Well-to-Wheel Analysis of Greenhouse Gas Emissions of Automotive Fuels in the Japanese Context

- Well-to-Tank Report -

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TOYOTA MOTOR CORPORATION

Mizuho Information & Research Institute, Inc.

This report is available as an ADOBE pdf file on the MHIR website at http://www.mizuho-ir.co.jp/english/

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Preface

According to the diversification of automotive fuels and powertrain technologies, advanced technology vehicles such as hybrid electric vehicles with gasoline and diesel, and various fuel cell based vehicles, have been under research and development extensively. Against this background, in order to evaluate the greenhouse gas emission reduction potentials, we focuses on estimating Well-to-Tank (= consideration of the fuel from resource recovery to delivery to the vehicle tank) greenhouse gas emissions of automotive fuels to be used in Japan for present and near future. Further, by adding these well-to-tank results, we show Well-to-Wheel (=integration of the well-to-tank and tank-to-wheel components) greenhouse gas emissions under the specific condition of driving a sedan.

We hope that these data of this study will be useful for those who are planning to conduct fuel-cycle analysis in the future.

Study Organization

This study was carried out the project team that was organized by environment-related organizations in Mizuho Information & Research Institute, Inc. In addition, in order to ensure Well-to-Tank data impartiality, efforts were made to improve credibility by seeking varied advice, ranging from third party evaluations by specialists (Advisory Committee) up to obtaining calculation methods from the data sources.

The participants of this project were as follows:

<Advisory Committee>

(Chairman)	Hisashi ISHITANI	Graduate School of Media and Governance, Keio University
	Masaki IKEMATSU	General Manager, Fuel Cell Testing Dept., Nippon Oil Corporation
	Fumihiro NISHIMURA	General Manager, Siting & Environment, The Federation of Electric Power Companies
	(Takao KITAHARA	Deputy General Manager, Siting & Environment, The Federation of Electric Power Companies)
	Kiyokazu MATSUMOTO	General Manager, Environment Dept., The Japan Gas Association
	Kiyoshi NAKANISHI	Senior Director of Research, Genesis Research Institute, Inc. (Advisor, Toyota Motor Corporation)
	Shigeki KOBAYASHI	IPCC Coordinating Lead Author (Senior Researcher, Strategic Planning Office, Toyota Central R&D Labs., Inc.)

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(Representative)	Hirohiko HOSHI	Senior Staff Engineer, Fuel & Lubricant Department

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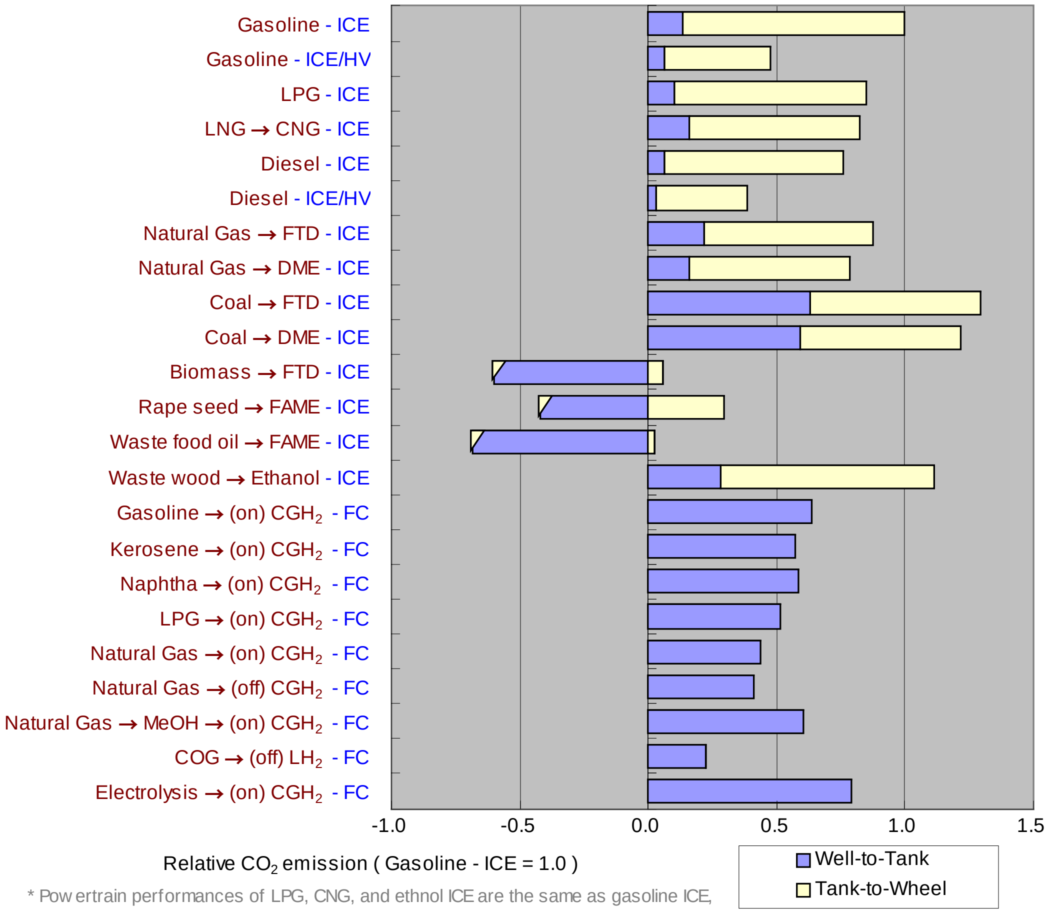
Acknowledgments

We would like to thank members of Advisory Committee and specialists at the various institutions that supported our study during the process of hearing and editing this report.

Executive Summary

With the impending practical application of fuel cell vehicles (FCV), the choice of propulsion systems, along with gasoline and hybrid vehicles is increasing, while on the other hand, the diversification of fuels is also progressing. From this background, Toyota Motor Corporation (TMC) commissioned Mizuho Information & Research Institute, Inc. (MHIR) to conduct this study with the objective of establishing a foundational understanding needed to consider the potential of various technologies and automotive fuels in the reduction of environmental load.

The calculations of this study mainly concern Well-to-Tank (=consideration of the fuel from extraction of primary energy to vehicle fuel tank) energy consumption, greenhouse gas (GHG) emissions and energy efficiency of current and near future automotive fuels in Japan. The results of this study were subsequently combined with data related to Tank-to-Wheel (=assessing vehicle architecture, powertrain and fuel effects) studies previously conducted by TMC, and a case study showing Well-to-Wheel (=integration of the Well-to-Tank and Tank-to-Wheel components) GHG emissions under fixed conditions of driving sedan type vehicles, was calculated (See figure below).



* Powertrain performances of LPG, CNG, and ethnol ICE are the same as gasoline ICE, and powertrain performances of FTD, DME, and FAME ICE are the same as diesel ICE.

(See page 104 "3.2 Case study: Tank-to-Wheel and Well-to-Wheel GHG emissions" for more details on preconditions of the calculation.)

Figure Well-to-Wheel GHG emissions under fixed conditions of driving sedan type vehicles

Regarding Well-to-Tank studies, the fuel production pathways considered were; 21 petroleum based fuels, 20 natural gas based fuels, 8 coal based fuels, 19 biomass resource related fuels (3 bio-diesel fuels, 10 dry biomass based fuels, 6 wet biomass based fuels), power grid mix (Japan average) and hydrogen production through electrolysis, 6 byproduct hydrogen pathways, totaling 76 pathways. No fixed timeframe was set for the data collected, with efforts focusing on understanding and organizing existing data. Additionally, in order to ensure data impartiality, efforts were made to improve credibility by seeking varied advice, ranging from third party evaluations by specialists (Advisory Committee) up to obtaining calculation methods from the data sources. Moreover, where data used in calculation has a broad range, the range is indicated through minimum to maximum values.

Furthermore, for Well-to-Wheel, in concurrence with previous research for the “10-15 mode run” (example of calculations made in this study), which is mainly a comparatively low-speed run, significantly superior results were obtained for hybrid electric vehicles (gasoline, diesel) in relation to GHG emissions. For synthetic fuels such as Fischer-Tropsch Diesel Oil and Dimethyl Ether (DME), and hydrogen, large variations in Well-to-Tank GHG emissions were apparent depending on the primary energy used as feedstock, and it is clear that an important aspect of future considerations will be the production of fuels through low GHG emission pathways. Moreover, regarding hydrogen, during transition, hydrogen derived from fossil fuels such as natural gas has also shown results similar to that of hybrid electric vehicles, and depending on trends in CO_2 capture and storage, possibilities of further reductions in GHG emissions with these pathways are conceivable. In addition, fuels derived from biomass resources have comparatively low GHG emission values, and future utilization is anticipated.

The credibility and applicability of calculations in this study depends greatly on calculation preconditions such as implemented load distribution methods and quality of data. In reality, some fuels such as petroleum products, city gas, liquefied petroleum gas (LPG) and electricity are already in industrial use, while biomass resources, synthetic fuels, hydrogen, and so on, are still in the early stages of technological development. In addition, even where calculation results of this study are based on actual values, as there is a high degree of uncertainty concerning future technological innovation, market size, new laws and regulations, and such, many problems exist concerning the simple comparison of these fuels. Furthermore, regarding load distribution between main products and co-products/byproducts, although this study has been conducted under the premise that, in principle, byproducts will be disposed of, the usage of certain byproducts has been considered in prior studies although the possibility of realizing this usage is unclear (load distribution considerations). Also, regarding the sphere of the system, the environmental load from the production process of byproduct hydrogen feedstock such as coke oven gas (COG) has not been taken into consideration in this study. For these reasons, the calculation results of this study are not unlike preliminary approximations, and in order to contribute further to the initial objectives, the consistency of preconditions and the accuracy of data used in calculations must be improved, and the credibility of the results must be enhanced.

The emphasis of this study is on Well-to-Tank analysis. In future, these results will be combined with various Tank-to-Wheel analysis results and basic data, and various further analyses are scheduled in relation to overall efficiency from extraction of primary energy to actual vehicle fuel consumption “Well-to-Wheel”. At such a time, it may also become necessary to modify or adjust the calculation results of this study in order to comply with analysis preconditions.

Well-to-Wheel analysis results will be an important factor in the selection of future technologies and fuels.

However, technologies and fuels that will be implemented in the future will not be determined by this factor alone. This is because a variety of other factors such as cost, infrastructure, completeness of the technology, supply potential and usability will also be taken into consideration. In future, it will be necessary to seek out optimum vehicle/fuel combinations according to the energy circumstances, available infrastructure and regulations that apply in each country or region. See page 104 “3.2 Case study: Tank-to-Wheel and Well-to-Wheel GHG emissions” for more details on preconditions of the calculation.

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1. Goal and Scope in This Study

1.1 Goal

With the impending practical application of fuel cell vehicles (FCV), the choice of propulsion systems, along with gasoline and hybrid vehicles is increasing, while on the other hand, the diversification of fuels is also progressing. With this background, for the continued utilization of motor vehicles in society, it is the objective of this study to establish the foundational understanding needed to consider the potential of various technologies and fuels, concerning the reduction environmental load, without sacrificing the convenience of mobility.

Specifically, the investigation and compilation of various fuel production pathways for potential automotive fuels with future technologies are taken into consideration, with incremental calculations for Well-to-Wheel energy consumption, GHG emissions and energy efficiency for each pathway.

1.2 Scope

The lifecycle of an automobile consists of the fuel supply cycle (resource extraction to production to fuel tank), the vehicle cycle (vehicle manufacture, running, disposal/recycling) and other related infrastructure cycles (See Figure 1.1). Of these cycles, this study focuses mainly on the fuel supply cycle within Japan, with Well-to-Tank calculations for energy consumption, GHG emissions and energy efficiency.

In addition, as a separate case study, reference data was calculated for Well-to-Wheel GHG emissions relevant to the running stage of the vehicle cycle under predetermined conditions.

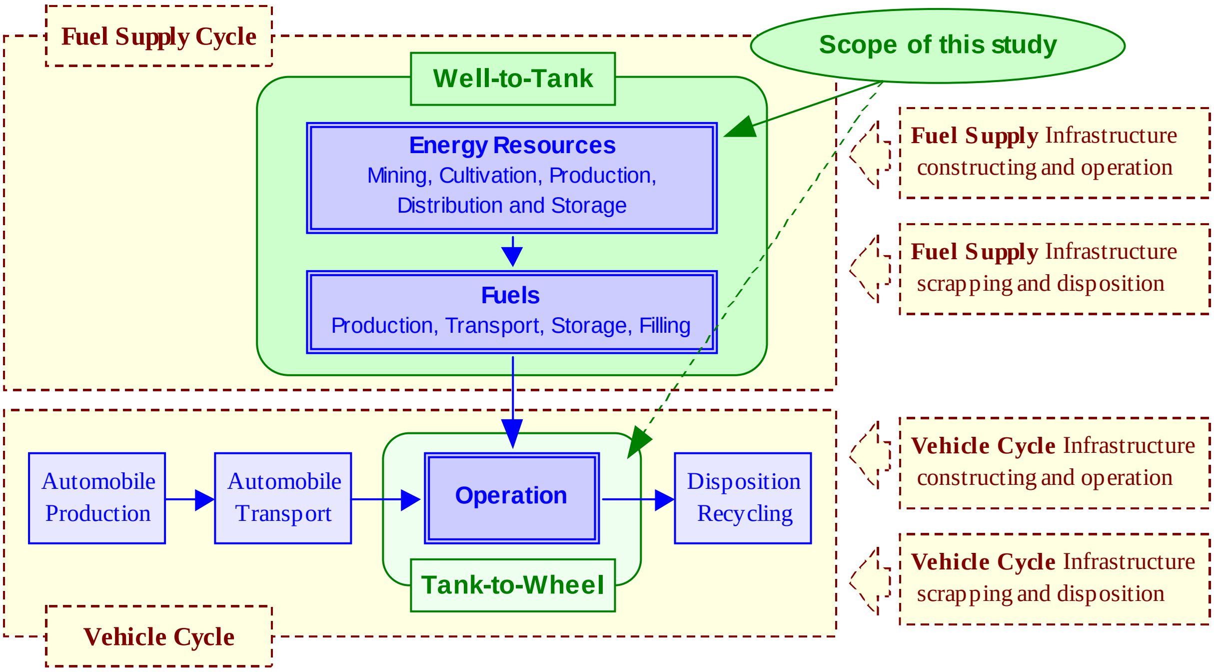


Figure 1.1 Scope of this study

1.2.1 Fuels and fuel production pathways

To begin with, following the compilation of fuel production pathways applicable for automotive fuels in Japan, the fuel production pathways to be considered were selected from the perspectives of (1) Already realized, (2) High probability of realization in the future, (3) Strong repercussion effect in the event of realization.

The fuel production paths considered in this study are shown in Table 1.1 ((A) Petroleum Based, (B) Natural Gas Based, (C) Coal Based, (D) Biomass Resource Related, (E) Power grid mix (Japan average), (F) Byproduct Hydrogen).

Table 1.1 (A) Fuels and fuel production paths – Petroleum Based

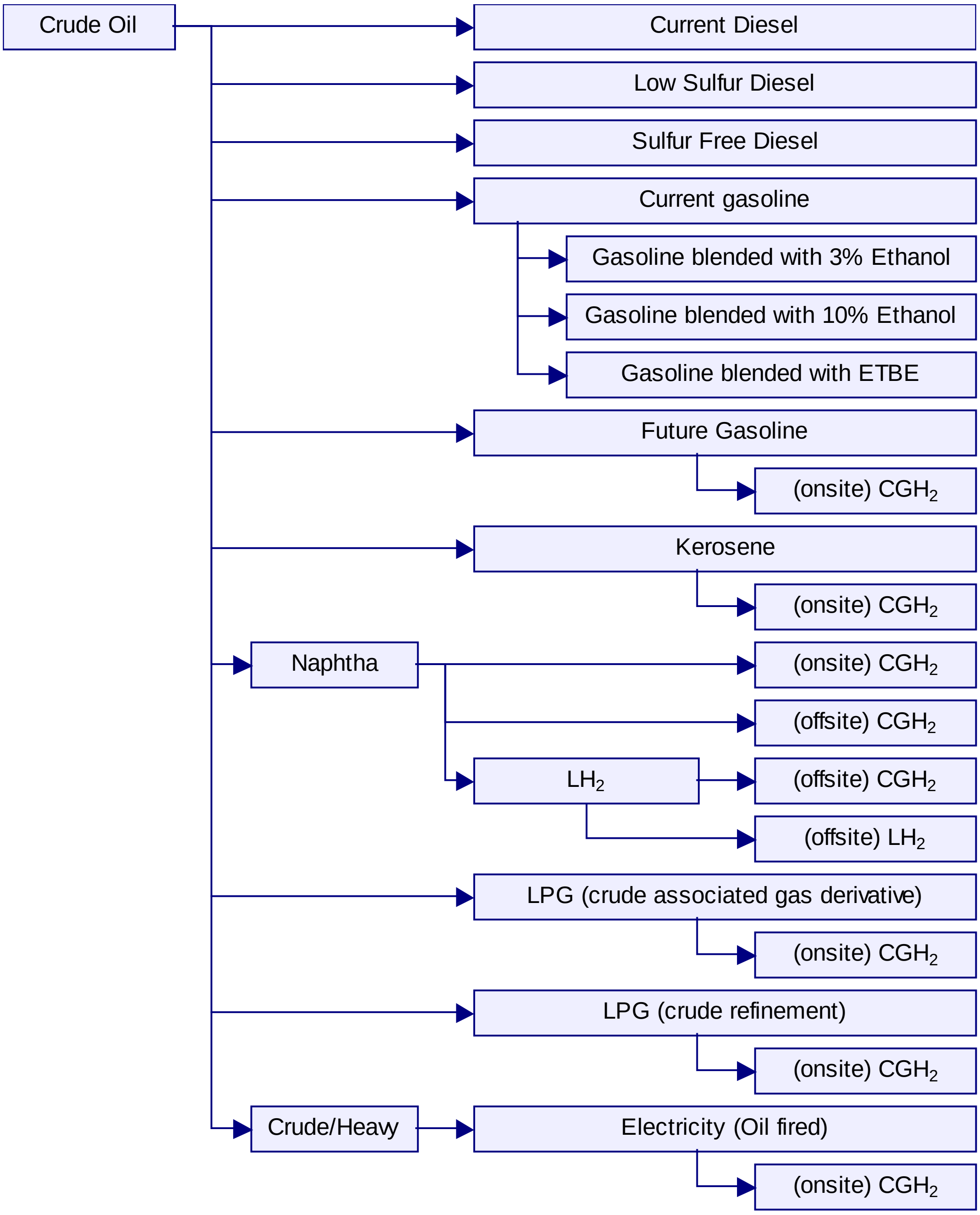


Table 1.1 (B) Fuels and fuel production paths – Natural Gas Based

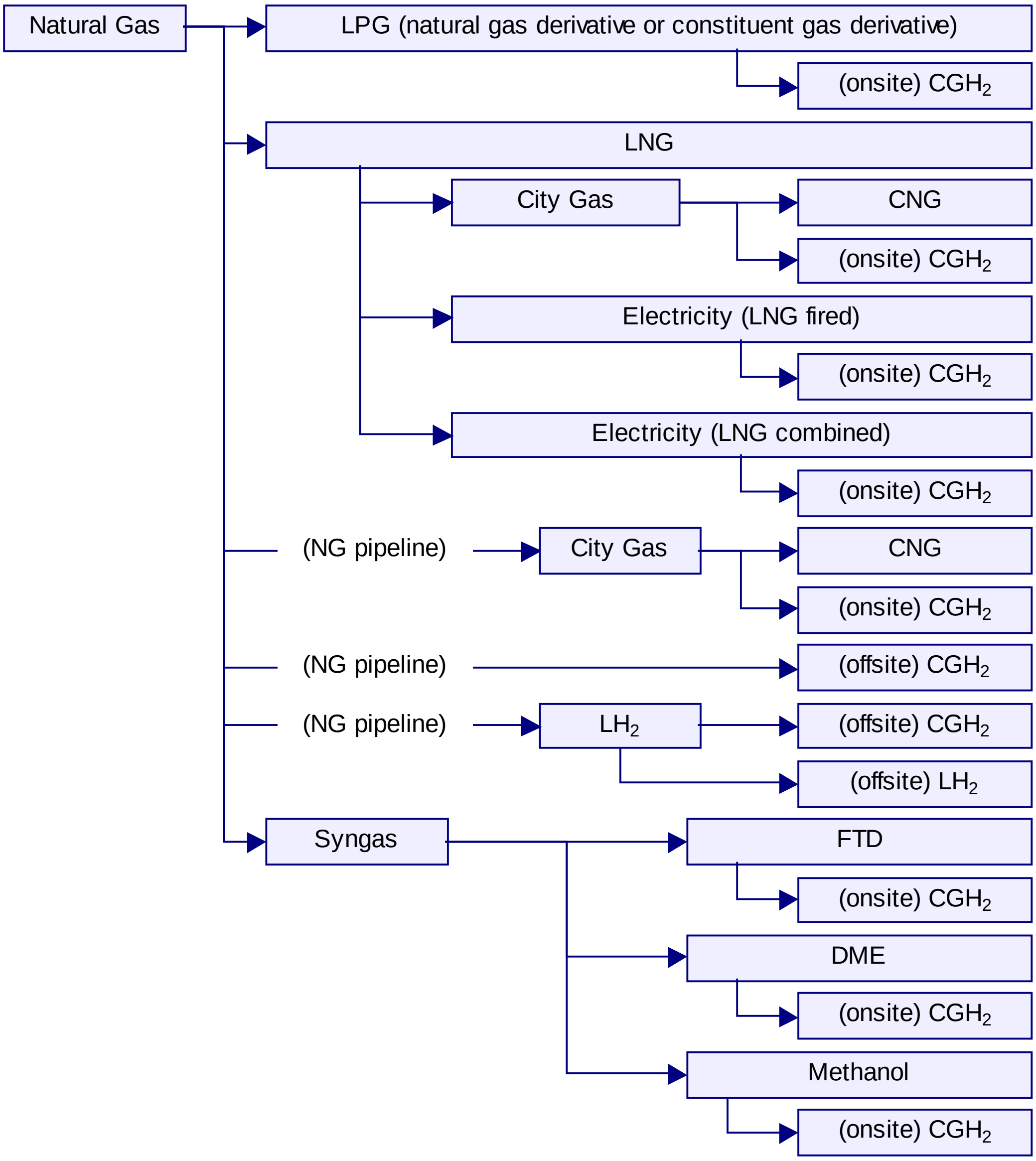


Table 1.1 (C) Fuels and fuel production paths – Coal Based

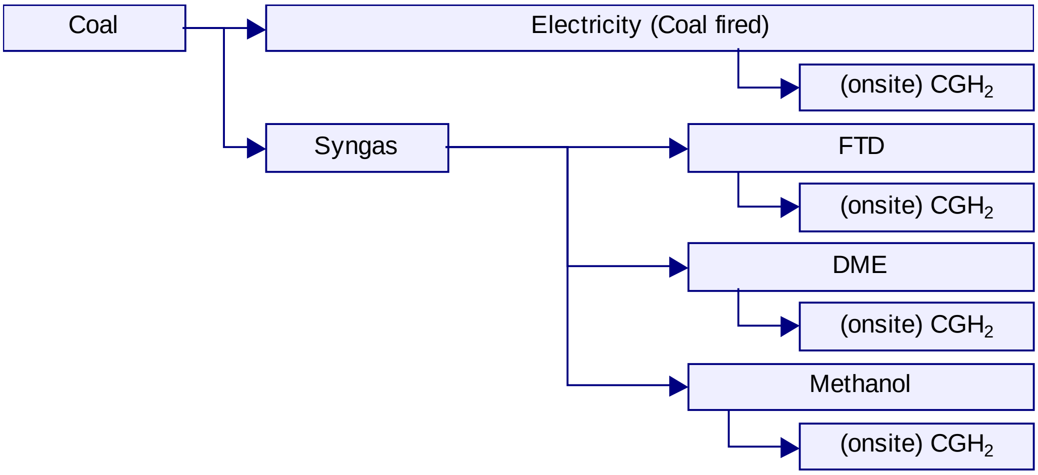


Table 1.1 (D) Fuels and fuel production paths – Biomass Resources Related

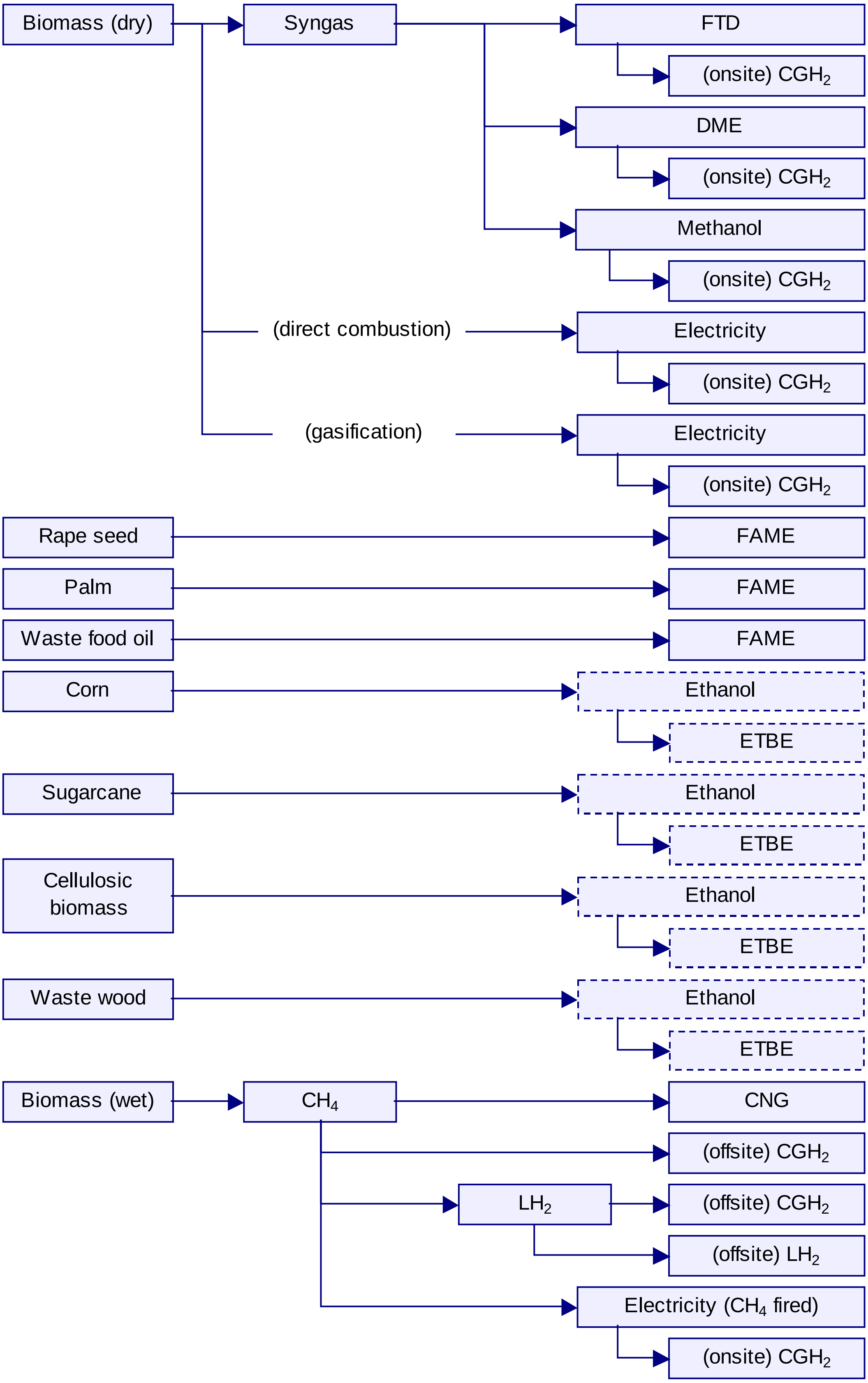


Table 1.1 (E) Fuels and fuel production paths – Power Grid Mix (Japan average)

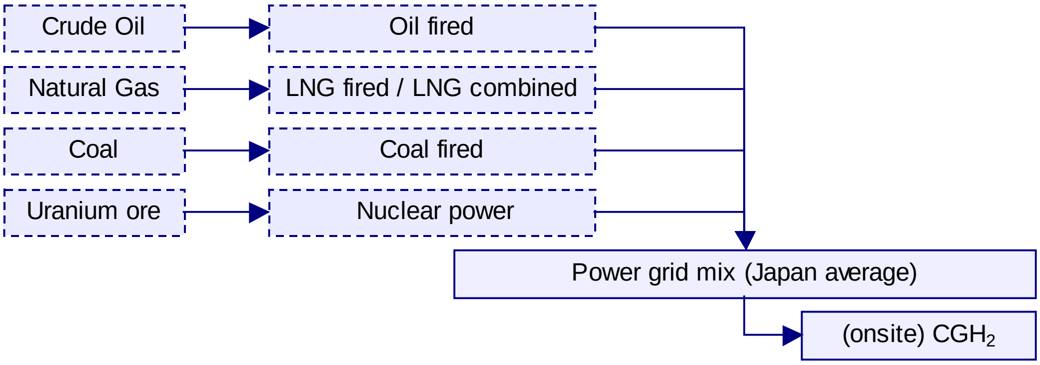
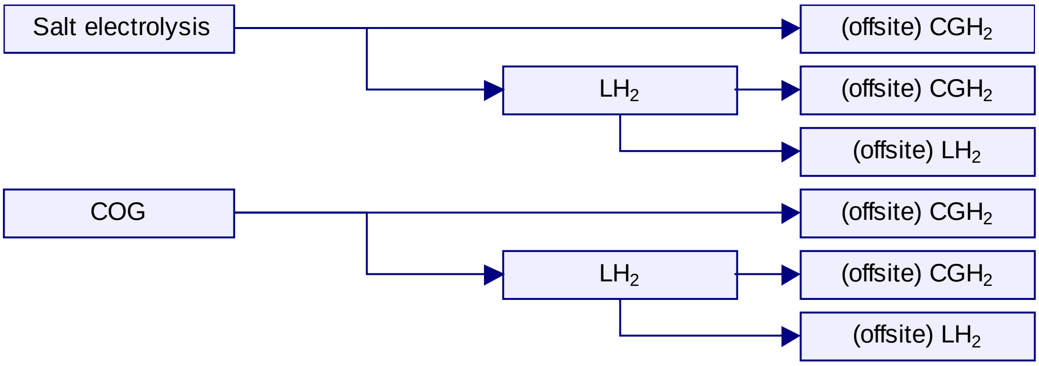


Table 1.1 (F) Fuels and fuel production paths – Byproduct Hydrogen



Furthermore, for this study, in order to conduct efficient data calculations, the processes forming the fuel production pathways shown in Table 1.1 were classified into the following groups.

(1) Petroleum Based Fuel Production Pathways → See 2.1
(2) Natural Gas Based Fuel Production Pathways → See 2.2
(3) Fuel Production Pathways from Biomass Resources → See 2.3
(4) Synthetic Fuel Production Pathways → See 2.4
(5) LPG Production Pathways → See 2.5
(6) Electricity (Electric generation pathways) → See 2.6
(7) Hydrogen Production Pathways → See 2.7

The compilation procedures and calculation methods used for each unit process data are described in “2. Well-to-Tank Data Compilation Procedures and Calculation Methods”. The results of Well-to-Tank energy consumption, GHG emissions and energy efficiency calculations derived through the combination of this process data and the conclusions drawn are discussed in “3. Results and conclusions”.

1.2.2 Data categories

Within this study, issues related to the following were considered as environmental load issues.

[Energy consumption]

- Energy consumption (lower heating value) [MJ]
- Energy efficiency (lower heating value) [%]

[Emission to air]

- GHG emissions: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O) [kg]

Furthermore, in light of the objectives of the study, only the above issues were considered, and emissions to air, water and land other than the above were excluded from evaluation.

Additionally, regarding calculating category indicator results within climate change, referring to Intergovernmental Panel on Climate Change (IPCC) [2001], the Global Warming Potential (GWP) 100-year factor, frequently used as an index to show the magnitude of climate change, was used as the characterization factor. The following reasons can be given regarding the use of the 100-year factor:

- The lifespan of CO_2 in the atmosphere is 120 years,
- IPCC recommends a time horizon of 100 years.

Regarding emissions other than CO_2 (CH_4, N_2O), evaluation was conducted through conversion to equivalent CO_2 in accordance with the GWP 100-year factor.

$$\text{GWP indicator result [kg eq-}CO_2\text{]} = \text{GHG emission [kg]} * \text{GWP 100-year factor [kg eq-}CO_2\text{/kg]}$$

The GWP 100-year factor used in this study is shown in Table 1.2 (IPCC [2001]).

Table 1.2 Characterization factor

GHG emission	GWP
Carbon Dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous Oxide (N_2O)	296

1.2.3 Calculation procedures

This study employed the “Conventional Process-based LCA Method”, studying data per process within the lifecycle from the production of each fuel up to supply to the vehicle.

Unless specifically stated otherwise, the data shown in Table 1.3 in relation to fossil fuel combustion and the use of electricity, was used to calculate energy consumption and CO_2 emissions for each process. Therefore, input/output in relation to fossil fuel combustion was converted to energy input/output by multiplying the heating values given in Table 1.3, or in relation to electricity usage, by multiplying the energy consumption values per kWh shown in Table 1.4. Subsequently, energy consumption and CO_2 emissions were calculated by multiplying the heating values and CO_2 emission factors during combustion given in Tables 1.3 and 1.4.

In this study, energy efficiency of a pathway was calculated as the simple product of the numerator, taken as the energy (heating value) of the product of each process, and the denominator, calculated as the sum of the energy (heating value) of the resources injected into the process and the energy consumed in the process.

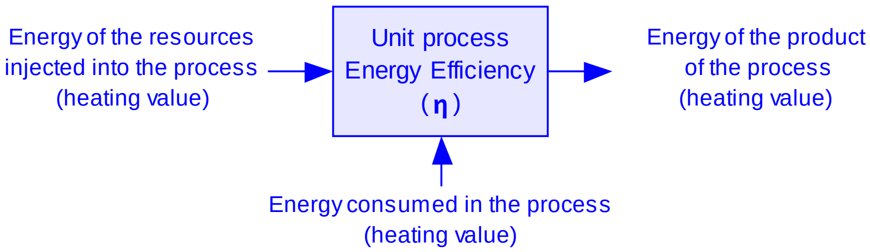


Figure 1.2 Energy efficiency of the unit process

$$\eta = \frac{\text{Energy of the product of the process (heating value)}}{\text{Energy of the resources injected into the process + Energy consumed in the process (heating value)}}$$

Regarding heating value, for general LCA purposes, higher heating value (= value which includes the condensation heat (latent heat of vaporization) of moisture in the fuel and steam generated through combustion in the heating value. HHV) is used. However, as the operating temperature of the combustion engine of this study is high and latent heat recovery for steam is difficult, it was decided that lower heating value (= value that does not include the condensation heat of steam. LHV) would be used as the basis for calculations in this study. Furthermore, as the reference materials from which the CO_2 emission factors were quoted used HHV, LHV was calculated from this using the conversion factor shown below (Institute of Energy Economics, Japan (IEEJ) [1999]).

- Coal : LHV ← HHV * 0.96
- Oil : LHV ← HHV * 0.93
- LNG : LHV ← HHV * 0.90
- LPG : LHV ← HHV * 0.92

Additionally, regarding conversion factors for petroleum based fuels, in principle, the values given in New Energy and Industrial Technology Development Organization (NEDO) [1995] were used and shortfalls were covered using International Energy Agency (IEA) values given by K.K.Sekiyutsushinsha [2002]. For reference, NEDO [1995] conversion factors were calculated to equalize Yuasa *et al.* [1991] CO_2 emission factors and Science and Technology Agency [1992] CO_2 emission factors.

Table 1.3 Heating values and CO_2 emission factors

	Factor		Heating Value			CO_2emission factor	
		Ref.	HHV	LHV	Ref.	[kg-CO_2]	Ref.
Coal for coking (import)			28.9 MJ/kg	27.7 MJ/kg	3)	2.61 kg/kg	4)
Coal for general use (import)			26.6 MJ/kg	25.5 MJ/kg	3)	2.39 kg/kg	4)
Coal for general use (domestic)			22.5 MJ/kg	21.6 MJ/kg	3)	1.97 kg/kg	4)
Anthracite (import)			27.2 MJ/kg	26.1 MJ/kg	3)	2.45 kg/kg	4)
Coke			30.1 MJ/kg	28.9 MJ/kg	3)	3.25 kg/kg	4)
Coke Oven Gas			21.1 MJ/Nm^3	19.0 MJ/Nm^3	3)	0.85 kg/Nm^3	4)
Blast Furnace Gas			3.4 MJ/Nm^3	3.1 MJ/Nm^3	3)	0.37 kg/Nm^3	4)
Oxygen Steel Furnace Gas			8.4 MJ/Nm^3	7.6 MJ/Nm^3	3)	0.91 kg/Nm^3	4)
Crude oil	0.8596 kg/L	1)	38.2 MJ/L 44.4 MJ/kg	35.5 MJ/L 41.3 MJ/kg	3)	2.64 kg/L 3.07 kg/kg	4)
NGL / gas-condensate	0.7365 kg/L	1)	35.3 MJ/L 47.9 MJ/kg	32.8 MJ/L 44.6 MJ/kg	3)	2.40 kg/L 3.26 kg/kg	4)
LPG	0.5500 kg/L	2)	50.2 MJ/kg	46.2 MJ/kg	3)	2.94 kg/kg	4)
Naphtha	0.7274 kg/L	1)	34.1 MJ/L 46.9 MJ/kg	31.7 MJ/L 43.6 MJ/kg	3)	2.22 kg/L 3.06 kg/kg	4)
Gasoline	0.7532 kg/L	1)	34.6 MJ/L 45.9 MJ/kg	32.2 MJ/L 42.7 MJ/kg	3)	2.38 kg/L 3.16 kg/kg	4)
Jet Fuel	0.7834 kg/L	2)	36.7 MJ/L 46.8 MJ/kg	34.1 MJ/L 43.6 MJ/kg	3)	2.46 kg/L 3.14 kg/kg	4)
Kerosene	0.7990 kg/L	1)	36.7 MJ/L 45.9 MJ/kg	34.1 MJ/L 42.7 MJ/kg	3)	2.51 kg/L 3.15 kg/kg	4)
Diesel	0.8299 kg/L	1)	38.2 MJ/L 46.0 MJ/kg	35.5 MJ/L 42.8 MJ/kg	3)	2.64 kg/L 3.19 kg/kg	4)
A-Heavy fuel oil	0.8430 kg/L	2)	39.1 MJ/L 46.4 MJ/kg	36.4 MJ/L 43.1 MJ/kg	3)	2.80 kg/L 3.32 kg/kg	4)
B-Heavy fuel oil	0.9000 kg/L	2)	40.4 MJ/L 44.9 MJ/kg	37.6 MJ/L 41.7 MJ/kg	3)	2.91 kg/L 3.23 kg/kg	4)
C-Heavy fuel oil	0.9130 kg/L	1)	41.7 MJ/L 45.7 MJ/kg	38.8 MJ/L 42.5 MJ/kg	3)	2.99 kg/L 3.27 kg/kg	4)
Lubricant	0.8800 kg/L	1)	40.2 MJ/L 45.7 MJ/kg	37.4 MJ/L 42.5 MJ/kg	3)	2.89 kg/L 3.29 kg/kg	4)
Asphalt & other res. oil prds			42.3 MJ/kg	39.3 MJ/kg	3)		
Hydrocarbon Oil			41.0 MJ/L	38.2 MJ/L	5)	3.12 kg/L	5)
Petroleum Coke			35.6 MJ/kg	33.1 MJ/kg	3)	3.31 kg/kg	4)
Refinery Gas			44.9 MJ/Nm^3	41.8 MJ/Nm^3	3)	2.41 kg/Nm^3	4)
Hydrocarbon oil gas			39.4 MJ/Nm^3	35.4 MJ/Nm^3	5)	2.04 kg/Nm^3	5)
Associated gas			48.3 MJ/Nm^3	43.5 MJ/Nm^3	7), 8)	2.67 kg/Nm^3	7)
Off gas			39.3 MJ/L	36.6 MJ/L	6)	2.05 kg/L	6)
LNG	0.7173 kg/Nm^3	1)	54.5 MJ/kg	49.1 MJ/kg	3)	2.77 kg/kg	4)
Natural gas (domestic)			40.9 MJ/Nm^3	36.8 MJ/Nm^3	3)	2.09 kg/Nm^3	4)
City Gas 13A			46.1 MJ/Nm^3	41.4 MJ/Nm^3	9)	2.36 kg/Nm^3	4)

[Source]
1) NEDO [1995]
2) K.K.Sekiyutsushinsha [2002] *IEA basis
3) ANRE [2002-1]
4) MOE [2002-1]
5) PEC [2000]
6) PEC [2002-2]
7) Shigeta, J. [1990]
8) PEC [1998]
9) IEEJ [1999]

Table 1.4 Energy consumptions[*1] and CO_2 emissions from fuel combustion at power generation sector in Japan

	per 855,488*10^6 kWh[*2]			per kWh of power generated					
	Energy consumption			Energy consumption				CO_2 emission factor	
	HHV	LHV		HHV	LHV		%		
Coal (import)	1,525	1,464	* 10^{15} J	1.78	1.71	MJ	(18.1%)	0.1604	kg-CO_2
Crude Oil	296	275	* 10^{15} J	0.35	0.32	MJ	(3.5%)	0.0239	kg-CO_2
C-HFO	484	450	* 10^{15} J	0.57	0.53	MJ	(5.8%)	0.0405	kg-CO_2
Diesel	9	8	* 10^{15} J	0.01	0.01	MJ	(0.1%)	0.0007	kg-CO_2
Naphtha	4	4	* 10^{15} J	0.00	0.00	MJ	(0.0%)	0.0003	kg-CO_2
NGL	2	2	* 10^{15} J	0.00	0.00	MJ	(0.0%)	0.0002	kg-CO_2
LNG	2,107	1,896	* 10^{15} J	2.46	2.22	MJ	(25.1%)	0.1251	kg-CO_2
LPG	20	18	* 10^{15} J	0.02	0.02	MJ	(0.2%)	0.0014	kg-CO_2
Natural gas	22	20	* 10^{15} J	0.03	0.02	MJ	(0.3%)	0.0013	kg-CO_2
COG	61	55	* 10^{15} J	0.07	0.06	MJ	(0.7%)	0.0029	kg-CO_2
LDG / BFG	146	131	* 10^{15} J	0.17	0.15	MJ	(1.7%)	0.0184	kg-CO_2
Wastes	19	19	* 10^{15} J	0.02	0.02	MJ	(0.2%)	0[*3]	kg-CO_2
Geothermal	29	29	* 10^{15} J	0.03	0.03	MJ	(0.3%)	0[*3]	kg-CO_2
Hydro	787	787	* 10^{15} J	0.92	0.92	MJ	(9.4%)	0[*3]	kg-CO_2
Nuclear	2,892	2,892	* 10^{15} J	3.38	3.38	MJ	(34.4%)	0[*3]	kg-CO_2
Total	8,403	8,051	* 10^{15} J	9.82	9.41	MJ	(100.0%)	0.375	kg-CO_2

*1) Actual values of FY2000 in Japan

*2) Amount supplied from power producers to final energy consumption

*3) CO_2 emissions at waste power generation, geothermal power generation, hydropower generation and nuclear power generation are considered as 0.

