oil only from the U.S.

domestic sources by combining regional scaling factors from GHGenius and the share of crude import in the U.S. It is calculated that the recovery energy of the U.S. domestic crude oil is 11,596 $kJ/GJ_{Process}$. Then, by adopting this recovery energy of the U.S with the aforementioned average scaling factor for Korea from GHGenius, the average recovery energy of the crude oil imported into Korea is determined as 11,370 $kJ/GJ_{Process}$.

Thirdly, we also used the report published by international association of Oil & Gas Producers (OGP). OGP releases annual report on the production activities of its member companies. The report includes comprehensive statistics, such as gaseous emissions, recovery energy, and flaring from oil and gas fields, which cover about the one third of the world oil and gas production. The OGP recovery energy is presented in the form of averaged value by region. For example, the average recovery energy to produce 1 ton of hydrocarbon in the Middle East is 0.24 GJ (OGP 2013). By using this OGP recovery energy by region and the crude import data from KPA, the average recovery energy of crude oil used in Korea is calculated as 9,945 $kJ/GJ_{Process}$.

Fourthly, Toyota Corporation in Japan (TMC 2004) published a report in 2004, which estimated on average, the energy corresponding to 60 scf of natural gas required to produce 1 barrel of crude oil used in Japan. The value can be converted into 11,017 $kJ/GJ_{Process}$. It is noted that Japan

depends on the import for more than 99 % of its crude oil demand and the Middle East takes about 80 % of the total import quantity, which is very similar as in Korea. Therefore, we also considered this value for our analysis.

Finally, the fifth source is Ecoinvent database (Ecoinvent 2014). Ecoinvent, the international Life Cycle Inventory (LCI) database supported by Swiss Federal Offices, provides data on all the material and energy inputs and outputs which are consumed or produced to make unit quantity of product. We refer to the dataset about the average crude oil produced in the Middle East, which leads to 13,626 $kJ/GJ_{Process}$ as the recovery energy, by summing all the energy contents of material and energy uses in the process. When considering major proportion of crude oil import from the Middle East, this value was also included in our analysis.

To summarize, the estimated recovery energies of crude oil imported into Korea from multiple references are shown in Fig. 3.1 The recovery energy calculated from GHGenius is considerably higher while the others are very similar to one another. It is noted that the value from GREET is far lower than that from GHGenius, even though the same regional scaling factors are used to derive both values, which implies that the reference U.S. recovery energy suggested in GHGenius is relatively higher than the other. In our analysis, we decided to use the average recovery energy calculated from all of these references except GHGenius without

further information on its difference. The average recovery energy is 11,490 $kJ/GJ_{Process}$ with an error range from 9,945 $kJ/GJ_{Process}$ to 13,626 $kJ/GJ_{Process}$, and the sensitivity of the value will be examined in section 4.

3.1.2. Flaring and venting emissions

During the recovery process of the crude oil, considerable amount of associated gases from the oil production field are either flared or vented.

For flaring, the U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. Energy Information Administration (EIA) publish two separate reports of the world flaring data annually (U.S. NOAA 2012; U.S. EIA 2014). NOAA estimates global flaring volume based on lights index values of image data acquired from satellites. EIA uses International Energy Statistics (IES) data which provide global CO_2 emissions from gas flaring.

It is noted that the flaring data from these references are reported as total volume of associated gas flared both from crude oil and natural gas production fields, and thus further allocation of this total amount to the oil field should be considered. It is generally considered that flaring is performed for associated natural gas produced as a byproduct of crude oil in the oil production field, mainly due to the lack of infrastructure treating natural gas. Therefore, the larger portion of the total flared gas can be attributed to crude oil production. According to the Energy International

Inc. (EII) estimation, 85 % of the total flared gas is allocated to the crude oil fields in the present study. (ANL 2012; EII 1994).

For venting, the calculation is based on the assumption that the mass ratio of vented gas to flared gas is 20 % (CAPP 2002), and the CH_4 content in vented gas is 82.3 % while the rest are treated as CO_2 (Burnham et al. 2011).

Based on these data and assumptions, the regional quantities of CO_2 and CH_4 emissions from flaring and venting in the crude oil fields are determined. Finally, by combining with the crude oil import data from KPA, the average flaring and venting emissions associated with the crude oil imported into Korea are evaluated. With the two data sources for flaring, i.e. EIA and NOAA, the range of the results is derived as 1,016-1,102 g $CO_2/GJ_{Process}$ and 57.0-61.9 g $CH_4/GJ_{Process}$, and the uncertainty will be shown as an error bar.

3.1.3. Calculation of GHG emissions

To calculate the total GHG emission during recovery process of crude oil imported in Korea, there are three parts of the GHG emissions, as discussed in Fig. 2.2.

Firstly, the emission from the combustion of process fuel is evaluated. The average energy use of the process fuel is already calculated in section 3.1.1, and the process fuel share should be considered additionally.

In the Ecoinvent dataset used in estimating energy use, there is an estimated average process fuel share during crude recovery process in the Middle East, which is 60 % for diesel and 40 % for district or industrial heat. In this study, it is assumed that all the heat is generated from natural gas boiler with 90 % thermal efficiency, and thus the process fuel share becomes 57 % for diesel and 43 % for natural gas (Ecoinvent 2014). The emission factors for the combustion of these process fuels are provided in GREET model (ANL 2012).

Secondly, the life-cycle GHG emissions of each process fuel, i.e. diesel and natural gas, are added to the combustion emission. Finally, non-combustion GHG emissions are added to the total emissions, which include CO_2 and CH_4 emission from flaring and venting, and non-combustion CH_4 emission during processing of crude oil. For the latter, the value of 7.867 g $CH_4/GJ_{Process}$ is obtained from GREET (Burnham et al. 2011).

3.2. Crude oil import

All crude oil used in Korea is imported by ocean tankers from oversea countries. In evaluating the GHG emissions associated with this process, transport distance is the most significant parameter. Information on crude oil exporters and their exporting quantities to Korea is based on the KPA data. To estimate transport distances from oversea countries to Korean

refineries, a web-based, voyage-distance calculator (Voyage Calculator 2014) was used. By weight-averaging the distances with crude import quantities from those countries, the average transport distance is calculated as 12,315 km. For energy use and GHG emissions from the operation of the ocean tankers, the same specifications were used as those in GREET (ANL 2012) and the specifications are summarized in Table 3.1.

3.3. Petroleum refining

Petroleum refining is the process that transforms crude oil into various petroleum products such as gasoline, diesel, kerosene, residual oil, petrochemical feedstock, etc. In general, refining process is the most energy-intensive process in the life cycle of petroleum-based fuel production, and the key parameter in the petroleum refining process is refining energy.

3.3.1. Refining energy

Since a refinery inherently produces multiple petroleum products in a single or combined chemical processes, it is difficult to determine the individual energy consumption for a specific product. Moreover, the details of the refining process, in general, are not open to public, and the processes are often different among oil companies. Therefore, in many of

WTW analyses, the total energy use from all the refinery processes are evaluated first, and then are allocated to individual product. The allocation can be accomplished either in refinery level or process level, and we applied both to Korean situation in this study.

In a refinery-level analysis, the allocation can be achieved by using mass, energy content, or market price share of individual product as weighting factor. Although the refinery-level allocation has the virtue of simplicity and applicability only requiring the refinery-level input and output data, it cannot reflect the detailed refining processes that can affect different products. It is therefore recommended that an allocation should be accomplished at the process level, whenever possible, by the international LCA standard ISO 14040 (ISO 2006). There have been various approaches (Wang et al. 2004; Bredeson et al. 2010; NETL 2008) to allocate refining energy at the process level. In this study, we referred to the U.S. National Energy Technology Laboratory (NETL) study (NETL 2008), which provides an approach most readily applicable to Korean situation.

3.3.1.1. Total refining energy

To determine the total energy use in the refinery, we referred to the supply and calorific value data for all the process fuels from Korea Energy Management Corporation (KEMCO). They contain total volumes and heating values of process fuel uses of all the Korean refineries in

2012, which were officially submitted to Korean government. It is noted that KEMCO data also covers the energy use from the production of additives, such as MTBE.

Additionally, the energy use from the production of hydrogen, which is used in various refining processes, is separately evaluated. There are three kinds of hydrogen, depending on its production process, i.e. captive hydrogen, co-product hydrogen, and merchant hydrogen. Captive hydrogen is the one produced from on-site hydrogen plant in refinery. Co-product hydrogen is produced mainly from catalytic reforming process as a co-product, and merchant hydrogen is produced from off-site hydrogen plant and transported to refinery. The production energy of co-product and captive hydrogen is already accounted for in the total process fuel energy by KEMCO, but the energy related with merchant hydrogen is not included in the report, which should be separately added to calculate the total refining energy use.

In KEMCO data, annual production quantity only for captive hydrogen is specified as 107,505 MMscf. Without better information, based on the proportion between three types of hydrogen productions in the U.S. refineries (NETL 2008), we estimated that the annual hydrogen production quantities in Korea were 124,420 MMscf for co-product hydrogen and 54,756 MMscf for merchant hydrogen. The production energy of co-product hydrogen is assumed to be the same as total energy

consumption of catalytic reformer and associated hydrotreater (45,419 TJ), which is calculated from the specific energy consumption for those processes (384 Btu/scf H_2) from the NETL report (NETL 2008). Here, it is noted that all the energy use during catalytic reforming process is only attributed to hydrogen, despite the presence of other product species, which is based on the findings from the simulation result of a refinery model (Bredeson et al. 2010). On the other hand, production energy for both captive and merchant hydrogen is calculated as 3,630 TJ and 1,849 TJ, by assuming that the hydrogen is mainly produced in a steam-methane-reformer (SMR) and the specific production energy is 32 Btu/scf H_2 estimated by NETL (NETL 2008).

Finally, Fig. 3.2 summarizes the total energy usage of the refining process in Korea. The dotted line represents the refinery boundary, whose data are from KEMCO. The total of 276,379 TJ of process fuels were used for all the processes except for hydrogen production, while the reforming process is a major energy-consumer (45,419 TJ) in the production of hydrogen. Again, the energy use for merchant hydrogen is not reported, and thus separately evaluated in this study, which is added to the total energy use of refining process.

3.3.1.2. Refinery-level allocation

In refinery-level allocation, it is assumed that a petroleum product with

higher share of energy content, mass, or market price in the total products is responsible for more energy use during refining. The production volumes of Korean refineries from KPA and the calorific values from Korean Energy Act (Korea MOTIE 2013) are used to derive the energy contents of individual products. Additionally, by using the standard densities of the petroleum products from KPA and the average export price of the products in 2012 from Korea petroleum information system (Petronet 2014), we can also make a list of mass and market price of every product. After allocating the total energy use according to the shares of these different values, the allocated energy of process fuels is divided by the energy content of each product, which is to evaluate the intensive refining energy, i.e. refining energy per unit energy of each product. The intensive refining energies for gasoline, diesel, LPG, and residual oil are shown in Fig. 3.3. Here, LPG and residual oil are included for comparison, since the former is one of the major transportation fuels in Korea and the latter is an important process fuel for industrial uses.

By its definition, the energy content-based allocation results in the same intensive refining energy for every product. In the mass-based allocation, all the products have similar refining energies, because most petroleum products have similar mass-based heating values about ~40 MJ/kg. However, in the market price-based method, refining energy of gasoline is relatively higher than those of others due to its higher market price per

unit energy, while residual oil being the opposite. In every allocation method, refining energy of gasoline is greater than or equal to that of diesel. However, as mentioned above, refinery-level allocation hardly reflects the details of refining process. Thus, process-level allocation is considered in the next section.

3.3.1.3. Process-level allocation

As mentioned earlier, the allocation method suggested by the NETL report is adopted for process-level analysis in this study. The report contains a comprehensive analysis of WTW GHG emissions from petroleum-based transportation fuels distributed in the U.S., providing detailed information on the allocation method as well as the raw data (NETL 2008). In their study, petroleum products are classified into seven product categories: gasoline, diesel, kerosene and kerosene-based jet fuel, residual oil, coke, light ends, and heavy ends. The light ends include still gas, refinery gases, special naphtha, and petrochemical feedstocks, while the heavy ends refer to asphalt and road oil, lubricants, waxes, and miscellaneous matters. In evaluating refining energy of each product category, the total energy use is divided into two energy pools i.e. the energy use except for hydrogen production and the hydrogen production energy, as similarly in Fig. 3.2. Then, to calculate the refining energies of the individual products, they use certain allocation factors that are based

on the analysis of the detailed processes in refinery. In this regard, the NETL compiles the data for the specific energy use of a certain refining process and the energy consumption shares of individual products in the designated process, by investigating substantial references, such as those reported in *Hydrocarbon Processing*, *Oil and Gas Journal* and various handbooks (Meyer 2004; Gary 2007). These data along with the nationwide daily operating quantities of the individual refining processes can lead to the allocation factors. The readers are referred to the NETL report for further details (NETL 2008).

In the first and second rows of Table 3.2, the resultant energy use fractions of individual products divided by their production volume fractions in the U.S. are shown for both energy pools, i.e. refining energy except hydrogen production and hydrogen production energy, respectively. Then, the volume fractions of Korean refinery products, which are reclassified from KPA production data (in the third row of Table 3.2) are multiplied to the values in the first and second rows, which again are re-normalized to give the energy use fractions as shown in the fourth and fifth rows in the table. Since the ratio of the energy use fraction over volume fraction implies the efficiency of making a product, the above calculation is based on the assumption that the Korea and the U.S. refineries will have the same ratios among refining efficiencies of individual products. By combining the total energy use in Fig. 3.2 and the

fractions in the fourth and fifth rows of Table 3.2, the energy uses of individual products in Korean refineries can be calculated as in the last row of Table 3.2.