[Source] ANRE [2002-1]

Power generation process data based on the average electricity configuration of the relevant country was referenced regarding electricity input into overseas processes. Energy consumption values of each country (China, Indonesia, Malaysia, India, United Kingdom, France, Holland, European Union, Russia, United States, Canada, Brazil, South Africa, and Australia) during power generation and CO_2 emission factors during fuel combustion are shown in Table 1.5.

Table 1.5 Energy consumptions and CO_2 emissions from fuel combustion at power generation sector by country (per kWh: receiving end basis, actual results of CY2001)

Country	Energy consumption			CO_2 emission factor		Loss	Source
	HHV	LHV					
China	12.68	12.19	MJ	1.034	kg-CO_2	0.083	IEA [2003-2]
Indonesia	12.49	11.75	MJ	0.767	kg-CO_2	0.135	IEA [2003-2]
Malaysia	9.48	8.62	MJ	0.492	kg-CO_2	0.060	IEA [2003-2]
India	18.42	17.68	MJ	1.490	kg-CO_2	0.294	IEA [2003-2]
UK	11.10	10.57	MJ	0.564	kg-CO_2	0.088	IEA [2003-1]
France	11.52	11.46	MJ	0.069	kg-CO_2	0.062	IEA [2003-1]
Holland	10.88	10.06	MJ	0.637	kg-CO_2	0.039	IEA [2003-1]
EU	10.72	10.37	MJ	0.420	kg-CO_2	0.063	IEA [2003-2]
Russia	18.07	16.87	MJ	0.927	kg-CO_2	0.141	IEA [2003-2]
USA	12.09	11.61	MJ	0.712	kg-CO_2	0.061	IEA [2003-1]
Canada	7.43	7.24	MJ	0.264	kg-CO_2	0.079	IEA [2003-1]
Brazil	6.05	5.94	MJ	0.111	kg-CO_2	0.159	IEA [2003-2]
South Africa	14.15	13.62	MJ	1.206	kg-CO_2	0.091	IEA [2003-2]
Australia	13.90	13.29	MJ	1.157	kg-CO_2	0.082	IEA [2003-1]

2. Well-to-Tank Data Compilation Procedures and Calculation Methods

2.1 Petroleum Based Fuel Production Pathways

2.1.1 Abstract

Fuels derived from petroleum include current diesel, low sulfur diesel, ultra low sulfur diesel, current gasoline, future gasoline, kerosene, naphtha, LPG and heavy fuel oil. Of these, concerning diesel and gasoline (including future types), which are both currently used as fuels for motor vehicles, this study assumes that the supply route would remain similar to that of existing routes (same applies to on-board reforming type FCVs). Post-petroleum refining LPG is handled comprehensively in “2.5 Liquefied Petroleum Gas (LPG) Production Pathways”. Regarding other petroleum based products; this study assumes that such products will be supplied to vehicles following some form of conversion.

(1) Diesel

Colorless or fluorescent russet colored petroleum products with gravity ranging from 0.805-0.850, boiling range 180-350 degrees C, distilled after the kerosene fraction during crude distillation. Although the main usage is in automotive, rail and shipping industries, diesel fuel is also used in ceramic and steel industries as well as for supplementary fuel in electricity production. The characteristics of diesel include ignitability, low temperature fluidity (high Cetane Number), good viscosity and low sulfur content. In particular, in line with environmental measures, sulfur content was lowered to less than 0.2 wt% from the previous content of less than 0.5 wt% in 1992, and subsequently lowered to less than 0.05 wt% from October 1997.

Furthermore, permissible limits of sulfur content in diesel fuel will be amended to 0.005 wt% in 2005 (Ministry of the Environment (MOE) [2003-1]). Moreover, MOE [2003-2] reports that from 2007 it will be appropriate to set 0.001 wt% as the permissible limit target value. For these reasons, this study defines diesel with 0.05 wt% sulfur content as “current diesel”, 0.005 wt% sulfur content as “low sulfur diesel” and 0.001 wt% sulfur content as “ultra low sulfur diesel”, and seeks to quantify each type.

(2) Gasoline

Gasoline refers to petroleum products obtained from crude at the lowest boiling fraction (about 30-220 degrees C), which are in liquid form at normal temperature. Variations in production technique separate gasoline into natural gasoline, straight-run gasoline, reformed gasoline, cracked gasoline, synthetic gasoline, and so on. In chemical terms, all these are hydrocarbon compounds ranging from carbon number 4-12. Although gasoline is separated into industrial grade and fuel grade depending on usage, gasoline for automotive usage falls into the latter category and is manufactured through the mixture of a variety of gasoline components. The most important aspect of automotive gasoline is the anti-knock property, indicated by the octane number. In Japan, the octane number for regular gasoline is approximately 90 and the octane number for premium gasoline is approximately 100. The removal of lead from gasoline has been in practice for regular gasoline since February 1975, and since October 1983 for premium gasoline. In addition, concerning aromatic and olefin content, many oil companies implement self-regulation as part of their environmental measures. Furthermore, concerning benzene, a figure of less than 5% was adopted as the standard since the liberalization of manufactured imports in April 1996.

As with diesel, from 2005 the permissible limit of sulfur content in gasoline will be amended from 0.01 wt% to 0.005 wt% (MOE [2003-1]). For these reasons, this study defines gasoline with 0.01 wt% sulfur content as “current gasoline” and 0.005 wt% sulfur content as “future gasoline”, and seeks to quantify each type.

(3) Kerosene

The name “kerosene” predates the invention of the automobile and can be said to be a legacy of a time when diversification of petroleum products had not occurred and kerosene, as a source of light, was the only petroleum product in use. The kerosene fraction has a gravity ranging from 0.78-0.83, and a boiling range of 145-300 degrees C. Specifically, during crude distillation, the distillation of the kerosene fraction takes place between the distillation of gasoline and diesel, with sulfur content and other impurity removal and refining mainly conducted through hydro-treatment, producing a colorless or citrine transparent product with a petroleum odor. The carbon-hydrogen ratio (C/H Ratio) within kerosene constituents is 6-7, specifically 86-88 wt％ carbon to 12-14 wt％ hydrogen. Kerosene is not used directly as a fuel for automobiles and in this study, kerosene is considered as a resource for hydrogen production through steam reforming.

(4) Naphtha

In many cases, the term “naphtha”, as used in United States, refers to heavy gasoline, whereas in Japan the term is largely used in reference to unrefined gasoline (semi-product gasoline). The boiling range is about 30-200 degrees C. The main use of naphtha, when shipped as naphtha, is petrochemical, specifically as a resource for thermal cracking in the production of ethylene, propylene, butadiene, and so on. As with kerosene, naphtha is considered in this study mainly as a resource for hydrogen production through steam reforming.

(5) LPG

LPG is a hydrocarbon with carbon number 3 or 4, specifically propane, propylene, butane, butylene, or other petroleum products with these as the main constituents. Although LPG is a gas under normal temperature and pressure conditions, it can easily be converted to liquid form at relatively low pressures and moderate cooling. Colorless and odorless, with a liquid gravity of 0.50-0.58, and gas gravity at 1.5-2.0 in relation to air at 1.0, LPG accumulates in low places in the event of leakage. In Japan, as a fuel for automobiles, LPG is mainly used in taxis.

(6) Heavy Fuel Oil

Heavy fuel oils are used for internal combustion in diesel engines and gas turbines, and for external combustion in boilers and all types of industrial furnaces, as a mineral oil with suitable qualities, with types and quality standards set forth in the Japanese Industrial Standards (JIS). Heavy fuel oil products are produced through the mixture of high viscosity oils such as topper residue, vacuum residue and solvent deasphalting residue with low viscosity oils such as straight-run diesel and cracked diesel, in accordance with the desired properties, such as viscosity, sulfur content, pour point, flash point and carbon residue content. In this study, heavy fuel oils are considered as fuels for power generation.

Above content is drawn from Japan National Oil Corporation (JNOC) [1986], Taki [1997], Japan Petroleum Institute (JPI) [1998].

2.1.2 Procedures for data collection of unit process

The fuel production pathway flow for petroleum based fuels examined in this study are shown in Figure 2.1.1:

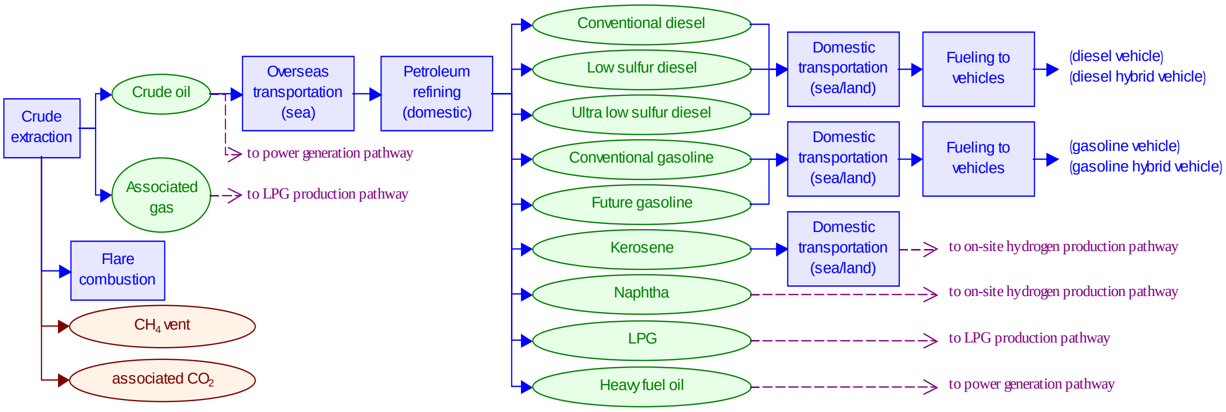


Figure 2.1.1 Pathway flow for petroleum based fuels

Regarding the refining process of petroleum products overseas and processes related to the import of such products, in relation to diesel and gasoline currently used as automobile fuel, as the amount refined overseas is small in comparison to the amount refined domestically (less than 3%), the omission of these processes is considered appropriate. On the other hand, while it is also a petroleum product, in relation to naphtha, which is mainly for petrochemical purposes, the amount refined and imported from overseas is greater than the amount refined domestically (see Table 2.1.1). Accordingly, when considering naphtha as an intermediary product in the production pathway of automobile fuels, the consideration of overseas petroleum refining processes and naphtha import processes (transportation via sea) may become necessary. However, as the information necessary for the creation of inventory data regarding overseas refining processes was unobtainable, for this study, these processes have been treated as beyond the system boundary.

Table 2.1.1 Amount of domestic and imported production of petroleum products [Unit: 10^3 kL]

	Diesel	Gasoline	Naphtha	Kerosene	A-heavy fuel	C-heavy fuel
Domestic	41,530 (97.0%)	58,216 (98.0%)	18,501 (39.7%)	27,366 (93.1%)	28,166 (96.7%)	32,332 (97.6%)
Imported	1,306 (3.0%)	1,215 (2.0%)	28,129 (60.3%)	2,030 (6.9%)	973 (3.3%)	780 (2.4%)

[Source] METI [2002]

(1) Crude Extraction

<i> Existing Study

As gas production generally accompanies crude extraction, the majority of oil fields use this associated gas as the energy source for the operation of the extraction facilities. The amount of associated gas required for the extraction of crude, based only on information from the Arabian Oil Co., Ltd., as shown in Institute of Applied Energy (IAE) [1990] (p.118), stands at 23 SCF/B[1], while Petroleum Energy Center (PEC) [1998] (p.17) gives a figure of 50-60 SCF/B based on the results of a hearing survey conducted with oil fields in the UAE and Saudi Arabia, both major suppliers of crude to Japan (60 SCF/B is used for calculation purposes). In addition, following on from PEC [1998], PEC [2002-2] (p.18) also uses 60 SCF/B for calculation purposes.

<ii> This Study

60 SCF/B, used both in PEC [1998] and PEC [2002-2], is also used in this study. For the composition of associated gas, the composition given in IAE [1990], used by both PEC [1998] and Shigeta [1990], was adopted. This is the weighted average derived from the composition of associated gases of Middle East oil fields. From this composition and the higher heating value set out for each gas in PEC [1998], it is possible to calculate the heating values for associated gases and CO_2 emission factors during combustion.

(2) Flare Combustion

<i> Existing Study

Associated gas excess to the requirements of the crude extraction process is burnt off at the flare stack. Shigeta [1990] and PEC [1998] (p.20) calculate flare stack energy expenditure and CO_2 emissions. Shigeta [1990] sets out the associated gas oil ratio (Gas Oil Ratio, GOR) for Middle East light crude oil fields, Middle East heavy crude oil fields, Southeast Asia and China (source unknown). On the other hand, PEC [1998] reasons that the Middle East and Indonesia account for the majority of crude imports to Japan and sets out GOR for each country. Where available, information from the Information Center for Petroleum Exploration and Production (ICEP) database was used, and unknown values were estimated from API gravity and location. Calculations in either report are based on flare ratio figures (proportion of associated gases burnt off at the flare stack) given in Organization of the Petroleum Exporting Countries (OPEC) Annual Reports (1987 Report used by Shigeta [1990], 1995 Report used by PEC [1998]). In addition, while PEC [2002-2] (p.19) follows the calculation method used in PEC [1998], flare ratio settings have been updated using data from the 1999 OPEC Annual Statistical Bulletin.

<ii> This Study

This study follows the calculation methods used in PEC [1998]. Regarding crude import volume, from the relationship with data gathered in relation to domestic petroleum refining, although the data is slightly dated, actual values from 1997 given in Ministry of International Trade and Industry (MITI) [1998] were used. In

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[1] 1 SCF (standard cubic feet) = 0.0263 Nm^3, 1B (barrel) = 158.9873 litre

addition, GOR values set out for each country in PEC [1998] were used. Flare ratios for each country were calculated from total production and flare amount figures of the natural gas production volume breakdown given in OPEC [2001]. In addition, regarding Middle East countries for which flare related information was not available, weighted average values calculated using values from Middle East countries with clear flare ratios and import volumes were used.

(3) Associated CO_2

<i> Existing Study

Regarding CO_2 content of associated gas (emissions into the atmosphere) other than from in-house consumption or flared; IAE [1990] and Shigeta [1990] calculate values based on the associated gas composition.

<ii> This Study

According to IAE [1990], as the percentage of CO_2 in associated gas is 5.8%, associated CO_2 volume was calculated by multiplying the desired associated gas volume by this percentage.

(4) CH_4 Vent

<i> Existing Study

Regarding CH_4 vent during crude extraction, the carbon equivalent is given in Central Research Institute of Electric Power Industry (CRIEPI) [1992] (p.32) and IEEJ [1999] (p.23). Of these, the basis for the figure given in CRIEPI [1992] is unclear. In addition, IEEJ [1990] assumes that there is no CH_4 vent during crude extraction and that leakage occurs only during associated gas production, and a theoretical calculation is used to calculate the value.

<ii> This Study

Calculations in this study are based on values given in IEEJ [1999]. Furthermore, although the heating value given in this literature is HHV and CO_2 emissions are given as the carbon equivalent when the characterization factor for CH_4 global warming is set at 21, this study conducts calculation into CO_2 equivalent using the value 23, shown in Table 1.2. In addition, this study has also taken energy loss through CH_4 vent into consideration.

(5) Overseas Transportation (Sea)

<i> Existing Study

Large ocean tankers are used to transport crude oil from crude producing countries to Japan. While IAE [1990] (p.38) states that Southeast Asia and China use 100,000 t tankers and the Middle East/other regions use 250,000 t tankers, PEC [1998] (p.33) states 80,000 t tankers for China, 100,000 t tankers for North

America and Oceania, and 250,000 t tankers for the Middle East and other regions, with both calculating fuel consumption factor per region from the fuel consumption of each ocean tanker.

Regarding calculations, while IAE [1990] considered only the passage, PEC [1998] (p.34) also takes fuel consumption while moored and for cargo heating for high viscosity crude into consideration. Regarding calculation method, PEC [1998] sought the weighted average of shipping distance based on import volume for each region and used this figure to calculate fuel consumption for one voyage. IAE [1990] gives no details concerning calculation method.

PEC [2002-2] follows the calculation methods used in PEC [1998].

<ii> This Study

In this study, using the ocean tanker sizes specified in PEC [1998], energy consumption and GHG emissions are calculated inclusive of fuel consumption while moored and for cargo heating.

This study specifies ocean tanker size and shipping distance for each crude producing country and ascertains fuel consumption per voyage per country, and uses the weighted average value relative to import volume in order to calculate fuel consumption per kg of crude. Furthermore, fuel consumption per kg crude for external transportation (sea) was calculated separately for refining or electricity generation depending on intended usage.

Regarding crude import volume, from the relationship with data gathered in relation to domestic petroleum refining, although the data is slightly dated, actual values from 1997 given in MITI [1998] were used. In addition, the marine shipping distance was calculated as the distance from the port of shipment of the crude producing country to the Yokohama Port. Furthermore, regarding Brunei, Iraq, Equatorial Guinea and Congo, as data concerning the distance of crude produced in these countries from the port of shipment was not available, data from relatively nearby countries and regions was substituted.

(6) Refining in Japan

<i> Existing Study

In Shigeta [1990] and PEC [1997] (p.52), energy consumption and environmental burden per unit quantity of petroleum product is calculated from the material balance in the petroleum product producing industry (gross production volume of petroleum products, and input of raw materials/ingredients).

PEC [2000] conducts further subdivision of the refining process of petroleum products and constructs a process flow diagram (PFD). Although energy consumption per product calculations are made based on this diagram, material balance data is cited for product yield settings (p.33-34). CO_2 emissions were calculated from energy consumption during refining per product, derived from material balance data and the PFD, under the assumption that CO_2 emissions are proportionate to energy consumption, as it was considered impossible to gather detailed and accurate data representative of all refineries in Japan for each subdivided refining process and fuel input for each (p.40).

PEC [2002-2] (p.30) also subdivides the refining process and configures a PFD, and calculates energy consumption for each product (current gasoline, future gasoline, current diesel, low sulfur diesel, naphtha) during the refining process, citing JPI [1998] and others, as the calculation basis for heat efficiency. This literature also uses material balance data for CO_2 emissions calculations, multiplying the weighted average value derived from annual total emissions per fuel type in relation to the CO_2 emissions index for the heating value of each fuel type used, by energy consumption per product within the refining process.

All reports source material balance data from the “Yearbook of Production, Supply and Demand of Petroleum, Coal and Coke”. Shigeta [1990] from the 1987 edition, PEC [1997] from the 1995 edition, PEC [2000] from the 1997 edition and PEC [2002-2] from the 2000 edition.

<ii> This Study

This study adopted the calculation method used in PEC [2000] to calculate energy consumption and GHG emissions. Although this selection was based on the need to calculate data regarding kerosene, heavy fuel oils and LPG not covered in PEC [2002-2], as the calculations of both these reports are based on the same reasoning, it was inferred that the difference between these reference materials would have little effect on calculation results.

The “Yearbook of Production, Supply and Demand of Petroleum, Coal and Coke” edition used here is the 1997 edition (MITI [1998]). Furthermore, although PEC [2000] uses only actual performance data of refiners, as actual values per refiner given in MITI [1998] were insufficient, general data (inclusive of refiners, lubricant manufacturers, other related industries) was used.

To begin, energy consumption for petroleum refining was calculated. For calculation purposes figures given in MITI [1998] for fuel consumption (p. 50-53), input and yield (p. 68-71), and electricity usage (p.150) were used. Energy consumption (LHV) associated with the consumption of these fuels was 511,514 TJ/year, and CO_2 emissions $31{,}859*10^3$ t-CO_2/year. Furthermore, on top of this energy consumption, PEC [2000] (p. 40-41) includes in-house consumption of catalytic coke and CO gas, and subsequently, this study also includes these factors (LHV/HHV ratio 0.93 for coke, 0.9 for CO gas).

To follow, these were then allocated to each petroleum product using energy consumption per product ratios calculated in PEC [2000] (p.33-34) using the PFD. That is to say, allocation was conducted using the ratio between energy consumption for each product given in PEC [2000] (p.33-34) and their average values (67 L-FOE/kL).

Regarding low-sulfur diesel, according to the trial calculations in PEC [2000] (p.45), the installation of ultra deep hydrodesulfurization unit will increase energy consumption by almost 1.5 times from 42 to 61 L-FOE/kL-Diesel, and increase the overall average for petroleum products from 68 to 71 L-FOE/kL-product. On the other hand, a report referenced by PEC [2002-2] (p.31) states that hydrogen consumption necessary for the desulfurization of 50ppm sulfur content would be 1.3 to 1.5 times greater than for 500ppm. Therefore, for this study, calculations for the required energy consumption for the production of low-sulfur diesel were made based on the trial calculation results of PEC [2000].

In addition, as no information regarding energy consumption for ultra low sulfur diesel and future gasoline was obtainable, calculations were based on the assumption that the ratio in relation to the average would be 2 times that of current diesel for ultra low sulfur diesel at approximately 1.2, and 2.0 for future gasoline.

Furthermore, regarding the process yield of the petroleum refining process (ratio of petroleum products in relation to processed crude volume), the ratio of total petroleum product volume (weight) in relation to processed crude volume (weight) was used.

(7) Domestic Transportation (Sea/Land)

<i> Existing Study

Shigeta [1990] cites CO_2 emissions during domestic transportation at a uniform 10% of CO_2 emissions during marine shipping. In addition, in PEC [1998] (p.43-51) based on the actual transportation status of petroleum products and fuel usage data gathered by the Petroleum Association of Japan (PAJ) in order to formulate the “Oil Industry Voluntary Action Plan for Global Environment Conservation”, environmental burden was calculated specifying three transportation types (tanker lorries, coastal tankers, tanker truck). Environmental load calculations in PEC [2002-2] (p. 48-50) are based on PAJ [2000].

<ii> This Study

This study cites data used in PEC [2002-2]. Specifically, energy consumption and GHG emissions during transportation of "white oil" (gasoline, diesel oil, kerosene, naphtha, LPG) and "black oil" (heavey fuel oil) were calculated using the data given on p.49 of the report regarding the domestic overland transportation process of petroleum products, and data given on p.50 regarding coastal transportation. Regarding fuel consumed, diesel was considered as the fuel for the domestic overland transportation process, while for the coastal transportation process, fuel consumption was split into 90% C-heavy fuel oil while under way and 10% A-heavy fuel oil for port entry/exit, based on information provided in PEC [1998] (p.45). In addition, for final results, energy consumption and GHG emissions were calculated based on values obtained through the distribution of fuel consumption over transportation volume, for both domestic overland and coastal transportation.

(8) Fueling to Vehicles

No particular consideration has been given in either this or prior studies concerning energy consumption and GHG emissions during the fueling to vehicles with diesel or gasoline. In addition, this study set the value of such at zero following confirmation through hearing surveys that levels were practically insignificant.

2.1.3 Calculation results

Regarding the production pathways of petroleum based fuels, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.1.2 (energy consumption), Table 2.1.3 (GHG emissions) and Table 2.1.4 (energy efficiency).

Table 2.1.2 WTT energy consumption of petroleum based fuel production pathways [MJ/MJ]

		Conventional diesel	Low sulfur diesel	Ultra low sulfur diesel	Conventional gasoline	Future gasoline	Kerosene	Naphtha	A heavy fuel oil	C heavy fuel oil
Crude oil extraction	Operation	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
	Flare combustion	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Overseas transportation		0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
Petroleum refining		0.043	0.059	0.082	0.139	0.151	0.031	0.054	0.067	0.064
Domestic transportation		0.005	0.005	0.005	0.005	0.005	0.005	-	-	-
Fueling to vehicles		0.000	0.000	0.000	0.000	0.000	-	-	-	-
Total		0.078	0.094	0.118	0.175	0.187	0.066	0.084	0.097	0.094

Table 2.1.3 WTT GHG emissions of petroleum based fuel production pathways [g eq-CO_2/MJ]

		Conventional diesel	Low sulfur diesel	Ultra low sulfur diesel	Conventional gasoline	Future gasoline	Kerosene	Naphtha	A heavy fuel oil	C heavy fuel oil
Crude oil extraction	Operation	0.76	0.76	0.76	0.76	0.76	0.76	0.74	0.75	0.76
	Flare combustion	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.39
	Associated CO_2	0.33	0.33	0.33	0.33	0.33	0.33	0.32	0.33	0.33
	CH_4 vent	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.04	0.04
Overseas transportation		0.92	0.92	0.92	0.92	0.92	0.92	0.90	0.91	0.92
Petroleum refining		2.66	3.64	5.08	8.59	9.36	1.91	3.33	4.14	3.94
Domestic transportation		0.37	0.37	0.37	0.41	0.41	0.39	-	-	-
Fueling to vehicles		0.00	0.00	0.00	0.00	0.00	-	-	-	-
Total		5.45	6.43	7.88	11.42	12.19	4.72	5.70	6.54	6.38

Table 2.1.4 WTT energy efficiency of petroleum based fuel production pathways (LHV)

	Conventional diesel	Low sulfur diesel	Ultra low sulfur diesel	Conventional gasoline	Future gasoline	Kerosene	Naphtha	A heavy fuel oil	C heavy fuel oil
Crude oil extraction	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982	0.982
Overseas transportation	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
Petroleum refining	0.948	0.934	0.915	0.869	0.860	0.957	0.955	0.934	0.9233
Domestic transportation	0.995	0.995	0.995	0.995	0.995	0.995	-	-	-
Fueling to vehicles	1.000	1.000	1.000	1.000	1.000	-	-	-	-
Total	0.916	0.902	0.883	0.839	0.830	0.924	0.927	0.907	0.896

2.2 Natural Gas Based Fuel Production Pathways

2.2.1 Abstract

Natural gas has low energy density and incurs high shipping costs. In order to reduce this shipping cost, it will be necessary to physically or chemically improve the energy density of natural gas. Physical methods of improvement include liquefaction through cooling to produce liquefied natural gas (LNG), compression to produce compressed natural gas (CNG), and hydration for transportation of natural gas in hydrated form.

On the other hand, chemical improvement involves conversion into different substances through chemical processes applied at the wellhead, and mainly involves the conversion of gas into a liquid fuel, hence the technology is called Gas-to-Liquid (GTL). This section concentrates on LNG (physical improvement) and products derived from LNG (e.g. city gas). GTL is covered in “2.4 Synthetic Fuel Production Pathways”.

(1) LNG

Natural gas, composed mainly of CH_4, is chilled to ultra low temperatures and liquefied following the removal of impurities such as moisture, sulfur compounds and CO_2 to produce LNG. Natural gas liquefies at approximately -160 degrees C, and is reduced in volume to one six-hundredth that of gas through liquefaction, facilitating convenience of transportation and storage. Accordingly, conversion to LNG for temporary storage is used as a method of peak shaving for natural gas, and LNG conversion of natural gas for transportation is used in cases of transoceanic transportation where natural gas transportation via pipeline is not possible.

The main uses of LNG are for electricity and city gas.

(2) City Gas

City gas refers to “gaseous fuels supplied to gas appliances within buildings through gas pipelines from the gas production facilities of licensed gas industry companies (e.g. Tokyo Gas, Osaka Gas) in accordance with the Gas Utility Industry Law”. City gas is adjusted to comply with heating values stipulated in supply regulations through refining and mixing feedstock such as LPG, coal, coke, naphtha, heavy fuel oils and natural gas.

Currently, there are seven types of city gas in use throughout Japan, with different feedstock, production methods and heating values (See Table 2.2.1).

Table 2.2.1 Standard heating values of city gas by gas group

Gas group	Standard heating values
13A	10,000 - 15,000 kcal/m^3
12A	9,070 - 11,000 kcal/m^3
6A	5,800 - 7,000 kcal/m^3
5C	4,500 - 5,000 kcal/m^3
L1	4,500 - 5,000 kcal/m^3
L2	4,500 - 5,000 kcal/m^3
L3	3,600 - 4,500 kcal/m^3

[Source] Japan Gas Association website

Of these, the composition of city gas type 13A, the most commonly used type in within Japan, is shown in Table 2.2.2.

Table 2.2.2 The composition of city gas type 13A

Composition		Content [wt%]
Methane	CH_4	70 - 80
Ethane	C_2H_6	< 10
Propane	C_3H_8	10 - 20
Butane	C_4H_{10}	< 10

[Source] Japan Gas Association website

In this study, concerning supply pathways, other than cases where processing and liquefaction take place at overseas production sites prior to importation as LNG, cases of direct overseas transportation via pipeline (from Sakhalin) were also considered. In addition, for methods fueling to automobiles, other than cases of compressed city gas (CNG vehicles), the direct fueling of LNG (LNG vehicles), which may become popular in the future, was also considered.

2.2.2 Procedures for data collection of unit process

The fuel production pathway flow for natural gas based fuels examined in this study are shown in Figure 2.2.1:

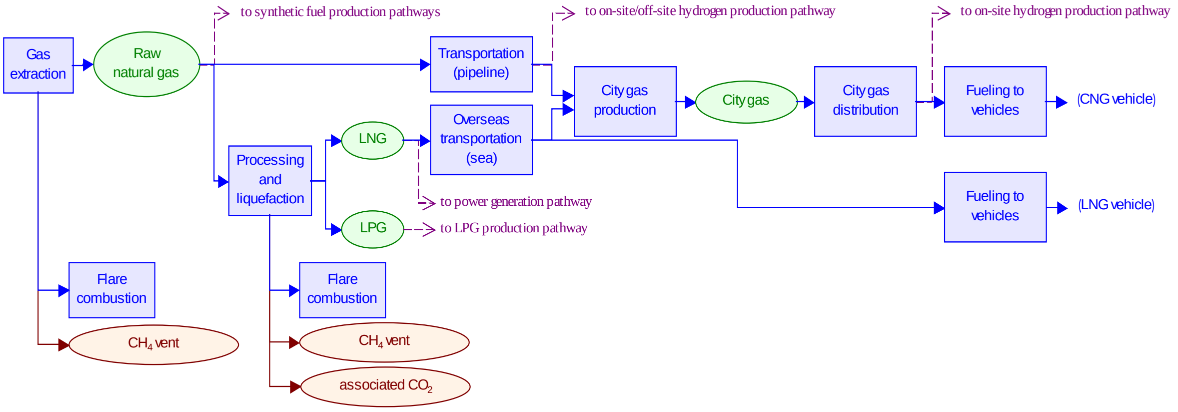


Figure 2.2.1 Pathway flow for natural gas based fuels production

(1) Natural Gas Extraction

<i> Existing Study

Shigeta [1990] calculates CO_2 emissions from extraction and production (liquefaction) processes based on volume of raw natural gas as feedstock, obtained through the consideration of raw natural gas composition for each producing region and the 1987 import volume ratio.
NEDO [1996] (p.101) adopts the input volumes of A-heavy fuel oil as fuel used during exploration / extraction of natural gas based on data from the Bontang gas fields, Indonesia.

Tamura *et al.* [1999] conducted fields surveys in five source countries/regions of LNG for city gas (Alaska, Indonesia, Malaysia, Brunei, Australia), and calculated the weighted average value through the import volume ratio (1997) for CO_2 emissions based on data obtained from four of these source countries/regions excluding Alaska. Calculations using similar calculation methods and based on similar data are conducted in IEEJ [1999] (p.24). For co-produced LPG, condensate, and so on, both give distributed values on a calorific basis. In addition, apart from the Japan average, IEEJ [1999] also conducts calculations regarding LNG for city gas based on import volume ratio.

PEC [2002-2] calculates energy efficiency based on IEEJ [1999]. In addition, Okamura *et al*. [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

This study cites Okamura *et al.* [2004]. However, regarding energy consumption, calculations are made from heating value based fuel ratio data using the entrance to liquefaction facilities as the reference point, obtained from a hearing survey conducted with the Japan Gas Association (JGA) in relation to the content of Okamura *et al.* [2004].

(2) Processing and Liquefaction

<i> Existing Study

IAE [1990] (p.121) provides data for LNG import volumes, raw natural gas composition, raw natural gas processing volumes, natural gas consumption and CO_2 emissions for each country of origin (actual values for 1987). Ogawa *et al.* [1998] calculates fuel ratios from this data and estimates CO_2 emissions from LNG import volumes per gas producing country for 1996. In addition, Hondo *et al.* [1999] also includes Australia as a gas producing country, and uses similar methods to determine the natural gas volumes required for liquefaction. The fuel efficiency determined from the results of these reports is approximately 88 %.

NEDO [1996] gives energy consumption during liquefaction as 9 vol% of natural gas produced, and states that 6 vol% of natural gas produced is associated gas (mainly CO_2). According to these values, fuel efficiency during liquefaction, excluding associated gas, is approximately 90 %.

Although Tamura *et al.* [1999] and IEEJ [1999] (p.24) both calculated the weighted average value through the import volume ratio (1997) for CO_2 emissions based on data obtained from fields surveys conducted in five source countries/regions of LNG for city gas, there are slight discrepancies in the results. Both reports give distributed values on a calorific basis for co-produced LPG, condensate, and so on.

PEC [2002-2] (p.53) calculates fuel efficiency based on IEEJ [1999], with a given result of 92 %.

In addition, Okamura *et al.* [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

As with the natural gas production (extraction) process, this study cites Okamura *et al*. [2004]. However, regarding energy consumption, calculations are made from heating value based fuel ratio data using the entrance to liquefaction facilities as the reference point, obtained from a hearing survey conducted with the

JGA in relation to the content of Okamura *et al.* [2004].

(3) Flare Combustion

<i> Existing Study

Shigeta [1990] does not conduct calculations for flared gas as the liquefaction facilities and the gas wells of the Japan LNG project are interlinked, and in comparison to the amount of gas consumed in the liquefaction process, the amount flared is practically insignificant. Ogawa *et al.* [1998] gives 4 % as the worldwide average flare combustion ratio in relation to natural gas production for 1996, while also stating that for modern LNG production facilities, the flare combustion ratio is 1 % as the amount of natural gas burnt during production is lower.

Tamura *et al.* [1999] and IEEJ [1999] (p.24) handle flare combustion during extraction and during liquefaction separately, calculating the weighted average value through the import volume ratio (1997) for CO_2 emissions based on data from the previously mentioned fields surveys conducted in five source countries/regions of LNG for city gas, but there are slight discrepancies in the results. Both reports give distributed values on a calorific basis for co-produced LPG, condensate, and so on.

PEC [2002-2] (p.53) calculates fuel efficiency based on IEEJ [1999].

In addition, Okamura *et al.* [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

As with the other processes, this study cites Okamura *et al.* [2004]. However, regarding energy consumption, calculations are made from heating value based fuel ratio data using the entrance to liquefaction facilities as the reference point, obtained from a hearing survey conducted with the JGA in relation to the content of Okamura *et al.* [2004].

(4) Associated CO_2

<i> Existing Study

IAE [1990] multiplies the raw natural gas input to liquefaction plants given per gas producing country by the CO_2 content percentage of raw natural gas, and calculates associated CO_2 by obtaining the weighted average through the import volume ratio of 1987. Based on this, Ogawa *et al.* [1998] conducts similar calculations using import data for 1996.

Tamura *et al*. [1999] gives the weighted average value of wellheads for CO_2 content.

Other than the previously mentioned fields surveys conducted in five source countries/regions of LNG for city gas, IEEJ [1999] (p.24) also applies and reflects data for Arun, Qatar and Abu Dhabi, taken from 1996 survey materials from the JNOC, and gives the results of calculations for emissions by heating value (distributed values on a calorific basis for co-produced LPG, condensate, and so on).

In addition, Okamura *et al*. [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

Okamura *et al.* [2004] is also cited here.

(5) CH_4 Vent

<i> Existing Study

As with flare combustion, Ogawa *et al.* [1998] estimates CH_4 vent ratio at approximately 1 % in relation to natural gas production volume. Although the basis is unclear, CRIEPI [1992] (p.32) gives amounts for CH_4 vent during extraction and liquefaction.

Tamura *et al.* [1999] and IEEJ [1999] (p.24) both separate the source of leakage into each production/liquefaction process, and calculate CH_4 vent by obtaining the weighted average value from import volume (1997) based on data from the previously mentioned field surveys conducted in five source countries/regions of LNG for city gas, but there are slight discrepancies in the results. Both reports give distributed values on a calorific basis for co-produced LPG, condensate, and so on.

In addition, Okamura *et al.* [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

As with the other processes, this study cites Okamura *et al.* [2004]. However, regarding energy consumption, calculations are made from heating value based fuel ratio data using the entrance to liquefaction facilities as the reference point, obtained from a hearing survey conducted with the JGA in relation to the content of Okamura *et al*. [2004].

In addition, regarding the characterization factor for global warming, conversions back into CO_2 equivalent are conducted using the value used in this study (see Table 1.2).

(6) Overseas Transportation (Sea)

<i> Existing Study

IAE [1990] (p.125) calculates CO_2 emissions per unit weight of LNG from the fuel consumption during passage of 125,000 m^3 class LNG vessels (return trip, boil off gas (BOG) and petroleum fuel usage), and the import volumes and distance from each gas producing country.

NEDO [1996] (p.105) calculates the amount of A-heavy fuel oil required for transportation of the annual LNG requirement for a LNG combined cycle plant (513,000 tons), using a 125,000 m^3 capacity (53,750 t) vessel with a mileage of 63 kg-A-heavy fuel oil/km over a distance of 5,000km, taking the return trip into consideration.

Hondo *et al.* [1999] asserts that the fuel during passage is the BOG of LNG and calculates the environmental burden of transportation per unit weight of LNG from the boil off ratio of a 125,000 m^3 class LNG vessel, import volume and distance from each gas producing country, and fuel consumption while moored (LNG usage).

Tamura *et al*. [1999] calculates the CO_2 emission factors for t-km from the actual records (1997) of LNG transportations from the Bontang gas fields in Indonesia, and then calculates CO_2 emissions per unit heat of LNG during overseas transportation using the weighted average of shipping distance from each country and import volume (1997). Furthermore, the fuels used are BOG and C-heavy fuel oil.

IEEJ [1999] (p.25) calculates CO_2 emissions of LNG during overseas transportation by using the weighted average of import volume ratio (1997) and actual data for 1997 gathered from 44 of the 65 LNG shipping vessels that carry LNG to Japan, in relation to BOG and C-heavy fuel oil consumption, LNG load, and shipping distance.

In addition, Okamura *et al.* [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999].

<ii> This Study

This study cites Okamura *et al.* [2004]. However, regarding energy consumption, calculations are made from data pertaining to LNG vessel fuel consumption, LNG load, weighted average values for transportation distances one-way, obtained from a hearing survey conducted with the JGA in relation to the content of Okamura *et al.* [2004]. Furthermore, separate calculations were conducted for overall LNG and LNG for city gas.

(7) Overseas Transportation via Pipelines

<i> Existing Study

Regarding the transportation of natural gas via pipelines, as a report focusing on supply within Japan, the Economic Research Center, Fujitsu Research Institute (FRI-ERC)[2000] report calculates CO_2 emissions, and states that for a shipping distance of less than 16,000 km, transportation via pipeline is better than LNG transportation.

<ii> This Study

In this study, energy consumption and GHG emissions are calculated from data related to pipeline transportation obtained through hearing surveys (approximately 50 kW per km pipeline for 880 MCF/day natural gas output). Furthermore, the power generating efficiency of natural gas output energy (assuming generation through natural gas) is 15 %.

Regarding transportation distance, the pipeline transportation distance considered in this study (2,000 km) is the distance from Sakhalin to Japan, given in Koide [2000] as the distance from Korsakov to Niigata (approx 1,400 km) plus the distance from Niigata to Fukui (approx 600 km).

In addition, regarding the heating value and CO_2 emission factors for natural gas produced in Sakhalin, calculations were made using global natural gas composition data given in the Agency for Natural Resources and Energy (ANRE)[1992] (p.110) for natural gas produced in the former Soviet Union.

(8) City Gas Production and Distribution

<i> Existing Study

Although Tamura *et al.* [1999] and IEEJ [1999] (p.25) both calculate CO_2 emissions based on actual energy consumption figures (1996) for processes such as re-gasification of LNG and heating value adjustment for the domestic LNG facilities of three gas companies, there are slight discrepancies in the results. Both reports consider environmental burden from the upstream process for LPG input for heating value adjustment, and also considers CO_2 reductions from the cold usage of LNG. Regarding the distribution process, as the energy from the pump that pressurizes LNG before re-gasification is used, this is already included in the city gas production process.

Based on values given in IEEJ [1999], PEC [2002-2] (p.60) calculates fuel efficiency to be 99.8 %.

In addition, Okamura *et al.* [2004] gives data calculated after the addition of survey details related to the Middle East Project (Qatar, Oman) to the survey results of IEEJ [1999]. As with IEEJ [1999], LPG for heating value adjustment and cold usage of LNG are also considered.

<ii> This Study

The environmental burden of the city gas production process itself can be calculated using statistics given in ANRE [2002-2]. However, it is difficult to calculate the environmental burden for in-house consumption of LNG, city gas, and so on, from this information alone. Therefore, calculations in this study are based on the hearing survey conducted with the JGA in relation to the content of Okamura *et al.* [2004].

Although Okamura *et al.* [2004] considers the CO_2 emissions reduction effect of cold usage, this study does not consider aspects that are not directly related to the production process of automotive fuels.

(9) Fueling to Vehicles

<i> Existing Study

PEC [2002-2] gives 95 % as the energy efficiency of the compression/fueling process for CNG vehicles at service stations, the default value of the model developed at the U.S. Argonne National Laboratory (ANL) for the evaluation of environmental effect of automotive fuels “GREET 1.6” (ANL [2001]). From the assumption that the power source for the compression device is either natural gas or electricity, and that both will be used in equal measure, calculations are based on the assumption that for the U.S., CNG vehicles will be filled with natural gas compressed to 3,000 lb/in^2 (= approx. 200 kg/cm^2). Furthermore, “GREET 1.6” gives the default value for the energy efficiency of compression devices using natural gas as 93 %, and 97 % for devices using electricity.

<ii> This Study

Of the natural gas powered vehicles currently in use, CNG vehicles are the most common. In Japan, compression devices (normally 250 m^3/h) are used to compress medium pressure gas received through pipelines to pressures higher (approx. 25 MPa) than the maximum fueling pressure for vehicles (20 MPa).

In this study, calculations for energy consumption and GHG emissions of the fueling process for CNG and

LNG vehicles are based on natural gas fueling station data obtained through a hearing survey conducted with the JGA and others.

[Fueling to CNG vehicle]

Given that the rated output of a 250 m^3/h compression device is 55 kW (medium pressure A) and 75 kW (medium pressure B), energy consumption is calculated under the assumption that, for both, the compression device is operated at 85 % rated power when fueling to a CNG vehicle.

[Fueling to LNG vehicle]

Regarding LNG vehicles, energy consumption estimations for fueling to LNG vehicles are made based on the LNG pump discharge rate and the output of electric motors given in Organization for the Promotion of Low Emission Vehicles (LEVO) [2003] (p.86). In addition, natural vaporization of LNG while in storage is also considered.

2.2.3 Calculation results

Regarding the production pathways of natural gas based fuels, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.2.3 (energy consumption), Table 2.2.4 (GHG emissions) and Table 2.2.5 (energy efficiency).

Table 2.2.3 WTT energy consumption of natural gas based fuel production pathways [MJ/MJ]

		LNG	City gas to CNG vehicle	
			From LNG (conventional)	From pipeline gas
Natural gas extraction	Operation	0.011	0.011	0.011
	Flare combustion	0.002	0.002	0.002
Processing / liquefaction	Operation	0.102	0.100	-
	Flare combustion	0.009	0.008	-
Overseas transportation	Sea	0.036	0.030	-
	Pipeline	-	-	0.054
Production / distribution	Operation	-	0.004	0.004
	LPG addition	-	0.005	0.005
Fueling to vehicles		0.000	0.046	0.046
Total		0.161	0.206	0.120
Reduction by cold heat utilization			△ 0.004	

Table 2.2.4 WTT GHG emissions of natural gas based fuel production pathways [g eq-CO_2/MJ]

		LNG	City gas to CNG vehicle	
			From LNG (conventional)	From pipeline gas
Natural gas extraction	Operation	0.56	0.54	0.48
	Flare combustion	0.17	0.17	0.15
	CH_4 vent	0.25	0.24	0.22
Processing / liquefaction	Operation	6.11	5.60	-
	Flare combustion	0.48	0.39	-
	Associated CO_2	2.17	1.77	-
	CH_4 vent	0.64	0.55	-
Overseas transportation	Sea	2.28	1.89	-
	Pipeline	-	-	3.09
Production / distribution	Operation	-	0.21	0.21
	LPG addition	-	0.34	0.34
Fueling to vehicles		0.01	1.82	1.82
Total		12.68	13.52	6.30
Reduction by cold heat utilization			△ 0.34	

Table 2.2.5 WTT energy efficiency of natural gas based fuel production pathways (LHV)

		LNG	City gas to CNG vehicle	
			From LNG (conventional)	From pipeline gas
Natural gas extraction		0.987	0.987	0.987
Processing / liquefaction		0.901	0.903	-
Overseas transportation	Sea	0.965	0.971	-
	Pipeline	-	-	0.949
Production / distribution of city gas		-	0.998	0.998
Fueling to vehicles		1.000	0.983	0.983
Total		0.858	0.848	0.918

2.3 Fuel Production Pathways from Biomass Resources

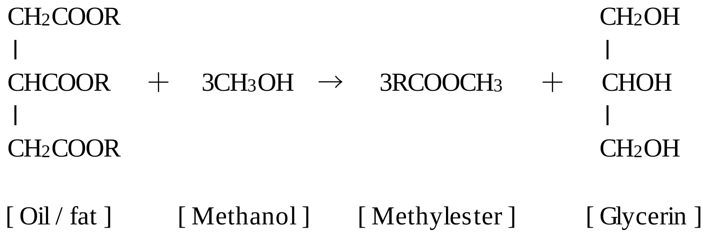
2.3.1 Abstract

Although the term “Biomass”, a compound term consisting of “bio” signifying organisms and “mass” signifying quantity or weight, is generally used in biology, it has in recent years come to be used frequently in reference to subjects such as “Organisms as a resource for energy and industrial materials” (Yamaji *et al.* [2000]) and “Substantial plant based substances that can be used for energy” (Yokoyama [2001]). From the perspective of usage as fuel, biomass can be categorized into liquid fuel production processes and gaseous fuel (intermediate product) production processes.

This section looks into bio-diesel fuel (BDF) production (esterification) and ethanol conversion as methods of liquid fuel production, and CH_4 fermentation as a method of gaseous fuel production. Furthermore, regarding CH_4 fermentation, this section focuses on the process up to distribution into the natural gas supply line after production following fermentation, and considers the processes after this point (e.g. fueling to CNG vehicle, syngas production, hydrogen production) to be the same as for natural gas.

(1) BDF

Bio diesel fuel (BDF) is a general term used in reference to methyl esters of higher fatty acid obtained when a transesterification reaction takes place between vegetable oils (ester of glycerin and higher fatty acids) and methanol in the presence of a catalyst. The chemical reaction to obtain BDF is as follows.



$$\begin{array}{ccccccc} CH_2COOR & & & & & & CH_2OH \\ | & & & & & & | \\ CHCOOR & + & 3CH_3OH & \rightarrow & 3RCOOCH_3 & + & CHOH \\ | & & & & & & | \\ CH_2COOR & & & & & & CH_2OH \\ [\text{Oil / fat}] & & [\text{Methanol}] & & [\text{Methylester}] & & [\text{Glycerin}] \end{array}$$

There are a variety of fatty acids that compose vegetable oil, depending on the resource, such as rapeseed and palm. In addition, as there is no single variety of fatty acid that is ester bonded to glycerin, the composition is complex. Although the structures of the molecules are not fixed, the term BDF is used since the physical and chemical properties are similar to that of diesel. Research into BDF is currently in progress in countries such as Italy (rapeseed oil, sunflower oil), France (rapeseed oil, sunflower oil, palm oil, soybean oil), the U.S. (soybean oil) and Malaysia (palm oil).

Table 2.3.1 Comparison of properties of diesel and BDF

		Diesel	BDF in Town A			Diesel	BDF in Town A
Density (15℃)	g/cm^2	0.8299	0.8866	Carbon residue content	mass%	0.1 or less	0.05
Kinematic viscosity (40℃)	mm^2/s	1.7-2.7 or over	4.688	Sulfur content	mass%	0.20 or less	less than 0.01
Flash point (COC)	℃	45 - 50 or over	190	Heating value (cal)	kcal/kg	10,997	9,507
Pour point	℃	+5 - -30 or less	2.5	Heating value (J)	MJ/kg	46.0	39.8

[Source] Energy Policy Division, Natural Resources and Energy Department, Kansai Bureau of Economy, Trade and Industry (METI Kansai) [2002]

(2) Ethanol

Ethanol conversion technology, which uses microorganisms, has been long established in the manufacturing processes of alcoholic beverages. Relative to this, the oil shock of the 1970s triggered research and development into the production of ethanol for fuel, with Brazil promoting sugar (molasses) and the U.S. corn as the resource for ethanol production.

In the ethanol yielding reaction, 1) starch is saccharified by amylase to become glucose, 2) through many microorganisms, one glucose molecule is broken down into two pyruvic acid molecules and eventually into two ethanol molecules.

$$(C_6H_{10}O_5)_n + n\,H_2O \rightarrow n\,C_6H_{12}O_6$$

$$C_6H_{10}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Of the progress of biotechnology in recent years, ethanol conversion using cellulosic biomass resources is drawing particular attention. In this process, ethanol is produced after the saccharification of cellulosic biomass using acid saccharification or cellulase saccharification through a fermentation process using yeasts and bacteria cultivated through genetic recombination to enable the fermentation of both hexose and pentose. Research into this process is being vigorously pursued in countries such as the U.S., and plans for industrialization are being promoted (the diagram shows an example of a current bio-ethanol production process concept).

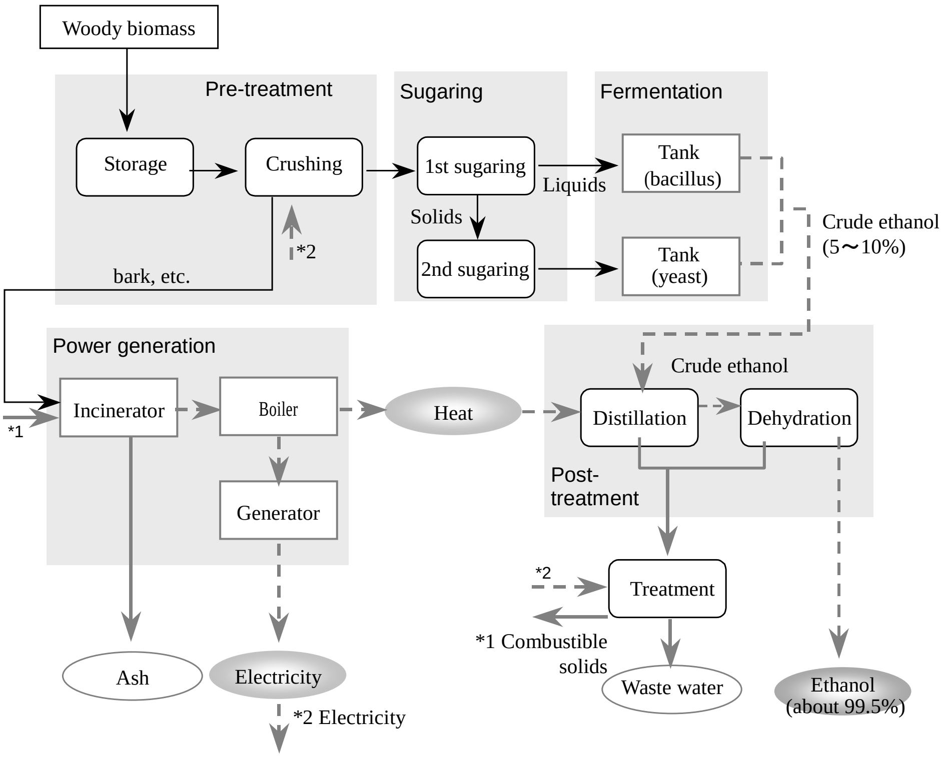


Figure 2.3.1 Example of bioethanol production process in current technology

(3) Biogas

Biogas is the final product of the CH_4 fermentation process, composed mainly of CH_4 and CO_2, and is also known as digestion gas. CH_4 fermentation is a process in which a diversity of anaerobic microorganisms degrade organic matter, and has long been in use as a method of processing effluent containing waste materials and organic impurities. As CH_4 fermentation is an anaerobic process, in comparison to an aerobic process, it does not require ventilation, and in addition, has the advantage of allowing CH_4 gas recovery. On the other hand, there are disadvantages related to the slow speed of the process, necessitating large-scale facilities. However, increased importance is now placed on the effective utilization of biomass energy, and from this perspective, instead of waste processing, the development of technology to exploit the availability of CH_4 is currently being promoted.

Biomass to which CH_4 fermentation can be applied include food waste, livestock manure, agricultural waste, and so on. CH_4 fermentation is anaerobic and progresses of its own accord in the right temperatures for degradation, pH, and in the absence of inhibitors (heavy metals such as Cr and Cu, cyan, some organics such as phenol, and NH_3). As long as these conditions are met, CH_4 gas will be generated without any particular action being required at the final processing facility.

As CH_4 fermentation progresses in stages with a diversity of anaerobic bacteria, the process is a complex system. First, the high-molecular organic substances such as proteins and carbohydrates, contained in biomass are degraded into low-molecular constitutional units such as amino acids and monosaccharides, by hydrolytic and acid producing bacteria, generating acetic acid and other organic acids. Next, the CH_4 producing bacteria, a strict anaerobe, degrades the molecules to the final product such as CH_4 and CO_2.

As CH_4 fermentation is a microbial process, it is affected by temperature. In general, although the process is separated into low temperature, medium temperature range of 30-35 degrees C and a high temperature range of 50-55 degrees C, since the degradation speed increases with fermentation temperature, high temperature fermentation is increasingly being adopted as this will lead to the downsizing of processing vats.

As CH_4 gas obtained from processes such as the above contains small amounts of substance such as H_2S, further refining may be necessary depending on usage. The main forms of energy required for the CH_4 fermentation process are heating energy required to maintain fermentation temperature, and energy required to convey the reaction mixture and pump the CH_4 gas.

2.3.2 Procedures for data collection of unit process

In relation to fuel production pathways using biomass resources as the source, in view of the fact that the scope of the reference materials and finer details concerning conditions cannot be fully understood, this study organizes and presents data that clarifies energy consumption range and CO_2 emissions range, and data typifying processes and resource/energy input, as calculation results.

In biomass production, along with the feedstock for energy conversion, byproducts are cultivated simultaneously. Specifically, energy is also consumed in the cultivation process in areas other than for the parts that can be used for energy conversion (for example, seeds from rapeseed and corn). However, as this is essential to the cultivation of the parts that can be used for energy conversion, this study treats all energy consumed as energy required for the production of the energy conversion feedstock.

Carbon ingested during the biomass production stage is treated as an assimilated amount and is given as a negative value. The given amount for assimilated carbon is a value equivalent to that of the amount generated during combustion (carbon balance zero).

Additionally, in the energy conversion process, only the heating value of the biomass resource is considered in cases where biomass is used as the in-house heat source (e.g. ethanol conversion of sugarcane), and data is created with CO_2 emissions generated from biomass resource combustion as zero.

Regarding the byproduct emissions from each process, some may be utilized as in-house energy sources or as animal feed. However, the purpose of byproducts vary depending on value (e.g. quality and cost), and although processing as waste will be necessary where the value is low, calculations in this study are based on the premise that byproducts will be disposed of.

(1) BDF

The BDF production pathway flow examined in this study are shown in Figure 2.3.2:

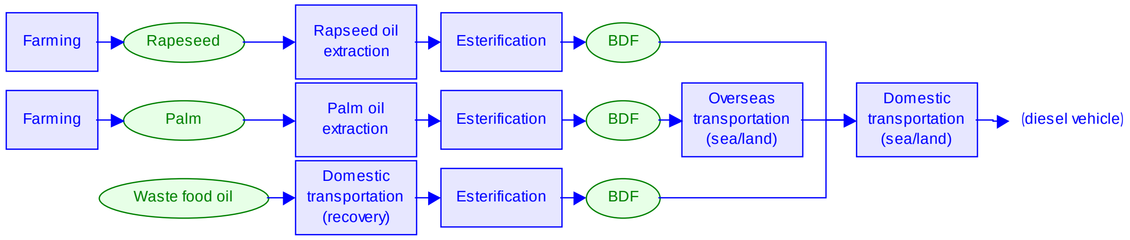


Figure 2.3.2 Pathway flow for BDF production

1) Farming

<i> Existing Study

Biomass resources used in BDF production (esterification) include oil crops such as palm, soybean, rapeseed and sunflower, and the waste food oils originating from these crops.

Energy input for palm production is considered in Fuel Policy Subcommittee (FPS) [2003].

Regarding rapeseed, European rapeseed farming data is presented in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1, and similar data for the UK is compiled in ETSU [1996].

Regarding waste food oil, from the waste materials perspective, although the production energy is beyond the sphere of the system, the Kansai Bureau of Economy, Trade and Industry [2002] report provides figures for the generation of waste food oil per household, while the Ministry of Agriculture, Forestry and Fishery (MAFF) General Food Policy Bureau – Consumption and Lifestyle Division [2001] provides figures for the generation of waste food oil per individual.

<ii> This Study

N_2O emissions from soil have been calculated using the emission factors (15.6 [kg-N_2O/t-N]) for direct emissions [Synthetic Fertilizer] given in MOE [2002-2] (p.II-79). This is based on a flux study of N_2O from fields conducted nationwide, and is an estimated value which takes crop species into consideration. Specifically, N_2O emissions from the farming process were calculated by multiplying the amount of nitrogen input to farming with this emission factor.

Regarding farming of BDF production pathway, this study considers rapeseed and palm. For rapeseed, as rapeseed production in Canada and Australia, the two major rapeseed import sources (producing countries) to Japan, is in decline, import was not assumed and the study focuses on domestic production. In addition, concerning palm, farming in Malaysia is assumed.

[Rapeseed farming]

Regarding the rapeseed farming process, as there is no detailed data for rapeseed cultivation in Japan, estimates were made from assumed fertilizer input and energy consumption values derived through hearing surveys conducted in Aomori, Japan’s largest rapeseed producing region, and publications (Aomori Prefecture, Agriculture and Forestry Dept. [1994]). Regarding the production processes for fertilizer and insecticide, calculations were made using information given in Turhollow, A.F. *et al.* [1991].

[Palm farming]

Calculations for the palm farming process are based on FPS [2003]. Since palm production is mainly a manual process, energy for processes such as cultivation was assumed to be zero, and calculations were made only for energy consumption through fertilizer input.

[Waste food oil]

Regarding waste food oils, since the premise is the collection and use of oils generated as a waste product, energy consumption and GHG emissions related to waste food oil generation are ignored.

2) Transportation (Harvestry)

<i> Existing Study

Regarding palm harvesting, FPS [2003] gives the average shipping distance as 10 km.
On the other hand, regarding the collection of waste food oils, calculations in the Mitsubishi Research Institute (MRI), *et al.* [2002] (p. II.84) assume that a medium sized truck (fuel consumption 3.5 km/L) will travel an average 3 km per t of collected waste cooking oil.

<ii> This Study

Energy regarding rapeseed harvesting is treated as zero, as energy for harvesting has already been considered as a part of cultivation in the farming process. In addition, regarding palm harvest, although there a large variations depending on harvest area, energy consumption is treated as zero in this study as energy consumption related to harvesting represents only a small part of the energy consumption for the overall BDF production pathway.
Regarding the collection of waste food oils, as with MRI, *et al.* [2002], calculations were based on the assumption that a medium sized truck (fuel consumption 3.5 km/L) will travel an average 3 km per t of collected waste food oil.
In addition, regarding transportation from harvest location to BDF production facility, as it is important that conversion to BDF at the harvest location is practical and that for BDF production from high quality raw palm oil, free fatty acid is not generated, proximity between raw palm oil production facility and BDF production facility is desirable (NEDO [2003-2]), therefore the energy for transportation from harvest location to BDF production facility is treated as zero.

3) BDF Production (Oil Extraction)

<i> Existing Study

Regarding oil extraction, data related to raw oil production from rapeseed in Japan is provided in FPS [2003].

In addition, entries concerning oil extraction can be found in ETSU [1996], Shaine Tyson [1998], Sheehan, J. *et al.* [1998], Kadam, K.L. *et al.* [1999], Armstrong, A.P. *et al.* [2002], Ahlvik, P. *et al.* [2002], and EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1, and so on.

<ii> This Study

Prior studies concerning oil extraction from rapeseed give figures for overall energy input (MJ), although some are unclear as to energy type. In addition, of those that do give clear indication of energy type, many involve the use of natural gas, which cannot be assumed in relation to oil extraction from rapeseed in Japan. Therefore, this study uses data provided in ETSU [1996] (p.97, p.156-157), which uses only electricity as the energy related to oil extraction from rapeseed.

In addition, regarding palm, as the related data was unobtainable, energy consumption and GHG emissions calculations were conducted using data provided in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 (p.40), a relatively recent document regarding oil extraction from rapeseed[2]. Furthermore, NEDO [1992] was used for reference concerning palm oil yield from palm (excluding surplus material).

4) BDF Production (Refining)

<i> Existing Study

Regarding the refining process required for esterification, inventory data concerning the refining of rapeseed oil (raw oil) is provided in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 (p.40).

<ii> This Study

Regarding the refining of rapeseed oil (raw oil), data provided in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 (p.40) has been used. In addition, regarding palm oil (raw oil), as the related data was unobtainable, it was assumed to be included in the BDF production (esterification) process.

5) BDF Production (Esterification)

<i> Existing Study

In relation to the BDF production process, NEDO [2003-2] shows FS results relative to BDF production on a scale of 15,000,000 t per year. The process assumed here is the ECB Enviro Berlin AG process.

Regarding BDF production from soybean oil, information based on examples in the U.S. is compiled in Sheehan, J. *et al.* [1998]. The example given in the study is not of mechanical oil extraction but of oil extraction through the use of solvents.

Regarding rapeseed oil, EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 studies energy input for a hypothetical plant on a production scale of 20,000 t/year, using a 10,000-15,000 t/year system currently in operation in the EU for reference. It is considered in this system that materials remaining above ground after

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[2] Regarding oil expression from palm, although the use of electricity or natural gas is anticipated, as there are cases in Malaysia where oil expression is conducted manually, there may be cases where energy consumption and GHG emissions of this process are not taken into consideration.

rapeseed harvest are partly used as an energy resource and that all in-house power is provided through natural gas.

In addition, although BDF production is gradually progressing in Japan, in principle, the focus is on waste food oil. In many cases, data related to energy input is derived from materials based on hearing surveys.

<ii> This Study

[Esterification of rapeseed oil]

As existing research has considered the input of energy resources other than electricity in relation to the esterification of rapeseed oil, the following four cases were considered in this study.

Case 1) Use of rapeseed straw
Case 2) Use of natural gas
Case 3) Use of electricity + natural gas
Case 4) Use of electricity only

The cases here consider cases where electricity is purchased from the networks, and cases where in-house co-generation is conducted using rapeseed straw or natural gas to provide electricity.

In addition, regarding energy consumption and GHG emissions in the process leading to methanol production, calculations were based on relatively recent studies with natural gas as the resource, conducted by PEC [2002-2] and General Motors, *et al.* [2002], giving fuel efficiency at 67 % (worst case scenario).

[Esterification of palm oil]

Esterification of palm oil is studied in NEDO [2003-2] (p.97), and this data is also used in this study.

[Esterification of waste food oil]

Regarding processes of esterification of waste food oil already in progress in Japan, as there are only examples of electricity for energy input, in this study, the esterification of rapeseed oil (Case 4) is also applied to waste food oil.

6) Overseas Transportation (Sea/Land)

<i> Existing Study

In FPS [2003], calculations are made with distance from South-East Asia to Japan at 5,000 km (one-way) and a crude oil tanker (0.059 MJ/t-km) as the tanker.

<ii> This Study

This study also conducted calculations with distance from South-East Asia to Japan set at 5,000 km. (one-way). In addition, the tanker in this study is a 100,000 t class crude oil tanker.

7) Domestic Transportation (Sea/Land)

<i> Existing Study

In FPS [2003], calculations are made with the average domestic shipping distance (round trip) set at approximately 209 km for transportation undertaken by tank lorry from distribution base to gas station.

<ii> This Study

In this study, data related to the domestic transportation of diesel calculated in “2.1 Petroleum Based Fuel Production Pathways” has been substituted.

(2) Ethanol

The ethanol production pathway flow examined in this study are shown in Figure 2.3.3:

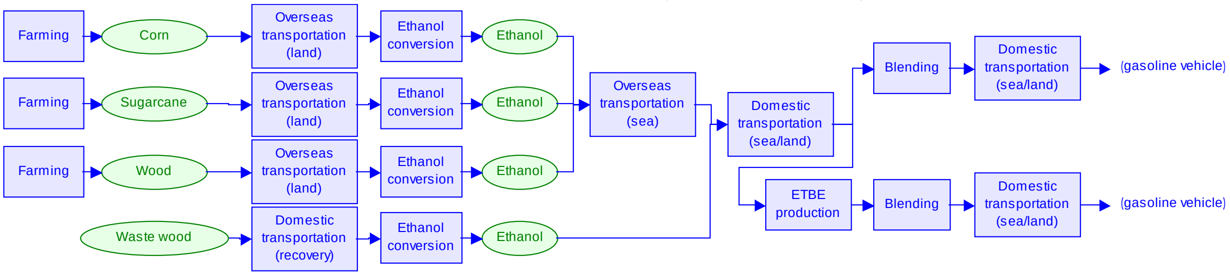

Figure 2.3.3 Pathway flow for ethanol production

Ethanol is not supplied directly into a vehicle, but is used as a blend with gasoline or converted into ethyl tertiary butyl ether (ETBE) and then blended with gasoline. Assuming blending with current gasoline calculated in “2.1 Petroleum Based Fuel Production Pathways”, this study focuses on three fuels types; 3 % ethanol blend gasoline, 10 % ethanol blend gasoline and gasoline/ETBE blend.

1) Farming

<i> Existing Study

Regarding corn farming, the results of studies in North America have been compiled by Marland, G. *et al.* [1991], Lorenz, D. *et al.* [1995], Levelton Engineering Ltd. *et al.* [2000], Aden, A. *et al.*, and variations can be seen depending on fertilizer input and irrigation.

A report on sugarcane farming in Brazil can be found in Isaias de Carvalho Macedo [1998]. The energy for cultivation reported in the study is mainly diesel, fertilizer and insecticide, with both average and optimum data compiled in the report. Mechanization of harvesting is currently at 20%, with the report indicating future mechanization up to 50 %.

Data pertaining to fertilizer, insecticide and energy input related to cultivation is compiled in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 for wheat, and ETSU [1996] for winter wheat. In particular, wheat drying is included along with machinery fuel in data related to diesel in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1. EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 also compiles data related to sugar beet farming.

For data regarding cellulosic biomass farming, an example of hybrid poplar is compiled in Lorenz, D. *et al.* [1995]. As little fertilizer is used and there is no irrigation, energy input is low in comparison to other crops such as corn.

Regarding waste wood, as the use of waste materials generated from the demolition of houses and so on is assumed, energy input and GHG emissions are treated as zero.

<ii> This Study

[Corn farming]

As a number of reports from prior studies are available regarding corn farming, these reports were compared and data given for the maximum energy consumption case (Lorenz, D. *et al.* [1995]) and the minimum energy consumption case (Marland, G. *et al.* [1991]) has been used to calculate energy consumption and GHG emissions. This data also includes energy consumption related to fertilizer production, irrigation, corn drying, and so on.

[Sugarcane farming]

Regarding sugarcane farming, calculations for energy consumption and GHG emissions were based on average data and optimum data provided in Isaias de Carvalho Macedo [1998]. This data also includes energy for fertilizer production, insecticide and cultivation. As Isaias de Carvalho Macedo [1998] cites everything in terms of input energy, CO_2 emissions were calculated under the assumption that energy for cultivation referred mainly to cultivation related machinery, and that fuel for such would be diesel.

[Cellulosic biomass farming]

Regarding cellulosic biomass farming, energy consumption and GHG emissions calculations were based data provided in Lorenz, D. *et al.* [1995]. Ethanol conversion using cellulosic biomass has yet to be industrialized, and the results here are from trial calculations from theoretical values for hybrid poplar.

2) Overseas Transportation (Land) / Domestic Transportation (Collection)

<i> Existing Study

Energy figures for the transportation of sugarcane to ethanol conversion plants in Brazil are given in Isaias de Carvalho Macedo [1998]. A lecture given by the Nanotech Department of Mitsui & Co., Ltd., stated that transportation of sugarcane was conducted mainly by truck, and that profitability for such transportation to a distillery could only be maintained within a 50 km radius of the distillery.

<ii> This Study

In this study, calculations are based on 10 t trucks (fuel consumption 3.5 km/L) and a shipping distance of 50 km (one-way). Transportation related to domestic waste wood collection is treated in the same manner.

3) Ethanol Conversion

<i> Existing Study

Many reports in the U.S., such as Lorenz, D. *et al.* [1995] and Graboski, M.S. [2002], compile data regarding corn based ethanol conversion. There are two types of pre-treatment process that can be used in corn based ethanol production, the dry-mill process and the wet-mill process, and energy input varies depending on the pre-treatment process.

In the dry-mill process, corn is ground and water added to produce corn slurry. Once enzymes have hydrolyzed the slurry, the resulting sugar content undergoes ethanol conversion. Fermentation residue is dried and gathered, and sold on as DDGS (Distillers Dried Grains with Solubles).

In the wet-mill process, sugar content undergoes ethanol conversion once the corn oil, in particular the nutrients known as gluten feed and gluten meal, has been separated.

ETSU [1996] compiles data related to ethanol conversion using wheat as the feedstock, summarizing energy input for a system that extracts starch after the wheat has been ground and conducts ethanol conversion on a scale of approximately 140 t/d. Here, the source of in–house electricity is wheat-straw and natural gas, and the byproduct is DDGS for use as animal feed. Although similar studies have been undertaken in EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1, the scale of the plant is unclear.

Energy input related to cellulosic biomass ethanol production in the U.S. is compiled in Lorenz, D. *et al.* [1995]. This reports shows the results of a process simulation of the U.S. Arkenol, Inc. process on an industrial scale, and provides data ranging from biomass farming through to ethanol production.

Average data and optimum data is compiled in Isaias de Carvalho Macedo [1998] regarding molasses based ethanol conversion in Brazil.

Regarding ethanol conversion of cellulosic biomass, Kadam, K.L. *et al.* [1999] compiles process simulation results regarding ethanol conversion following two types of pre-treatment process, the acid degradation process currently under development and the enzymatic hydrolysis process under consideration for future development. In addition, Kadam, K.L. [2000] conducts a similar study into the ethanol conversion of bagasse in India. These studies assume a production scale of 800 t/d.

In addition, EUCAR, CONCAWE, & JRC/IES [2003] Appendix 1 also compiles data regarding the ethanol conversion of sugar beet fibre remaining after juicing.

<ii> This Study

[Ethanol conversion from corn]

Regarding the ethanol conversion of corn, there are differences in energy consumption depending on whether the corn degradation pre-treatment is conducted using the dry-mill or the wet-mill process. In this study, following consideration and comparison of Levelton Engineering Ltd. *et al.* [2000] (Canada) and Graboski, M.S. [2002] (U.S.) for the dry-mill process, and Marland, G. *et al.* [1991] and Graboski, M.S. [2002] (U.S.) for the wet-mill process, energy consumption and GHG emissions were calculated based on data provided for maximum energy consumption (Marland, G. *et al.* [1991]) and minimum energy consumption (Levelton Engineering Ltd. *et al.* [2000]).

[Ethanol conversion from sugarcane]

Regarding the ethanol conversion of sugarcane, calculations for energy consumption and GHG emissions were based on average data and optimum data provided in Isaias de Carvalho Macedo [1998].

Regarding the ethanol conversion of sugarcane, there are many cases where bagasse (sugarcane residue) combustion is used to power steam turbines for power generation. When calculating GHG emissions in this study, GHG emissions for purchased power equivalent to power generated through bagasse combustion were also studied for comparison purposes. Calculations here for total bagasse generation are based on material balance data given in Japan Energy Research Center [2002] (p.102).

[Ethanol conversion from cellulosic biomass]

Regarding the ethanol conversion of cellulosic biomass, the process using acid as a pre-treatment for biomass saccharification, has been included.

Regarding the ethanol conversion of cellulosic biomass, energy consumption and GHG emissions calculations are based on data provided in Kadam, K.L. *et al.* [1999] (p.34). The calculations in this data separate cellulosic materials into shrubs, softwoods and rice straw, of which this study uses data for shrubs and softwoods.

Regarding the ethanol conversion of waste wood, data related to softwoods with comparatively similar compositions is applied, and conversion into heating value in Japan and re-calculation was conducted only in relation to natural gas consumption.

4) Overseas Transportation (Sea)

<i> Existing Study

In FPS [2003], calculations are made with shipping distance from India to Japan at 8,900 km (one-way) and a crude oil tanker (0.068 MJ/t-km) as the tanker.

<ii> This Study

In this study, calculations are made under the assumption of transportation to Japan of, corn from the U.S. (Los Angeles: 4,849 miles), sugarcane from Brazil (Rio de Janeiro: 11,768 miles) and cellulosic biomass from Malaysia (Bintulu: 2,511 miles). In addition, assuming that the tanker used will be the same vessel as used for methanol, details given in NEDO [2001-3] for capacity of methanol vessels, and speed and fuel consumption for GTL vessels was substituted.

5) Domestic Transportation (Sea/Land)

<i> Existing Study

In FPS [2003], calculations are made with the average domestic shipping distance (round trip) set at approximately 209 km for transportation undertaken by tank lorry from distribution base to gas station.

<ii> This Study

In this study, data calculated in “2.1 Petroleum Based Fuel Production Pathways” in relation to the domestic transportation of gasoline has been substituted.

6) ETBE Production

Regarding the ETBE production from ethanol process, energy consumption calculations are based on Kadam, K.L. *et al.* [1999] (p.38) and “Regarding ETBE” found at the MOE website (http://www.env.go.jp/earth/ondanka/renewable/03/mat_03.pdf).

7) Blending

Energy consumption and GHG emissions of the blending process have been omitted, as the information required to create inventory data was unobtainable.

(3) Biogas (Methane Gas)

The CH_4 fermentation pathway flow examined in this study are shown in Figure 2.3.4:

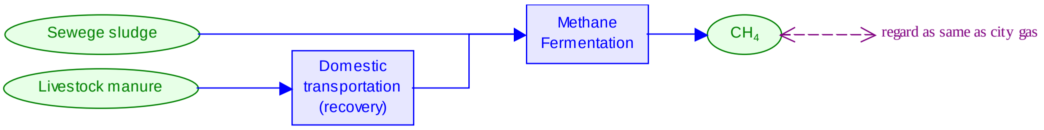

Figure 2.3.4　Pathway flow for CH_4 fermentation

1) Domestic Transportation (Collection)

CH_4 fermentation feedstock in Japan focuses on sewage sludge and livestock manure, and very little focus is placed on food waste and others.

Regarding sewage sludge, the main form of transportation is pipeline from the sewage plant, with some septic tank sludge shipped by sewage vacuum car. In addition, regarding livestock manure, in many cases the manure is accumulated in tanks at the farm and then shipped in by overland transportation (e.g. light trucks) owned by the farms. Therefore, calculations in this study are based on 2 t trucks (fuel: gasoline, fuel consumption: 6.0 km/L) and a shipping distance of 10 km (one-way).

2) CH_4 Fermentation

<i> Existing Study

The operational data for the system in Yagi Town, Kyoto Prefecture, in which digestive gas obtained through the CH_4 fermentation processing of livestock manure and bean curd lees is used for gas engine power generation, is shown in Ogawa *et al.* [2003].

The Central Purification Center (CPC) of Nagaoka-City, Niigata Prefecture, supplies digestive gas obtained through the CH_4 fermentation of sewage sludge to city gas holders.

<ii> This Study

Calculations are made in this study for energy consumption and GHG emissions in relation to the CH_4 fermentation processes of the previously mentioned Yagi system detailed in Ogawa *et al.* [2003] and the Nagaoka CPC example.

In recent years, although many small-scale CH_4 fermentation facilities have been established, the utilization of these in terms of CH_4 fermentation for automotive fuel production is considered difficult. On the other hand, the Yagi Bio-Ecology Center covered in this study is the most famous and largest livestock manure CH_4 fermentation facility in Japan.

In addition, the Nagaoka CPC is most representative of biogas generation through CH_4 fermentation for use as a substitute for city gas. In this study, energy consumption and GHG emissions calculations were based on data obtained through a hearing survey conducted in relation to the Nagaoka CPC.

3) Distribution

Regarding distribution to city gas holders, energy consumption and GHG emissions calculations were based on data obtained through a hearing survey conducted in relation to the Nagaoka CPC.

2.3.3 Calculation results

Regarding the fuel production pathways from biomass resources, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ BDF are shown in Table 2.3.2 (energy consumption), Table 2.3.3 (GHG emissions) and Table 2.3.4 (energy efficiency).

The results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ ethanol are shown in Table 2.3.5 (energy consumption), Table 2.3.6 (GHG emissions) and Table 2.3.7 (energy efficiency).

The results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ biogas are shown in Table 2.3.8 (energy consumption), Table 2.3.9 (GHG emissions) and Table 2.3.10 (energy efficiency).