As a result of the allocation, heavy ends are estimated to be most energy-intensive. It is known that the manufacturing process for the lubricating oil in the heavy ends category is most energy-intensive process in a refinery (Energetics 2007). The gasoline has the second largest refining energy intensity, mainly because the alkylation and the isomerization processes are predominantly attributed to gasoline product. The two processes have the highest level of specific energy requirement, about three times larger than that of atmospheric distillation (NETL 2008). On the contrary, the refining energies of the kerosene and residual oil are relatively low because these products need the less energy-intensive processes such as distillation and hydrotreating.

In summary, Table 3.3 lists the refining energy of gasoline and diesel from the process-level allocation, as compared to the refinery-level allocation. It is noted that the refining energy of gasoline by the former is higher than those by the latter, while the diesel being the opposite. In this study, we adopt the values from the process-level allocation, since they better reflect the energy uses from detailed processes, including the hydrogen production.

3.3.2. Calculation of GHG emissions

The GHG emissions from the refining process are summarized in Fig. 3.4. The similar steps are taken as with the refinery energy use in the previous section, i.e. the total GHG emission is evaluated first and then allocated to individual products. Again, the GHG emissions from hydrogen production and other refining processes are considered separately.

The GHG emissions data from KEMCO include the combustion emissions of process fuels in all the refining processes and the non-combustion emissions from catalytic regeneration and desulfurization. The data also cover the combustion and the non-combustion emissions associated with hydrogen production in the refineries, i.e. captive hydrogen and co-product hydrogen. It is again noted that the emission from the production of merchant hydrogen is not covered in the KEMCO data, since the merchant hydrogen is produced outside the refinery.

In order to separately account for the GHG emissions regarding hydrogen production from the total GHG emissions in the KEMCO report, we calculated the combustion and the non-combustion emissions from the production of captive hydrogen (3,674 kton) and co-product hydrogen (2,627 kton) as in the followings. The combustion emission from the captive hydrogen production is evaluated based on the SMR process (NETL 2008), while the corresponding non-combustion emission is directly from the KEMCO database. The combustion emission of catalytic

reforming process for co-product hydrogen is assumed to be 14 % of the total GHG emission in KEMCO data, since the catalytic reforming process consumes 14 % of process fuels in refineries. There is no non-combustion emissions considered for co-product hydrogen production. Finally, the emission associated with the production of merchant hydrogen outside the refinery is calculated similarly as captive hydrogen, by assuming that hydrogen is produced mainly from the SMR process.

In addition to the direct emissions from the refining process, the GHG emissions regarding the life cycle of the process fuels should be added, as explained in Fig. 2.2. According to KEMCO data, the share of the process fuels used in the whole refinery is 55 % for still gas, 22 % for electricity, 21 % for residual oil, and 2 % for coke. By assuming that the share is the same for individual refining processes, the life-cycle emissions of process fuels are calculated, whose values are shown in gray boxes in Fig. 3.4. Finally, for the captive and merchant hydrogen production, the life-cycle emission of feedstock to the SMR process, i.e. natural gas, is also calculated.

In allocating these GHG emissions to individual products, we also used the energy use fraction and the hydrogen use fraction in the fourth and fifth rows of Table 3.2, respectively. Then, in order to calculate the intensive GHG emission, the GHG emission of the product is divided by the energy content of the individual product. The intensive GHG

emissions from the refining process of various petroleum products are shown in Fig. 3.5. The black portion (bottom) represents the amount of GHG emission from hydrogen production, and the gray portion (top) from the other processes. The refining GHG emissions among products show the similar trend with the refining energy in Table 3.2. However, it is noted that the trend can be slightly different, because the hydrogen production process emits about twice higher GHG emissions per energy use as compared to the other refining processes. Therefore, although the same amount of energy is used to produce different products, the more GHG emissions will be produced with the product using more hydrogen. For gasoline and diesel, the difference of the GHG emissions is somewhat smaller than for the energy use, because diesel has more use of hydrogen than gasoline.

3.4. Petroleum distribution

Petroleum distribution process consists of two stages. Firstly, petroleum products are transported from refineries to oil storage depots which are located near the major cities. Secondly, products are distributed from oil storage depots to gas stations. In calculating the average distribution distance, the regional petroleum consumption and refinery location data, provided by KPA, are used with the assumption that products will be delivered to each gas station from the nearest refinery. The average

distribution distances of gasoline and diesel are calculated as 202 km and 277 km, respectively. We also estimated the average share of various distribution modes by using the KPA and the Korean pipeline corporation data, which is 47 % for pipeline, 32 % for truck, 20 %, for barge, and 1 % for train. The specifications of the distribution modes and VOC leakages associated with each means of distribution are assumed to be the same as in the U.S. (ANL 2012) without better data available in Korea.

3.5. Vehicle operation

In vehicle operation, or PTW process, automotive fuels are combusted to operate a vehicle. For the PTW analysis of gasoline and diesel, we considered all the domestic gasoline and diesel vehicle models released in 2012: 64 gasoline models and 55 diesel models. For the calculation of GHG emission, we referred to official fuel economy (km/L) and CO_2 emission data (g/km) (KEMCO 2014). These values are measured over the combined cycle of FTP-75 city mode and HWFET highway mode. Because non-CO_2 (CH_4, N_2O) emissions of individual models are not officially available, we referred to the emission factor (g/GJ_{Final_fuel}) of automotive fuels developed by Korean Ministry of Land, Infrastructure and Transport (Table 3.4). By using the fuel economy and the calorific value data from Korean Energy Act (Korea MOTIE 2013), these emission

factors were further converted into the emissions per kilometer.

Table 3.1 Specifications of ocean tanker for crude oil import

Payload (kton)	100
Average speed (km/h)	31
Power (HP)	19,170
Energy intensity (Btu/ton-mile)	38

Table 3.2 Calculation of refining energy using NETL result

	Gasoline	Diesel	Kero-sene	Residual oil	Coke	Light ends	Heavy ends
NETL energy use fraction (w/o hydrogen production) /Product volume fraction	1.075	0.954	0.604	0.682	1.193	0.748	2.015
NETL hydrogen use fraction /Product volume fraction	1.052	1.084	0.680	0.716	1.003	0.668	1.757
Korean product volume fraction	0.259	0.299	0.028	0.099	0.002	0.242	0.070
Korean energy use fraction	0.286	0.293	0.017	0.070	0.002	0.186	0.145
Korean hydrogen use fraction	0.280	0.333	0.020	0.073	0.002	0.166	0.127
Korean refining energy (w/ hydrogen production) [$kJ/GJ_{Process}$]	**68,526**	**56,662**	**36,693**	**36,107**	**36,076**	**51,705**	**109,433**

Table 3.3 Refining energy of gasoline and diesel

Refining energy ($kJ/GJ_{Process}$)	Gasoline	Diesel
Refinery-level energy-based allocation	59,296	59,296
Refinery-level mass-based allocation	61,582	59,579
Refinery-level market price-based allocation	68,128	61,378
Process-level NETL-based allocation	68,526	56,662