Table 2.3.2 WTT energy consumption of BDF production pathways [MJ/MJ]

	BDF from rapeseed					BDF from palm		BDF from waste food oil
	Straw	Natural gas	Electricity + Natural gas	Electricity	CO_2 emission maximum case	Including oil extraction	Excluding oil extraction	
Farming	0.107	0.107	0.110	0.113	0.153	0.128	0.128	-
Recovery	-	-	-	-	-	-	-	0.001
Oil extraction	0.223	0.223	0.229	0.236	0.223	0.068	0.000	-
Oil refining	0.010	0.010	0.011	0.011	0.010	↓	↓	↓
Esterification	0.271	0.241	0.101	0.055	0.241	0.076	0.076	0.055
Overseas transportation	-	-	-	-	-	0.011	0.011	-
Domestic transportation	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Total	0.616	0.586	0.456	0.420	0.633	0.289	0.220	0.061

Table 2.3.3 WTT GHG emissions of BDF production pathways [g eq-CO_2/MJ]

	BDF from rapeseed					BDF from palm		BDF from waste food oil
	Straw	Natural gas	Electricity + Natural gas	Electricity	CO_2 emission maximum case	Including oil extraction	Excluding oil extraction	
Farming	13.9	13.9	14.3	14.8	13.6	14.4	14.4	-
Recovery	-	-	-	-	-	-	-	0.1
Oil extraction	8.9	8.9	9.1	9.4	8.9	3.9	0.0	-
Oil refining	0.6	0.6	0.6	0.6	0.6	↓	↓	↓
Esterification	1.4	13.3	5.2	2.4	13.3	3.7	3.7	2.4
Overseas transportation	-	-	-	-	-	0.8	0.8	-
Domestic transportation	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	25.2	37.1	29.7	27.6	36.8	23.2	19.4	2.9
Fixed CO_2	△76.2	△76.2	△76.2	△76.2	△76.2	△76.2	△76.2	△76.2

Table 2.3.4 WTT energy efficiency of BDF production pathways (LHV)

	BDF from rapeseed					BDF from palm		BDF from waste food oil
	Straw	Natural gas	Electricity + Natural gas	Electricity	CO_2 emission maximum case	Including oil extraction	Excluding oil extraction	
Farming	↓	↓	↓	↓	↓	↓	↓	-
Recovery	↓	↓	↓	↓	↓	↓	↓	↓
Oil extraction	↓	↓	↓	↓	↓	↓	↓	-
Oil refining	↓	↓	↓	↓	↓	↓	↓	↓
Esterification	0.738	0.756	0.853	0.896	0.713	0.932	0.985	0.994
Overseas transportation	-	-	-	-	-	0.989	0.989	-
Domestic transportation	0.994	0.994	0.994	0.994	0.994	0.994	0.994	0.994
Total	0.734	0.751	0.848	0.891	0.709	0.916	0.969	0.988

Table 2.3.5 WTT energy consumption of ethanol production pathways [MJ/MJ]

	Ethanol from corn		Ethanol from sugarcane (bagasse utilization)		Ethanol from sugarcane (power grid utilization)		Ethanol from foreign wood		Ethanol from domestic waste wood
	(worst)	(best)	(average)	(best)	(average)	(best)	(worst)	(best)	
Farming	0.328	0.258	0.076	0.067	0.076	0.067	0.280	0.105	-
Overseas transportation (land)	0.013	0.012	↑	↑	↑	↑	0.046	0.017	-
Recovery	-	-	-	-	-	-	-	-	0.017
Ethanol production	0.648	0.611	0.843	0.748	0.081	0.072	2.307	1.366	1.634
Overseas transportation (sea)	0.057	0.057	0.133	0.133	0.133	0.133	0.031	0.031	-
Domestic transportation	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Total	1.055	0.946	1.060	0.957	0.299	0.281	2.673	1.527	1.660

Table 2.3.6 WTT GHG emissions of ethanol production pathways [g eq-CO_2/MJ]

	Ethanol from corn		Ethanol from sugarcane (bagasse utilization)		Ethanol from sugarcane (power grid utilization)		Ethanol from foreign wood		Ethanol from domestic waste wood
	(worst)	(best)	(average)	(best)	(average)	(best)	(worst)	(best)	
Farming	32.14	28.23	6.94	6.04	6.94	6.04	25.15	9.40	-
Overseas transportation (land)	0.96	0.89	↑	↑	↑	↑	3.39	1.27	-
Recovery	-	-	-	-	-	-	-	-	1.27
Ethanol production	55.06	34.82	0.00	0.00	1.52	1.35	143.49	84.91	93.31
Overseas transportation (sea)	4.39	4.39	10.28	10.28	10.28	10.28	2.40	2.40	-
Domestic transportation	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
Total	93.21	68.98	17.87	16.97	19.39	18.32	175.09	98.64	95.24
Fixed CO_2	△71.28	△71.28	△71.28	△71.28	△71.28	△71.28	△71.28	△71.28	△71.28

Table 2.3.7 WTT energy efficiency of ethanol production pathways (LHV)

	Ethanol from corn		Ethanol from sugarcane (bagasse utilization)		Ethanol from sugarcane (power grid utilization)		Ethanol from foreign wood		Ethanol from domestic waste wood
	(worst)	(best)	(average)	(best)	(average)	(best)	(worst)	(best)	
Farming	↓	↓	↓	↓	↓	↓	↓	↓	↓
Overseas transportation (land)	↓	↓	↓	↓	↓	↓	↓	↓	↓
Recovery	-	-	-	-	-	-	-	-	↓
Ethanol production	0.588	0.590	0.533	0.562	0.924	0.931	0.282	0.408	0.377
Overseas transportation (sea)	0.946	0.946	0.882	0.882	0.882	0.882	0.970	0.970	-
Domestic transportation	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991
Total	0.552	0.554	0.466	0.492	0.809	0.815	0.271	0.392	0.374

Table 2.3.8 WTT energy consumption of CH_4 gas production pathways [MJ/MJ]

	Livestock manure	Sewage sludge
Recovery	0.054	-
CH_4 fermentation	0.521	0.584
Distribution	0.194	0.194
Fueling to vehicles	0.046	0.046
Total	0.814	0.823

Table 2.3.9 WTT GHG emissions of CH_4 gas production pathways [g eq-CO_2/MJ]

	Livestock manure	Sewage sludge
Recovery	4.0	-
CH_4 fermentation	15.0	16.8
Distribution	5.4	5.4
Fueling to vehicles	1.8	1.8
Total	26.3	24.1
Fixed CO_2	△ 57.0	△ 57.0

Table 2.3.10 WTT energy efficiency of CH_4 fermentation pathways (LHV)

	Livestock manure	Sewage sludge
Recovery	↓	-
CH_4 fermentation	0.835	0.861
Distribution	0.951	0.951
Fueling to vehicles	0.983	0.983
Total	0.780	0.804

2.4 Synthetic Fuel Production Pathways

2.4.1 Abstract

Gas-to-Liquid (GTL) technology, which converts natural gas to liquid fuel, has recently become the focus of attention. The background to this is that upstream there is an abundance of undeveloped gas fields and an increased need for development in gas producing countries, while midstream there is improved economic efficiency due to improved GTL technology, and downstream there is an increased need for clean fuels due to stricter environmental regulations (Suzuki [2001]).

Methods for the conversion of natural gas into liquid fuel can be divided into two broad categories, the indirect method, in which the gas is first converted into a highly reactive syngas (a mixture of CO and hydrogen) and then converted into FT synthetic oil, DME, methanol and so on, and the direct method, in which natural gas is converted directly to methanol and so on, without requiring initial conversion to syngas. Although the direct method was heavily researched in the 1980s in order to find a method of reducing costs related to the syngas production process, there were technical difficulties concerning the inhibition of carbon dioxide gas generation as a side reaction, and although research is still undertaken at universities and others, there is no current industry level research (Suzuki [2001]).

The synthetic fuel production process consists of three processes, the syngas production process, the FT synthesis (DME synthesis, methanol synthesis) process and the hydrocracking/product refining process.

(1) Syngas Production from Natural Gas

Reforming processes are applied to produce syngas from natural gas; these include the following four methods:

- Steam Reforming (SMR)
- Steam / CO_2 Reforming
- Autothermal Reforming (ATR)
- Partial Oxidation (POX)

The H_2/CO molar ratio for the composition of syngas generated from the above four methods is different for each gas (See Figure 2.4.1).

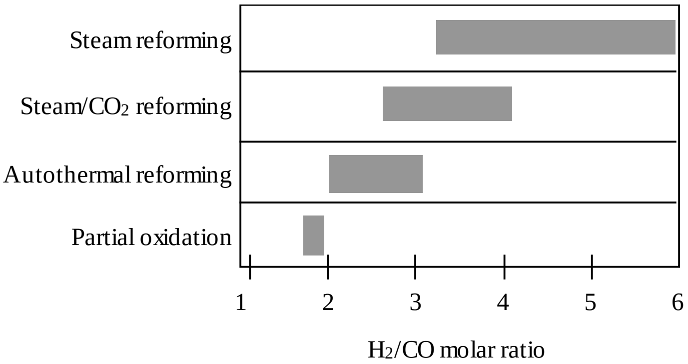

Figure 2.4.1 Relation between syngas production process and H_2/CO molar ratio
([Source] Asaoka, *et.al* [2001])

1) Steam Reforming (SMR)

This process has the greatest track record. Generally, this method uses a reaction between the hydrocarbons in the feedstock and steam, in the presence of a nickel catalyst, at 600-850 degrees C and 2-3 MPa. The chemical formula is as follows.

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

As this is a strong endothermic reaction, the method is characterized by the need for the heat source (Sato [2001]).

2) Steam / CO_2 Reforming

This method combines the steam reforming reaction and the CO_2 reforming reaction, using steam and CO_2 as oxidizing agents to convert natural gas into syngas. Although the optimum H_2/CO ratio of syngas for a FT reaction is 2, as steam reforming of natural gas generates a H_2/CO ratio greater than 3, a CO_2 reformer is added to allow adjustment through CO_2 reforming. JNOC is also conducting research and development of this process, which allows CO_2 contained in the feedstock gas to be utilized along with the natural gas as part of the feedstock without requiring removal.

3) Autothermal Reforming (ATR)

This reforming method combines the partial oxidization process (an exothermic reaction) with the steam reforming process (an endothermic reaction) in order to improve thermal efficiency, while maintaining thermal balance through one or two reactors. Autothermal reforming uses pure oxygen. As with the steam reforming process, a nickel catalyst is used (Sato [2001]).

4) Partial Oxidation (POX)

By providing less oxygen than would be required for complete combustion in the absence of a catalyst, this method causes incomplete combustion and uses the heat obtained from the exothermal reaction for gasification. As no catalyst is used, no problems occur even if impurities are present in the feedstock. This method can be applied to many hydrocarbons other than natural gas, such as coal, heavy oil and biomass.
Pure oxygen or air is used as the oxidizing agent. The chemical reaction formula is as follows (Sato [2001]).

$$CH_4 + (1/2)\ O_2 \rightarrow CO + 2H_2$$

(2) FT Synthesis, DME Synthesis and Methanol Synthesis

Possible processes following on from syngas include FT synthesis, DME synthesis and methanol synthesis. However, as each process has its own suitable H_2/CO molar ratio[3], a process combined with a reforming process to attain the suitable H_2/CO molar ratio is desirable.

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[3] Although for methanol synthesis the ratio is (H2 - CO_2) / (CO + CO_2), this shall also be cited henceforth as H_2/CO ratio

- FT synthesis : $2H_2 + CO \rightarrow (1/n)(CH_2)_n + H_2O$ + 167 kJ/mol
- DME synthesis (direct) : $3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2$ + 244.9 kJ/mol
- Methanol synthesis : $CO + 2H_2 \rightarrow CH_3OH$ + 90 kJ/mol
  $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$ + 49 kJ/mol

The reaction formula for each is shown below. As is apparent from the reaction formula, the H_2/CO molar ratio suitable for FT synthesis and methanol synthesis is 2, and the ratio suitable for DME synthesis is 1. Therefore, for FT synthesis and methanol synthesis, the reforming processes that attain a H_2/CO molar ratio in the region of 2, as shown in Fig 2.4.1, namely the autothermal reforming process and the partial oxidization process are suitable. Although a FT synthesis process using Steam/CO_2 reforming has recently been developed, as this reforming process is able to attain H_2/CO molar ratio=2, it is also extremely suited to FT synthesis.

* FT synthesis, DME synthesis, methanol synthesis through the gasification of coal or biomass

Where gasification of coal or biomass is conducted, a wet gas cleaning process is first applied, as substances such as tar are present in the syngas. Afterwards, depending on the CH_4 concentration present in the syngas, the gas is passed through a reformer and then on to a process to attain the suitable H_2/CO molar ratio for the subsequent stages. If the H_2/CO molar ratio is greater than required at this point, surplus H_2 is generated causing deterioration in efficiency.

As with the reforming of natural gas, when coal is gasified a syngas containing H_2 and CO is generated, but as the hydrogen content in coal is low the H_2/CO molar ratio of the gas is $H_2/CO \leqq 1$.

With the gasification of biomass, the composition of the generated syngas varies depending on the type of gasification furnace (furnace shape, different amounts of steam, oxygen/air input during gasification). H_2/CO molar ratios can be either $H_2/CO \leqq 1$ or $H_2/CO \geqq 1$.

As FT synthesis and methanol synthesis require a syngas with H_2/CO molar ratio=2, for syngas with H_2/CO molar ratio$\leqq 2$, the following shift reaction is used to adjust ratio to H_2/CO molar ratio=2.

$$\text{Shift reaction : } CO + H_2O \leftrightarrow CO_2 + H_2$$

An example of biomass gasification including CH_4 reforming and FT synthesis process flow is shown in Figure 2.4.2.

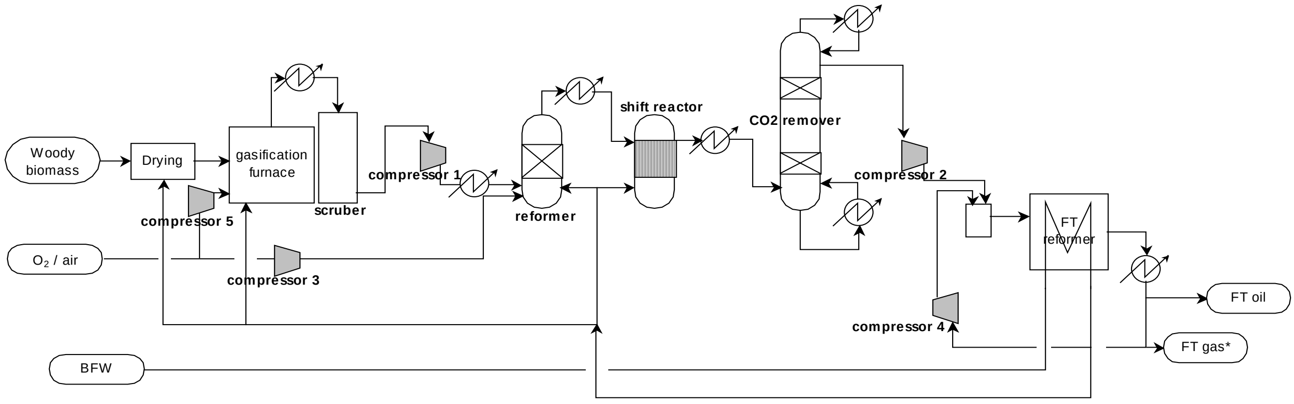

Figure 2.4.2 Process flow of biomass gasification and FT synthesis

(3) Hydrocracking of Hydrocarbons

Although, a range of products such as naphtha, kerosene and diesel can be derived from FT synthesis, the principal constituent of these is normal paraffin with a variety of carbon chains. In this process, each product is obtained through distillation following the hydrocracking of hydrocarbons obtained through FT synthesis. The principal qualities and characteristics of synthetic fuels are shown in Table 2.4.1 and Table 2.4.2.

Table 2.4.1 The principal qualities of synthetic fuels

			FT Diesel		Methanol	DME
			Sasol SSPD Diesel	Shell SMDS Diesel	CH_3OH	C_2H_6O
Molecular weight					32.04	46.07
Composition ratio	C	wt%	84.9	84.91	37.5	52.2
	H	wt%	15.1	14.97	12.6	13.1
	N	wt%		0.67		
	O	wt%	0	0	49.9	34.7
Density	15/15℃	kg/L	0.7698	0.7845	0.796	0.667
	0℃, 1atm	kg/m^3				2.05
Freezing point		℃			-97.5	
Boiling point		℃	159 - 352	210 - 338	65	-25
Vapor pressure	@38℃	kPa			32	
	@38℃	Psi			4.6	
Specific heat		kJ/ (kg-k)			2.5	2.99
Kinematic viscosity	@20℃	mPa-s			0.59	< 1
	@20℃	CSt			0.74	
	@40℃	CSt	2.08	3.57		
Water solubility	@21℃	Moisture vol%			100	
Electrical conductivity		mhos/cm			$4.4 * 10^{-7}$	
Latent heat of evapolation		kJ/kg			1,178	467.13
Higher heating value		MJ/kg	46.7	47.2	22.7	31.7
		MJ/L	35.9	37.0	18.1	21.1
Lower heating value		MJ/kg		44.0	19.7	28.8
		MJ/L		34.5	15.8	19.2
Flash point		℃	59	72	11	
Auto ignition temperature		℃			464	235
Combustion limit	Lower limit	vol%			7.3	3.4
	Upper limit	vol%			36.0	18.6
Theoretical air/fuel ratio					6.45	9.0
Velocity of diffusion flame		m/s			2 - 4	0.54
Octane number	RON				108.7	
	MON				88.6	
Cethane number			> 74.8	> 74		55 - 60
Source			Myburgh, *et al* [2000]	Norton, *et al.* [1998]	Bechtold [1997] Bosch [2000] EIA[1994]	Kajitani, *et al.* [1998] Bosch [2000]

Table 2.4.2 Properties of synthetic fuels

([Source] 1):Suzuki [2001], 2):Nakamura [2002], 3):PEC [2002-1], 4):JHFC website)

	Advantage	Disadvantage
FT diesel	・No need to develop new infrastructure and technology to be used, since its property is almost the same as petroleum-based diesel (As with other FT synthetic oils). 1) ・Easily comply with quality standard of automobile diesel regulation due to its property of high cetane number and low aromatic content. 1) ・Experience as commercially operated plants.2) ・Also valuable as a blending material of petroleum products. 3)	・Could worsen fuel efficiency because its density is relatively low. 1) ・Poor lubrication due to its low sulfur and aroma contents, while low expansivity of seal due to its high paraffin with low aroma content. 3)
FT kerosene	・Superior in combustion quality due to its low sulfur content and high smoke point. 3) ・Has a potential to be used as a fuel for household fuel cell besides an alternative of kerosene. 3) ・Expected to be used as an aviation fuel (in South Africa, a mixed fuel of FT kerosene and petroleum-based jet fuel has been utilized). 3)	・The existing petroleum-based kerosene is sufficient in quality, so the issue is how much degree of premium it would be able to gain. 2)
FT naphtha	・Suitable for petrochemical naphtha as a feedstock for ethylene degradation due to its high paraffin content. 3) ・Expected as a fuel for fuel cell vehicles due to its few sulfur and aroma contents. 3)	・If used at conventional internal combustion engine for gasoline, its low octane number needs to be increased by means such as alkylation. 2)
DME	・Similar property to LPG, so that infrastructure for LPG would be available. 2) ・R&D has been underway to use it as a substitute fuel of diesel (fuel for diesel engine) besides LPG substitute. 2)	・Used for a limited purpose such as aerosol propellant as the CFC substitute so far, so the market is quite small. 2) ・Its properties as a fuel, such as combustion quality, have not been sufficiently figured out.2) ・Infrastructure building and technology developments are necessary in order to use it as a fuel 2) ・There are other issues to be solved such as production specification as a fuel, safety recognition, establishment of standard for use.2)
Methanol	・Methanol vehicle is classified as low emission vehicles in Japan. 2) ・For the use of a fuel for fuel cell vehicles, it can be reformulated in lower reaction temperature in comparison with other fuels. 4)	・One of the toxic agents designated by "Poisonous and Deleterious Substances Control Law". 2) ・If used as automobile fuel, fuel efficiency tends to get worse because of its low heating value, although its octane number is high. 2) ・Unsuitable for diesel engine due to its low cetane number. 2)

2.4.2 Procedures for data collection of unit process

The synthetic fuel production pathway flow examined in this study is shown in Figure 2.4.3. Of these pathways, this study acquired prior studies related to FT synthetic oil, DME, methanol production from natural gas, FT synthetic oil production from coal, FT synthetic oil, DME, methanol production from biomass. Prior studies related to other pathways, specifically DME and methanol production from coal, could not be acquired. Consequently, this study has attempted to make estimates for these pathways. Specifically, in relation to all synthetic fuel production pathways, including these pathways, conditions were set for a particular process, and energy efficiency estimates were made according to those conditions. Conditions set for the estimates and the estimates are shown in “(10) Energy Efficiency Estimates” at the end of this section.

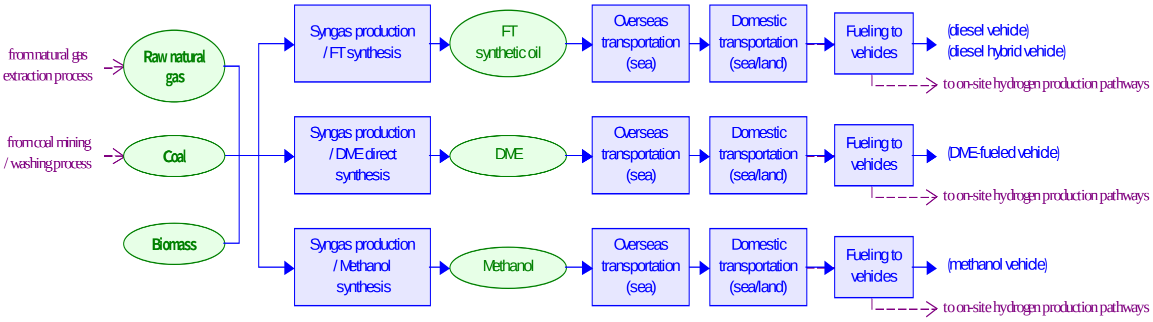

Figure 2.4.3 Pathway flow for synthetic fuels production

(1) FT Synthetic Oil Production Pathway from Natural Gas

<i> Existing Study

Table 2.4.3 shows data calculated in prior studies. As the range of fuel types studied varies with each report, fuel types are also clearly indicated.

Table 2.4.3 Energy efficiencies and carbon efficiencies regarding natural gas based FT synthetic oil production pathways in existing studies

Reference	Feedstock	Product	Energy efficiency or energy consumption	CO_2 emission or carbon efficiency	Cogeneration, etc.
Wang, M.Q. et al. [1999] (Argonne National Lab.)	Natural gas	FT diesel	66 %	76 %	Energy efficiency takes into account the Btu in steam.
	Natural gas	FT diesel	49 %	76 %	Energy efficiency does not take into account the Btu in steam.
	Natural gas	FT diesel	57 %	73 %	Design does not include steam or electricity export.
	Flared gas	FT diesel	55 %	73 %	Flared gas as feedstock. No electricity cogeneration. Incremental.
	Flared gas	FT diesel	57 %	73 %	Flared gas as feedstock. No electricity cogeneration. Leap-forward.
Marano, J.J et al.[2001] (E^2S, LLC)	Natural gas (Pipeline)	FT synthetic oil	59.1 %	57 %	With conventional product upgrading.
	Associated gas	FT synthetic oil	57.3 %	39.3 %	Associated gas as feedstock.
	Associated gas	FT synthetic oil	57.1 %	39.2 %	Associated gas as feedstock. Once-through power generation.
Argonne National Lab. [2001]	Natural gas	FT diesel, naphtha	61 - 65 %	75 - 85 %	Without steam or electricity export.
	Natural gas	FT diesel, naphtha	53 - 57 %	75 - 85 %	Excluding energy in co-products.
Ahlvik, P. et al.[2001] (Ecotraffic)	Natural gas	FT synthetic oil	57 %		
Wang, M.Q.[2001] (Argonne National Lab.)	Natural gas	FT diesel	62 %	78.3 %	Mossgas Design. Standalone.
	Natural gas	FT diesel	54 %	68.4 %	Rentech Design. Standalone.
	Natural gas	FT diesel	49.6 %	68.4 %	Rentech Design. With electricity cogeneration.
	Natural gas	FT diesel	57 %	72 %	Syntroleum Design. Standalone.
	Natural gas	FT diesel	49 %	72 %	Syntroleum Design. With steam cogeneration.
	Flared gas	FT diesel	57 %	65 %	Flared gas as feedstock. Syntroleum Design. Standalone.
PEC[2002-2]	Natural gas	FT diesel	49 - 66 %	1,370 - 2,780 g-CO_2/kg-FTD	
GM, et al. [2002]	Natural gas	FT diesel	61 - 65 %	15.8 - 21.5 g-CO_2/MJ-FTD	
	Natural gas	FT naphtha	61 - 65 %	17.3 - 23.0 g-CO_2/MJ-FTN	
Shell Gas & Power [2002]	Natural gas	FT synthetic oil	60 - 65 %	80 - 82 %	SMDS (Shell Middle Distillate Synthesis)

Data given in Bechtel Corporation [1998] has been used to calculate some of the data given in Marano, J.J *et al.* [2001]. In addition, Beer, T., *et al.* [2001] (p.128) adopts values for fuel efficiency (taking calorific value of steam into account) and carbon efficiency (for FT diesel) as given in Wang, M.Q., *et al.* [1999] (p.34).
PricewaterhouseCoopers [2003] was released in May 2003 as the final report of a study on SMDS (Shell Middle Distillate Synthesis) technology, developed by Shell. Shell Gas & Power [2002] and some other reports are thought to be publications generated by this study.

<ii> This Study

In this study, energy consumption and GHG emissions calculations for the FT synthetic oil production from natural gas process are based on PricewaterhouseCoopers [2003], which focuses on new technologies and provides comparatively detailed data. As the report assumes a SMDS plant in the Middle East with unit heating value for natural gas feedstock at 43.2 MJ/kg, this study also uses this value. In addition, as the report also implements load distribution through weight, this study also follows suit.

(2) DME Production Pathway from Natural Gas

<i> Existing Study

Table 2.4.4 shows data calculated in prior studies.

Table 2.4.4 Energy efficiencies and carbon efficiencies regarding natural gas based DME production pathways in existing studies

Reference	Feedstock	Product	Energy efficiency or energy consumption	CO_2 emission or carbon efficiency	Cogeneration, etc.
Hansen, J. B. et al.[1995] (Haldor Topsøe)	Natural gas	DME		0.44 t-CO_2/t-DME	
Wang, M.Q. et al.[1999] (Argonne National Lab.)	Natural gas	DME	69 %	0.446 t-CO_2/t-DME	No electricity cogeneration. incremental
	Natural gas	DME	70 %	0.446 t-CO_2/t-DME	No electricity cogeneration. leap-forward
	Flared gas	DME	68 %	0.446 t-CO_2/t-DME	Flared gas as feedstock. No electricity cogeneration. incremental
	Flared gas	DME	69 %	0.446 t-CO_2/t-DME	Flared gas as feedstock. No electricity cogeneration. leap-forward
NEDO [2001-3]	Natural gas	DME	71 %	0.112 g-C/10kcal	Natural gas input : 1.114 Nm^3 / t-DME
Haldor Topsøe[2001]	Natural gas	DME	71.2 %	355 kg-CO_2/t-DME 12.3 g-CO_2/MJ-DME	
Ahlvik, P. et al.[2001] (Ecotraffic)	Natural gas	DME	74 %		

Of the above prior studies, the report of a study conducted by Denmark's Haldor Topsøe A/S into the company's own DME direct synthesis technology (Haldor Topsøe [2001]), provides specific input/output data related to the entire plant based on actual measurements, although it does not go into analysis of each individual process (see Figure.2.4.4).

<ii> This Study

For calculation purposes, this study uses data given in Haldor Topsøe [2001] for reference, as the basis for calculation is comparatively clear (see Figure.2.4.4).

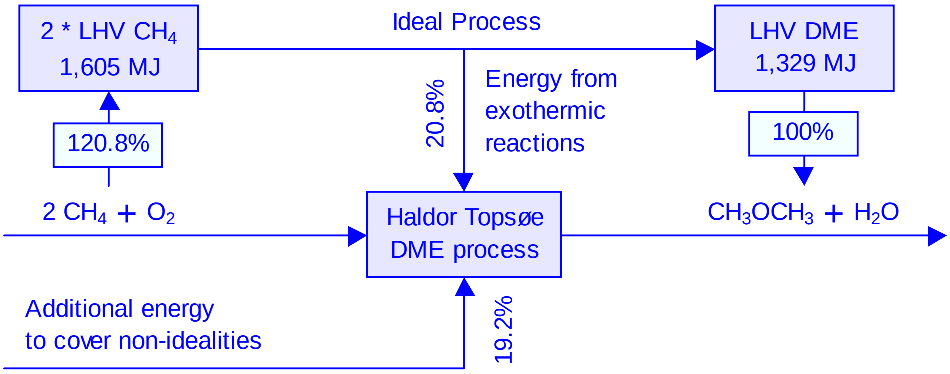

Figure 2.4.4 DME direct synthesis process by Haldor Topsøe

(3) Methanol Production Pathway from Natural Gas

<i> Existing Study

Table 2.4.5 shows data calculated in prior studies.

Table 2.4.5 Energy efficiencies and carbon efficiencies regarding natural gas based methanol production pathways in existing studies

Reference	Feedstock	Product	Energy efficiency or energy consumption	CO_2 emission or carbon efficiency	Cogeneration, etc.
IAE [1990]	Natural gas	Methanol	7.1 $*10^6$ kcal/t-MeOH	315.8 kg-CO_2/t-MeOH	Energy cosumption includes energy as feedstock.
Wang, M.Q. et al.[1999] (Argonne National Lab.)	Natural gas	Methanol	67 %		Incremental.
	Natural gas	Methanol	70 %		Leap-forward
	Flared gas	Methanol	65 %	65 %	Incremental.
	Flared gas	Methanol	67 %	67 %	Leap-forward
Argonne National Lab. [2001]	Natural gas	Methanol	67.5 %		Without steam or electricity export.
	Natural gas	Methanol	64 %		Excluding energy in co-products.
Ahlvik, P. et al.[2001] (Ecotraffic)	Natural (hydrogen-rich)	Methanol	70 %	90 %	
PEC[2002-2]	Natural gas	Methanol	67 - 70 %	710 - 820 g-CO_2/kg-MeOH	
GM, et al. [2002]	Natural gas	Methanol	67.3 - 69.4 %	12.4 - 14.9 g-CO_2/MJ-MeOH	

<ii> This Study

Unlike FT synthetic oil and DME, for the methanol production from natural gas process, there is no data with a clear basis for calculation. Consequently, in this study, energy consumption and GHG emissions for the methanol production from natural gas process were calculated for two cases, from worst (67%) and optimum (70%) fuel efficiency figures given in PEC [2002-2] and General Motors, *et al.* [2002]. Furthermore, CO_2 emissions calculations were made according to the method used in IAE [1990]. Specifically, according to the following procedure.

1) Calculation of carbon content in natural gas used for feedstock and for fuel
2) Calculation of carbon content in the produced methanol product
3) Difference in carbon content converted to CO_2 weight, result given as CO_2 emissions

However, although IAE [1990] subtracts associated CO_2 from the CO_2 emissions calculated in this manner and notes associated CO_2 separately, this study stops at figures for CO_2 emissions inclusive of associated CO_2. In addition, methanol heating values and carbon content (%) are as given in Table 2.4.1 and ANRE [1992] was used as reference for properties of natural gas used as feedstock and fuel. Regarding natural gas producing regions, although places indicated in PEC [2002-1] (p.119) may be considered such as Malaysia, Indonesia, Australia, Iran and Qatar, where plant construction is planned, this study uses simple averages derived from data regarding three countries (Malaysia, Indonesia (Badak), Australia) mentioned in ANRE [1992].

(4) FT Synthetic Oil Production Pathway from Coal

<i> Existing Study

Table 2.4.6 shows data calculated in prior studies. Regarding the FT synthetic oil production from coal process, Marano, J.J *et al.*[2001] calculates fuel efficiency and carbon efficiency for several cases according to coal producing region and production technology. These calculations are based on data given in Bechtel Corporation [1998].

Table 2.4.6 Energy efficiencies and carbon efficiencies regarding coal based FT systhetic oil production pathways in existing studies

Reference	Feedstock	Product	Energy efficiency or energy consumption	CO_2 emission or carbon efficiency	Cogeneration, etc.
Marano, J.J et al.[2001] (E^2S, LLC)	Coal (Illinois)	FT synthetic oil	50.4 %	40.1 %	Shell Design. With conventional product upgrading.
	Coal (Illinois)	FT synthetic oil	52 %	41.1 %	Shell Design. With ZSM-5 product upgrading.
	Coal (Illinois)	FT synthetic oil	47.4 %	37.7 %	Shell Design. With conventional product upgrading + fluidized-bed catalytic cracking for wax conversion.
	Coal (Wyoming)	FT synthetic oil	49.3 %	39.1 %	Shell Design. With conventional product upgrading.

<ii> This Study

[Mining / washing process of imported coal]

As data obtained through hearing surveys with industry related to the coal mining process, Hondo *et al.* [1999] gives figures for fuel input (diesel, gasoline, electricity) per unit weight during coal mining and coal washing for open-pit and underground coal mining in Australia, and calculates environmental burden for the entire lifecycle of imported coal consumption in Japan. These values are also used in CRIEPI [2000] (p.19).

In this study also, energy consumption and GHG emissions were calculated for the extraction process and washing process of imported coal based on data given in Hondo *et al.* [1999], the extraction method at the imported coal source and actual import volumes. Furthermore, regarding energy consumption and CO_2 emission factors during power generation in each country, data reflecting the power generation circumstances of each was created and applied.

[FT synthetic oil production process]

As with methanol production from natural gas, regarding the FT synthetic oil production from coal process, there is no data with a clear basis for calculation. Consequently, in this study, energy consumption and GHG emissions for the FT synthetic oil production from coal process were calculated for two cases, from worst (47.4%) and optimum (52%) fuel efficiency figures given in Marano, J.J *et al*. [2001]. Furthermore, CO_2 emissions calculations were made according to the method used in IAE [1990]. Here, the carbon content in feedstock coal is the weighted average of carbon content (%) in coal from each country and import ratio.

(5) FT Synthetic Oil Production Pathway from Biomass

<i> Existing Study

Table 2.4.7 shows data calculated in prior studies for FT synthetic oil, DME and methanol production from biomass processes.

Table 2.4.7 Energy efficiencies and carbon efficiencies regarding coal based synthetic fuel production pathways in existing studies

Reference	Feedstock	Product	Energy efficiency or energy consumption	CO_2 emission or carbon efficiency	Cogeneration, etc.
Marano, J.J et al.[2001] (E^2S, LLC)	Biomass (Maplewood)	FT synthetic oil	51 %	37.2 %	With conventional product upgrading and once-through power generation. BCL Design.
Ahlvik, P. et al.[2001] (Ecotraffic)	Biomass	FT synthetic oil	45 %		
Ahlvik, P. et al.[2001] (Ecotraffic)	Biomass	DME	57 %		
Ahlvik, P. et al.[2001] (Ecotraffic)	Biomass	Methanol	54 %	104 g-CO_2/MJ-MeOH	Excluding by-product : hot water.
	Biomass	Methanol	65 %	104 g-CO_2/MJ-MeOH	Including by-product : hot water for district heating.

<ii> This Study

Regarding the FT synthetic oil production from biomass process, energy consumption and GHG emissions were calculated for two cases, from worst (45%) and optimum (51%) fuel efficiency figures given in Ahlvik, P. [2001] and Marano, J.J *et al*. [2001].

(6) DME Production Pathway from Biomass

<i> Existing Study

Shown in Table 2.4.7.

<ii> This Study

Regarding the DME production from biomass process, energy consumption and GHG emissions were calculated from fuels efficiency figures (57%) given in Ahlvik, P. [2001].

(7) Methanol Production Pathway from Biomass

<i> Existing Study

Shown in Table 2.4.7.

<ii> This Study

Regarding the methanol production from biomass process, energy consumption and GHG emissions were calculated for two cases, from worst (54%) and optimum (65%) fuel efficiency figures given in Ahlvik, P. [2001] and Marano, J.J *et al.* [2001].

(8) Overseas Transportation (Sea)

<i> Existing Study

In relation to GTL (FT synthetic oil), NEDO [2001-3] (p. I-124 - I-130) assumes an 80,000 t shipping vessel, and provides fuel consumption data for passage and while moored at loading/unloading ports. In addition, although the report gives the standard vessel size for methanol as 45,000 t, no fuel consumption data is provided. Although there is also no shipping vessel data given for DME, vessels are considered to have the same structural and functional properties as LPG vessels.

PEC [2002-2] gives the vessel size for both GTL and methanol as 50,000 t, with import sources (producing countries) stated as the Southeast Asia, the Middle East and Australia.

<ii> This Study

Regarding FT synthetic oil, this study uses data given for GTL vessels in NEDO [2001-3]. Other than the omission of energy for cargo heating, which is not required for GTL, this data is the same as data for 80,000 t crude oil tankers given in PEC [1998] and PEC [2002-2].

Regarding DME, LPG vessel data used later in “2.5 Liquid Petroleum Gas Production Pathways” also applies here. This data is based on data given in IEEJ [1999] for overseas transportation of LPG, while for vessel speed, figures given in PEC [1998] for crude oil tankers have been substituted.

Regarding methanol, figures given for methanol vessel capacity in NEDO [2001-3] are used, while figures given in the report for GTL vessel speed and fuel consumption have been substituted.

Furthermore, regarding the import sources (producing countries) of each synthetic fuel, for natural gas based fuels, for the five countries (Malaysia, Indonesia, Australia, Iran, Qatar) given in PEC [2002-1] as having a high probability of becoming GTL suppliers to Japan, simple averages were calculated from data per country to obtain final values. For coal based fuels, suppliers were considered based on the actual import volume of coal given in METI [2002], and the weighted average was calculated from the actual import volume as the final value. Australia is considered for biomass based fuels.

(9) Domestic Transportation (Sea/Land)

<i> Existing Study

Regarding the transportation process of synthetic fuels in Japan, NEDO [2001-3] states that GTL and methanol can be handled through the same supply route as gasoline, and DME can be handled through the same route as LPG. In addition, PEC [2002-2] also states that the environmental burden related to the transportation process of GTL and methanol in Japan is the same as for petroleum products.

<ii> This Study

In this study, for FT synthetic oil and methanol, data calculated in “2.1 Petroleum Based Fuel Production

Pathways" for the domestic transportation of diesel has been substituted, while for DME, data related to the domestic transportation of LPG has been substituted.

(10) Energy Efficiency Estimates

In this study, in relation to each synthetic fuel production path, conditions were set for a particular process, and energy efficiency estimates were made according to those conditions.

Regarding the production processes of synthetic fuels from all feedstock types, existing information is insufficient as the number of operational facilities is limited. Therefore, in this study, for reference purposes, energy efficiency estimates were made by calculating material balance and heat balance for the main production processes of each fuel from feedstock, in order to estimate the general energy efficiency of each process. The natural gas considered here is pure CH_4. In addition, as each process involves an exothermic reaction under pressure, calculations were conducted under the assumption that the heat recovered from the main process is used to power the compressor which is the main powered equipment in the process, while energy consumption of processes other than the main process, which was thought to be comparatively small, were not considered in the calculations. The conditions set are shown below.

<i> Syngas production process

Settings for the operating conditions of reformers are shown in Table 2.4.8.

Table 2.4.8 Operating conditions of natural gas reformer

Reforming method	Temperature [℃]	Pressure [MPa]
Steam reforming	850	2.1
Steam/CO_2 reforming	850	2.1
Partial oxidation	1,300	2.1
Autothermal reforming	1,050	2.1
Coal gasification (Shell)	1,371	2.4
Woody biomass	982	3.4

The composition of syngas from natural gas reforming were calculated from equilibrium composition under operating conditions shown in Table 2.4.8 for the reaction combinations given below.

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad \text{(formula 1)}$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad \text{(formula 2)}$$

$$CH_4 + CO_2 \Leftrightarrow 2CO + 2H_2 \qquad \text{(formula 3)}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \text{(formula 4)}$$

Regarding coal gasification and woody biomass, calculations cannot be made as there are no clear reaction formulas such as those above, and data based on actual measurements given in Williams, R.H, *et al*. [1995] and Tijmensen, M.JA. [2000] has been used.

<ii> H_2/CO molar ratios

H_2/CO molar ratios obtained from equilibrium calculations using the above "formula 1" - "formula 4" are shown in Table 2.4.9. "Formula 4" is used for partial oxidation and autothermal reforming.

Table 2.4.9 H_2/CO molar ratio in syngas

Reforming method	H_2/CO molar ratio
Steam reforming	3
Steam/CO_2 reforming	2
Partial oxidation	1.7
Authothermal reforming	2
Coal gasification (Shell)	0.5
Woody biomass	1.4

<iii> Achieve the appropriate H_2/CO molar ratios

When the syngas has a higher H_2/CO molar ratio than required for the subsequent process, the process progresses without any additional action.

On the other hand, when the syngas has a lower H_2/CO molar ratio than required for the subsequent process, a CO shift reaction is introduced to achieve the appropriate H_2/CO molar ratio. As the CO shift reaction is exothermic, values of removed heat were also calculated.

For syngas from biomass, as there is substantial CH_4 residue, the introduction of a CO shift reaction after passage through a reformer was assumed. The heat required by the reformer was assumed to be provided by heat recovered from the subsequent process.

<iv> Calculate the volume of the fuel produced

For the volume of fuel produced in the subsequent process, values were set for CO [kmol] in the syngas, product molecular weight [kg/kmol] and CO conversion rate (CO reaction rate in syngas) [-] (set at 0.95), and calculations were made according to the following formula.

(Synthetic Product Volume [kg])
= (CO [kmol]) * (Product Molecular Weight [kg/kmol]) * (CO conversion rate [-])

For FT synthetics, although various carbon number compounds are generated, FT oil was treated as the total of C5+ constituents (carbon number greater than C5). C_1 - C_4 gas constituents are used as gases (Tijmensen, M.JA. [2000] assumes in-house use for IGCC power generation).

In addition, the constituent ratio of carbon numbers *n* in FT synthetic oil have been calculated using chain growth probability α through $\alpha^{(n-1)} * (1-\alpha)$, as shown in Figure 2.4.5.

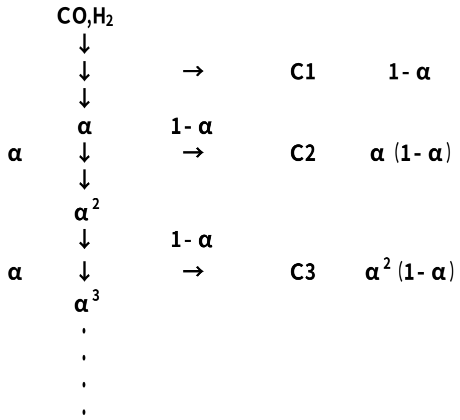

Figure 2.4.5 Composition of FT synthetics

<v> Calculate the product efficiency

Efficiency was then calculated from the product volume obtained through the above using the following formula.

(Product Efficiency [%])
= (Product Volume [kg] * Heating Value [MJ/kg]) / (Feedstock and Fuel Heating Value [MJ]) * 100

2.4.3 Calculation results

Regarding the synthetic fuel production pathways, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.4.10 (energy consumption), Table 2.4.11 (GHG emissions) and Table 2.4.12 (energy efficiency).

Table 2.4.10 WTT energy consumption of synthetic fuel production pathways [MJ/MJ]

	From natural gas				From coal		From biomass				
	FT synthetic oil	DME	Methanol		FT synthetic oil		FT synthetic oil		DME	Methanol	
			best	worst	best	worst	best	worst		best	worst
Upstream process of feedstock	0.017	0.016	0.016	0.017	0.028	0.030	0.074	0.084	0.066	0.058	0.070
Fuel synthesis	0.514	0.404	0.429	0.493	0.923	1.110	0.961	1.222	0.754	0.538	0.852
Overseas transportation	0.017	0.036	0.069	0.069	0.012	0.012	0.013	0.013	0.026	0.050	0.050
Domestic transportation	0.005	0.011	0.010	0.010	0.005	0.005	0.005	0.005	0.011	0.010	0.010
Total	0.553	0.468	0.524	0.589	0.968	1.156	1.052	1.324	0.858	0.657	0.983

* Reference values estimated in this study (tentative calculation) [see (10)]

	From natural gas						From coal			From biomass		
	FT synthetic oil		DME		Methanol		FT synthetic oil	DME	Methanol	FT synthetic oil	DME	Methanol
	best	worst	best	worst	best	worst						
Upstream process of feedstock	0.016	0.023	0.014	0.018	0.019	0.024	0.025	0.028	0.033	0.112	0.062	0.082
Fuel synthesis	0.446	1.025	0.260	0.606	0.678	1.102	0.719	0.695	0.731	1.956	0.649	1.178
Overseas transportation	0.017	0.017	0.036	0.036	0.069	0.069	0.012	0.025	0.047	0.013	0.026	0.050
Domestic transportation	0.005	0.005	0.011	0.011	0.010	0.010	0.005	0.011	0.010	0.005	0.011	0.010
Total	0.484	1.070	0.322	0.671	0.777	1.205	0.761	0.759	0.821	2.085	0.749	1.321

Table 2.4.11 WTT GHG emissions of synthetic fuel production pathways [g eq-CO_2/MJ]

	From natural gas				From coal		From biomass				
	FT synthetic oil	DME	Methanol		FT synthetic oil		FT synthetic oil		DME	Methanol	
			best	worst	best	worst	best	worst		best	worst
Upstream process of feedstock	1.28	1.19	1.21	1.27	10.86	11.87	5.01	5.68	4.48	3.93	4.73
Fuel synthesis	20.00	12.33	15.63	19.42	54.63	54.97	0.00	0.00	0.00	0.00	0.00
Overseas transportation	1.34	2.78	5.28	5.28	0.93	0.93	0.99	0.99	2.03	3.87	3.87
Domestic transportation	0.36	0.84	0.80	0.80	0.36	0.36	0.36	0.36	0.84	0.80	0.80
Total	22.99	17.14	22.93	26.77	66.78	68.14	6.36	7.03	7.35	8.61	9.41
Fixed CO_2							△70.76	△70.76	△66.46	△69.00	△69.00

* Reference values estimated in this study (tentative calculation) [see (10)]

	From natural gas						From coal			From biomass		
	FT synthetic oil		DME		Methanol		FT synthetic oil	DME	Methanol	FT synthetic oil	DME	Methanol
	best	worst	best	worst	best	worst						
Upstream process of feedstock	1.23	1.72	1.07	1.36	1.42	1.78	9.76	9.87	10.38	7.56	4.22	5.57
Fuel synthesis	14.88	49.20	8.21	28.68	30.44	55.54	48.07	50.69	50.61	0.00	0.00	0.00
Overseas transportation	1.34	1.34	2.78	2.78	5.28	5.28	0.93	1.91	3.65	0.99	2.03	3.87
Domestic transportation	0.36	0.36	0.84	0.84	0.80	0.80	0.36	0.84	0.80	0.36	0.84	0.80
Total	17.82	52.63	12.90	33.66	37.94	63.40	59.13	63.31	65.43	8.91	7.08	10.24
Fixed CO_2										△70.76	△66.46	△69.00

Table 2.4.12 Energy efficiency of synthetic fuel production pathways (LHV)

	From natural gas				From coal		From biomass				
	FT synthetic oil	DME	Methanol		FT synthetic oil		FT synthetic oil		DME	Methanol	
			best	worst	best	worst	best	worst		best	worst
Upstream process of feedstock	0.987	0.987	0.987	0.987	0.993	0.993	↓	↓	↓	↓	↓
Fuel synthesis	0.661	0.712	0.700	0.670	0.520	0.474	0.497	0.439	0.556	0.634	0.527
Overseas transportation	0.983	0.965	0.936	0.936	0.988	0.988	0.987	0.987	0.974	0.952	0.952
Domestic transportation	0.995	0.989	0.990	0.990	0.995	0.995	0.995	0.995	0.989	0.990	0.990
Total	0.638	0.671	0.640	0.613	0.508	0.463	0.489	0.431	0.536	0.597	0.496

* Reference values estimated in this study (tentative calculation) [see (10)]

	From natural gas						From coal			From biomass		
	FT synthetic oil		DME		Methanol		FT synthetic oil	DME	Methanol	FT synthetic oil	DME	Methanol
	best	worst	best	worst	best	worst						
Upstream process of feedstock	0.987	0.987	0.987	0.987	0.987	0.987	0.993	0.993	0.992	↓	↓	↓
Fuel synthesis	0.692	0.494	0.793	0.623	0.596	0.476	0.582	0.590	0.578	0.330	0.591	0.448
Overseas transportation	0.983	0.983	0.965	0.965	0.936	0.936	0.988	0.976	0.955	0.987	0.974	0.952
Domestic transportation	0.995	0.995	0.989	0.989	0.990	0.990	0.995	0.989	0.990	0.995	0.989	0.990
Total	0.668	0.477	0.748	0.587	0.545	0.435	0.568	0.565	0.542	0.324	0.570	0.422

2.5 Liquefied Petroleum Gas Production Pathways

2.5.1 Abstract

LPG is a hydrocarbon with carbon number 3 or 4, specifically propane, propylene, butane, butylene, or other petroleum products with these as the main constituents (see 2.1.1 (5)).
LPG production methods include the following three methods.

1） Gas associated with crude oil from oil fields is separated and refined and LPG is collected (associated gas derivative)
2） Gas extracted from gas fields (mainly CH_4) is separated and refined, and LPG is collected (raw natural gas derivative)
3） Collection as a byproduct gas at petroleum refineries/petrochemical plants (from petroleum refining)

Of these, the process of 2) up to the processing/liquefaction process is calculated in “2.2 Natural Gas Based Fuel Production Pathways”, and the process of 3) up to the petroleum refining process is calculated in “2.1 Petroleum Based Fuel Production Pathways”. Here, along with calculations for the LPG production from associated gas pathways of 1), weighted average values for actual LPG supply and demand ratio in Japan (associated gas derivative 61.4%, raw natural gas derivative 15.4%, petroleum refining derivative 23.2% (Source: IEEJ [1999] (p.37))) were also calculated for each pathway.

2.5.2 Procedures for data collection of unit process

LPG production pathway flow examined in this study are shown in Figure 2.5.1:

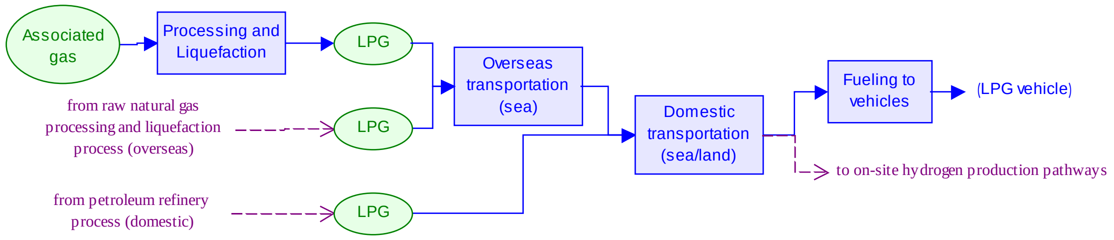

Figure 2.5.1 Pathway flow for LPG production

(1) Processing and Liquefaction of Associated Gas

<i> Existing Study

The CO_2 emissions values given on a calorific basis for the production (extraction) process, accompanying flare combustion and CH_4 vent, in IEEJ [1999] (p.35), are the same values calculated for petroleum products inventory data in the report. In addition, as data could not be obtained for the processing/liquefaction process, a simulation was conducted based on the specifications of an overseas processing/liquefaction plant of the same scale. Furthermore, the report contains no mention of associated CO_2, even in the petroleum products section, and seems to assume that CO_2 will not be generated even in the processing/liquefaction process of LPG from associated gas.

<ii> This Study

For the production (extraction) process, this study uses the calculation results of "2.1 Petroleum Based Fuel Production Pathways". In addition, regarding the processing/liquefaction process, CO_2 emissions are quoted from simulation values in IEEJ [1999] (p.50), and energy consumption was calculated according to the data upon which the same simulation was based.

(2) Overseas Transportation (Sea)

<i> Existing Study

IEEJ [1999] (p.35) considers the tank capacity and stowage factor of a standard LPG shipping vessel, assumes the fuel used to be C-heavy fuel oil and A-heavy fuel oil and, taking the propane and butane ratio of LPG for each region into account, cites weighted averages for CO_2 emissions based on import distribution ratios for 1997.

<ii> This Study

This study cites values given in IEEJ [1999] (p.51) for data related to LPG vessels, and calculates import distribution ratio using actual figures for 2001. Regarding LPG vessel speed, which is not mentioned in IEEJ [1999], the value given in PEC [1998] for 80,000 t and 100,000 t crude oil tankers (15.1 knots) was used.

Furthermore, although IEEJ [1999] considers LPG vessel tank capacity in m^3 units, as LPG is shipped in liquid form over the marine shipping process, unit notation here has been changed to kL to avoid confusion.

(3) Domestic Transportation (Sea/Land)

<i> Existing Study

Although IEEJ [1999] gives figures for CO_2 emissions for domestic LPG transportation under the assumption of overland transportation (tank lorry) and coastal transportation (coastal tanker), the reasoning behind the calculations is not clear.

<ii> This Study

In this study, values for the domestic transportation process of petroleum based fuel production pathways (gasoline) have been substituted.

(4) Fueling to Vehicles

As the main constituent of LPG for vehicles is butane, as with gasoline the energy consumption for supply to vehicles is considered negligible. Consequently, this study treats this value as zero.

2.5.3 Calculation results

Regarding the LPG production pathways, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.5.1 (energy consumption), Table 2.5.2 (GHG emissions) and Table 2.5.3 (energy efficiency).

Table 2.5.1 WTT energy consumption of LPG production pathways [MJ/MJ]

		From associated gas	From raw natural gas	From petroleum refinery	Weighted average
Shares		61.4%	15.4%	23.2%	100%
Extraction	Operation	0.012	0.011	0.011	0.012
	Flare combustion	0.006	0.002	0.006	0.005
Processing / liquefaction	Operation	0.059	0.099	-	0.052
	Flare combustion	-	0.009	-	0.001
Overseas transportation		0.035	0.035	0.011	0.030
Petroleum refining		-	-	0.116	0.027
Domestic transportation		0.007	0.007	0.007	0.007
Fueling to vehicles		0.000	0.000	0.000	0.000
Total		0.120	0.163	0.151	0.134

Table 2.5.2 WTT GHG emissions of LPG production pathways [g eq-CO_2/MJ]

		From associated gas	From raw natural gas	From petroleum refinery	Weighted average
Shares		61.4%	15.4%	23.2%	100%
Extraction	Operation	0.75	0.49	0.70	0.70
	Flare combustion	0.37	0.15	0.35	0.34
	CH_4 vent	0.04	0.22	0.03	0.06
Processing / liquefaction	Operation	3.36	5.34	-	2.88
	Flare combustion	-	0.42	-	0.06
	CH_4 vent	-	0.56	-	0.09
Associated CO_2		0.00	1.90	0.30	0.36
Overseas transportation		2.72	2.72	0.85	2.28
Petroleum refining		-	-	7.16	1.66
Domestic transportation		0.52	0.52	0.52	0.52
Fueling to vehicles		0.00	0.00	0.00	0.00
Total		7.76	12.32	9.93	8.96

Table 2.5.3 WTT energy consumption of LPG production pathways (LHV)

	From associated gas	From raw natural gas	From petroleum refinery	Weighted average
Shares	61.4%	15.4%	23.2%	100%
Extraction	0.982	0.987	0.982	-
Processing / liquefaction	0.944	0.901	-	-
Overseas transportation	0.966	0.966	0.988	-
Petroleum refining	-	-	0.950	-
Domestic transportation	0.993	0.993	0.993	-
Fueling to vehicles	1.000	1.000	1.000	-
Total	0.889	0.853	0.916	0.890

2.6 Electricity (Electric Power Generation Pathways)

2.6.1 Abstract

Power generation can be broadly classified into hydroelectric power generation, thermal power generation, nuclear power generation, and other power generation methods using natural energy such as solar power, wind power, geothermal power and biomass power generation which uses waste wood. From the perspective of automotive fuel production, electricity can be used in electric vehicles and in electrolysis for hydrogen production.

(1) Hydroelectric Generation

This method of generation utilizes the power of falling water (potential energy) to turn generators and produce electricity. As this system can be activated and deactivated at short notice, it can be used to supply power at peak power consumption times during the day and to respond to sharp variations in demand. For a nation like Japan, relying mainly on imports for energy, hydroelectric power generation, which utilizes the abundant water resources, is a valuable purely domestic energy source in which much hope is placed.

(2) Thermal Power Generation

This method burns fossil fuels such as petroleum, LNG and coal in boilers to produce high-temperature/ high-pressure steam, which is then used to turn turbines and generate electricity. This system provides high output power generation and also allows output to be adjusted to demand, performing a central role in present day power generation. There are four types of thermal power generation:

<i> Steam power

Fuel is burned in boilers to produce high-temperature/high-pressure steam, which is used to turn turbines and generate electricity. At present, thermal power generation accounts for an overwhelmingly large proportion of power generation capacity and output.

<ii> Internal combustion power

Internal combustion engines such as diesel engines are used to generate electricity. This is used in small-scale power generation mainly on isolated islands.

<iii> Gas turbine power

Combustion gas from fuels such as kerosene and diesel are used to turn turbines and generate electricity. This method is used in response to demand at peak times.

<iv> Combined cycle thermal power

This is a new power generation method with excellent heat efficiency, which combines gas turbines and steam turbines. This system can easily be activated and deactivated at short notice, and allows instantaneous response to sharp variations in demand.

(3) Nuclear Power Generation

With nuclear power generation, the heat generated by the nuclear fission of uranium within a nuclear reactor is used to produce high-temperature/high-pressure steam, which is used to turn turbines and generate electricity. Although there are a number of nuclear reactor types, reactors most commonly in use in Japan are light water reactors.

Light water reactors are the reactor type most commonly in use throughout the world, using moderators (substance which retards the speed of neutrons generated through fission to facilitate subsequent fission), coolants (fluid used to remove heat generated by fission from reactor core) and light water (normal water).

There are two types of light water reactor, (1) the Boiling Water Reactor (BWR) and (2) the Pressurized Water Reactor (PWR), with both reactor types in equal use in Japan. BWR is a method in which steam generated inside the reactor is sent directly to the turbine. After turning the turbine, the steam is cooled in a condenser, reduced to water, and then returned to the reactor. On the other hand, the PWR method sends hot water generated in the reactor to a steam generator, where this water converts water running in a separate system to steam, which is then used to turn turbines.

(4) Solar Power Generation

This is a power generation method that utilizes solar batteries (photoelectric cells), which produce electricity when exposed to light. While this energy source is “clean” and inexhaustible, it requires vast surface area to generate large amounts of power, is subject to the weather, and cannot be utilized at night. Japan leads the world in the implementation of solar power generation, and although there are still many problems to solve, the use of solar power as a distributed power source is increasing.

(5) Wind Power Generation

This method generates electricity by utilizing wind to turn windmills, which turn generators. Since the Oil Crisis of 1973, wind power generation gained prominence throughout the world, especially in the U.S. and Canada, as the new energy to replace oil. The low energy density of wind, the high-energy fluctuation, and issues concerning durability and reliability due to the severe climate in locations in Japan applicable for wind power generation, remain to be solved.

(6) Geothermal Power Generation

Geothermal power generation is a method that generates electricity by turning turbines using steam generated underground. According to no fuel costs, the high operating rate and a cheap and safe energy source, it has already been industrialized. Problems with this method include difficulties in constructing high capacity power plants, plant sites limited to volcanic zones, and the high cost and time involved in investigating suitable sites.

(7) Biomass Power Generation

Through thermochemical conversion such as direct combustion and gasification, or biochemical conversion such as CH_4 fermentation, biomass energy is converted into steam or gas and used to generate electricity. The former mainly uses dry biomass such as wood and rice straw, while the latter uses wet biomass such as livestock waste, raw garbage and sewage sludge. For the power generation method, steam turbines, gas turbines and gas engines are used.

For direct combustion-steam turbine power generation, biomass is burned directly in a boiler and the resulting steam is used to turn a turbine and generate electricity. This method is currently the most common. Stoker and fluid bed furnaces are commonly used direct combustion furnaces. Problems with biomass power generation using steam turbines include low generating efficiency.

Gasification-gas turbine power generation exhibits higher generating efficiency in comparison to steam turbine power generation, and with the advantage of requiring smaller initial investment, this method is drawing attention as the biomass power generation method of the near future. In addition, since gas turbine power generation exhibits high efficiency even on a small scale, it is an effective system for distributed power generation, such as biomass power generation.

CH_4 fermentation-gas engine power generation generates power through gas engines which use gas obtained from the CH_4 fermentation of animal manure, raw garbage, sewage sludge, and so on (generally CH_4: 60-70%, CO_2: 30-40%). Rather than energy use, the main objectives are related to control of waste processing problems such as bad smells and landfill site acquisition, and the inhibition of CH_4, a greenhouse gas, and in general the scale of individual plants is small. When considering energy use as the main objective, problems such as lengthy fermentation time are apparent.

Furthermore, for considerations of energy efficiency during power generation in this study, the effects of power conversion are treated as virtually non-existent in relation to hydroelectric, solar, wind and geothermal power generation, and efficiency is considered only in terms of the power generated. Consequently, calculations conducted here are for energy consumption, GHG emissions and energy efficiency over the lifecycle, from extraction of feedstock to power generation, in relation to all types of thermal, nuclear and biomass power generation.

Descriptions of the above power generation methods are from The Federation of Electric Power Companies of Japan website (http://www.fepc.or.jp/hatsuden/index.html) and Saka [2001].

2.6.2 Procedures for data collection of unit process

Power generation pathway flow examined in this study are shown in Figure 2.6.1:

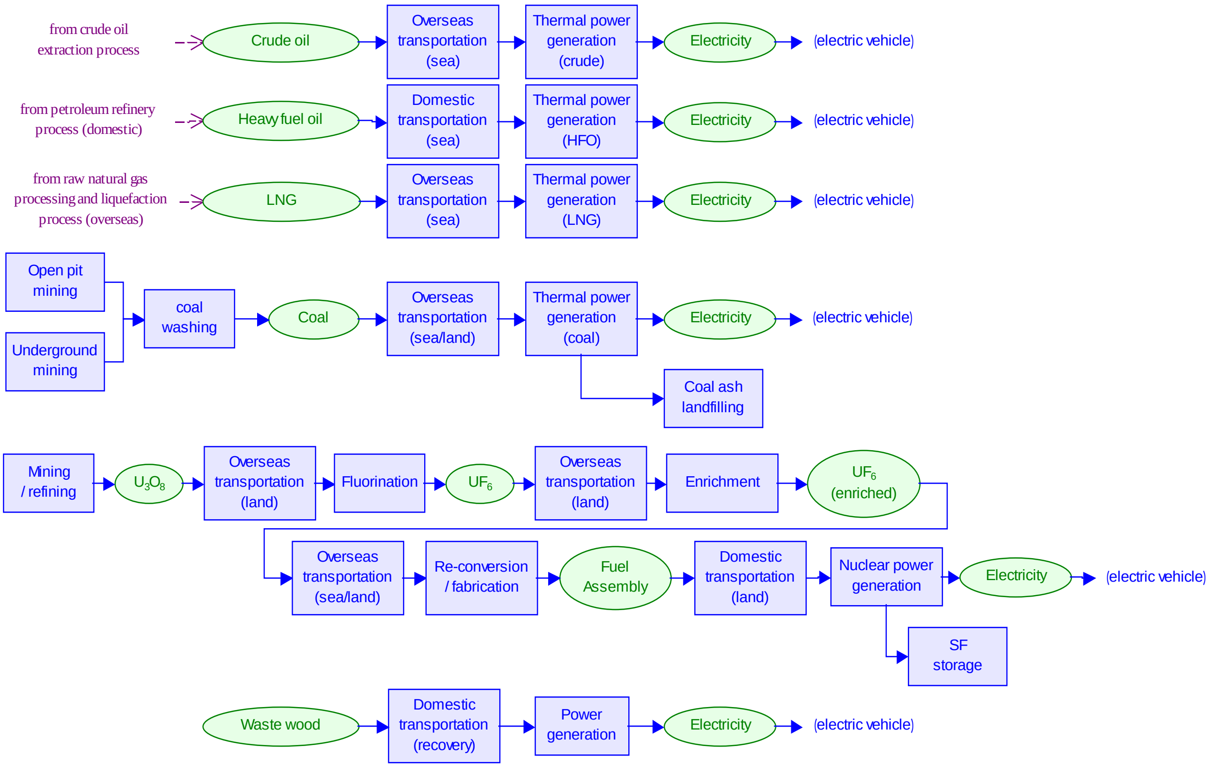

Figure 2.6.1 Pathway flow for power generation

(1) Petroleum Fired Thermal Power Generation

<i> Existing Study

IAE [1990] (p.144) calculates CO_2 emissions for the power generation stages based on the FY1988 annual average values for generating efficiency (38.84%), power distribution efficiency (37.18%) and in-house ratio (4.27%).

CRIEPI [1991] (p. 19-27) calculates the energy input and energy balance of petroleum fired thermal power generation, assuming values for petroleum fired plant capacity (generating end output) at 1,000 MW, capability factor 75 %, generating efficiency (generating end) 39 % and in-house ratio 6.1 %. Although the later studies implemented by CRIEPI (CRIEPI [1992], [1995]) have some adjustments, they are based on data given in CRIEPI [1991]. In addition, CRIEPI [2000] re-estimates GHG emissions over the lifecycle of petroleum fired power generation technology using technology and import conditions of power generation fuels for 1996 as a point of reference. All studies conducted by CRIEPI consider not only the fuel lifecycle, but also construction of power plant and so on.

<ii> This Study

[Overseas transportation (sea)]

Regarding overseas transportation (sea) of crude for power generation, calculation results given in “2.1 Petroleum Based Fuel Production Pathways” are used.

[Domestic transportation]

Regarding the domestic transportation of heavy fuel oils, calculation results given in “2.1 Petroleum Based Fuel Production Pathways” are used.

[Petroleum fired thermal power generation]

Petroleum fired thermal power plant energy consumption and GHG emissions (based on sending end) were calculated based on year 2000 actual values for fuel consumption, generating end heat efficiency, in-house ratio, power generation (sending end, receiving end), distribution loss ratio and distribution loss, given in ANRE [2002-3] for petroleum fired thermal power plants.

Other than the above, with regards to the operating process of petroleum fired power plants, CRIEPI [2000] (p.26) also calculates consumption of limestone and ammonia required for desulfurization and denitration. This study also follows this example. Inventory data for limestone and ammonia production is cited from NEDO [1995] (p.130). This inventory data was researched and created by National Institute for Resources and Environment (current National Institute of Advanced Industrial Science and Technology), a subordinate body of the Agency of Industrial Science and Technology.

(2) LNG Fired and LNG Combined Cycle Thermal Power Generation

<i> Existing Study

IAE [1990] (p.145-146) calculates CO_2 emissions for the power generation stages based on the FY1988 annual average values for generating efficiency (LNG: 39.29 %, LNG combined cycle 42.42 %), power distribution efficiency (LNG: 37.82 %, LNG combined cycle: 41.38 %) and in-house ratio (LNG: 3.75 %, LNG combined cycle: 2.45 %).

CRIEPI [1991] (p.27-31) calculates the energy input and energy balance of LNG fired thermal power generation, assuming values for LNG fired plant capacity (generating end output) at 1,000 MW, capability factor 75 %, generating efficiency (generating end) 39 % and in-house ratio 3.5 %. Although the later studies implemented by CRIEPI (CRIEPI [1992], [1995]) have some adjustments, they are based on data given in CRIEPI [1991]. In addition, CRIEPI [2000] re-estimates GHG emissions over the lifecycle of LNG fired power generation technology using technology and import conditions of power generation fuels for FY1996 as a point of reference. All studies conducted by CRIEPI consider not only the fuel lifecycle, but also construction of power plant and so on.

<ii> This Study

[Overseas transportation (sea)]

Regarding overseas transportation (sea) of LNG for power generation, calculation results given in "2.2 Natural Gas Based Fuel Production Pathways" are used.

[LNG fired and LNG combined cycle thermal power generation]

LNG fired and LNG combined cycle thermal power plant energy consumption and GHG emissions (based on sending end) were calculated based on FY2000 actual values for fuel consumption, generating end heat efficiency, in-house ratio, power generation (sending end, receiving end), distribution loss ratio and distribution loss, given in ANRE [2002-3] for LNG fired and LNG combined cycle thermal power plants.

In addition, as with petroleum fired thermal power generation, regarding the operating process of LNG fired and LNG combined cycle thermal power plants, CRIEPI [2000] (p.26) calculates consumption of limestone and ammonia required for desulfurization and denitration. This study also follows this example.

(3) Coal Fired Thermal Power Generation

<i> Existing Study

IAE [1990] (p.147) calculates CO_2 emissions for the power generation stages based on the FY1988 annual average values for generating efficiency (39.37 %), power distribution efficiency (36.26 %) and in-house ratio (7.96 %).

CRIEPI [1991] (p.11-19) calculates the energy input and energy balance of coal fired thermal power generation, assuming values for coal fired plant capacity (generating end output) at 1,000 MW, capability factor 75 %, generating efficiency (generating end) 39 % and in-house ratio 7.4 %. Although the later studies implemented by CRIEPI (CRIEPI [1992], [1995]) have some adjustments, they are based on data given in CRIEPI [1991]. In addition, CRIEPI [2000] re-estimates GHG emissions over the lifecycle of coal fired power generation technology using technology and import conditions of power generation fuels for 1996 as a point of reference. All studies conducted by CRIEPI consider not only the fuel lifecycle, but also construction of power plant and so on.

<ii> This Study

[Coal mining / washing]

As data obtained through hearing surveys with industry related to the coal mining process, Hondo *et al.* [1999] gives figures for fuel input (diesel, gasoline, electricity) per unit weight during coal mining and coal washing for open-pit and underground coal mining in Australia, and calculates environmental burden for the entire lifecycle of imported coal for power generation consumed in Japan. These values are also used in CRIEPI [2000] (p.19).

In this study also, energy consumption and GHG emissions were calculated for the extraction process and washing process of imported coal based on data given in Hondo *et al.* [1999], the extraction method at the imported coal source and actual import volumes. Furthermore, regarding energy consumption and CO_2 emission factors during power generation in each country, data reflecting the power generation circumstances of each was created and applied.

Regarding CH_4 vent, values per country were taken from IEEJ [1999] (p.13) and the weighted average was calculated using import volumes given in ANRE [2002-1].

[Overseas transportation (land / sea)]

Regarding overland transportation of coal at the producing region, both IEEJ [1999] (p.6) and CRIEPI [2000] (p.17) conduct calculations on the assumption that all transportation of coal for export from the producing region to the shipping port takes place via rail. In addition, although there are various electrification conditions concerning the railways of each country, the use of diesel engines is assumed, and consequently the fuel consumed is diesel. Regarding fuel consumption factor, values given in Ministry of Transport (MOT) Transport Policy Bureau [2000] are used.

This study also adopted the same calculation methods used in prior studies. The overland transportation distances in the producing country were taken from values (one-way) given in IEEJ [1999] (p.12). Energy consumption and GHG emissions for the overland transportation of coal in the producing country were calculated using the weighted average of these values multiplied by fuel consumption factor (0.0126 L/t-km), and import volumes given in ANRE [2002-1].

Regarding the overseas transportation (sea) of coal, energy consumption and GHG emissions for the overseas transportation of coal was calculated using values taken from NEDO [1996] (p.105-106) for average vessel size for transportation (50,000 t deadweight tonnage), speed (15 knots) and fuel consumption (60 kg-C-heavy fuel oil/km), and import volume and distance from port of shipment to Japan. In addition, regarding loading and unloading (energy consumption through handling), values given in IAE [1990] (p.138) were used. Although the values given here are for electricity consumption (0.95 kWh/t) per t coal at Tomakomai Port, Hokkaido, since there is generally little difference in energy consumption through handling for either loading or unloading (IAE [1990]), this study substitutes values for energy consumption per t coal at Tomakomai Port for energy consumption at the port of shipment for each country.

[Coal fired thermal power generation]

Coal fired thermal power plant energy consumption and GHG emissions (based on sending end) were calculated based on year 2000 actual values for fuel consumption, generating end heat efficiency, in-house ratio, power generation (sending end, receiving end), distribution loss ratio and distribution loss, given in ANRE [2002-3] for coal fired thermal power plants.

As with other forms of thermal power generation, regarding the operating process of coal fired thermal power plants, CRIEPI [2000] (p.26) calculates consumption of limestone and ammonia required for desulfurization and denitration. This study also follows this example.

[Coal ash landfilling]

CRIEPI [2000] (p.27) calculates energy consumption required for coal ash landfilling from data obtained through hearing surveys with related industry. This study also follows this example.

(4) Nuclear Power Generation

<i> Existing Study

CRIEPI [1991] (p.31-36) conducts calculations for PWR light water reactors assuming plant capacity at 1,000 MW, capability factor 75 %, and in-house ratio 3.4 %. Furthermore, regarding data from each process, from uranium extraction to enrichment, shaping and transportation, as no publicly disclosed data was available in Japan, U.S. data (Asad T. Amr [1981]) has been used for reference.

CRIEPI [2000] (p. 27-32) conducts calculations for the nuclear fuel production process using Institute for Policy Sciences (IPS) [1977], and calculations for the power generation process (plant operation), energy consumption per unit power generation, based on average values of eight power plants obtained through hearing surveys conducted with electricity companies. However, as some data could not be obtained in relation to uranium enrichment for nuclear power generation, analysis has been conducted under the assumption that all enrichment will be conducted in the U.S. using the gas diffusion method. In addition, power generation systems, which reprocess spent fuel and use the resultant MOX fuel, have not been considered.

Consequently, CRIEPI [2001], released the following year, uses data that more accurately reflects actual status concerning uranium enrichment, and provides analyses of CO_2 emissions over the nuclear power generation lifecycle that reflects actual status in Japan. Furthermore, analysis is also provided concerning the possible effects the nuclear fuel cycle currently being planned in Japan may have on CO_2 emissions over the entire lifecycle.

Furthermore, all the above CRIEPI studies consider not only the fuel lifecycle, but also construction of power plant and so on.

<ii> This Study

In principle, this study used CRIEPI [2001] for reference. However, in order to be consistent with other fuel production pathways, power plant construction and so on, was excluded from evaluation. In addition, only the basic BWR and PWR systems were considered, and recycling systems that use MOX fuel produced from reprocessed spent nuclear fuel are also excluded from evaluation.

[Mining / Refining]

Annual energy consumption and data per kWh were calculated based on data for nuclear fuel requirements and energy consumption for the production of 1 t-U yellow cake. Uranium ore mining is assumed to be at 5,000 t-ore per day through open-pit mining. In relation to refining, considerations are for facilities with an annual yellow cake production capacity of 1,350 t-U and a serviceable life of thirty years. The data is from IPS [1977].

[Conversion (Fluorination)]

Annual energy consumption and data per kWh were calculated based on data for resource requirements and energy consumption for the production of 1 t-U UF_6. Considerations are for facilities with an annual UF_6 production capacity of 5,000 t-U and a serviceable life of thirty years. The data is from IPS [1977].

[Enrichment]

Enrichment methods taken into consideration are the gas diffusion method (overseas) and the centrifugal separation method (domestic and overseas).

Gas diffusion facilities (overseas) with a production capacity of 8,750 t-SWU[4]/year and serviceable life of 30 years, centrifugal separation facilities (domestic) with a production capacity of 600 t-SWU/year and serviceable life of 40 years, and centrifugal separation facilities (overseas) with a production capacity of 1,000 t-SWU/year and serviceable life of 30 years, are considered. According to CRIEPI [2001], basic data for gas diffusion (overseas) and centrifugal separation (overseas) is from IPS [1977], while basic data for centrifugal separation (domestic) is taken from internal papers of the Tokyo Electric Power Company (TEPCO) Energy/Environment Technology Research Institute.

Annual consumption and data per kWh were calculated based on data for resource requirements and energy consumption to produce 1 t-U of enriched UF_6.

[Re-conversion / Fabrication]

Annual consumption and data per kWh were calculated based on data for resource requirements and energy consumption to produce 1 t-U of fuel assembly. Considerations are for facilities with an annual production capacity of 900 t-U and a serviceable life of 30 years. The data is generally cited from IPS [1977].

[Domestic transportation (sea)]

Although CRIEPI [2000] calculates data for each transportation process, this study cites aggregate data given in CRIEPI [2001].

[Power generation]

Nuclear fuel requirements for 1 year were estimated using the following formula (CRIEPI [2000] (p.28)).

[Nuclear Fuel Consumption]
= [Generating Capacity] * 365 * [Capability factor] / ([Combustion degree] * [Heat Efficiency])

Energy consumption and GHG emissions were calculated from fuel consumption for supplementary boilers used for power plant heating and so on. These are average values of eight power plants obtained through hearing surveys conducted with electricity companies.

[Storage of spent fuel assembly]

Data per kWh was calculated based on energy consumption data for the storage of one BWR spent fuel assembly for one year. Here, data given in CRIEPI [2001] for naturally ventilated facilities with dry cask storage capacity of 860 assemblies of 8 * 8 fuel is cited as given, with calculations conducted for a 50-year-storage term. Data for the interim storage of spent fuel was sourced from TEPCO Energy/Environment Technology Research Institute internal papers.

On the other hand, regarding PWR, CRIEPI [2001] cites BWR data, as data for the long-term interim storage of spent PWR fuel was not available. Consequently, this study has also adopted this method.

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[4] Separative Work Unit

(5) Biomass Power Generation (Direct combustion-steam turbine power generation)

<i> Existing Study

Although biomass comes in a variety of forms such as raw garbage and woody biomass, power generation through incineration has long since been implemented for municipal waste containing raw garbage. Hokkaido University Graduate School of Engineering [1998] conducts a life cycle analysis of municipal waste incineration power plants. Regarding woody biomass studied in this study, Ohki *et al*. [2002] provides data concerning woodchip fired boiler power generation currently implemented or planned in Japan.

<ii> This Study

Calculations in this study are based on Ohki *et al*. [2002]. As biomass power plants normally operate using part of the power generated from biomass for in-house power, all plant operating energy is derived from biomass, and therefore CO_2 emissions derived from fossil fuels can be treated as zero. However, as the plant consumes chemicals for exhaust gas treatment, calculations include energy required for the production of these chemicals.

(6) Biomass Power Generation (Gasification-gas turbine power generation)

<i> Existing Study

The power generation system considered here is the IGCC system (combination of gas turbine power generation and boiler power generation from exhaust heat), which generates electricity using syngas obtained through the gasification of biomass. Regarding municipal waste including raw garbage, although many domestic furnace makers have developed gasification melting power generation systems, since the majority of these involve normal boiler power generation without gas turbines, they are not included in the gasification power generation of prior studies mentioned here. Mann, M.K., *et al*. [1997] uses a simulation to provide a life cycle analysis of woody biomass (hybrid poplar) gasification power generation. Details of actual gasification power plants are given in Krister Ståhl, *et al*. [2000]. This report provides general data (e.g. generating efficiency) for a gasification power plant using woody biomass currently in operation in Varnamo, Sweden.

<ii> This Study

Calculations in this study are based on Mann, M.K., *et al.* [1997] (p.21), which contains all the necessary data. Although the majority of energy consumed can be attributed to power for operation, as all this power is generated in-house through biomass, CO_2 emissions derived from fossil fuels can be treated as zero. In addition, as exhaust gas treatment only involves dust in the exhaust gas, the use of chemicals is not considered. Krister Ståhl, *et al*. [2000] gives a figure of 32 % for generating efficiency (net), which is generally in the same range as Mann, M.K. *et al.* [1997].

(7) Biomass Power Generation (CH_4 fermentation-gas engine power generation)

<i> Existing Study

Operational data for actual gas engine power plants using digestion gas obtained through CH_4 fermentation (gas containing CH_4 gas) are given in Ogawa *et al*. [2003]. The plant generates 3,200 kWh/day through the CH_4 fermentation of livestock manure, bean curd lees and sewage sludge from in-house wastewater processing facilities.

Facilities which compost dehydrated cake remaining after CH_4 fermentation are also included.

<ii> This Study

Calculations in this study are based on Ogawa *et al*. [2003], which provides detailed data on actual operations. Power consumed by facilities which compost dehydrated cake remaining after CH_4 fermentation is calculated as beyond the sphere of the system. As previously mentioned, the main raw biomass is livestock manure and bean curd lees, which differs from dry biomass such as wood, in that the water content is extremely high. Consequently, the in-house wastewater treatment load is high, and although the gas engine generating efficiency is comparatively high at 29 %, the overall generating efficiency of the plant (net) is low.

(8) Distribution Loss

Distribution loss occurring during distribution from large-scale intensive power plants, such as all thermal and nuclear power plants, to consumers, is calculated based on values for power generation at sending end and receiving end, given in ANRE [2002-1].

Furthermore, the same value for distribution loss has been applied to petroleum fired, LNG fired and LNG combined cycle, coal fired and nuclear power generation.

2.6.3 Calculation results

Regarding electricity (power generation pathway), calculation results for energy consumption, GHG emissions and energy efficiency during 1MJ power generation are shown in Table 2.6.1 (energy consumption), Table 2.6.2 (GHG emissions) and Table 2.6.3 (energy efficiency).

Table 2.6.1 WTT energy consumption of power generation pathways [MJ/MJ]

	Thermal				Nuclear		Biomass			Japan average (2000FY)
	Petroleum	LNG	LNG combined	Coal	BWR	PWR	Direct combustion	Gasification	CH_4 fermentation	
Total upstream process	0.181	0.386	0.333	0.115	0.119	0.155	0.506	0.089	0.553	0.259
(Crude oil)	(0.031)	(0.002)	(0.000)							(0.002)
(Heavy fuel oil)	(0.146)	(0.006)		(0.002)						(0.014)
(LNG)		(0.374)	(0.333)							(0.099)
(Coal)				(0.112)						(0.016)
(Nuclear fuel)					(0.119)	(0.155)				(0.127)
(others)	(0.004)	(0.004)	(0.001)	(0.001)			(0.506)	(0.089)	(0.553)	(0.001)
Fuel combustion (power generation)	1.770	1.527	1.081	1.662	0.002	0.002	5.150	0.761	0.479	1.614
Ash landfilling, SF storage, etc.					0.004	0.004				0.004
Distribution loss										
Total	1.951	1.913	1.414	1.777	0.125	0.160	5.656	0.850	1.032	1.877

Table 2.6.2 WTT GHG emissions of power generation pathways [g eq-CO_2/MJ]

	Thermal				Nuclear		Biomass			Japan average (2000FY)
	Petroleum	LNG	LNG combined	Coal	BWR	PWR	Direct combustion	Gasification	CH_4 fermentation	
Total upstream process	12.54	30.25	26.21	21.70	5.72	7.41	45.34	7.97	41.17	18.71
(Crude oil)	(2.31)	(0.14)	(0.01)							(0.18)
(Heavy fuel oil)	(9.96)	(0.43)		(0.15)						(0.93)
(LNG)		(29.44)	(26.17)							(7.77)
(Coal)				(21.51)						(3.70)
(Nuclear fuel)					(5.72)	(7.41)				(6.06)
(others)	(0.26)	(0.25)	(0.04)	(0.04)			(45.34)	(7.97)	(41.17)	(0.08)
Fuel combustion (power generation)	205.13	145.26	117.54	250.89	0.12	0.12				104.20
Ash landfilling, SF storage, etc.				0.01	0.16	0.16				0.15
Distribution loss										
Total	217.66	175.51	143.75	272.60	6.00	7.70	45.34	7.97	41.17	123.06

Table 2.6.3 WTT energy efficiency of power generation pathways (LHV)

	Thermal				Nuclear		Biomass			Japan average (2000FY)
	Petroleum	LNG	LNG combined	Coal	BWR	PWR	Direct combustion	Gasification	CH_4 fermentation	
Total upstream process	0.928	0.858	0.858	0.964	↓	↓	0.674	0.921	0.653	0.948
(Crude oil)	(0.972)									(0.972)
(Heavy fuel oil)	(0.891)									(0.891)
(LNG)		(0.858)	(0.858)							(0.858)
(Coal)				(0.964)						(0.964)
(Nuclear fuel)					↓	↓				—
(others)							(0.674)	(0.921)	(0.653)	—
Fuel combustion (power generation)	0.402	0.431	0.513	0.417	0.966	0.957	0.145	0.372	0.292	0.383
Ash landfilling, SF storage, etc.				1.000	↑	↑				1.000
Distribution loss	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959
Total	0.358	0.354	0.422	0.386	0.927	0.918	0.094	0.329	0.183	0.348

2.7 Hydrogen Production Pathways

2.7.1 Abstract

Hydrogen is a nonmetallic element, atomic number 1, represented by the atomic symbol “H”. It is the lightest and most common element in the universe and exists profusely in water, organic compounds and life forms. Hydrogen is colorless, odorless and highly combustible. Lately, from the global environment perspective, hydrogen energy, which produces only water on combustion, is drawing attention.