Table 3.4 Non-CO_2 emission factors of gasoline and diesel in Korea

	Gasoline	Diesel
CH_4 (g/GJ_{Final_fuel})	3.0	1.5
N_2O (g/GJ_{Final_fuel})	5.4	4.2

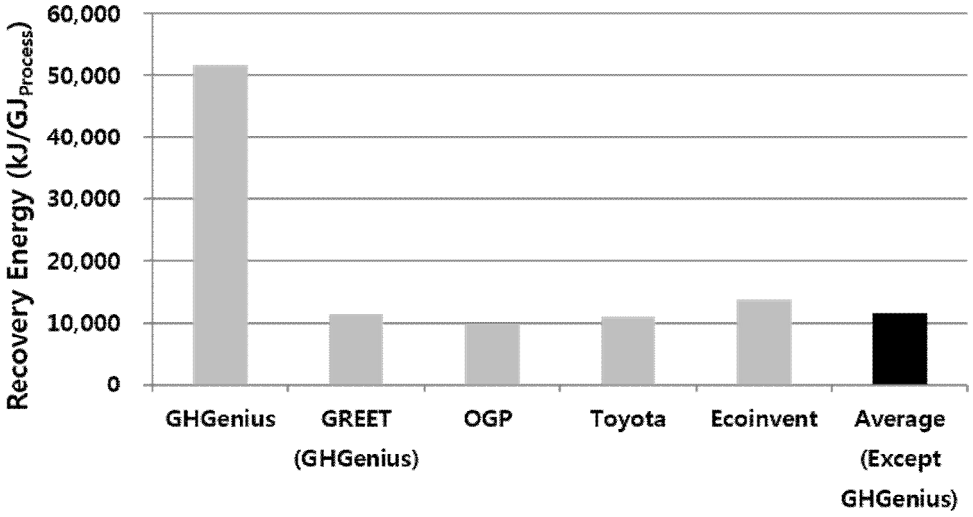


Figure 3.1 Recovery energy of crude oil used in Korea

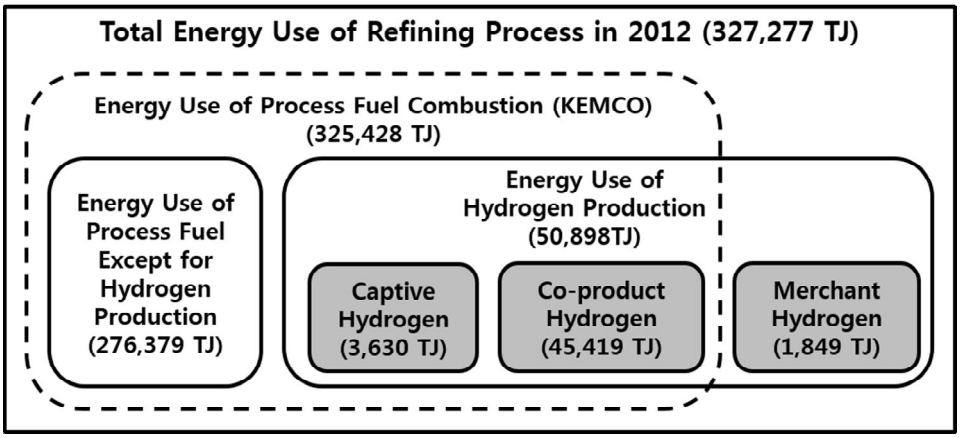


Figure 3.2 Energy use of petroleum refining process in Korea

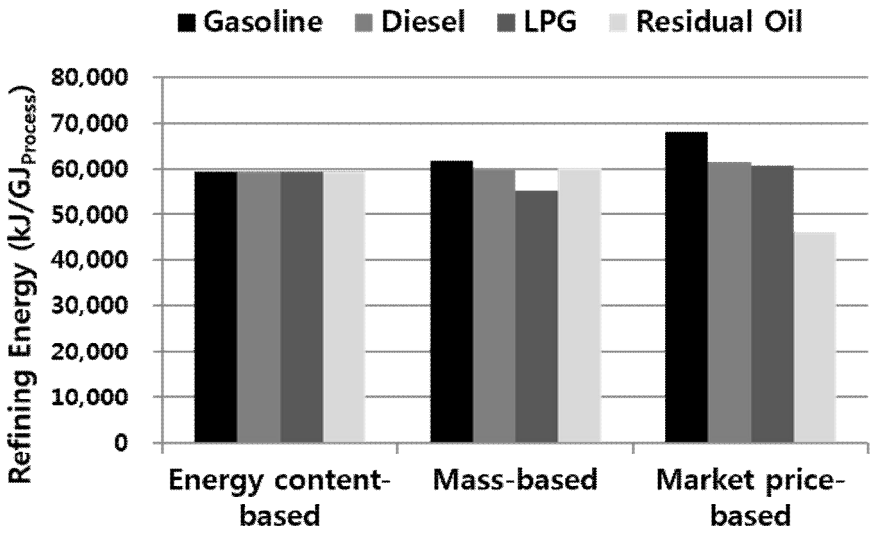


Figure 3.3 Refining energy of petroleum product by refinery-level allocation

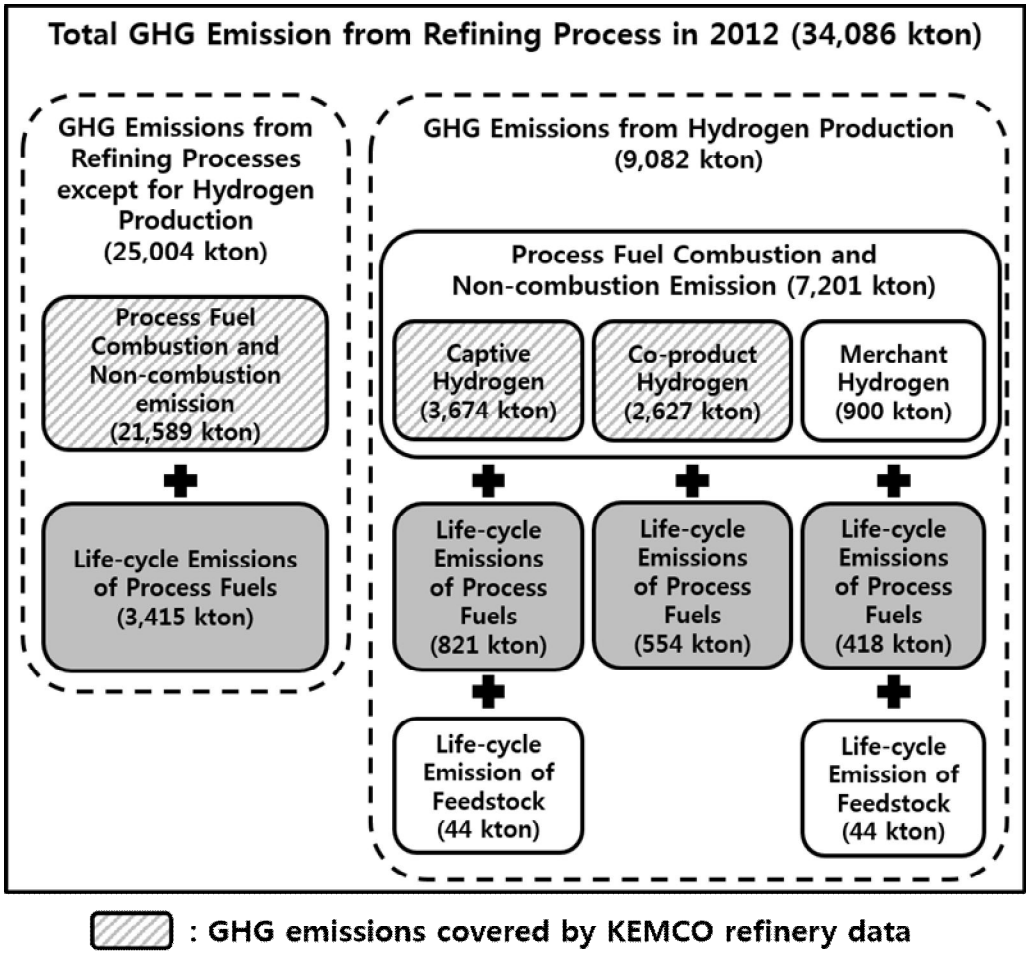


Figure 3.4 GHG emission from petroleum refining process in Korea

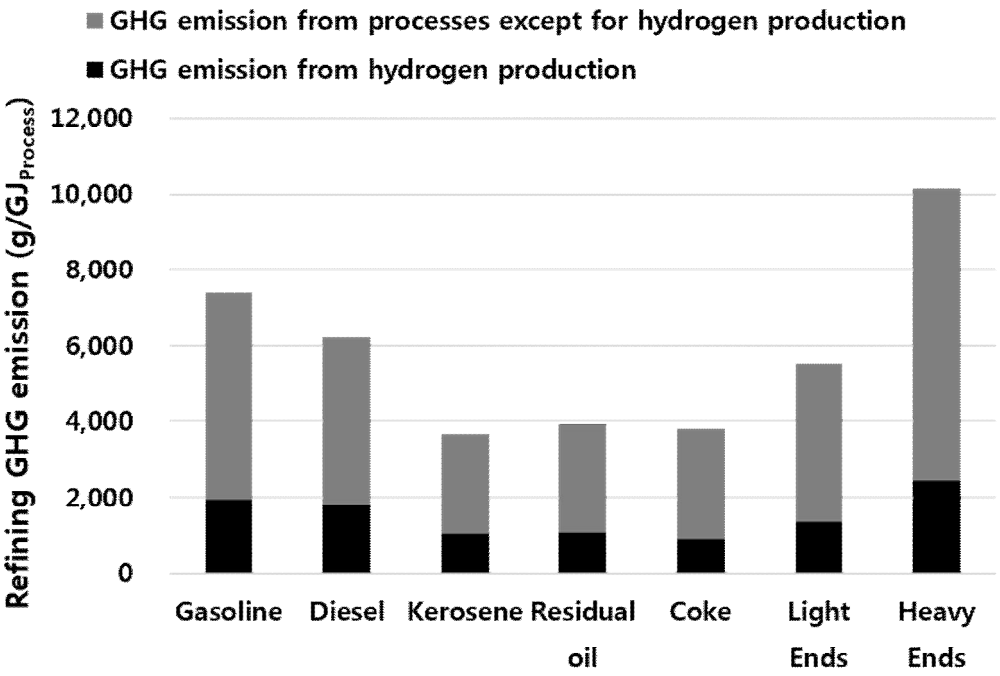


Figure 3.5 GHG emissions of petroleum products in Korea

4. Results

In this section, we present the WTP GHG emissions and energy uses of Korean gasoline and diesel in section 4.1, the total WTW results in section 4.2, and the sensitivity analysis results on the uncertainties of major parameters in section 4.3.

4.1. WTP GHG emissions and energy uses

Table 4.1 lists the values of WTP GHG emissions and energy uses for gasoline and diesel fuels, broken into four processes. The GHG emissions are shown in CO_2 equivalent. It is noted that there is small difference in the values of crude oil recovery and crude oil import processes between gasoline and diesel, although both fuels share these processes. This is because gasoline has slightly higher fuel leakages during the whole WTP processes than diesel, and thus requires somewhat more gasoline that should be produced to compensate for the leaked amount. The significant difference between gasoline and diesel comes from the refining process. The GHG emission from the refining process of gasoline is 1.2 times higher than that of diesel, which leads to the difference about 1,000 g CO_2 eq./GJ_{Final_fuel} in the WTP GHG emission. In the distribution process, the slightly longer distribution distance of diesel fuel contributes to slightly larger GHG emission.

Figures 4.1 (gasoline) and 4.2 (diesel) show the WTP results as compared