Various supply and production methods have been proposed concerning the supply of hydrogen as an automotive fuel for FCVs.

(1) Hydrogen Production by Stream Reforming

Steam reforming is a method in which steam is added to a hydrocarbon feedstock to promote a reforming reaction and produce a syngas containing hydrogen.

Promising feedstock for steam reforming include methanol, city gas (natural gas), LNG, LPG, desulfurized gasoline and so on, and a field test of a refueling station for hydrogen from reformed natural gas has been conducted (NEDO [2001-2]).

(2) Byproduct Hydrogen

Byproduct hydrogen refers to hydrogen that is obtained as a byproduct of another process. Byproduct hydrogen can be broadly classified into three categories:

- Hydrogen from salt electrolysis: Hydrogen that is produced during the electrolysis of industrial salt to produce caustic soda. Hydrogen refueling stations providing salt electrolysis hydrogen are already in operation
- Hydrogen from coke oven gas refining: Hydrogen contained in coke oven gas produced during the carbonization of coal to produce coke for the iron and steel industry
- Hydrogen from petroleum industry: Hydrogen produced for the hydrogenation process through the steam reforming, partial oxidization and so on, of naphtha (although not strictly a byproduct, surplus production can occur and is therefore classified as byproduct hydrogen)

Figure 2.7.1. shows the domestic production capability and supply capacity of each byproduct hydrogen category.

Domestic hydrogen production ability :
238,3 [10^8Nm^3/year] (NEDO [2001-1])

from salt electrolysis 13.6 [10^8Nm^3/year]
from coke oven gas refining 88.7 [10^8Nm^3/year]
from petroleum industry 136.0 [10^8Nm^3/year]

→

Domestic hydrogen supply ability :
92.7 [10^8Nm^3/year] (NEDO [2001-1])

from salt electrolysis 12.4 [10^8Nm^3/year]
* value taken sold hydrogen from hydrogen production calculated from caustic soda production

from coke oven gas refining 53.2 [10^8Nm^3/year]
* 60% recover rate is considered as supply ability

from petroleum industry 27.1 [10^8Nm^3/year]
* hydrogen from surplus production of facilities

Figure 2.7.1 Domestic production capability and supply availability of byproduct hydrogen

(3) Hydrogen Production by Water Electrolysis

Water electrolysis is a method of producing hydrogen through the electrolysis of water. The electrolysis efficiency of the solid polymer electrolyte membrane, also used in fuel cells, is drawing attention, and a field test for a solid polymer electrolyte membrane electrolysis-hydrogen refueling station has been conducted (NEDO [2001-1]). In addition, through the development of a reversible cell, namely an electrolysis cell that can function as a fuel cell, an attempt has been made, by the solid polymer electrolyte membrane electrolysis-hydrogen refueling station, to generate the additional value of power load equalization through hydrogen production using surplus power (IAE [2002]).

Other methods include the thermolysis (IS Process) process, currently being researched by the Japan Atomic Energy Research Institute (JAERI) from the perspective of utilizing heat supplied from high temperature gas reactors.

※ Properties of hydrogen

The properties of hydrogen applied in this study are as follows.

Chemical symbol	H	
Atomic weight	1.00794	－
Molecular weight	2.0158	－
Density at normal condition	0.08989	kg/m^3
[Triple point]		
Temperature	13.803	K
	-259.347	℃
Pressure	0.0704	bar
Solid staturation density	86.48	kg/m^3
Liquid staturation density	77.019	kg/m^3
Gas staturation density	0.1256	kg/m^3
Latent heat of fusion	58.2	kJ/kg
Latent heat of evaporation	449	kJ/kg
[Boiling point at atmospheric pressure]		
Temperature	20.268	K
	-252.882	℃
Latent heat of evaporaion	446	kJ/kg
Liquid saturation density	70.779	kg/m^3
Gas saturation density	1.3378	kg/m^3
[Critical point]		
Temperature	32.976	K
	-240.174	℃
Pressure	12.928	bar
Density	31.426	kg/m^3
[Stable isotope (natural content)]		
H (protium)	99.9885	%
D (deuterium)	0.0115	%

[Explosive combustion]		
Explosive limit (air mixture, 20℃, 1atm)	4～75	%
Spontaneous ignition temperature (air mixture, 1atm)	570	℃
Explosive limit (oxygen mixture, 20℃, 1atm)	4～94	%
Spontaneous ignition temperature (oxygen mixture, 20℃, 1atm)	560	℃
Minimum ignition energy	0.02	mJ
Quenching distance (atmospheric, 1atm, normal temperature)	0.06	cm
Theoretic air/fuel weight ratio	34.3	－
Diffusion coefficient (atmospheric, 0℃, 1atm)	0.611	m^2/s
Higher heating value (0℃, 1atm)	12,790	kJ/m^3
Lower heating value (0℃, 1atm)	10,780	kJ/m^3
Standard enthalpy of formation (25℃, 1atm)		
H_2O (gaseous)	-241.82	kJ/mol
H	217.97	kJ/mol
H_2	0	kJ/mol
O_2	0	kJ/mol
Standard Gibbs energy of formation (25℃, 1atm)		
H_2O (gaseous)	-228.59	kJ/mol
H	203.26	kJ/mol
H_2	0	kJ/mol
O_2	0	kJ/mol
Standard entropy of formation (25℃, 1atm)		
H_2O (gaseous)	188.72	J/mol/K
H	114.6	J/mol/K
H_2	130.57	J/mol/K
O_2	205.03	J/mol/K

[Source] http://www.enaa.or.jp/WE-NET/phs/butsu.html

2.7.2 Procedures for data collection of unit process

Hydrogen production pathway flow examined in this study are shown in Figure 2.7.2 (onsite) and Figure 2.7.3 (offsite):

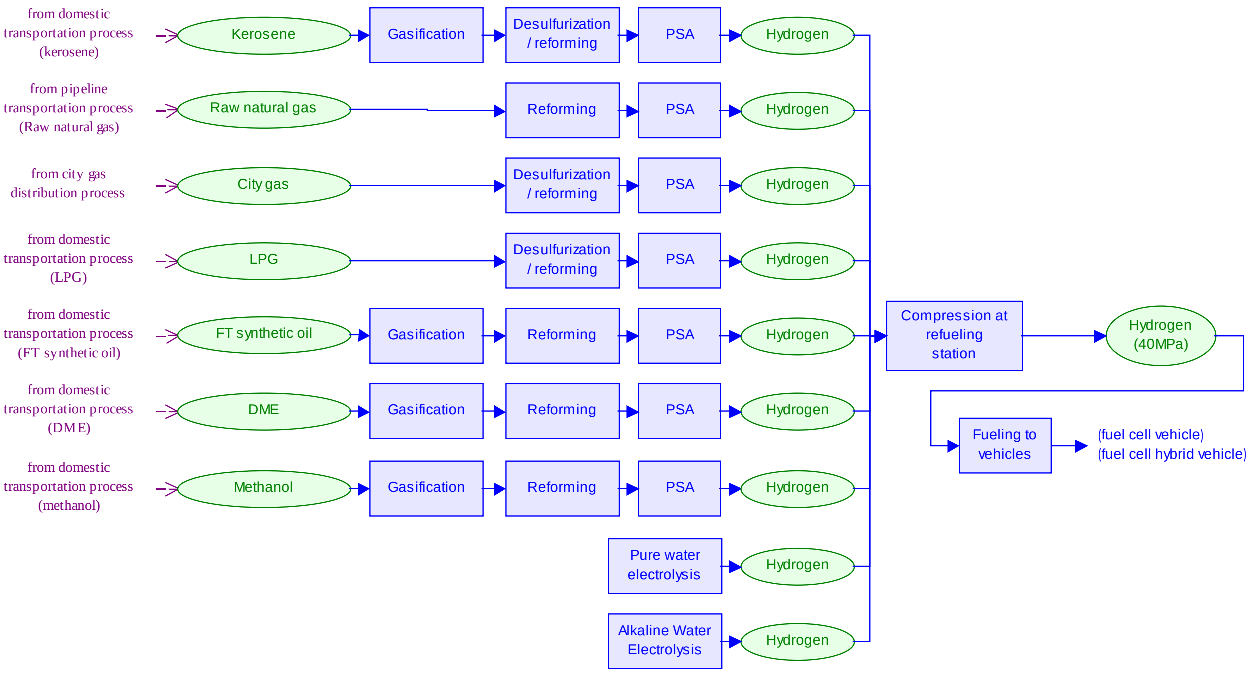


Figure 2.7.2 Pathway flow for on-site hydrogen production

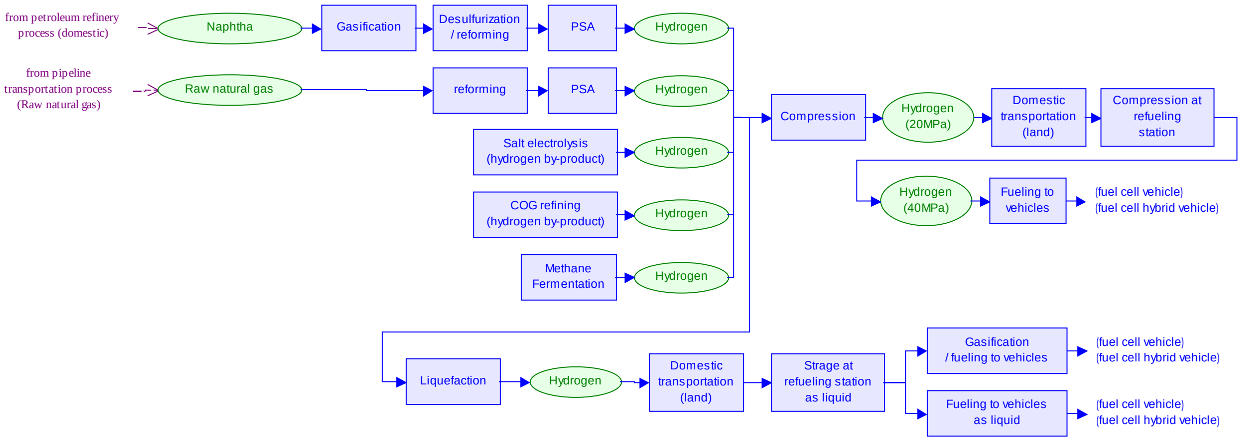


Figure 2.7.3 Pathway flow for off-site hydrogen production

The data calculation for the processes that compose these pathways are organized into (1) hydrogen production, (<i> steam reforming ((A) city gas reforming, (B) naphtha reforming, (C) methanol reforming, (D) gasoline reforming, (E) LPG reforming, (F) DME reforming, (G) reforming of kerosene and FT synthetic oil), <ii> coke oven gas (COG) refining, <iii> salt electrolysis, <iv> water electrolysis ((A) solid polymer electrolysis, (B) pure water electrolysis, (C) alkali water electrolysis, (D) packaged water electrolysis, (E) reversible cell pure water electrolysis), <v> CH_4 fermentation) + compression for storage & fueling/ compression or liquefaction for distribution, (2) transportation (compressed hydrogen transportation, liquefied hydrogen transportation), (3) storage & fueling.

Furthermore, regarding the “heating value of hydrogen supplied to a vehicle” required for energy efficiency calculations, in this study the FCV fuel tank is taken as the point of transfer of hydrogen, and for compressed hydrogen, the pressure energy required to compress hydrogen to 35 MPa or 40 MPa at 25 degrees C is added to the heating value of hydrogen at standard atmospheric pressure, as shown below:

$$E_{press} = R \times T_{\mathrm{H2}} \times \ln\left(P_{\mathrm{H2}}/P_0\right)$$

Where, R : gas constant (8.3151 [$\mathrm{Jmol^{-1}K^{-1}}$])
T_{H2} : temperature of hydrogen (298.15 [K])
P_{H2} : standard atmospheric pressure (101.325 [kPa])
P_0 : pressure of gaseous hydrogen (35,000 [kPa])

In addition, as for liquefied hydrogen, as information related to the specific heat for hydrogen at 20 K (gas) could not be obtained, for energy efficiency calculations, the heating value of hydrogen at standard atmospheric pressure was also applied to liquefied hydrogen.

Table 2.7.1 Heating values of compressed hydrogen used in this study

		HHV	LHV
Atmospheric pressure (25°C)	MJ/kg	142.3	119.9
	$\mathrm{MJ/Nm^3}$	12.79	10.78
20 MPa (25°C)	MJ/kg	148.8	126.4
	$\mathrm{MJ/Nm^3}$	13.37	11.36
35 MPa (25°C)	MJ/kg	149.5	127.1
	$\mathrm{MJ/Nm^3}$	13.44	11.43
40 MPa (25°C)	MJ/kg	149.6	127.3
	$\mathrm{MJ/Nm^3}$	13.45	11.44

For energy consumption and GHG emissions calculations for each process from hydrogen production to supply to vehicle, conversion to energy consumption [MJ] at the point where electricity as energy input is consumed is calculated as 1 kWh = 3.6 MJ and CO_2 emissions are treated as zero, with increases in these values given separately depending on the electricity source (e.g. thermal, nuclear, biomass). This is because these values differ according to the electricity source (e.g. thermal, nuclear, biomass).

(1) Hydrogen Production + Compression for Storage & Fueling / Compression or Liquefaction for Distribution

<i> Steam Reforming

In many cases, hydrogen production through hydrocarbon reforming consists of the following two processes:

Reforming process	・A process to generate hydrogen by means of reforming reactions such as steam reforming and partial oxidation. ・This term will comprehend not only reforming reaction itself but also accompanying reactions such as an aqueous reaction in which byproduct CO generated by reforming reaction is further reformed to hydrogen. (This definition applies to this study.)
Refining process	・A process to purify hydrogen from hydrogen-contained gas obtained from reforming process. ・Methods to be used for refining process include membrane separation, cryogenic separation, pressure swing absorption (PSA), and so on.

The source of CO_2 emissions generated through hydrocarbon reforming is as follows:

- CO_2 derived from fuel (fossil fuel, electricity)
- CO_2 derived from feedstock (hydrocarbons)

CO_2 derived from feedstock refers to the carbon content discharged as CO_2 from the hydrocarbon used as hydrogen feedstock. In this study, calculations for CO_2 emissions from feedstock also use the CO_2 emission factors during combustion given in Table 1.3. This is because theoretically, all carbon content in the hydrocarbon is converted to CO_2 regardless of the applied reforming process, and the resulting CO_2 is considered to be equivalent to CO_2 emissions attributed to the complete combustion of the hydrocarbon. An example is given below.

- Steam reforming:

[reforming reaction] $C_nH_m + nH_2O \rightarrow nCO + (n+m/2)\,H_2$

[aqueous reaction] $nCO + nH_2O \rightarrow nH_2 + nCO_2$

From hydrocarbon C_nH_m 1 mol, n mol CO_2 is generated. Although there are cases where, after the reforming reaction, part of the gas containing hydrogen ($nCO+ (n+m/2)\,H_2$) is not directed to the water reaction and is used as fuel for the reforming reaction, in this case also, all CO is converted to CO_2 and overall CO_2 generation is n mol from C_nH_m 1 mol.

- Partial oxidation:

[partial oxidation] $C_nH_m + nO_2 \rightarrow nCO_2 + m/2\,H_2$

(A) City gas reforming

Prior studies related to hydrogen production through city gas reforming include the “Hydrogen Utilization – International Clean Energy Systems Technology (WE-NET)” conducted by NEDO. Calculations in this study are also based on WE-NET.

Two sets of data are calculated here, current status data based on specifications provided in the feasibility study for a 100 Nm^3/h, 300 Nm^3/h, 500 Nm^3/h class hydrogen station, NEDO [2002-1] (p.17), and updated data in which improvements in reforming efficiency (70%→80%) shown in NEDO [2003-1] (p. 64-65) are reflected in the current status data.

Regarding the allocation of power consumption other than for reforming/refining, values given in NEDO [2003-1] for a 300 Nm^3/h case have been used.

City gas input into the process has two different roles, one as the feedstock for hydrogen and the other as the heat source for the reforming reaction, and the ratio between these two roles is reported to be Feedstock: Fuel = 4.2: 0.2 (Tabata [2002]). However, as variations in this ratio may occur due to the size of reformer, and as the values calculated in this study for energy consumption, GHG emissions and energy efficiency do not vary, the total city gas input is treated as feedstock in this study.

Moreover, the properties of the hydrogen produced are 0.8 MPa, purity above 99.99 %, and for impurities, less than 10 ppm CO and less than 100 ppm CO_2 (NEDO [2002-1], [2002-2]).

(B) Naphtha reforming

Although much reference data is available for hydrogen production through naphtha reforming, as this method was established in the refinery and petrochemical industries long before hydrogen production for FCVs, the availability of reliable data is limited. Of these, this study selected the highly reliable studies of Nakajima *et al*. [1993], PEC [2003], NEDO [1995] and Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) [2004] for reference.

B-1) Nakajima, *et al.* [1993]

There is a hydrogen production process using naphtha steam reforming known as the Topsøe method, developed by Denmark's Haldor Topsøe A/S. The company that the authors of this report belong to, the Chiyoda Corporation, had already established 20 facilities using this method in Japan and 5 facilities abroad by 1991. At the time, there were 136 such facilities worldwide.

B-2) PEC [2003]

This refers to a case where the PSA process was added on to the petrochemical industry's 1 million Nm^3/day class hydrogen production device.

Preconditions for inventory data calculation are taken from feedstock and utilities data for the hydrogen production device given in PEC [2003].

B-3) NEDO [1995]

While the process in Nakajima *et al.* [1993] and PEC [2003] obtains hydrogen through PSA refining after naphtha steam reforming, the process in NEDO [1995] obtains hydrogen through the partial oxidization of naphtha and aqueous reaction. Although the data in NEDO [1995] pertains to the hydrogen production process in oil refineries and petrochemical plants, there is also a statement saying "this data was created through surveys as publications regarding the production of hydrogen could not be obtained", and it is unclear whether the given values are from hearing surveys or from calculations based on assumptions.

B-4) JHFC [2004]

JHFC [2004] (p. 35-36) provides field test results for the Yokohama-Asahi Hydrogen Station. Calculations here are based on data for 50 Nm^3/h capacity reformers during rated operation.

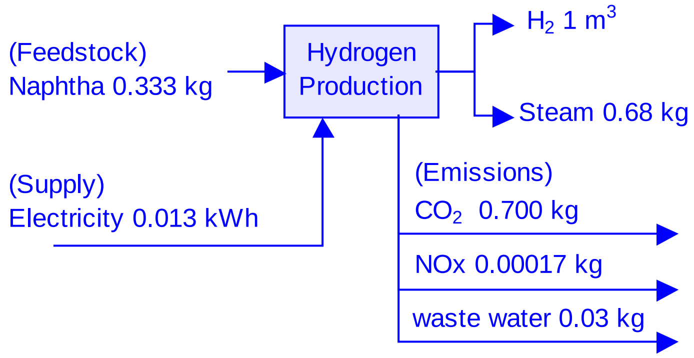


Figure 2.7.4 Hydrogen production process by NEDO [1995]

(C) Methanol reforming

Regarding hydrogen production through methanol reforming, NEDO [2001-3] provides diagrams and process specifications in relation to the high-purity hydrogen production method, with an established commercial performance record, owned by the Mitsubishi Gas Chemical Company, Inc. (MGC). In addition, JHFC [2004] provides field test results for the Kawasaki Hydrogen Station. This study focuses on these two cases.

C-1) NEDO [2001-3]

The MGC has an established commercial performance record for the on-site generation of high-purity hydrogen from methanol, using a combination of steam reforming and PSA.

Methanol steam reforming is conducted in a cracking reactor at an ambient temperature of 240-290 degrees C in the presence of a copper based catalyst. Steam is removed from the resulting hydrogen compound gas using coolers and steam-water separators, and the gas is refined into high-purity hydrogen gas through PSA separation/refining apparatus.

Pre-conditions for inventory data calculation are taken from high-purity hydrogen production process specifications given in NEDO [2001-3] (p. II-32).

C-2) JHFC [2004]

JHFC [2004] (p.37-38) provides field test results for the Kawasaki Hydrogen Station. Calculations here are based on data for 50 Nm^3/h capacity reformers during rated operation.

(D) Gasoline reforming

Regarding hydrogen production through gasoline reforming, JHFC [2004] (p.34-35) provides field test results for desulfurized gasoline at the Yokohama-Daikoku Hydrogen Station. Calculations here are based on data for 30 Nm^3/h capacity reformers during rated operation

(E) LPG reforming

Regarding hydrogen production through LPG reforming, NEDO [2001-3] provides examples of trial calculations made by applying the naphtha reforming model of Nakajima *et al.* [1993] to LPG. In addition, JHFC [2004] provides field test results for the Senju Hydrogen Station, Tokyo. This study focuses on these two cases.

E-1) NEDO [2001-3]

NEDO [2001-3] (p.II-31) conducts trial calculations for energy balance (desk study) when the naphtha reforming model of Nakajima *et al*. [1993] is applied to LPG.

E-2) JHFC [2004]

JHFC [2004] (p.36-37) provides field test results for the Senju Hydrogen Station. Calculations here are based on data for 50 Nm^3/h capacity reformers during rated operation.

(F) DME reforming

The hydrogen production system through DME reforming given in NEDO [2001-3] (p. Ⅱ -33) is fundamentally the same as the methanol fueled system, and assumes a steam reforming reaction taking place in the presence of a catalyst at temperatures between 250-450 degrees C.

NEDO [2001-3] estimates DME reforming efficiency based on these assumptions. Specifically, based on reference materials related to the methanol reforming hydrogen production device of MGC mentioned in C-1) of this study, the material balance for the DME steam reforming reaction is estimated, and reforming efficiency is also assessed through trial calculations per unit utility. Here, DME reactivity (excluding temperature) and PSA hydrogen separation efficiency is considered equivalent to a methanol plant.

(G) Kerosene / FT synthetic oil reforming

Data related to hydrogen production through the reforming of kerosene and FT synthetic oil could not be obtained for this study. Consequently, using data related to hydrogen production through the reforming of naphtha and desulfurized gasoline, given in JHFC [2004] for reference, resources required for the production of 1 kg hydrogen were assumed to be 4.8 kg kerosene or FT synthetic oil, and 7 kWh electricity.

<ii> Hydrogen Production through COG Refining

Other than hydrogen, rest gas (fuel gas that does not contain hydrogen) is produced during the separation and refining process. Hydrogen can also be recovered from byproduct gases such as coke oven gas (COG), blast furnace gas (BFG) and Linz-Donawitz converter gas (LDG), produced in new iron and steel manufacturing processes. Of these, COG has the highest hydrogen ratio.

COG contains more than 50 % hydrogen, and high purity hydrogen can be recovered with ease following the removal of impurities and PSA refining. Regarding hydrogen production through COG refining, this study calculates energy consumption and GHG emissions based on data given in NEDO [2002-1]. Although data related to hydrogen production through COG refining is also given in PEC [2003], the source for this data is NEDO [2002-1], and the two are basically the same. Furthermore, this study does not take energy consumption and GHG emissions during the production of the COG feedstock into consideration.

In the process of hydrogen production through COG refining, other than hydrogen, REST gas (fuel gas that does not contain hydrogen) is produced during the PSA separation and refining of hydrogen contained in the COG. Although NEDO [2002-1] (p.10) provides specifications for five cases of average hydrogen production capacity (556 Nm^3/h, 1,669 Nm^3/h, 5,562 Nm^3/h, 16,685 Nm^3/h, 55,617 Nm^3/h), as the feedstock / utility consumption for 16,685 Nm^3/h and 55,617 Nm^3/h is equal to that of 5,562 Nm^3/h, these have been omitted from this study.

<iii> Hydrogen Derived from Caustic Soda Production through Salt Electrolysis

One method of hydrogen supply involves the utilization of byproduct hydrogen derived from caustic soda production through salt electrolysis. As the main objective of this process is the production of caustic soda, the environmental burden generated here is considered non-attributable to hydrogen. However, in cases where this hydrogen is already utilized as a heat source, as extra energy will be required to supplement this usage, usage of byproduct hydrogen can be misjudged unless some manner of environmental burden is considered for byproduct hydrogen.

Regarding the salt electrolysis process, data given in Plastic Waste Management Institute (PWMI) [1993] is frequently cited. By using the product (NaOH, chlorine, hydrogen) weight composition ratio to distribute burden data given in PWMI [1993], it is possible to apportion environmental burden to byproduct hydrogen from salt electrolysis, however, for this study, processes related to byproduct hydrogen production through salt electrolysis are treated as beyond the sphere of the system.

<iv> Hydrogen Production through Water Electrolysis

Although hydrogen production through water electrolysis is an important industrial hydrogen production method, this method has not gained much attention in Japan, as the production of hydrogen directly from carbonaceous fuel resources is cheaper in comparison. However, with the WE-NET concept of hydrogen production through water electrolysis using cheap overseas hydroelectric power, this technology has been reviewed, and technological development in this field is progressing.

In this study, energy consumption and GHG emissions calculations regarding hydrogen production through water electrolysis are based on specifications for the solid polymer electrolysis hydrogen production device currently marketed by Hitachi Zosen Corporation (HITZ), and data given in NEDO [2003-1] and IAE other [2002].

(A) On-site water electrolysis hydrogen production device (Hitachi Zosen Corporation)

The on-site water electrolysis hydrogen production device of the HITZ is a highly efficient system using a solid polymer water electrolysis cell, which achieves on-site hydrogen production without using any alkalis or other chemical solutions. There are three levels of hydrogen production capability (0.5 Nm^3/h, 1.0 Nm^3/h, 3.0 Nm^3/h) and each is currently marketed. Data calculations are based on the specifications for these water electrolysis hydrogen production devices.

(B) Pure water electrolysis hydrogen production device (NEDO [2003-1])

Energy consumption and GHG emissions for hydrogen production through pure water electrolysis are calculated from data given in NEDO [2003-1]. Although facility scale is from 100-500 Nm^3/h, power and utility consumption per unit is fixed.

(C) Alkali water electrolysis hydrogen production device (NEDO [2003-1])

Energy consumption and GHG emissions for hydrogen production through alkali water electrolysis are calculated from data given in NEDO [2003-1].

(D) Packaged water electrolysis hydrogen production device (NEDO [2003-1])

Energy consumption and GHG emissions for hydrogen production using packaged pure water electrolysis and packaged alkali water electrolysis devices are calculated from data given in NEDO [2003-1].

(E) Hydrogen production using reversible cell device (IAE [2002])

IAE other [2002] introduces a pure water electrolysis device, which uses reversible cells (reversible cell stack capable of water electrolysis and fuel cell operation) as a power load equalization system for installation into buildings. Calculations for energy consumption and GHG emissions for hydrogen production using this reversible cell were conducted using specification data (calculations based on assumptions) for hydrogen/air systems provided in IAE other [2002] for reference.

From the above, 4.3-6.2 kWh was derived for energy consumption during the production of 1 Nm^3 hydrogen. In general, energy consumption for 1 Nm^3 hydrogen through water electrolysis is said to be 4.5-6.2 kWh (Ishiguro [1981]), 4.8-5.3 kWh (Electrochemical Society of Japan (ECSJ) [2000]), and the value indicated in (E) (4.3 kWh) (based on assumption) is an estimated value for ideal conditions. In addition, (A) (5.5-6.0 kWh) is for an actual device, and is considered an appropriate value taking into account the comparatively small size of the device.

<v> Hydrogen Production through CH_4 Fermentation

In this study, hydrogen production through CH_4 fermentation is treated as equivalent to hydrogen production through city gas reforming (see “<i> (A) City gas reforming”).

<vi> Compression for Storage & Fueling/ Compression or Liquefaction for Distribution

For hydrogen transportation or supply to FCVs, it is necessary to increase energy density through compression or liquefaction. Here, process data is calculated in relation to compression or liquefaction for transportation purposes when hydrogen is produced off-site.

(A) Compression for distribution (0.8 MPa → 19.6 MPa)

Calculations are based on data given in NEDO [2002-1] (p.11) for a 556-55,617 Nm^3/h class off-site hydrogen station. Furthermore, this data is for the transportation process of pure hydrogen, obtained from COG refining, for delivery to an off-site hydrogen refueling station as compressed hydrogen.

Regarding the pressure of compressed hydrogen, this study uses the value, 19.6 MPa, given in NEDO [2003-1] (p.56).

(B) Liquefaction for distribution (0.8 MPa → 0.0708 kg/L)

Calculations are based on data given in NEDO [2002-1] (p.12) for a 556-55,617 Nm^3/h class off-site hydrogen station. Furthermore, this data is for the transportation process of pure hydrogen, obtained from COG refining, for delivery to an off-site hydrogen refueling station as liquefied hydrogen.

(2) Transportation (Compressed / Liquefied)

<i> Transportation of Compressed Hydrogen

NEDO [2003-1] (p.56) states, “transportation of compressed hydrogen from an off-site hydrogen production plant to a station will be in hydrogen trailers carrying multiple long copper containers, towed by a tractor”. According to the same document, for a trailer carrying 22 * 715 L containers, the disposable load is 2,460 Nm^3/vehicle. This study also uses this data. The tractor fuel consumption value of 3km/L-diesel, given in NEDO [2000] (p.45), was adopted.

In addition, assuming transportation to prefectures in the Kanto area, shipping distance was set at a round trip value of 100 km.

<ii> Transportation of Liquefied Hydrogen

Calculations for energy consumption and GHG emissions during transportation of liquefied hydrogen are based on the liquefied hydrogen load value, 14,561 Nm^3/vehicle (lorry), given in NEDO [2002-1] (p.15) and the fuel consumption value, 2.2km/L-diesel (lorry), given in JHFC [2004] (p.90).

In addition, assuming transportation to prefectures in the Kanto area, shipping distance was set at a round trip value of 100 km.

(3) Storage & Fueling

<i> High Pressure Fueling of Compressed Hydrogen (19.6 MPa)

NEDO [2002-1] (p.16) provides data related to three examples of off-site hydrogen station, 100 Nm^3/h, 300

Nm^3/h, 500 Nm^3/h (high-pressure storage & high-pressure fueling, average 10 MPa → 40 MPa), regarding the further compression of compressed hydrogen shipped by trailer for high-pressure fueling of FCVs. In addition, JHFC [2004] (p.38) provides field test results for a mobile hydrogen station (19.6 MPa → 35 MPa). For this study, the values given in JHFC [2004], which are close to actual values, were used.

(A) NEDO [2002-1]

The power consumed during high-pressure refueling of compressed hydrogen to a FCV, calculated based on specifications provided in NEDO [2002-1] (p.16) for high-pressure storage & high-pressure fueling stations, is 0.12-0.15 $kWh/Nm^3\text{-}H_2$.

(B) JHFC [2004]

Calculations are based on data given in JHFC [2004] (p.38). Here, the pressure of compressed hydrogen supplied to a FCV is 35 MPa.

<ii> High Pressure Fueling of Liquefied Hydrogen (0.0708 kg/L)

In this process, the liquefied hydrogen is stored as liquefied hydrogen and supplied through high-pressure fueling to a FCV as compressed hydrogen (40 MPa). NEDO [2002-1] (p.16) provides data related to three examples of off-site hydrogen station, 100 Nm^3/h, 300 Nm^3/h, 500 Nm^3/h (liquefied storage & high-pressure fueling, average 0.0708 kg/L→40 MPa), regarding this process. Here, data calculated based on specifications for liquefied storage – high-pressure fueling stations, provided in NEDO [2002-1] (p.16), is used.

<iii> Fueling as Liquefied Hydrogen (0.0708 kg/L)

In this process, the liquefied hydrogen is stored as liquefied hydrogen and supplied to a FCV without change during fueling. NEDO [2002-1] (p.17) provides data related to three examples of off-site hydrogen station, 100 Nm^3/h, 300 Nm^3/h, 500 Nm^3/h (liquefied storage & liquefied fueling, average 0.0708 kg/L→40 MPa), regarding this process. Here, data calculated based on specifications for liquefied storage & liquefied fueling stations, provided in NEDO [2002-1] (p.17), is used.

2.7.3 Calculation results

The calculation results for hydrogen production pathways are indicated separately for on-site (hydrocarbon reforming, on-site water electrolysis) and off-site (compressed hydrogen transportation → compressed hydrogen fueling, liquefied hydrogen transportation → compressed hydrogen fueling, liquefied hydrogen transportation → liquefied hydrogen fueling).

Regarding the no-site hydrocarbon reforming, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.7.2 (energy consumption), Table 2.7.3 (GHG emissions) and Table 2.7.4 (energy efficiency).

Table 2.7.2（A） WTT energy consumption of hydrogen production pathways [MJ/MJ]
(on-site hydrocarbon reforming (city gas, petroleum products))

	City gas reforming				Desulfurized gasoline reforming	Kerosene reforming	LPG reforming					
	From LNG		From pipeline				From raw natural gas		From associated gas		From petroleum refinery	
	(Conventional)	(Improved)	(Conventional)	(Improved)			(NEDO)	(JHFC)	(NEDO)	(JHFC)	(NEDO)	(JHFC)
Feedstock production	0.23	0.20	0.11	0.09	0.33	0.11	0.24	0.27	0.18	0.20	0.23	0.25
H2 production (reforming)	0.08	0.08	0.08	0.08	0.11	0.09	0.33	0.05	0.33	0.05	0.33	0.05
Compression / fueling	0.09	0.09	0.09	0.09	0.10	0.12	0.09	0.15	0.09	0.15	0.09	0.15
Total (*1)	0.40	0.37	0.28	0.27	0.54	0.32	0.66	0.46	0.60	0.39	0.64	0.44
Additional energy consumption to generate 1kWh=3.6MJ electric power by means of power generation [MJ/MJ-H_2]												
(Petroleum)	+0.33	+0.33	+0.33	+0.33	+0.41	+0.41	+0.24	+0.38	+0.24	+0.38	+0.24	+0.38
(LNG)	+0.32	+0.32	+0.32	+0.32	+0.40	+0.40	+0.24	+0.38	+0.24	+0.38	+0.24	+0.38
(LNG combined)	+0.24	+0.24	+0.24	+0.24	+0.29	+0.30	+0.18	+0.28	+0.18	+0.28	+0.18	+0.28
(Coal)	+0.30	+0.30	+0.30	+0.30	+0.37	+0.37	+0.22	+0.35	+0.22	+0.35	+0.22	+0.35
(Japan average) (*2)	+0.32	+0.32	+0.32	+0.32	+0.39	+0.39	+0.24	+0.37	+0.24	+0.37	+0.24	+0.37
(*1) + (*2)	0.72	0.69	0.60	0.59	0.93	0.72	0.90	0.83	0.83	0.76	0.88	0.81

Table 2.7.2（B） WTT energy consumption of hydrogen production pathways [MJ/MJ]
(on-site hydrocarbon reforming (synthetic fuels))

	FT synthetic oil reforming					DME reforming		Methanol reforming			
	From natural gas	From coal		From biomass		From natural gas	From biomass	From natural gas		From biomass	
		(best)	(worst)	(best)	(worst)			(best)	(worst)	(best)	(worst)
Feedstock production	0.97	1.70	2.04	1.85	2.33	0.58	1.07	0.56	0.79	0.70	1.32
Hydrogen production (reforming)	0.09	0.09	0.09	0.09	0.09	0.21	0.21	0.17	0.24	0.17	0.24
Compression / fueling	0.12	0.12	0.12	0.12	0.12	0.09	0.09	0.09	0.08	0.09	0.08
Total (*1)	1.18	1.91	2.25	2.06	2.54	0.89	1.37	0.83	1.11	0.97	1.64
Additional energy consumption to generate 1kWh = 3.6MJ electric power by means of power generation [MJ/MJ-H_2]											
(Petroleum)	+0.41	+0.41	+0.41	+0.41	+0.41	+0.23	+0.23	+0.21	+0.63	+0.21	+0.63
(LNG)	+0.40	+0.40	+0.40	+0.40	+0.40	+0.23	+0.23	+0.20	+0.62	+0.20	+0.62
(LNG combined)	+0.30	+0.30	+0.30	+0.30	+0.30	+0.17	+0.17	+0.15	+0.46	+0.15	+0.46
(Coal)	+0.37	+0.37	+0.37	+0.37	+0.37	+0.21	+0.21	+0.19	+0.58	+0.19	+0.58
(Japan average) (*2)	+0.39	+0.39	+0.39	+0.39	+0.39	+0.23	+0.23	+0.20	+0.61	+0.20	+0.61
(*1) + (*2)	1.58	2.31	2.64	2.46	2.94	1.11	1.60	1.03	1.72	1.17	2.25

Table 2.7.3（A） WTT GHG emissions of hydrogen production pathways [g eq-CO_2/MJ] (on-site hydrocarbon reforming (city gas, petroleum products))

	City gas reforming				Desulfurized gasoline reforming	Kerosene reforming	LPG reforming					
	From LNG		From pipeline				From raw natural gas		From associated gas		From petroleum refinery	
	(Conventional)	(Improved)	(Conventional)	(Improved)			(NEDO)	(JHFC)	(NEDO)	(JHFC)	(NEDO)	(JHFC)
Feedstock production	17.1	14.9	6.6	5.7	21.4	8.1	18.4	20.2	11.6	12.7	14.9	16.3
H2 production / Compression												
CO2 from feedstock	83.3	72.3	83.3	72.3	129.6	125.9	95.4	104.5	95.4	104.5	95.4	104.5
Total (*1)	100.4	87.2	89.8	78.0	151.0	134.0	113.8	124.7	107.0	117.2	110.2	120.8
Additional GHG emission to generate 1kWh=3.6MJ electric power by means of power generation [g eq-CO_2/MJ-H_2]												
(Petroleum)	+37.0	+37.0	+37.0	+37.0	+45.4	+45.7	+27.2	+42.8	+27.2	+42.8	+27.2	+42.8
(LNG)	+29.8	+29.8	+29.8	+29.8	+36.6	+36.8	+22.0	+34.5	+22.0	+34.5	+22.0	+34.5
(LNG combined)	+24.4	+24.4	+24.4	+24.4	+30.0	+30.2	+18.0	+28.3	+18.0	+28.3	+18.0	+28.3
(Coal)	+46.3	+46.3	+46.3	+46.3	+56.9	+57.2	+34.1	+53.6	+34.1	+53.6	+34.1	+53.6
(Japan average) (*2)	+21.0	+21.0	+21.0	+21.0	+25.7	+25.9	+15.4	+24.2	+15.4	+24.2	+15.4	+24.2
(*1) + (*2)	121.3	108.1	110.8	99.0	176.7	159.9	129.2	148.9	122.4	141.4	125.6	145.0

Table 2.7.3（B） WTT GHG emissions of hydrogen production pathways [g eq-CO_2/MJ] (on-site hydrocarbon reforming (synthetic fuels))

	FT synthetic oil reforming					DME reforming		Methanol reforming			
	From natural gas	From coal		From biomass		From natural gas	From biomass	From natural gas		From biomass	
		(best)	(worst)	(best)	(worst)			(best)	(worst)	(best)	(worst)
Feedstock production	40.5	117.6	120.0	14.2	15.8	21.4	11.1	24.6	35.9	10.7	14.8
Hydrogen production / Compression								12.1		12.1	
CO2 from feedstock	125.9	125.9	125.9	1.3	1.3	96.9	14.1	74.0	92.4		
Total (*1)	166.4	243.5	245.9	15.5	17.1	118.3	25.1	110.7	128.3	22.8	14.8
Additional GHG emission to generate 1kWh = 3.6MJ electric power by means of power generation [g eq-CO_2/MJ-H_2]											
(Petroleum)	+45.7	+45.7	+45.7	+45.7	+45.7	+26.1	+26.1	+23.2	+70.6	+23.2	+70.6
(LNG)	+36.8	+36.8	+36.8	+36.8	+36.8	+21.1	+21.1	+18.7	+57.0	+18.7	+57.0
(LNG combined)	+30.2	+30.2	+30.2	+30.2	+30.2	+17.3	+17.3	+15.3	+46.7	+15.3	+46.7
(Coal)	+57.2	+57.2	+57.2	+57.2	+57.2	+32.7	+32.7	+29.1	+88.5	+29.1	+88.5
(Japan average) (*2)	+25.9	+25.9	+25.9	+25.9	+25.9	+14.8	+14.8	+13.2	+40.0	+13.2	+40.0
(*1) + (*2)	192.3	269.4	271.8	41.4	43.0	133.1	39.9	123.8	168.3	35.9	54.8

Table 2.7.4（A） WTT energy efficiency of hydrogen production pathways (LHV) (on-site hydrocarbon reforming (city gas, petroleum products))

	City gas reforming				Desulfurized gasoline reforming	Kerosene reforming	LPG reforming					
	From LNG		From pipeline				From raw natural gas		From associated gas		From petroleum refinery	
	(Conventional)	(Improved)	(Conventional)	(Improved)			(NEDO)	(JHFC)	(NEDO)	(JHFC)	(NEDO)	(JHFC)
Feedstock production	0.863	0.863	0.934	0.934	0.830	0.924	0.853	0.853	0.889	0.889	0.916	0.916
H2 production (reforming)	0.650	0.743	0.650	0.743	0.536	0.555	0.654	0.591	0.654	0.591	0.654	0.591
Compression / fueling	0.971	0.971	0.971	0.971	0.968	0.949	0.971	0.925	0.971	0.925	0.971	0.925
Total (*1)	0.545	0.622	0.590	0.674	0.431	0.486	0.541	0.467	0.565	0.486	0.582	0.501
Energy efficiency to generate 1kWh=3.6MJ electric power by means of power generation (LHV)												
(Petroleum)	0.358											
(LNG)	0.354											
(LNG combined)	0.422											
(Coal)	0.386											
(Japan average) (*2)	0.348											

Table 2.7.4（B） WTT energy efficiency of hydrogen production pathways (LHV) (on-site hydrocarbon reforming (synthetic fuels))

	FT synthetic oil reforming					DME reforming		Methanol reforming			
	From natural gas	From coal		From biomass		From natural gas	From biomass	From natural gas		From biomass	
		(best)	(worst)	(best)	(worst)			(best)	(worst)	(best)	(worst)
Feedstock production	0.638	0.508	0.463	0.489	0.431	0.671	0.536	0.640	0.613	0.597	0.496
Hydrogen production (reforming)	0.555	0.555	0.555	0.555	0.555	0.687	0.687	0.804	0.632	0.804	0.632
Compression / fueling	0.949	0.949	0.949	0.949	0.949	0.971	0.971	0.971	0.979	0.971	0.979
Total (*1)	0.336	0.267	0.244	0.257	0.227	0.447	0.357	0.500	0.379	0.466	0.307
Energy efficiency to generate 1kWh = 3.6MJ electric power by means of power generation (LHV)											
(Petroleum)	0.358										
(LNG)	0.354										
(LNG combined)	0.422										
(Coal)	0.386										
(Japan average) (*2)	0.348										

Regarding the on-site water electrolysis, the results of calculations for energy consumption, GHG emissions and energy efficiency during production of 1 MJ petroleum products are shown in Table 2.7.5 (energy consumption), Table 2.7.6 (GHG emissions) and Table 2.7.7 (energy efficiency).

Table 2.7.5 WTT energy consumption of hydrogen production pathways [MJ/MJ] (on-site water electrolysis)

	PEFC (Hitachi Zosen)			Pure water electrolysis	Alkali water electrolysis			Package type		Pure water electrolysis using reversible cell		
	HS2505	HS2510	HS2530		KOH100	KOH300	KOH500	PA-P	PA-K	40kW	500kW	1000kW
Hydrogen production (electrolysis)	2.00	1.84	1.84	1.50	1.78	1.64	1.65	2.07	1.60	1.44	1.44	1.44
Compression / fueling	↑	↑	↑	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Total (*1)	2.00	1.84	1.84	1.60	1.87	1.73	1.74	2.16	1.70	1.54	1.53	1.53
Additional energy consumption to generate 1kWh = 3.6MJ electric power by means of power generation [MJ/MJ-H_2]												
(Petroleum)	+3.90	+3.57	+3.57	+3.11	+3.65	+3.37	+3.39	+4.21	+3.30	+2.99	+2.98	+2.98
(LNG)	+3.82	+3.50	+3.50	+3.05	+3.57	+3.30	+3.33	+4.13	+3.24	+2.93	+2.92	+2.92
(LNG combined)	+2.83	+2.59	+2.59	+2.25	+2.64	+2.44	+2.46	+3.05	+2.39	+2.16	+2.16	+2.16
(Coal)	+3.55	+3.25	+3.25	+2.83	+3.32	+3.07	+3.09	+3.83	+3.01	+2.72	+2.71	+2.71
(Japan average) (*2)	+3.76	+3.45	+3.45	+3.00	+3.52	+3.25	+3.27	+4.06	+3.18	+2.88	+2.88	+2.88
(*1) + (*2)	5.77	5.28	5.28	4.59	5.39	4.98	5.02	6.23	4.88	4.42	4.41	4.41

Table 2.7.6 WTT GHG emissions of hydrogen production pathways [g eq-CO_2/MJ] (on-site water electrolysis)

	PEFC (Hitachi Zosen)			Pure water electrolysis	Alkali water electrolysis			Package type		Pure water electrolysis using reversible cell		
	HS2505	HS2510	HS2530		KOH100	KOH300	KOH500	PA-P	PA-K	40kW	500kW	1000kW
Hydrogen production (electrolysis)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Compression / fueling	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total (*1)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Additional GHG emission to generate 1kWh = 3.6MJ electric power by means of power generation [g eq-CO_2/MJ-H_2]												
(Petroleum)	+435.4	+399.1	+399.1	+346.9	+407.1	+375.9	+378.8	+470.2	+368.6	+333.6	+332.8	+332.9
(LNG)	+351.1	+321.8	+321.8	+279.7	+328.3	+303.1	+305.4	+379.2	+297.2	+269.0	+268.4	+268.4
(LNG combined)	+287.5	+263.6	+263.6	+229.1	+268.9	+248.3	+250.2	+310.6	+243.5	+220.3	+219.8	+219.9
(Coal)	+545.3	+499.8	+499.8	+434.4	+509.8	+470.8	+474.4	+588.9	+461.7	+417.8	+416.8	+416.9
(Japan average) (*2)	+246.6	+226.0	+226.0	+196.4	+230.5	+212.9	+214.5	+266.3	+208.8	+188.9	+188.5	+188.5
(*1) + (*2)	246.6	226.0	226.0	196.4	230.5	212.9	214.5	266.3	208.8	188.9	188.5	188.5

Table 2.7.7 WTT energy efficiency of hydrogen production pathways (LHV) (on-site water electrolysis)

	PEFC (Hitachi Zosen)			Pure water electrolysis	Alkali water electrolysis			Package type		Pure water electrolysis using reversible cell		
	HS2505	HS2510	HS2530		KOH100	KOH300	KOH500	PA-P	PA-K	40kW	500kW	1000kW
Hydrogen production (electrolysis)	0.499	0.544	0.544	0.665	0.562	0.611	0.606	0.483	0.624	0.694	0.695	0.695
Compression / fueling	↑	↑	↑	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971
Total (*1)	0.499	0.544	0.544	0.646	0.545	0.593	0.588	0.469	0.606	0.673	0.675	0.675
Energy efficiency to generate 1kWh = 3.6MJ electric power by means of power generation (LHV)												
(Petroleum)	0.358											
(LNG)	0.354											
(LNG combined)	0.422											
(Coal)	0.386											
(Japan average) (*2)	0.348											

In relation to off-site handling, depending on transportation method and fueling method, three cases were considered (compressed hydrogen transportation → compressed hydrogen fueling, liquefied hydrogen transportation → compressed hydrogen fueling, liquefied hydrogen transportation → liquefied hydrogen fueling).

Calculation results for each process ((A) compressed hydrogen transportation → compressed hydrogen fueling, (B) liquefied hydrogen transportation → compressed hydrogen fueling, (C) liquefied hydrogen transportation → liquefied hydrogen fueling) for energy consumption, GHG emissions and energy efficiency during the production of 1MJ hydrogen, are shown in Table 2.7.8 (Energy Consumption), Table 2.7.9 (GHG Emissions) and Table 2.7.10 (Energy Efficiency).

Table 2.7.8（A） WTT energy consumption of hydrogen production pathways [MJ/MJ]
(compressed hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.12	0.14	0.11	0.15					0.10	0.08	0.85	0.74
Hydrogen production / refining	0.30	0.80	0.004	0.07	0.15	0.15	0.11		0.08	0.08	0.08	0.08
Compression for distribution	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Domestic transport	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Compression / fueling	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Total (*1)	0.62	1.14	0.32	0.41	0.35	0.34	0.31	0.20	0.37	0.36	1.13	1.02
Additional energy consumption to generate 1kWh=3.6MJ electric power by means of power generation [MJ/MJ-H_2]												
(Petroleum)	+0.31	+0.33	+0.31	+0.43	+0.59	+0.58	+0.51	+0.30	+0.45	+0.45	+0.45	+0.45
(LNG)	+0.30	+0.32	+0.30	+0.42	+0.58	+0.57	+0.50	+0.29	+0.44	+0.44	+0.44	+0.44
(LNG combined)	+0.22	+0.24	+0.22	+0.31	+0.43	+0.42	+0.37	+0.22	+0.32	+0.32	+0.32	+0.32
(Coal)	+0.28	+0.30	+0.28	+0.39	+0.54	+0.53	+0.47	+0.27	+0.41	+0.41	+0.41	+0.41
(Japan average) (*2)	+0.30	+0.32	+0.30	+0.42	+0.57	+0.56	+0.50	+0.29	+0.43	+0.43	+0.43	+0.43
(*1) + (*2)	0.92	1.45	0.61	0.83	0.92	0.90	0.80	0.49	0.80	0.79	1.56	1.45

Table 2.7.8（B） WTT energy consumption of hydrogen production pathways [MJ/MJ]
(liquefied hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.12	0.14	0.11	0.15					0.10	0.08	0.85	0.74
Hydrogen production / refining	0.30	0.80	0.004	0.07	0.15	0.15	0.11		0.08	0.08	0.08	0.08
Liquefaction for distribution	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Domestic transport	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Gasification / compression / fueling	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Total (*1)	0.86	1.38	0.55	0.65	0.59	0.58	0.55	0.44	0.61	0.60	1.37	1.25
Additional energy consumption to generate 1kWh=3.6MJ electric power by means of power generation [MJ/MJ-H_2]												
(Petroleum)	+0.84	+0.86	+0.84	+0.96	+1.12	+1.11	+1.04	+0.83	+0.98	+0.98	+0.98	+0.98
(LNG)	+0.82	+0.84	+0.82	+0.94	+1.10	+1.09	+1.02	+0.81	+0.96	+0.96	+0.96	+0.96
(LNG combined)	+0.61	+0.62	+0.61	+0.70	+0.81	+0.81	+0.76	+0.60	+0.71	+0.71	+0.71	+0.71
(Coal)	+0.76	+0.78	+0.76	+0.88	+1.02	+1.01	+0.95	+0.75	+0.89	+0.89	+0.89	+0.89
(Japan average) (*2)	+0.81	+0.83	+0.81	+0.93	+1.08	+1.07	+1.01	+0.80	+0.94	+0.94	+0.94	+0.94
(*1) + (*2)	1.67	2.20	1.36	1.58	1.67	1.65	1.55	1.24	1.55	1.54	2.31	2.20

Table 2.7.8（C） WTT energy consumption of hydrogen production pathways [MJ/MJ] (liquefied hydrogen transportation→liquefied hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.12	0.14	0.11	0.15					0.10	0.08	0.85	0.74
Hydrogen production / refining	0.30	0.80	0.004	0.07	0.15	0.15	0.11		0.08	0.08	0.08	0.08
Liquefaction for distribution	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
Domestic transport	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fueling as liquid	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total (*1)	0.81	1.32	0.50	0.60	0.53	0.53	0.49	0.38	0.55	0.54	1.31	1.20
Additional energy consumption to generate 1kWh=3.6MJ electric power by means of power generation [MJ/MJ-H_2]												
(Petroleum)	+0.73	+0.75	+0.73	+0.86	+1.02	+1.00	+0.94	+0.72	+0.87	+0.87	+0.87	+0.87
(LNG)	+0.72	+0.74	+0.72	+0.84	+1.00	+0.99	+0.92	+0.71	+0.85	+0.85	+0.85	+0.85
(LNG combined)	+0.53	+0.54	+0.53	+0.62	+0.74	+0.73	+0.68	+0.52	+0.63	+0.63	+0.63	+0.63
(Coal)	+0.67	+0.68	+0.67	+0.78	+0.93	+0.92	+0.85	+0.66	+0.79	+0.79	+0.79	+0.79
(Japan average) (*2)	+0.71	+0.72	+0.70	+0.83	+0.98	+0.97	+0.90	+0.70	+0.84	+0.84	+0.84	+0.84
(*1) + (*2)	1.51	2.05	1.20	1.42	1.52	1.50	1.40	1.08	1.40	1.38	2.15	2.04

Table 2.7.9（A） WTT GHG emissions of hydrogen production pathways [g eq-CO_2/MJ] (compressed hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	8.4	9.9	7.7	9.9					5.7	5.0	24.6	21.4
Hydrogen production / refining	20.7	54.8										
Compression for distribution												
Domestic transport	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Compression / fueling												
CO2 from feedstock	83.0	66.6	94.4	121.6					83.3	72.3		
Total (*1)	115.5	134.6	105.4	134.8	3.3	3.3	3.3	3.3	92.4	80.6	27.9	24.7
Additional GHG emission to generate 1kWh=3.6MJ electric power by means of power generation [g eq-CO_2/MJ-H_2]												
(Petroleum)	+34.4	+36.5	+34.3	+48.4	+66.4	+64.9	+57.3	+33.4	+50.1	+50.1	+50.1	+50.1
(LNG)	+27.7	+29.4	+27.7	+39.0	+53.5	+52.4	+46.2	+26.9	+40.4	+40.4	+40.4	+40.4
(LNG combined)	+22.7	+24.1	+22.7	+32.0	+43.9	+42.9	+37.9	+22.0	+33.1	+33.1	+33.1	+33.1
(Coal)	+43.1	+45.7	+43.0	+60.6	+83.2	+81.3	+71.8	+41.8	+62.7	+62.7	+62.7	+62.7
(Japan average) (*2)	+19.5	+20.7	+19.4	+27.4	+37.6	+36.8	+32.5	+18.9	+28.4	+28.4	+28.4	+28.4
(*1) + (*2)	135.0	155.3	124.9	162.2	40.9	40.1	35.8	22.2	120.7	109.0	56.3	53.0

Table 2.7.9（B） WTT GHG emissions of hydrogen production pathways [g eq-CO$_2$/MJ] (liquefied hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case 1	case 2	case 3		(conventional)	(future)	(conventional)	(future)
Feedstock production	8.4	9.9	7.7	9.9					5.7	5.0	24.6	21.4
Hydrogen production / refining	20.7	54.8										
Liquefaction for distribution												
Domestic transport	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Gasification / compression / fueling												
CO2 from feedstock	83.0	66.6	94.4	121.6					83.3	72.3		
Total (*1)	112.9	132.0	102.9	132.2	0.8	0.8	0.8	0.8	89.8	78.1	25.4	22.1
Additional GHG emission to generate 1kWh=3.6MJ electric power by means of power generation [g eq-CO$_2$/MJ-H$_2$]												
(Petroleum)	+93.5	+95.6	+93.4	+107.5	+125.5	+124.1	+116.4	+92.5	+109.2	+109.2	+109.2	+109.2
(LNG)	+75.4	+77.1	+75.3	+86.7	+101.2	+100.0	+93.9	+74.6	+88.0	+88.0	+88.0	+88.0
(LNG combined)	+61.7	+63.1	+61.7	+71.0	+82.9	+81.9	+76.9	+61.1	+72.1	+72.1	+72.1	+72.1
(Coal)	+117.1	+119.7	+117.0	+134.6	+157.2	+155.4	+145.8	+115.8	+136.7	+136.7	+136.7	+136.7
(Japan average) (*2)	+53.0	+54.1	+52.9	+60.9	+71.1	+70.3	+65.9	+52.4	+61.8	+61.8	+61.8	+61.8
(*1) + (*2)	165.9	186.2	155.8	193.1	71.8	71.0	66.7	53.1	151.6	139.9	87.2	84.0

Table 2.7.9（C） WTT GHG emissions of hydrogen production pathways [g eq-CO$_2$/MJ] (liquefied hydrogen transportation→liquefied hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case 1	case 2	case 3		(conventional)	(future)	(conventional)	(future)
Feedstock production	8.4	9.9	7.7	9.9					5.7	5.0	24.6	21.4
Hydrogen production / refining	20.7	54.8										
Liquefaction for distribution												
Domestic transport	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Fueling as liquid												
CO2 from feedstock	83.0	66.6	94.4	121.6					83.3	72.3		
Total (*1)	112.9	132.0	102.9	132.2	0.8	0.8	0.8	0.8	89.8	78.1	25.4	22.1
Additional GHG emission to generate 1kWh=3.6MJ electric power by means of power generation [g eq-CO$_2$/MJ-H$_2$]												
(Petroleum)	+81.6	+83.7	+81.6	+95.7	+113.7	+112.2	+104.6	+80.6	+97.3	+97.3	+97.3	+97.3
(LNG)	+65.8	+67.5	+65.8	+77.1	+91.7	+90.5	+84.3	+65.0	+78.5	+78.5	+78.5	+78.5
(LNG combined)	+53.9	+55.3	+53.9	+63.2	+75.1	+74.1	+69.1	+53.3	+64.3	+64.3	+64.3	+64.3
(Coal)	+102.3	+104.9	+102.2	+119.8	+142.3	+140.5	+131.0	+101.0	+121.9	+121.9	+121.9	+121.9
(Japan average) (*2)	+46.2	+47.4	+46.2	+54.2	+64.4	+63.5	+59.2	+45.7	+55.1	+55.1	+55.1	+55.1
(*1) + (*2)	159.2	179.5	149.1	186.4	65.1	64.3	60.0	46.4	144.9	133.2	80.5	77.3

Table 2.7.10（A） WTT energy efficiency of hydrogen production pathways (LHV)
(compressed hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.927	0.927	0.927	0.927					0.936	0.936	0.861	0.861
Hydrogen production / refining	0.674	0.573	0.740	0.555	0.868	0.873	0.901		0.650	0.743	0.650	0.743
Compression for distribution	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950	0.950
Domestic transport	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959	0.959
Compression / fueling	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966	0.966
Total (*1)	0.549	0.467	0.604	0.452	0.764	0.768	0.792	0.880	0.536	0.612	0.492	0.563
Energy efficiency to generate 1kWh = 3.6MJ electric power by means of power generation (LHV)												
(Petroleum)	0.358											
(LNG)	0.354											
(LNG combined)	0.422											
(Coal)	0.386											
(Japan average) (*2)	0.348											

Table 2.7.10（B） WTT energy efficiency of hydrogen production pathways (LHV)
(liquefied hydrogen transportation→compressed hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.927	0.927	0.927	0.927					0.936	0.936	0.861	0.861
Hydrogen production / refining	0.674	0.573	0.740	0.555	0.868	0.873	0.901		0.650	0.743	0.650	0.743
Liquefaction for distribution	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735
Domestic transport	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
Gasification / compression / fueling	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995	0.995
Total (*1)	0.452	0.384	0.497	0.372	0.628	0.632	0.652	0.724	0.441	0.504	0.405	0.463
Energy efficiency to generate 1kWh = 3.6MJ electric power by means of power generation (LHV)												
(Petroleum)	0.358											
(LNG)	0.354											
(LNG combined)	0.422											
(Coal)	0.386											
(Japan average) (*2)	0.348											

Table 2.7.10（C） WTT energy efficiency of hydrogen production pathways (LHV) (liquefied hydrogen transportation→liquefied hydrogen fueling)

	Naphtha reforming				COG refining			Salt electrolysis	Raw natural gas reforming		CH4 fermentation / reforming	
	Topsøe	PEC	NEDO	JHFC	case.1	case.2	case.3		(conventional)	(future)	(conventional)	(future)
Feedstock production	0.927	0.927	0.927	0.927					0.936	0.936	0.861	0.861
Hydrogen production / refining	0.674	0.573	0.740	0.555	0.868	0.873	0.901		0.650	0.743	0.650	0.743
Liquefaction for distribution	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735	0.735
Domestic transport	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990	0.990
Fueling as liquid	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989
Total (*1)	0.449	0.382	0.494	0.370	0.625	0.628	0.648	0.720	0.438	0.501	0.403	0.460
Energy efficiency to generate 1kWh=3.6MJ electric power by means of power generation (LHV)												
(Petroleum)	0.358											
(LNG)	0.354											
(LNG combined)	0.422											
(Coal)	0.386											
(Japan average) (*2)	0.348											

3. Results and Conclusions

3.1 Well-to-Tank Analysis Results

(1) Energy Consumption [MJ/MJ-fuel (LHV)]

				Well-to-Tank		
				Best	Representative	Worst
Crude oil	Conventional diesel				0.078	
Crude oil	Low sulfur diesel				0.094	
Crude oil	Ultra low sulfur diesel				0.118	
Crude oil	Conventional gasoline				0.175	
Crude oil	Conventional gasoline	3% Ethanol blend gasoline		0.177		0.222
Crude oil	Conventional gasoline	10% Ethanol blend gasoline		0.182		0.338
Crude oil	Conventional gasoline	ETBE blend gasoline		0.177		0.218
Crude oil	Future gasoline				0.187	
Crude oil	Future gasoline	(on) Compressed Hydrogen			0.929	
Crude oil	Kerosene				0.066	
Crude oil	Kerosene	(on) Compressed Hydrogen			0.718	
Crude oil	Naphtha	(on) Compressed Hydrogen	(source:JHFC)		0.733	
Crude oil	Naphtha	(off) Compressed Hydrogen		0.612		1.455
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Compressed fueling)	1.360		2.203
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Fueling as liquid)	1.203		2.046
Crude oil	LPG from associated gas				0.120	
Crude oil	LPG from associated gas	(on) Compressed Hydrogen		0.763		0.833
Crude oil	LPG from petroleum refinery				0.151	
Crude oil	LPG from petroleum refinery	(on) Compressed Hydrogen		0.814		0.880
Crude oil	Crude / heavy fuel oil	Electricity			1.951	
Crude oil	Crude / heavy fuel oil	Electricity	(on) Compressed Hydrogen	4.512		6.375
Raw natural gas	LPG from raw natural gas				0.163	
Raw natural gas	LPG from raw natural gas	(on) Compressed Hydrogen		0.835		0.898
Raw natural gas	LNG				0.161	
Raw natural gas	LNG	City gas	(Fueling as CNG)		0.206	
Raw natural gas	LNG	City gas	(on) Compressed Hydrogen	0.693		0.724
Raw natural gas	LNG	Electricity (LNG thermal)			1.913	
Raw natural gas	LNG	Electricity (LNG thermal)	(on) Compressed Hydrogen	4.454		6.293
Raw natural gas	LNG	Electricity (LNG combined)			1.414	
Raw natural gas	LNG	Electricity (LNG combined)	(on) Compressed Hydrogen	3.691		5.215
Raw natural gas	(Pipeline transportation)	City gas	(Fueling as CNG)		0.120	
Raw natural gas	(Pipeline transportation)	City gas	(on) Compressed Hydrogen	0.585		0.599
Raw natural gas	(Pipeline transportation)	(off) Compressed Hydrogen		0.791		0.804
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Compressed fueling)	1.540		1.553
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Fueling as liquid)	1.383		1.396
Raw natural gas	Syngas	FT synthetic oil			0.553	
			<Estimation in this study>	<0.484>		<1.070>
Raw natural gas	Syngas	FT synthetic oil	(on) Compressed Hydrogen		1.579	
			<Estimation in this study>	<1.457>		<2.489>
Raw natural gas	Syngas	DME			0.468	
			<Estimation in this study>	<0.322>		<0.671>
Raw natural gas	Syngas	DME	(on) Compressed Hydrogen		1.112	
			<Estimation in this study>	<0.930>		<1.365>
Raw natural gas	Syngas	Methanol		0.524		0.589
			<Estimation in this study>	<0.777>		<1.205>
Raw natural gas	Syngas	Methanol	(on) Compressed Hydrogen	1.027		1.724
			<Estimation in this study>	<1.298>		<2.550>

(continued) Energy consumption

					Well-to-Tank		
					Best	Representative	Worst
Coal	Electricity					1.777	
Coal	Electricity	(on) Compressed Hydrogen			4.246		5.999
Coal	Syngas	FT synthetic oil			0.968		1.156
				<Estimation in this study>	<0.761>		
Coal	Syngas	FT synthetic oil		(on) Compressed Hydrogen	2.309		2.641
				<Estimation in this study>		<1.946>	
Coal	Syngas	DME		<Estimation in this study>		<0.759>	
Coal	Syngas	DME	(on) Compressed Hydrogen	<Estimation in this study>		<1.494>	
Coal	Syngas	Methanol		<Estimation in this study>		<0.821>	
Coal	Syngas	Methanol	(on) Compressed Hydrogen	<Estimation in this study>	<1.388>		<2.089>
Dry biomass (wood)	Syngas	FT synthetic oil			1.052		1.324
				<Estimation in this study>			<2.085>
Dry biomass (wood)	Syngas	FT synthetic oil		(on) Compressed Hydrogen	2.458		2.936
				<Estimation in this study>			<4.277>
Dry biomass (wood)	Syngas	DME				0.858	
				<Estimation in this study>		<0.749>	
Dry biomass (wood)	Syngas	DME		(on) Compressed Hydrogen		1.598	
				<Estimation in this study>		<1.462>	
Dry biomass (wood)	Syngas	Methanol			0.657		0.983
				<Estimation in this study>			<1.321>
Dry biomass (wood)	Syngas	Methanol		(on) Compressed Hydrogen	1.170		2.252
				<Estimation in this study>	<1.882>		<2.706>
Dry biomass (wood)	(Direct combustion)	Electricity				5.656	
Dry biomass (wood)	(Direct combustion)	Electricity		(on) Compressed Hydrogen	11.726		16.567
Dry biomass (wood)	(Gasification IGCC)	Electricity				0.850	
Dry biomass (wood)	(Gasification IGCC)	Electricity		(on) Compressed Hydrogen	4.365		6.167
Rapeseed	BDF				0.420		0.616
Palm	BDF				0.220		0.289
Waste food oil	BDF					0.061	
Sugarcane	Ethanol				0.281		1.060
Sugarcane	Ethanol	ETBE			0.209		0.476
Corn	Ethanol				0.946		1.055
Corn	Ethanol	ETBE			0.437		0.474
Plantation wood	Ethanol				1.527		2.673
Plantation wood	Ethanol	ETBE			0.637		1.030
Waste wood	Ethanol					1.660	
Waste wood	Ethanol	ETBE				0.682	
Wet biomass	CH_4	(Fueling as CNG)			0.814		0.823
Wet biomass	CH_4	(off) Compressed Hydrogen			1.449		1.561
Wet biomass	CH_4	(off) Liquefied Hydrogen		(Compressed fueling)	2.197		2.310
Wet biomass	CH_4	(off) Liquefied Hydrogen		(Fueling as liquid)	2.040		2.153
Wet biomass	CH_4	Electricity				1.032	
Wet biomass	CH_4	Electricity		(on) Compressed Hydrogen	3.797		5.365
Power grid (Japan average)						1.877	
Power grid (Japan average)	(on) Compressed Hydrogen				4.407		6.226
(Salt electrolysis)	(off) Compressed Hydrogen					0.487	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Compressed fueling)				1.235	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Fueling as liquid)				1.078	
(COG)	(off) Compressed Hydrogen				0.804		0.924
(COG)	(off) Liquefied Hydrogen	(Compressed fueling)			1.552		1.672
(COG)	(off) Liquefied Hydrogen	(Fueling as liquid)			1.395		1.515

(2) GHG Emissions [g-eq CO_2/MJ-fuel (LHV)]

				Well-to-Tank		
				Best	Representative	Worst
Crude oil	Conventional diesel				5.45	
Crude oil	Low sulfur diesel				6.43	
Crude oil	Ultra low sulfur diesel				7.88	
Crude oil	Conventional gasoline				11.42	
Crude oil	Conventional gasoline	3% Ethanol blend gasoline		10.17		13.18
Crude oil	Conventional gasoline	10% Ethanol blend gasoline		7.14		17.44
Crude oil	Conventional gasoline	ETBE blend gasoline		10.34		13.05
Crude oil	Future gasoline				12.19	
Crude oil	Future gasoline	(on) Compressed Hydrogen			176.68	
Crude oil	Kerosene				4.72	
Crude oil	Kerosene	(on) Compressed Hydrogen			159.87	
Crude oil	Naphtha	(on) Compressed Hydrogen	(source:JHFC)		163.43	
Crude oil	Naphtha	(off) Compressed Hydrogen		124.86		162.19
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Compressed fueling)	155.78		193.11
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Fueling as liquid)	149.07		186.40
Crude oil	LPG from associated gas				7.76	
Crude oil	LPG from associated gas	(on) Compressed Hydrogen		122.39		141.45
Crude oil	LPG from petroleum refinery				9.93	
Crude oil	LPG from petroleum refinery	(on) Compressed Hydrogen		125.64		145.01
Crude oil	Crude / heavy fuel oil	Electricity			217.66	
Crude oil	Crude / heavy fuel oil	Electricity	(on) Compressed Hydrogen	332.83		470.22
Raw natural gas	LPG from raw natural gas				12.32	
Raw natural gas	LPG from raw natural gas	(on) Compressed Hydrogen		129.22		148.93
Raw natural gas	LNG				12.68	
Raw natural gas	LNG	City gas	(Fueling as CNG)		13.52	
Raw natural gas	LNG	City gas	(on) Compressed Hydrogen	108.13		121.34
Raw natural gas	LNG	Electricity (LNG thermal)			175.51	
Raw natural gas	LNG	Electricity (LNG thermal)	(on) Compressed Hydrogen	268.37		379.16
Raw natural gas	LNG	Electricity (LNG combined)			143.75	
Raw natural gas	LNG	Electricity (LNG combined)	(on) Compressed Hydrogen	219.81		310.55
Raw natural gas	(Pipeline transportation)	City gas	(Fueling as CNG)		6.30	
Raw natural gas	(Pipeline transportation)	City gas	(on) Compressed Hydrogen	98.98		110.80
Raw natural gas	(Pipeline transportation)	(off) Compressed Hydrogen		108.99		120.71
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Compressed fueling)	139.92		151.63
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Fueling as liquid)	133.20		144.92
Raw natural gas	Syngas	FT synthetic oil			22.99	
			<Estimation in this study>	<17.82>		<52.63>
Raw natural gas	Syngas	FT synthetic oil	(on) Compressed Hydrogen		192.27	
			<Estimation in this study>	<183.17>		<244.48>
Raw natural gas	Syngas	DME			17.14	
			<Estimation in this study>	<12.90>		<33.66>
Raw natural gas	Syngas	DME	(on) Compressed Hydrogen		133.06	
			<Estimation in this study>	<127.78>		<153.65>
Raw natural gas	Syngas	Methanol		22.93		26.77
			<Estimation in this study>	<37.94>		<63.40>
Raw natural gas	Syngas	Methanol	(on) Compressed Hydrogen	123.84		168.32
			<Estimation in this study>	<139.94>		<217.40>

(continued) GHG emissions

					Well-to-Tank		
					Best	Representative	Worst
Coal	Electricity					272.60	
Coal	Electricity	(on) Compressed Hydrogen			416.82		588.90
Coal	Syngas	FT synthetic oil			66.78		68.14
				<Estimation in this study>	<59.13>		
Coal	Syngas	FT synthetic oil	(on) Compressed Hydrogen		269.41		271.79
				<Estimation in this study>		<255.92>	
Coal	Syngas	DME		<Estimation in this study>		<63.31>	
Coal	Syngas	DME	(on) Compressed Hydrogen	<Estimation in this study>		<230.43>	
Coal	Syngas	Methanol		<Estimation in this study>		<65.43>	
Coal	Syngas	Methanol	(on) Compressed Hydrogen	<Estimation in this study>	<248.41>		<318.84>
Dry biomass (wood)	Syngas	FT synthetic oil			△64.40		△63.73
				<Estimation in this study>			<△61.85>
Dry biomass (wood)	Syngas	FT synthetic oil	(on) Compressed Hydrogen		41.39		42.97
				<Estimation in this study>			<47.40>
Dry biomass (wood)	Syngas	DME				△59.11	
				<Estimation in this study>		<△59.38>	
Dry biomass (wood)	Syngas	DME	(on) Compressed Hydrogen			39.95	
				<Estimation in this study>		<39.50>	
Dry biomass (wood)	Syngas	Methanol			△60.40		△59.60
				<Estimation in this study>			<△58.76>
Dry biomass (wood)	Syngas	Methanol	(on) Compressed Hydrogen		35.95		54.77
				<Estimation in this study>	<38.30>		<56.27>
Dry biomass (wood)	(Direct combustion)	Electricity				45.34	
Dry biomass (wood)	(Direct combustion)	Electricity	(on) Compressed Hydrogen		69.45		98.12
Dry biomass (wood)	(Gasification IGCC)	Electricity				7.97	
Dry biomass (wood)	(Gasification IGCC)	Electricity	(on) Compressed Hydrogen		12.21		17.26
Rapeseed	BDF				△50.95		△39.10
Palm	BDF				△56.84		△52.95
Waste food oil	BDF					△73.28	
Sugarcane	Ethanol				△54.31		△51.89
Sugarcane	Ethanol	ETBE			△10.26		△9.43
Corn	Ethanol				△2.31		21.92
Corn	Ethanol	ETBE			7.60		15.92
Plantation wood	Ethanol				27.36		103.80
Plantation wood	Ethanol	ETBE			17.78		44.04
Waste wood	Ethanol					23.95	
Waste wood	Ethanol	ETBE				16.61	
Wet biomass	CH_4	(Fueling as CNG)			△32.93		△30.73
Wet biomass	CH_4	(off) Compressed Hydrogen			53.05		56.29
Wet biomass	CH_4	(off) Liquefied Hydrogen	(Compressed fueling)		83.97		87.21
Wet biomass	CH_4	(off) Liquefied Hydrogen	(Fueling as liquid)		77.26		80.50
Wet biomass	CH_4	Electricity				41.17	
Wet biomass	CH_4	Electricity	(on) Compressed Hydrogen		63.07		89.10
Power grid (Japan average)						123.06	
Power grid (Japan average)	(on) Compressed Hydrogen				188.49		266.30
(Salt electrolysis)	(off) Compressed Hydrogen					22.23	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Compressed fueling)				53.15	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Fueling as liquid)				46.44	
(COG)	(off) Compressed Hydrogen				35.79		40.93
(COG)	(off) Liquefied Hydrogen	(Compressed fueling)			66.71		71.85
(COG)	(off) Liquefied Hydrogen	(Fueling as liquid)			60.00		65.14

(3) Energy efficiency (LHV)

				Well-to-Tank		
				Best	Representative	Worst
Crude oil	Conventional diesel				0.916	
Crude oil	Low sulfur diesel				0.902	
Crude oil	Ultra low sulfur diesel				0.883	
Crude oil	Conventional gasoline				0.839	
Crude oil	Conventional gasoline	3% Ethanol blend gasoline		0.838		0.822
Crude oil	Conventional gasoline	10% Ethanol blend gasoline		0.836		0.782
Crude oil	Conventional gasoline	ETBE blend gasoline		0.833		0.803
Crude oil	Future gasoline				0.830	
Crude oil	Future gasoline	(on) Compressed Hydrogen			0.431	
Crude oil	Kerosene				0.924	
Crude oil	Kerosene	(on) Compressed Hydrogen			0.486	
Crude oil	Naphtha	(on) Compressed Hydrogen	(source:JHFC)		0.452	
Crude oil	Naphtha	(off) Compressed Hydrogen		0.604		0.452
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Compressed fueling)	0.497		0.372
Crude oil	Naphtha	(off) Liquefied Hydrogen	(Fueling as liquid)	0.494		0.370
Crude oil	LPG from associated gas				0.889	
Crude oil	LPG from associated gas	(on) Compressed Hydrogen		0.565		0.486
Crude oil	LPG from petroleum refinery				0.916	
Crude oil	LPG from petroleum refinery	(on) Compressed Hydrogen		0.582		0.501
Crude oil	Crude / heavy fuel oil	Electricity			0.358	
Crude oil	Crude / heavy fuel oil	Electricity	(on) Compressed Hydrogen	0.241		0.168
Raw natural gas	LPG from raw natural gas				0.853	
Raw natural gas	LPG from raw natural gas	(on) Compressed Hydrogen		0.541		0.467
Raw natural gas	LNG				0.858	
Raw natural gas	LNG	City gas	(Fueling as CNG)		0.848	
Raw natural gas	LNG	City gas	(on) Compressed Hydrogen	0.622		0.545
Raw natural gas	LNG	Electricity (LNG thermal)			0.354	
Raw natural gas	LNG	Electricity (LNG thermal)	(on) Compressed Hydrogen	0.239		0.166
Raw natural gas	LNG	Electricity (LNG combined)			0.422	
Raw natural gas	LNG	Electricity (LNG combined)	(on) Compressed Hydrogen	0.285		0.198
Raw natural gas	(Pipeline transportation)	City gas	(Fueling as CNG)		0.918	
Raw natural gas	(Pipeline transportation)	City gas	(on) Compressed Hydrogen	0.674		0.590
Raw natural gas	(Pipeline transportation)	(off) Compressed Hydrogen		0.612		0.536
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Compressed fueling)	0.504		0.441
Raw natural gas	(Pipeline transportation)	(off) Liquefied Hydrogen	(Fueling as liquid)	0.501		0.438
Raw natural gas	Syngas	FT synthetic oil			0.638	
			<Estimation in this study>	<0.668>		<0.477>
Raw natural gas	Syngas	FT synthetic oil	(on) Compressed Hydrogen		0.336	
			<Estimation in this study>	<0.352>		<0.251>
Raw natural gas	Syngas	DME			0.671	
			<Estimation in this study>	<0.748>		<0.587>
Raw natural gas	Syngas	DME	(on) Compressed Hydrogen		0.447	
			<Estimation in this study>	<0.499>		<0.391>
Raw natural gas	Syngas	Methanol		0.640		0.613
			<Estimation in this study>	<0.545>		<0.435>
Raw natural gas	Syngas	Methanol	(on) Compressed Hydrogen	0.500		0.379
			<Estimation in this study>	<0.425>		<0.269>

(continued) Energy efficiency

					Well-to-Tank		
					Best	Representative	Worst
Coal	Electricity					0.386	
Coal	Electricity	(on) Compressed Hydrogen			0.260		0.181
Coal	Syngas	FT synthetic oil			0.508		0.463
				<Estimation in this study>	<0.568>		
Coal	Syngas	FT synthetic oil		(on) Compressed Hydrogen	0.267		0.244
				<Estimation in this study>		<0.299>	
Coal	Syngas	DME		<Estimation in this study>		<0.565>	
Coal	Syngas	DME	(on) Compressed Hydrogen	<Estimation in this study>		<0.377>	
Coal	Syngas	Methanol		<Estimation in this study>		<0.542>	
Coal	Syngas	Methanol	(on) Compressed Hydrogen	<Estimation in this study>	<0.423>		<0.335>
Dry biomass (wood)	Syngas	FT synthetic oil			0.489		0.431
				<Estimation in this study>			<0.324>
Dry biomass (wood)	Syngas	FT synthetic oil		(on) Compressed Hydrogen	0.257		0.227
				<Estimation in this study>			<0.171>
Dry biomass (wood)	Syngas	DME				0.536	
				<Estimation in this study>		<0.570>	
Dry biomass (wood)	Syngas	DME		(on) Compressed Hydrogen		0.357	
				<Estimation in this study>		<0.380>	
Dry biomass (wood)	Syngas	Methanol			0.597		0.496
				<Estimation in this study>			<0.422>
Dry biomass (wood)	Syngas	Methanol		(on) Compressed Hydrogen	0.466		0.307
				<Estimation in this study>	<0.329>		<0.261>
Dry biomass (wood)	(Direct combustion)	Electricity				0.094	
Dry biomass (wood)	(Direct combustion)	Electricity		(on) Compressed Hydrogen	0.063		0.044
Dry biomass (wood)	(Gasification IGCC)	Electricity				0.329	
Dry biomass (wood)	(Gasification IGCC)	Electricity		(on) Compressed Hydrogen	0.222		0.154
Rapeseed	BDF				0.891		0.734
Palm	BDF				0.969		0.916
Waste food oil	BDF					0.988	
Sugarcane	Ethanol				0.815		0.466
Sugarcane	Ethanol	ETBE			0.739		0.423
Corn	Ethanol				0.554		0.552
Corn	Ethanol	ETBE			0.502		0.501
Plantation wood	Ethanol				0.392		0.271
Plantation wood	Ethanol	ETBE			0.356		0.246
Waste wood	Ethanol					0.374	
Waste wood	Ethanol	ETBE				0.339	
Wet biomass	CH_4	(Fueling as CNG)			0.804		0.780
Wet biomass	CH_4	(off) Compressed Hydrogen			0.563		0.492
Wet biomass	CH_4	(off) Liquefied Hydrogen		(Compressed fueling)	0.463		0.405
Wet biomass	CH_4	(off) Liquefied Hydrogen		(Fueling as liquid)	0.460		0.403
Wet biomass	CH_4	Electricity				0.183	
Wet biomass	CH_4	Electricity		(on) Compressed Hydrogen	0.123		0.086
Power grid (Japan average)						0.348	
Power grid (Japan average)	(on) Compressed Hydrogen				0.235		0.163
(Salt electrolysis)	(off) Compressed Hydrogen					0.880	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Compressed fueling)				0.724	
(Salt electrolysis)	(off) Liquefied Hydrogen	(Fueling as liquid)				0.720	
(COG)	(off) Compressed Hydrogen				0.792		0.764
(COG)	(off) Liquefied Hydrogen	(Compressed fueling)			0.652		0.628
(COG)	(off) Liquefied Hydrogen	(Fueling as liquid)			0.648		0.625

3.2 Case Study: Tank-to-Wheel and Well-to-Wheel GHG Emissions

3.2.1 Assumptions about Tank-to-Wheel analysis

Tank-to-Wheel data derived from previous research studies conducted by TMC was used. The outline of this data is as follows.

(1) Vehicle Specification

Sedan type passenger vehicle, weight: 1,250 kg, displacement: 2,000cc, four-cylinder gasoline engine, automatic transmission.

(2) Running Conditions

The great effect that running conditions will have on Well-to-Wheel calculation results is acknowledged. Although various running conditions should be considered for evaluation purposes, as this study is classed as a reference case study, the running pattern used in Japan for fuel consumption measurements, the "10/15 mode run", has been used.