with those in other major countries, i.e. Japan, the U.S., and Europe. In the figures, error bars are also included to represent the accumulated uncertainties of data. The solid lines in the figures represent the WTP energy uses, which show similar trends as the WTP GHG emissions. The results for Japan are taken from the WTW report of Toyota (TMC 2004), the results for the U.S. directly from the GREET model (ANL 2012), and the results for Europe based on the WTW analysis performed by JEC (JRC-EUCAR-CONCAWE) (Edwards et al. 2011a, b). Overall, the WTP GHG emissions of Korean gasoline and diesel are lower than those of the U.S. and Europe, which is mainly due to the better refining efficiency from the newly-developed facilities. The results for Japan demonstrate smaller values than all the others. In their analysis, the amount of flaring and venting emissions in recovery process are estimated to be relatively small, and significantly low refining energy and GHG emissions are allocated to diesel fuel from their material balance analysis for a refinery.

4.2. WTW GHG emissions and energy uses

The WTW GHG emissions and energy uses are calculated for the various gasoline and diesel vehicles, which are expressed in kilometer-based unit. Figures 4.3 and 4.4 show the results plotted over the curb weight with the trend line and its coefficient of determination for each fuel. As expected, the heavier vehicles demonstrate overall higher WTW GHG

emissions and energy uses with lower fuel economies. In almost every vehicle weight, the diesel vehicles have better GHG emissions characteristics than gasoline vehicles in Korea.

For the details of the WTW results, we re-categorize the whole life cycle into feedstock production (crude oil recovery and import), fuel production (refining and distribution), and vehicle operation. We chose one sample vehicle model, i.e. Kia Motors Corporation's Sportage, which is available in both gasoline and diesel versions with the same engine size. The WTW results of Sportage gasoline and diesel models are presented in Fig. 4.5.

As shown in Fig. 4.5, the PTW GHG emission is responsible for up over 80 % of the total WTW GHG emission in both fuels. The WTW GHG emission and energy use of gasoline vehicle are higher than those of diesel vehicle for this specific model. It is noted that the relative difference between kilometer-based WTP results of gasoline and diesel (~30 %) in Fig. 4.5 are far greater than that between WTP energy-based WTP results (~10 %) in Table 4.1. This is because the better fuel economy of diesel vehicle results in the less use of diesel per kilometer and thus smaller production energies per kilometer.

4.3. Sensitivity analysis on key parameters

We performed sensitivity analysis to estimate the effect of data

uncertainties on the WTP results. For the analysis, the parameters are divided into two groups: the first group consists of the parameters that have ranges of values from multiple references, and the second group includes the parameters which are assigned to specific values by our own analyses and assumptions.

The parameters of the first group and their minimum and maximum values are presented in Table 4.2. It is noted that these parameters are all from the recovery process of crude oil. As discussed in section 3.1, several international references are used to estimate the ranges of these values without better domestic reference available. We conducted the sensitivity analysis by changing the individual parameter from the lowest to the highest value while fixing the other parameters, and evaluated the rate of change of the total WTP GHG emission.

Figure 4.6 shows the result of the sensitivity analysis on the parameters in the first group. The results for gasoline and diesel are quite similar to each other. For all three parameters, it is demonstrated that the changes in the WTP results are only less than 2 % and thus the uncertainties of the parameters in the first group have only a little effect on the final conclusions in our analysis.

The parameters in the second group are listed in Table 4.3. Here, the refining energy and the import and distribution distances are considered. Since these parameters are given specific values based on the single source with our own analysis and assumption, we changed the values by 10 % (max) and -10 % (min) to evaluate the sensitivity of the final results by each parameter variation.

Figure 4.7 shows the result of the sensitivity analysis on the parameters in the second group. The difference in the results between gasoline and diesel is small. The changes in the import and distribution distances lead to negligible effects under 1.5 % change in the total WTP GHG emission. On the other hand, the refining energy is estimated to be highly sensitive, which causes the change in the WTP result more than 5 %. In our analysis, the total refining energy from the official KEMCO data is accurate, and thus the allocation method has a major impact on the uncertainty of individual product's refining energy. In the present study, although we adopted the process-level allocation method based on the Korean refinery data and the NETL result, it would be desirable to have more detailed process-level data from Korean refineries or any validated refinery modeling results to further improve the accuracy of the WTP results.

Table 4.1 WTP results of gasoline and diesel in Korea

Process	GHG (g CO_2 eq./GJ_{Final_fuel})		Energy use (kJ/GJ_{Final_fuel})	
	Gasoline	Diesel	Gasoline	Diesel
Crude oil recovery	3,433-3,971	3,430-3,968	14,065-18,728	14,055-18,714
Crude oil import	1,345-1,354	1,344-1,353	16,090-16,117	16,078-16,155
Petroleum refining	6,981-7,062	5,876-5,944	93,214-94,101	77,021-77,753
Petroleum distribution	287-290	374-378	4,399-4,424	4,790-4,822
WTP total	**12,047-12,677**	**11,025-11,643**	**127,768-133,370**	**111,944-117,444**

Table 4.2 Key parameters which have multiple references

Key parameters	Min	Determined	Max
Recovery energy ($kJ/GJ_{Process}$)	9,945	11,490	13,626
Flaring and venting CO_2 emission ($g/GJ_{Process}$)	1,016	1,059	1,102
Flaring and venting CH_4 emission ($g/GJ_{Process}$)	57.05	59.48	61.61

Table 4.3 Key parameters which are determined by analyses and assumptions

Key parameters	Gasoline			Diesel		
	−10 %	Determined	+10 %	−10 %	Determined	+10 %
Refining energy ($kJ/GJ_{Process}$)	61,674	68,526	75,379	50,996	56,662	62,329
Import distance (km)	11,083	12,315	13,546	11,083	12,315	13,546
Distribution distance (km)	181	201	221	249	277	304

Figure 4.1 WTP GHG emission and energy use of gasoline

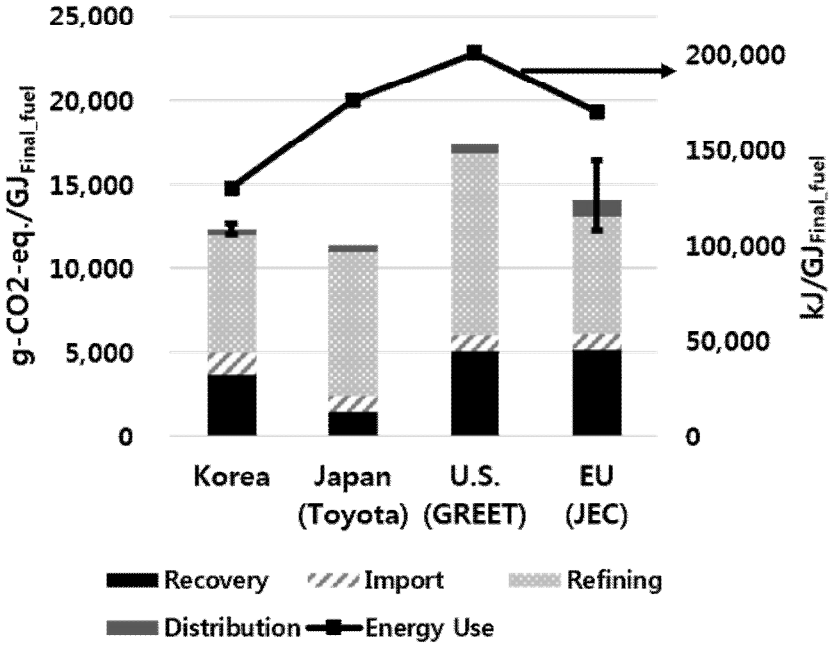


Figure 4.2 WTP GHG emission and energy use of diesel

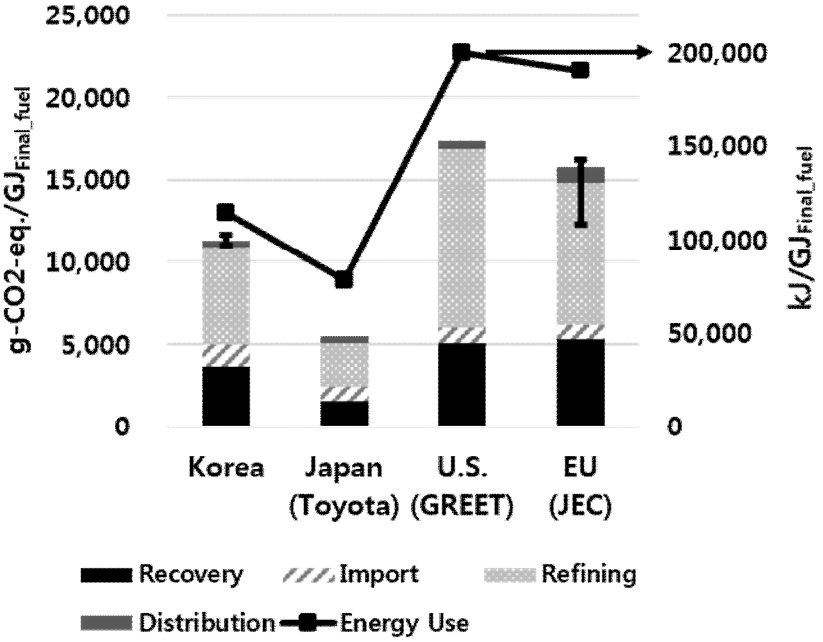


Figure 4.3 WTW GHG emissions of gasoline and diesel vehicles in Korea

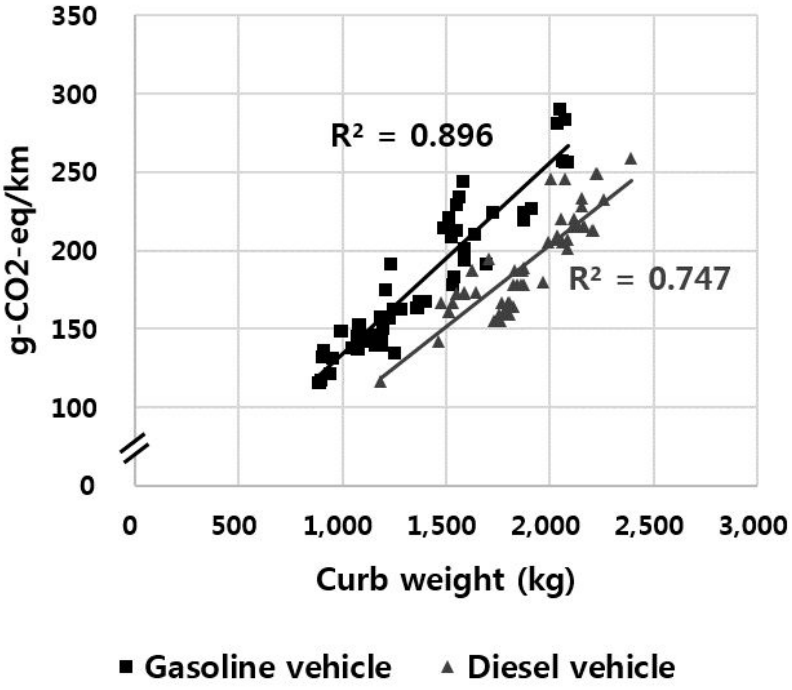


Figure 4.4 WTW energy uses of gasoline and diesel vehicles in Korea

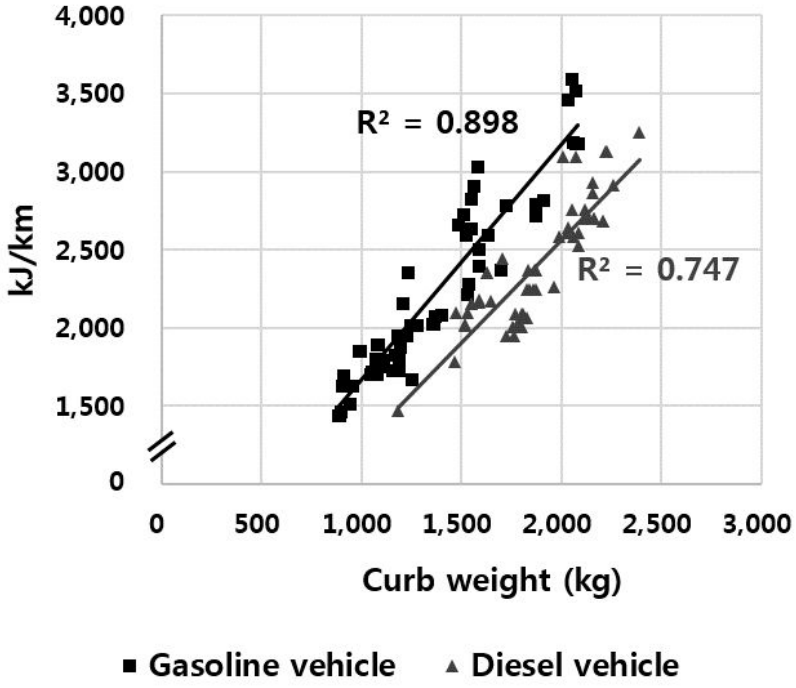


Figure 4.5 WTW GHG emission and energy use of Kia Sportage model

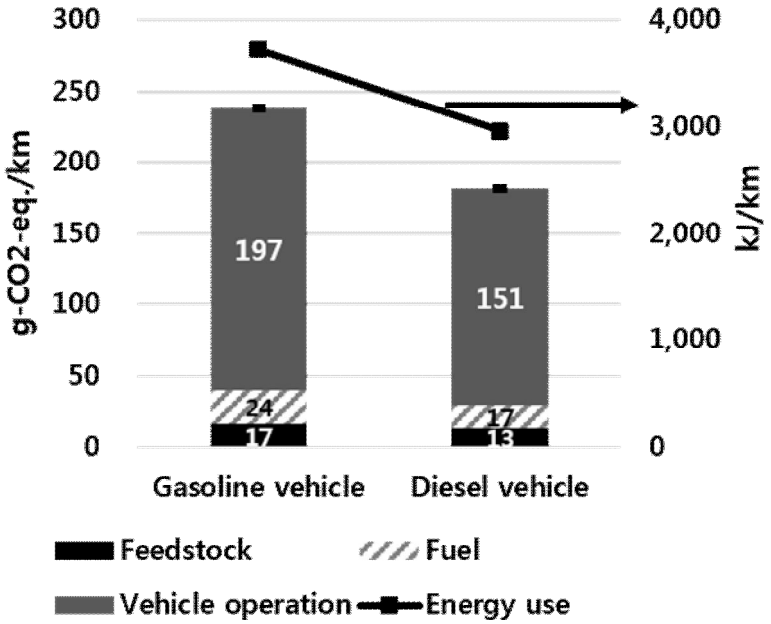


Figure 4.6 Results of sensitivity analysis on WTP GHG emission by key parameters in Table 4.2

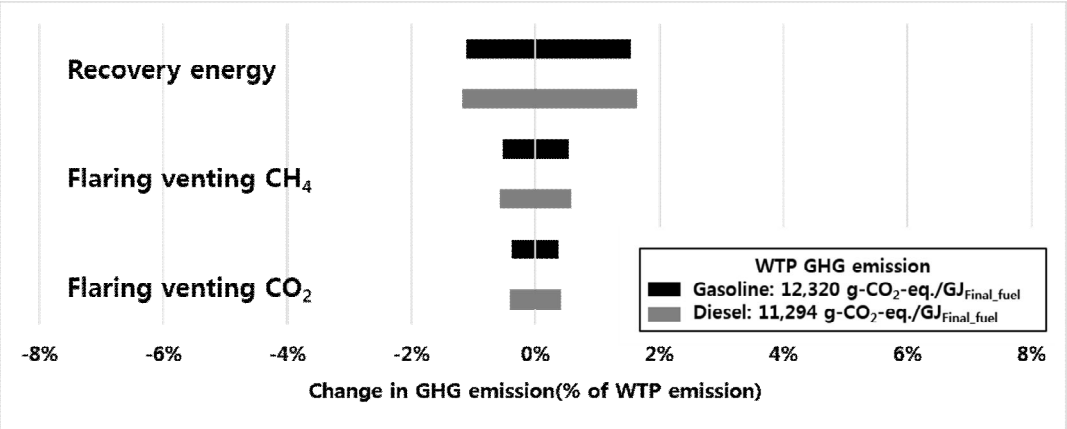
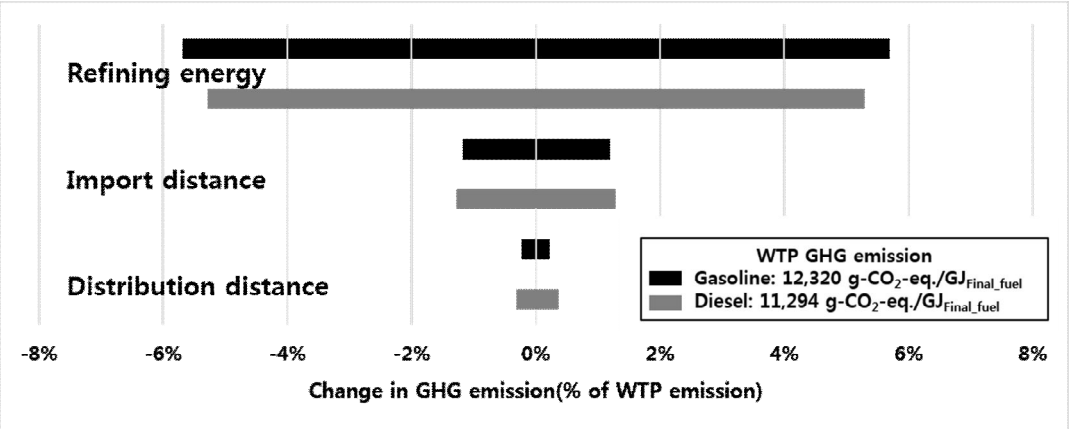


Figure 4.7 Results of sensitivity analysis on WTP GHG emission by key parameters in Table 4.3



5. Conclusions

In this study, the first comprehensive WTW analysis was performed for petroleum-based fuels, i.e. gasoline and diesel, in Korea. We evaluated the GHG emission and the energy use for every process of the whole fuel cycle.

As a result, the WTP GHG emissions of gasoline and diesel are calculated as 12,047-12,677 g CO_2 eq./GJ_{Final_fuel} and 11,025-11,643 g CO_2 eq./GJ_{Final_fuel}, respectively. The main difference between these fuels comes from the higher GHG emission in refining process of gasoline than diesel, mainly because several energy-intensive processes are exclusively attributed to gasoline product. The WTP energy uses of gasoline and diesel are evaluated as 127,768-133,370 kJ/GJ_{Final_fuel} and 111,944-117,444 kJ/GJ_{Final_fuel}, respectively, which show a similar trend with the GHG emissions. As compared to other major countries, such as Japan, the U.S., and Europe, the WTP GHG emissions of petroleum-based fuels in Korea are in the middle.

By including the vehicle operation (or PTW process), we estimated the WTW GHG emissions and energy uses of various vehicle models in Korea. The PTW GHG emission is responsible for most of the WTW GHG emission (up to 80 %) as well as the WTW energy use (up to 85 %) in both fuels. When the similar weight of vehicles are compared,

diesel models demonstrate overall lower WTW emissions than gasoline models, since the former has both the lower WTP GHG emissions and better fuel economy than the latter.

Additionally, we performed sensitivity analysis to estimate the effect of the uncertainties of key parameters. It is demonstrated that most parameters are of little importance to the final result but the refining energy has a significant impact on the result. Therefore, it is recommended that the further analysis on the refining process in Korea should be carried out, in order to improve the accuracy of the present result.

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요약

국내 원유기반 수송용 연료 전과정 온실가스 배출량 및 에너지 사용량 분석

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장재준

본 연구는 국내 원유 기반 연료 (휘발유, 경유) 의 전과정 (Well-to-Wheel) 온실가스 배출량과 에너지 사용량을 종합적으로 분석하는 것을 목적으로 한다. 국내에서 2015년부터 전과정 분석을 기반으로 한 신재생 에너지 연료 혼합 의무화 제도 (RFS) 가 시행될 예정이지만, 국내 수송용 연료에 대한 체계적인 전과정 분석 결과는 거의 존재하지 않는다. 따라서 본 연구에서 수행한 국내 연료에 특화된 전과정 분석 결과는 국내 정책입안자와 이해당사자들에게 기초 자료로 활용될 수 있을 것으로 기대된다.

전과정 분석 연구를 위해 국내 연료 생산 및 사용 전과정에 관한 데이터를 정부 기관과 국내 석유 업계 및 협회로부터 제공받았다. 해외 산지에 대해서는 문헌 조사를 수행하여 데이터를 수집하였다. 수집한 데이터를 바탕으로 미국 Argonne 국가 연구소에서 개발한 GREET 모델을 국내 실정에 맞게 수정하여 전과정 온실가스 배출 및 에너지 사용량을 계산하였다. 그리고 연료

생산 과정 중에 에너지 사용량이 가장 큰 석유 정제 과정에 대해서 별도로 추가적인 분석을 수행하였다. 정제 과정의 세부적인 공정을 고려한 공정 수준의 할당 방법을 이용하여 석유 제품별 정제 에너지를 계산하였다.

휘발유와 경유의 연료 생산 (Well-to-Pump) 과정의 온실가스 배출량은 각각 12,047-12,677 g CO_2 eq./GJ_{Final_fuel}과 11,025-11,643 g CO_2 eq./GJ_{Final_fuel}으로 계산되었다. 정제 과정에서 휘발유가 경유보다 온실가스 배출량이 큰 것이 결과값 차이의 주요한 원인이다. 다른 국가들과 비교하였을 때, 국내 원유기반 연료는 미국과 유럽에 비해 정제 효율이 높아 온실가스 배출량이 작고, 일본과는 원유 산지의 배출량 분석 결과의 차이로 인해 온실가스 배출량이 더 큰 것으로 나타났다. 2014년에 국내에 출시된 국산 승용차에 대해서 전과정 (Well-to-Wheel) 온실가스 배출량을 계산한 결과, 공차중량이 비슷할 경우 휘발유 차량이 경유 차량보다 온실가스 배출량이 큰 것으로 나타났다. 이는 경유가 생산 과정 온실가스 배출량이 작고, 경유 차량이 연비가 더 높기 때문이다. 결과의 신뢰도를 향상시키기 위해서는 상대적으로 불확실성이 높은 정제 과정에 대한 추가적인 분석이 필요하다.

주요어: 연료 생산 과정 분석, 전과정 분석, 수송용 연료, 원유기반 연료, 온실가스 배출

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