(3) Powertrains

The internal combustion engine, hybrid engine and fuel cell were selected as typical powertrains, and combined with the relevant fuels indicated in "3.1 Well-to-Tank Calculation Results for Evaluated Fuels".

The fuel consumption ratios and exhaust gas levels (emissions targets) for each powertrain in relation to the base vehicle is shown in Table 3.2.1.

Table 3.2.1 Mileage and emission target of representative powertrains covered in this study

Representative powertrain	Mileage[*1] (ratio of base value)	Emission target
Gasoline vehicle	1.00 (base value)	Lower than the new long-term regulation value for gasoline
Gasoline hybrid vehicle	2.31	↑
LPG vehicle	1.00	↑
Natural gas vehicle	1.00	↑
Diesel vehicle	1.25	Lower than the new short-term regulation value for diesel (complying with the acts for NOx and PM)
Diesel hybrid vehicle	2.44[*2]	↑
Fuel cell vehicle	3.75[*3]	0 (equivalent to the U.S. Tier-2 Bin 1)

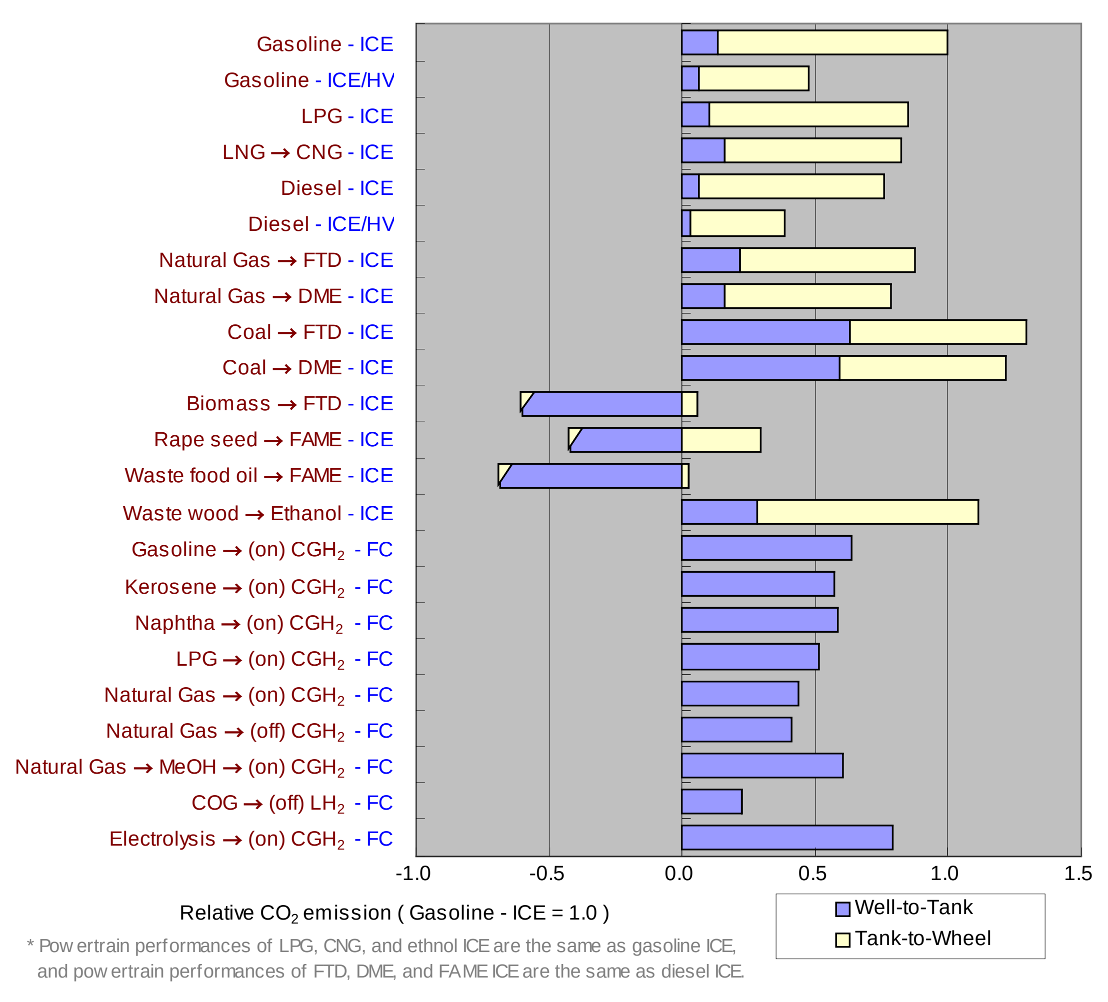
Note [*1]: Mileage per litre in which each fuel is converted into gasoline equivalence based on heating value. Represented in relative values to that of gasoline vehicle.

[*2] : Estimation from public documents [*3] : Future target

Regarding power performance, powertrain specifications were adjusted to generally match the base vehicle, taking the system weight and performance of each powertrain into consideration.

3.2.2 Well-to-Wheel GHG emissions under fixed conditions of driving sedan type vehicles

Well-to-Wheel GHG emissions under the condition described in 3.2.1 are shown in Figure 3.2.1



* Powertrain performances of LPG, CNG, and ethnol ICE are the same as gasoline ICE, and powertrain performances of FTD, DME, and FAME ICE are the same as diesel ICE.

Figure 3.2.1 An example of calculation of Well-to-Wheel GHG emissions

As with prior studies, at the comparatively slow running speed of the “10/15 mode run”, the superiority of the hybrid vehicle (gasoline, diesel) in relation to GHG emissions is significant.

For synthetic fuels such as Fischer-Tropsch diesel oil and Dimethyl ether (DME), and hydrogen, large variations in Well-to-Tank GHG emissions were apparent depending on the primary energy used as feedstock, and it is clear that an important aspect of future considerations will be the production of fuels through low GHG emission pathways. In addition, fuels derived from biomass resources have comparatively low GHG emission values, and future utilization is anticipated.

The calculation results for Well-to-Wheel GHG emissions indicated in this report represent a case study under a given set of conditions, and cannot be applied to discussion concerning the superiority of particular future automotive fuels and powertrains. Further evaluation from a comprehensive perspective encompassing the price of each vehicle and fuels (economical efficiency), supply, ease of use, and so on, is necessary.

3.3 Considerations and Future Tasks

3.3.1 Considerations about Well-to-Tank analysis

The calculations of this study mainly concern Well-to-Tank (=consideration of the fuel from extraction of primary energy to vehicle fuel tank) energy consumption, greenhouse gas (GHG) emissions and energy efficiency of current and near future automotive fuels in Japan. No fixed timeframe was set for the data collected, with efforts focusing on understanding and organizing existing data. Moreover, where data used in calculation has a broad range, the range is indicated through minimum to maximum values.

The fuel production pathways considered were; 21 petroleum based fuels, 20 natural gas based fuels, 8 coal based fuels, 19 biomass resource related fuels (3 bio-diesel fuels, 10 dry biomass based fuels, 6 wet biomass based fuels), power grid mix (Japan average) and hydrogen production through electrolysis, 6 byproduct hydrogen, totaling 76 pathways. The calculation results are as shown in “3.1 Well-to-Tank Analysis Results”.

(1) Petroleum Based Fuel Production Pathways → 2.1

For petroleum based fuel production pathways, focusing on fuels for current mainstream internal combustion engines, diesel and gasoline, this study considered low-sulfur diesel, ultra low sulfur diesel and future (sulfur-free) gasoline derived through ultra deep hydrodesulfurization, and biomass based ethanol and ETBE blend gasoline (hydrogen from reformed petroleum products will be mentioned later). Energy efficiency related to the production of these fuels is high at 0.83-0.92.

There are two main uncertain factors in the calculation of data related to petroleum based fuel production pathways. The first is the effect of sulfur content in crude. The effects of differences in producing region are greater than the effects of technological factors related to desulfurization. As the vast majority of crude oil currently consumed in Japan is imported from the Middle East, data calculated from statistical values, such as in this study, will tend to reflect the properties of Middle East crude. The sulfur content of Middle East crude is just under 2 %, with high aromatic content. On the other hand, the import of low sulfur content Russian and African crude has recently increased. African crude is a low-sulfur crude with properties similar to North Sea crude. Although North Sea crude is a top quality crude with less than 0.1% sulfur content, it is rarely imported into Japan. In addition, Russian crude is currently drawing the most attention, and this too has comparatively low sulfur content. Should these crude oils replace 20-30 % of the imported Middle East crude, the data given here may change dramatically (petroleum refining process including desulfurization). Such significant effects of sulfur content at source are a characteristic of petroleum based fuels (effects of differences in producing region).

The second is the effect of petroleum resources known as “unconventional resources” (= low-sulfur petroleum feedstock for refining produced through the processing of such as oil sands. Synthetic crude), which are not included in current statistics. The use of this feedstock is increasing rapidly in the U.S. In addition, statistics for Canada show that synthetic crude exceeded natural crude this year. Regarding price, crude is comparatively expensive at 40-50 dollars per barrel, whereas synthetic crude is less than 20 dollars per barrel. Moreover, as resource stocks are practically inexhaustible, depending on price, the importance of synthetic crude may increase in the future. However, on the other hand, problems do exist in that increase in synthetic crude usage will be accompanied by an increase in CO_2 emissions.

It is also necessary to consider the petroleum refining process as a factor specific to Japan. The characteristic of refining in Japan is that unlike the U.S., which uses thermal cracking to produce maximum gasoline, Japan uses mild cracking, applying large amounts of hydrogen to yield approximately 20% kerosene (there is almost no kerosene usage overseas). Although there are thermal cracking techniques using catalysts that can be applied to increase gasoline yield, as in the U.S., these will result in decreased energy efficiency. In reality, in comparison to the U.S., overall efficiency in Japan is said to be 2-4 % better. In addition, an uncertain factor in the future of the petroleum refining process in Japan is the positioning of C-heavy fuel oil. Until now, industrial use of C-heavy fuel oil centered on power companies, however this usage may be discontinued. Should current consumption conditions progress as they are, in the future, C-heavy fuel oil may be broken down into gasoline or diesel, resulting in a decrease in process efficiency.

(2) Natural Gas Based Fuel Production Pathways → 2.2

For natural gas based fuel production pathways, this study considered liquid natural gas (LNG), which physically enhances energy density, and compressed natural gas (CNG) derived from compressed city gas (hydrogen from reformed natural gas will be mentioned later). Regarding supply routes, other than LNG, a case study of pipeline transportation from Sakhalin was also undertaken.

Okamura *et al.* [2004] referenced in this study, gathers the latest information regarding the LNG Middle East project (Qatar, Oman) implemented from the perspective of diversification of LNG procurement, and analyzes the effects on GHG emissions over the LNG lifecycle (LNG used in Japan) with the addition of the Middle East LNG project. Okamura *et al.* [2004] reported that although the shipping distance doubled for the Middle East, representing a possibility of GHG emissions increasing for the overall lifecycle, as the CO_2 content of feedstock from the Middle East LNG project was lower, overall GHG emissions were also lower. Feedstock from Arun, Indonesia contains the most CO_2, however this is nearing depletion. Although Japan will cover the volume previously procured from Arun with imports from the Middle East, GHG emissions for the overall lifecycle will not increase. CO_2 content of feedstock from Sakhalin is also though to be low.

In addition, under the preconditions set in this study, the results showed that GHG emissions would be lower in the case of pipeline transportation from Sakhalin. The FRI-ERC [2000] report also states, “From the environmental perspective, if the shipping distance is less than 16,000 km, pipeline transportation is better than LNG, and for shorter distances of 2,000-3,000 km, pipeline transportation is significantly better”. There are currently many difficult problems of investment risk, politics and so on concerning pipeline transportation. When taken into consideration as a measure against global warming in the future, should the pipeline transportation of natural gas from neighboring countries become a possibility, it will be an attractive prospect worthy of implementation.

(3) Fuel Production Pathways from Biomass Resources → 2.3

For fuel production pathways from biomass resources, this study considered BDF from oil crops and waste food oil, ethanol and ETBE produced from cellulosic materials such as sugar/starch and wood (used as a blend with gasoline), and CH_4 fermentation (synthetic fuels from biomass will be mentioned later). As the conversion technology for biomass resources is still in the research stages, how the future is viewed from the current stages of research will be important.

In addition, considerations must be made concerning a variety of restrictions regarding introduction and dissemination. For example, the introduction and dissemination of BDF may involve restrictions in cost and production volume.

At present, with BDF usage in Japan, tax equivalent to tax on diesel is imposed when the BDF is blended with diesel (diesel excise duty). Assuming usage as a blend with diesel, the desirable Well-to-Tank BDF production cost, taking diesel excise duty into account, would be about 30 yen. In addition, according to data provided in reference materials, assuming daily production of about 200-300 L-BDF, in order to recover the cost of the esterification device within the serviceable life of the reclaimed oil production device (8 years), about 10-20 yen per liter BDF needs to be gained. In other words, large-scale production to exploit scale merit, and BDF dissemination on the premise of single BDF usage (not blended with diesel) will be necessary. Furthermore, for BDF production from agricultural products, as labor costs are a major burden in areas that cannot be mechanized, there are generally many cases of increased cost. Therefore, the maintenance of cost competitiveness through the use of waste cooking oils, which can be recovered free of charge (or inverse onerous contracts) is important.

On the other hand, on the production side, due to competition with food crops, the use of abandoned cropland and unused land is assumed for the cultivation of rapeseed. Currently, in Japan, although there are over 210,000 ha of abandoned cropland consisting of paddies, fields and orchards, approximately three quarters of this land is in plots of less than 5 ha. As a plot of land less than 5 ha can only be expected to produce about 3.7 kL-BDF per year, for a 1,500 kL/year class plant such as the one under consideration by Kyoto City, it will be necessary to cultivate rapeseed in 400 plots. In addition, as there will be great differences in the distribution of large-scale plots of unused land (greater than 30 ha) depending on region, from the perspective of nationwide dissemination, the utilization of unused plots is unrealistic. Consequently, the establishment of a scheme whereby as much waste cooking oil as possible is collected from homes in a metropolitan area, and the waste cooking oil generated by businesses is collected on a stable basis, is desired.

When considering these restrictions, the stable dissemination of BDF in Japan will most likely stem from BDF derived from imported palm oil, and this accompanied by the utilization of waste cooking oil is considered realistic. However, should political backing favor rapeseed (oil crop cultivation including rapeseed), dissemination may progress with the production of low-cost BDF through mechanized agricultural work. In addition, when the premise is of importation, attention must be paid to important points such as demand/supply balance with other countries and measures against country risk.

Following on, for the introduction and dissemination of ethanol, food demand and supply trends must be kept in mind when using saccharides (e.g. corn, sugarcane), and farming and waste treatment trends must be kept in mind when using cellulosic resources (e.g. wood, waste wood).

Although ethanol production using corn and other farinaceous crops as feedstock is currently being promoted, mainly in the U.S. and Europe, crops such as corn are also important food crops, and variations in climate can cause sharp increases in trading prices. This will also greatly affect the ethanol production cost. In fact, the effect of climate risk in relation to corn ethanol is said to be greater than that of country risk on crude prices.

The relationship with sugar production is thought to have great influence regarding sugarcane. This trend is particularly noticeable in Brazil where cane expression businesses directly produce ethanol. In addition, Brazil produces approximately 30 % of the worlds sugar and accounts for approximately 40 % of exports. This suggests the possibility that, if growers in Brazil focus on sugar production due to variations in international sugar prices, ethanol demand and supply may become restricted.

The ethanol conversion of cellulosic biomass is currently in the stages of technological development, and it is thought that the introduction and dissemination of this technology will be promoted in countries such as Japan that have difficulty in securing saccharide resources. Other than woody biomass, viable cellulosic resources include rice straw, wheat straw, wastepaper and so on. Although in many cases in the U.S., the target is wheat-straw, the same cannot be expected in Japan as paddy fields are not necessarily large-scale and are also dispersed, therefore the focus is expected to be on the utilization of construction generated wood (waste wood).

When considering these restrictions, implementation will progress for the time being with imported alcohol as the main source, with a changeover to cellulosic ethanol production in line with technological advancements. As it is difficult to imagine the import of corn from the U.S., this is not a realistic option for Japan.

(4) Synthetic Fuel Production Pathways → 2.4

For synthetic fuel production pathways, considerations were made for 3 types of primary energy (gas) that would be the source (natural gas, gas from coal cracking, biomass gasification gas) and 3 types of synthetic fuel (FT synthetic oil, DME, methanol), so calculations energy efficiency and so on were made regarding the 9 (= 3 * 3) production pathways these represent.

In this study, as existing studies were not available for all nine pathways, other than using prior research for reference in calculations of energy efficiency and so on, conditions were set for a given process, and estimates of energy efficiency were made under those conditions. Although the estimate results generally matched the results calculated using prior researches for reference, significant discrepancies were shown for some pathways. This is because the estimates for gas composition assumed total volume to be CH_4, however the reality was that some non-CH_4 constituents were included, and synthetic fuel is thought to be produced through a reforming method suitable for that composition (it is thought that for the production of all synthetic fuels from natural gas, the optimum reforming process is determined automatically according to the required H_2/CO ratio). In other words, in an industrialized facility, the optimum process has been adopted, and based on this the values given in reference literature are considered to be the good efficiency values. However, for the estimate results of this study, all four reforming process types were considered and trial calculations conducted for each with best and worst values given, resulting in the aforementioned discrepancies. In addition, since in some cases there was insufficient information for the conditions set for trial calculations, further information related to the process should be considered with a view to improving accuracy, and the trial calculation model should be studied.

Furthermore, unlike petroleum products and natural gas, which are already in industrial use, usage of synthetic fuels as automotive fuel does not have an established industrial usage base, and in relation to all these pathways, considerations into product quality as an automotive fuel have not been made. Regarding the production pathways of synthetic fuels as automotive fuels, improving the accuracy of calculation results derived from such considerations remains as a future objective.

(5) Liquefied Petroleum Gas Production Pathways → 2.5

For LPG production pathways, the LPG production methods used in Japan – collection of LPG through separation and processing of gas associated with crude oil (LPG from associated gas), collection of LPG through separation and processing of gas extracted from gas fields (LPG from raw natural gas), and collection of LPG as a byproduct from refineries and petrochemical plants (LPG from petroleum refining), were considered.

As an automotive fuel, LPG is supplied to established LPG vehicles already in use such as taxis, commercial vehicles and trucks. The propane/butane constituent ratio (weight) of LPG used in motor vehicles is about 20:80 in summer and about 30:70 in winter. In prior studies referenced in this study, information regarding the quality of these ratios is unclear. Regarding the production pathways of LPG as an automotive fuel, improving the accuracy of calculation results derived from such considerations remains as a future objective.

(6) Electricity (Electric Power Generation Pathways) → 2. 6

For electrical power (power generation pathways), petroleum fired thermal, LNG and LNG combined cycle, coal fired thermal, nuclear and biomass power generation, and the electricity mix from the average power generation structure of Japan, were considered. Electric power is used to recharge electric vehicles and for hydrogen production through water electrolysis.

Attention must be paid to data used in the calculation of CO_2 emissions and energy efficiency associated with electricity usage, as changes in this data will occur depending on perspective, such as the use of a single fossil fuel or the use of energy to power vehicles. From the perspective of how a fossil fuel should be used, it is appropriate to investigate how CO_2 emissions and energy efficiency is affected through the various pathways from one fossil fuel. On the other hand, from the perspective of what should be used to power motor vehicles, it is appropriate to consider energy use as 1 kWh = 3.6 MJ, regardless of the primary energy.

Regarding electricity generation mix (Japan average), when using the calculation results, attention must be paid to the fact that CO_2 emissions associated with electricity use are thinned out. If electricity is to provide energy for transportation, new power plants will be required, and considerations must be made into what will be used in the new power plants to supply the energy to meet the new demand.

In addition, for biomass power generation (direct combustion, steam gas turbine power generation, gasification gas turbine power generation, CH_4 fermentation gas engine power generation), differences in the composition of the input and processes (including reaction conditions) greatly affect the results. The calculation results of biomass power generation in this study are all derived from information relevant to a specific site, and may be uncertain and varied in comparison to the calculation results for all thermal and nuclear power generation. Improvement of accuracy here also remains as a future objective.

(7) Hydrogen Production Pathways → 2. 7

For hydrogen production pathways, following transportation to hydrogen stations in the form of petroleum products, city gas, pure water and so on, considerations were made for cases where hydrogen is produced through hydrogen production devices (on-site), and cases where hydrogen is produced at large-scale facilities such as a central plant and shipped out in the form of compressed or liquefied hydrogen (off-site).

Hydrogen for use as fuel for FCVs does not exist as elementary substance in a natural state, and as shown in pathways considered in this study, conventional energy sources must be relied upon for production (although GHG emissions associated with hydrogen production are practically zero when renewable energy is used, at present, such renewable energy is not in general use).

The majority of hydrogen production pathways considered in this study have not as yet reached levels suitable for practical application. In other words, much of the data used for calculation in this study is based on ideals, and the task remains as to how estimates should be made concerning deviation between these results and data that will become available following industrialization.

In addition, this study considers byproduct hydrogen as a secondary product. However, for ironworks and caustic soda plants where byproduct hydrogen is used effectively, it will be necessary to consider alternative fuels to supplement energy deficiencies incurred through the use of hydrogen as fuel for FCVs. In such cases (where utilization is sufficient), by the calculation results of this study, usage for FCVs will not be effective.

At this point, based on the calculation results of this study, hydrogen cannot be said to be particularly superior to conventional fuels. However, the attraction of hydrogen is in <i> no GHG emissions during use and <ii> can be extracted from various resources (diversity of feedstock). In addition, unlike CO_2 emissions from existing systems such as gasoline vehicles, CO_2 emissions from the hydrogen production process are generated in specific locations and may be recovered and sequestered. Depending on trends in the recovery and sequestration of CO_2, huge reductions can be expected in GHG emissions from hydrogen production pathways. Furthermore, depending greatly on regional characteristics, further improvements can be made on the energy efficiency of hydrogen such as through the use of waste heat from reforming for cogeneration. Taking all these points into consideration, it will be necessary to seek appropriate hydrogen production pathways.

3.3.2 Future Tasks

The credibility and applicability of calculations in this study depends greatly on calculation preconditions such as implemented load distribution methods and quality of data. In reality, some fuels such as petroleum products, city gas, LPG and electricity are already in industrial use, while biomass resources, synthetic fuels, hydrogen and so on are still in the early stages of technological development. In addition, even where calculation results of this study are based on actual values, as there is a high degree of uncertainty concerning matters such as future technological innovation, market size, new laws and regulations, many problems exist concerning the simple comparison of these fuels. Furthermore, regarding load distribution between main products and co-products/byproducts, although this study has been conducted under the premise that, in principle, byproducts will be disposed of, the usage of certain byproducts has been considered in existing studies although the possibility of realizing this usage is unclear (load distribution considerations). For these reasons, the calculation results of this study are not unlike preliminary approximations, and in order to contribute further to the initial objectives, the consistency of preconditions and the accuracy of data used in calculations must be improved, and the credibility of the results must be enhanced.

The emphasis of this study is on Well-to-Tank analysis. In future, these results will be combined with various Tank-to-Wheel analysis results and basic data, and various further analyses will be scheduled in relation to overall efficiency from extraction of primary energy to actual vehicle fuel consumption “Well-to-Wheel” (see Figure 3.2.1). At such a time, it may also become necessary to modify or adjust the calculation results of this study in order to comply with analysis preconditions.

Well-to-Wheel analysis results will be an important factor in the selection of future technologies and fuels. However, technologies and fuels that will be implemented in the future will not be determined by this factor alone. This is because a variety of other factors such as cost, infrastructure, completeness of the technology, supply potential and usability will also be taken into consideration. In future, it will be necessary to seek out optimum vehicle/fuel combinations according to the energy circumstances, available infrastructure and regulations that apply in each country or region.

4. References

・Titles in brackets are the original ones.

・Names of books, articles, and organizations in lower cases are tentative translation.

・Items are Japanese only unless otherwise noted.

- Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas [2002]"*Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*", prepared under Task No. BFP2.A410, National Renewable Energy Laboratory (NREL), U.S. DOE, NREL/TP-510-32438, Download at : http://www.afdc.doe.gov/pdfs/6483d.pdf (English)
- Agency of Natural Resources and Energy (ANRE), Ministry of International Trade and Industry (MITI, current Ministry of Economy, Trade and Industry (METI)) [1992]: "*Saishin-ban Karyoku Handobukku*" (Thermal power handbook -- Latest version), published by Denryoku Shinpo-sha Inc.
- Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry [2002-1]: "*Sougou Enerugii Toukei Heisei 13-nen-do-ban*" (Energy Balance Tables in Japan 2001)
- Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry [2002-2]: "*Gasu Jigyou Nenpou, Heisei 13-nen (2001-nen)*" (Gas Industry Manual (2001 edition))
- Agency for Natural Resources and Energy (ANRE), Ministry of Economy, Trade and Industry [2002-3]: "*Heisei 13-nen-do Denryoku Jukyuu no Gaiyou 51*" (2001 Outlook for Electric Supply and Demand)
- Argonne National Laboratory (ANL) [2001]: "*Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*", ver.1.6β, Download at : http://greet.anl.gov/greet1-6_beta.html (English)
- Armstrong, A.P., J. Baro, J. Dartoy, A.P. Groves, J. Nikkonen, and D.J. Rickeard [2002]: "*energy and green gas balance of biofuels for europe – an update*", prepared by the CONCAWE Ad Hoc Group on Alternative Fuels, report No.2/02 (English)
- Asad T. Amr [1981]: "*Energy Systems in the United States*", Energy, Power and Environment Series, Vol. 12, New York, NY, U.S.A. Marcel Dekker Incorporated, ISBN Number: 0824712757 (English)
- ASAOKA, Sachio, Mitsunori SHIMURA [2001]: "*Gousei Gasu Seizou Gijutsu*" (processing technologies of synthetic gas), PETROTECH, Vol. 24, No. 3, pp.226-229
- Bechtel Corporation [1998]: "*Baseline Design/Economics for Advanced Fischer-Tropsch Technology*", Technical Report, Report No. DE-AC22-91PC90027-01, sponsored by U.S. Department of Enegy, Download at : http://www.osti.gov/dublincore/gpo/servlets/purl/14176-YzKSu3/webviewable/ (English)
- Bechtold, R. L. [1997]: "*Alternative Fuels Guidebook Properties, Storage, Dispensing, and Vehicle Facility Modifications*", ISBN 0 7680 0052 1 (English)

- Beer, T., T. Grant, G. Morgan, J. Lapszewicz, P. Anyon, J. Edwards, P. Nelson, H. Watson, and D. Williams [2001]: "*Comparison of Transport Fuels*", Final Report (EV45A/2/F3C) to the Australian Greenhouse Office on the Stage 2 study of "Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles", by CSIRO in association with The University of Melbourne the Centre for Design at RMIT Parsons Australia Pty Ltd and Southern Cross Institute of Health Research, Download at : http://www.greenhouse.gov.au/transport/comparison/index.html (English)
- Bosch, R. [2000]: "*Automotive Handbook 5th Edition*", ISBN 0837606144 (English)
- Central Research Institute of Electric Power Industry (CRIEPI) [1991]: "*Hatshuden Puranto no Enerugii Shuushi Bunseki*", (Energy Analysis of Power Generation Plants), research report of Central Research Institute of Electric Power Industry, Y90015
- Central Research Institute of Electric Power Industry (CRIEPI) [1992]: "*Hatsuden Puranto no Ondanka Eikyou Bunseki*" (Greenhouse Effect Analysis of Power Generation Plants), research report of Central Research Institute of Electric Power Industry, Y91005
- Central Research Institute of Electric Power Industry (CRIEPI) [1995]: "*Hatsuden Shisutemu no Raifu Saikuru Bunseki*" (Life Cycle Analysis of Power Generation System), research report of Central Research Institute of Electric Power Industry, Y94009
- Central Research Institute of Electric Power Industry (CRIEPI) [2000]: "*Raifu Saikuru CO2 Haishutsu-ryo ni yoru Hatsuden Gijutsu no Hyouka – Saishin Deeta ni yoru Sai-suikei to Zentei Jouken no Chigai ni yoru Eikyou--*" (Evaluation of Power Generation Technologies based on Life Cycle CO2 Emissions – Re-estimation Using the Latest Data and Effects of the Difference of Conditions--), research report of Central Research Institute of Electric Power Industry, Y99009
- Central Research Institute of Electric Power Industry (CRIEPI) [2001]: "*Raihu Saikuru CO2 Haisyutsu-ryou ni yoru Genshi-ryoku Hatsuden Gijutsu no Hyouka*" (Evaluation of Nuclear Power Generation Technologies based on Life Cycle CO2 Emissions), research report of Central Research Institute of Electric Power Industry, Y01006
- Chemical Daily Co., Ltd., the [2002]: "*14120 no Kagaku Shouhin*" (14120 articles of chemical product)
- Consumer's life Division, General Food Policy Bureau, Ministry of Agriculture, Forestry and Fisheries (MAFF) [2001]: "*Heisei 13 nendo Shokuhin Shouhi Monitaa dai-1-kai Teiki Chousa*" (periodic survey for monitoring food consumption, FY2001 -- 1st survey)
- Department of Agriculture, Forestry and fisheries, Aomori Prefecture [1994]: "*Miryoku aru Nougyou Jitsugen ni muketa Shuyou Sakumotsu no Gijutsu Keiei Shihyou*" (technological and managerial indicators of major crops for achieving an attractive agriculture), appendix to the exercise plan for an attractive agriculture. potential direction to develop Aomori's agriculture
- Economic Research Center, Fujitsu Research Institute (FRI-ERC) [2000]: "*Paipu Rain to LNG no Ondanka-kouka Gasu Haisyutsu no Raihu Saikuru Asesumento Hikaku*" (comparison of life cycle assessment of GHG emissions by pipeline and by LNG), Oil and Gas Review, February 2000, pp.2-28
- Electrochemical Society of Japan, the [2000]: "*Dai 5-han, Denki Kagaku Binran*" (electrochemical handbook, 5th edition), Maruzen Co., Ltd., ISBN 4-621-04759-0 C3058

- Energy Information Administration (EIA) [1994]: "*Alternatives to Traditional Transportation Fuels 1994*", DOE/EIA-0585 (94) (English)
- Energy Policy Division, Natural Resources and Energy Department, Kansai Bureau of Ministry of International Trade and Industry [2002]: "*Junkan-gata Keizai Syakai no Keisei wo mezashita Baiomasu Enerugii Katsuyou Sokushin ni muketa Chousa – Kinki Chiiki ni okeru Baiomasu Enerugii Riyou no Tenbou – Chousa Houkoku-sho*" (study to promote biomass energy use towards creation of a society with recycling-based economy – prospect for biomass energy use in Kansai Region – study report)
- Energy Technology Support Unit (ETSU) [1996]: "*Alternative Road Transport Fuels – A Preliminary Life-cycle Study for the UK*", Volume 2, ISBN 0 11 515411 6
- EU Alternative Fuels Contact Group [2003]: "*Market Development of Alternative Fuels*", Download at : http://europa.eu.int/comm/energy_transport/en/envir_alternative_fuels_en.html (English)
- European Council for Automotive R&D (EUCAR), CONCAWE, and European Commission's Joint Research Centre (JRC/IES) [2003]: "*Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*", Well-to-Tank Report Version 1, December 2003, Download at : http://ies.jrc.cec.eu.int/Download/eh (English)
- Fuel Policy Subcommittee [2003]: "*Baiomasu Nenryou no CO2 Haisyutsu tou ni kansuru LCA (Raihu Saikuru Asesumento) Hyouka ni tsuite (2) – Waga Kuni de Soutei sareru Dounyuu Keitai e no LCA Tekiyou ni yoru Shisan Kekka--*" (LCA evaluation on CO2 emissions from biomass (2) – estimation result by applying LCA to the types to be possibly introduced in Japan--), handout material No.4-2 for the 9th meeting of Fuel Policy Subcommittee, Petroleum Subcommittee, Petroleum Committee, Advisory Committee for Natural Resources and Energy.
  Download at : http://www.meti.go.jp/report/data/g30723aj.html
- General Motors, Argonne National Laboratory (ANL), BP, Exxon Mobil, and Shell [2001]: "*Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis –*", Download at : http://greet.anl.gov/publications.html (English)
- General Motors, L-B-Systemtechnik GmbH, BP, Exxon Mobil, Shell, and TotalFinaElf [2002]: "*GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study*", Download at : http://www.lbst.de/gm-wtw/ (English)
- Graboski, M.S. [2002]: "*Fossil Energy Use in the Manufacture of Corn Ethanol*", Colorado School of Mines, prepared for the National Corn Growers Association (English)
- Haldor Topsøe [2001]: "*DME as a Transportation Fuel*", Download at http://www.topsoe.dk/site.nsf/vALLWEBDOCID/KVOO-5PGFAZ?open&returnid=BBNN-5PNJ3F (English)
- Hansen, J.B., B. Voss, F. Joensen, I.D. Siguroardottir [1995]: "*Large Scale Manufacture of Dimethyl Ether--A New Alternative Diesel Fuel From Natural Gas*", SAE 950063 (English)
- HONDO, Yuki, Yoji UCHIYAMA [1999]: "*Kokunai Enerugii Shouhi ni yori Yuuhatsu-sareru Kaigai deno Kankyou Huka*" (overseas environmental burden induced by Japan's domestic energy consumption), Proceedings of the 15th Conference on Energy, Economy, and Environment, pp.431-436

- Intergovernmental Panel on Climate Change (IPCC) [2001]: "*Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*" (English)
- International Energy Agency (IEA) [2003-1]: "*Energy Balances of OECD Countries 1971-2001*", 2003 Edition/CD-ROM (English)
- International Energy Agency (IEA) [2003-2]: "*Energy Balances of Non-OECD Countries 1971-2000*", 2003 Edition/CD-ROM (English)
- Isaias de Carvalho Macedo [1998]: "*Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996)*", Biomass and Bioenergy Vol.14, No.1, pp.77-81 (English)
- Isaias de Carvalho Macedo, Manoel Regis Lima Verde Leal and Suleiman Jose Hassuani (Centro de Tecnologia Copersucar) [1998]: "*Sugar cane residues for power generation in the sugar / ethanol mills in Brazil*", Energy for Sustainable Development, Volume V, No.1, March 2001 (English)
- ISHIGURO, Takayoshi [1981]: "*Kiso Kogyo Denki Kagaku*" (basic industrial electrochemistry), Sangyo Tosho Inc., ISBN4-7828-2521-8 C3058
- Institute for Policy Sciences, Japan, the [1977]: "*Enerugii Riyou Kouzou to Enerugii Shuushi ni kansuru Chosa*" (study on energy use structure and energy balance)
- Institute of Applied Energy, the (IAE) [1990]: "*Karyoku Hatsudensho Taiki Eikyou Hyouka Gijutsu Jissho Chousa Houkoku-sho*" (report of experimental study for atmospheric impact assessment technology of thermal power plants), research project commissioned by Agency of Natural Resources and Energy (ANRE), Ministry of International Trade and Industry (MITI). IAE-C8917
- Institute of Applied Energy, the (IAE), Takasago Thermal Engineering Co., Ltd. [2002]: "*Heisei 13-nendo Suiso wo Mochiita Denryoku Huka Heijun-ka Sisutemu ni kansuru Chousa Houkoku-sho*" (report of a research on electric load leveling system using hydrogen, FY2001), research project of strategic electric technology development (commissioned by Agency for National Resources and Energy, Ministry of Economy, Trade and Industry)
- Institute of Energy Economics, Japan, the (IEEJ) [1999]: "*Waga kuni ni okeru Kaseki Enerugii ni kansuru Raihu Saikuru Inbentori Bunseki*" (Life Cycle Inventory Analysis of Fossil Energies in Japan), handout material of 353rd Forum on Research Works
- Japan Energy Research Center Co., Ltd. [2001]: "*Ondan-ka Taisaku Kuriin Kaihatsu Mekanizumu Jigyou Chousa – Betonamu ni okeru Satoukibi kara Etanooru-ganyu-gasorin no Seizou ni kansuru Chousa Houkoku-sho*" (Feasibility Studies on Climate Change Mitigation Projects for Clean Development Mechanism – Report: Study on Production of Ethanol-containing Gasoline, with Ethanol Made from Sugar Cane Refuse in Vietnam), research project commissioned by Global Environment Centre Foundation
- Japan Environmental Management Association for Industry, the [2003]: "*Heisei 14-nendo Shin Enerugii Sangyou Gijutsu Sougou Kaihatsu Kikou itaku Seihin-tou Raihu Saikuru Kankyou Eikyou Hyouka Gijutsu Kaihatsu Seika Houkoku-sho*" (report of Development of Technology to Assess and Verify Life Cycle CO2 Emissions project, FY2002, commissioned by the New Energy and Industrial Technology Development Organization), CO2 Fixation and Utilization technologies development project

- Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) [2004]: “*Heisei 15 nendo Suiso Nenryou-denchi Jisshou Purojekuto JHFC Seminaa Shiryou*” (handouts for the JHFC Seminar FY2003 on Hydrogen and Fuel Cell Demonstration Project), held at Tokyo Prince Hotel on March 12, 2004, JHFC Activity Report I: “Domain of Hydrogen Stations/Test Results”; JHFC Activity Report II: “Development of Liquid Hydrogen Manufacturing Technology/Demonstrations”
- Japan Institute of Energy, the [2002]: “*Baiomasu Handobukku*” (Biomass Handbook), Ohmsha, Ltd. ISBN 4-274-02485-7 C3044
- Japan Petroleum Institute, the (JPI) [1998]: “*Sekiyu Seisei Purosesu*” (poetroleum refining process)
- Japan National Oil Corporation (now Japan Oil, Gas and Metals National Corporation) [1986]: “*Sekiyu Yougo Jiten*” (glossary of petroleum) (available online at http://oilresearch.jogmec.go.jp/glossary as “Sekiyu Tennen-Gasu Yougo Jiten” (glossary of petroleum & natural gas))
- Japan Shipping Exchange, Inc., the [1992]: “*Distance Tables For World Shipping (Eighth Edition)*” (English)
- JHFC Special Committee for Overall Efficiency Investigation, Japan Automobile Research Institute [2004]: “*Heisei 15 nendo ‘JHFC Sougou Kouritsu Kentou Kekka’ Chuukan Houkoku-sho*” (the results of the JHFC Overall Efficiency Investigation – FY2003 Interim Report), Download at: http://www.jhfc.jp/topics/pdf/h15houkoku.pdf
- K. Shaine Tyson, Editor [1998]: “*Biodiesel Reseach Progress 1992-1997*”, prepared for National Renewable Energy Laboratory (NREL), U.S. DOE, NREL/TP-580-24433, prepared by Information Resources, Inc., Download at : http://www.eere.energy.gov/biomass/pdfs/biodiesel_92-97.pdf (English)
- Kadam, K.L., V.J. Camobreco & B.E. Glazebrook, L.H. Forrest & W.A. Jacobson, D.C. Simeroth, W.J. Blackbum, and K.C. Nehoda [1999]: “*Environmental Life Cycle Implications of Fuel Oxygenate Production from California Biomass*”, Technical Report, prepared under Task No. WG900101, National Renewable Energy Laboratory (NREL), U.S. DOE, NREL/TP-580-25688, Download at : http://www.nrel.gov/docs/fy99osti/25688.pdf (English)
- Kadam, K.L. [2000]: “*Environmental Life Cycle Implications of Using Bagasse-Derived Ethanol as a Gasoline Oxygenate in Mumbai (Bombay)*”, prepared under Task No. WG88.0101, National Renewable Energy Laboratory (NREL), U.S. DOE, NREL/TP-580-28705 (English)
- Kajitani, S., Z. L. Chen, M. Oguma, M. Alam, K. TAI Rhee [1998]: “*Direct-Injection Diesel Engine Operated With Propane-DME Blend Fuel*”, SAE 982536 (English)
- KATANISHI, Shoji, Kazuhiko KUNITOMI, Masanobu TAKEI, Tetsuo NAKATA, Takashi WATANABE, Toru IZUMIYA [2002]: “*Kouon Gasu-ro Gasu-taabin Hatsuden Sisutemu (GTHTR300) yo Kou-nenshou-do Nenryou no Seiritsu-sei Hyouka (I)*” (Feasibility Study on High Burn up Fuel for Gas Turbine High Temperature Reactor (GTHTR300), (I)), Japanese journal of Atomic Energy Society of Japan, Vol.1, No.4, pp.373-383
- K.K. Sekiyutsushinsha [2002]: “Heisei 14 nen Sekiyu Siryou” (petroleum databook, FY2002)

- KOIDE, Yasuhiro [2000]: "*Ajia-Taiheiyou Chiiki no Tennen Gasu Jijo to LNG Jukyuu Doukou*" (natural gas status and LNG supply/demand trend in Asia-Pacific region), First Research Department, The Institute of Energy Economics, Japan (IEEJ),
  Download at: http://eneken.ieej.or.jp/data/old/pdf/azialng98.pdf
- Krister Ståhl, Magnus Neergaard, Jorma Nieminen [2000]: "*Värnamo Demonstration Programme – Final Report*", 1st World Conference on Biomass for Energy and Industry, Sevilla, Spain, 5-9 June 2000, pp.730-736 (English)
- Levelton Engineering Ltd. And (S&T)^2 Consulting Inc. [2000]: "*Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario*", R-2000-1, File: 499-0418 (English)
- Lorenz, D. and D. Morris [1995]: "*How Much Energy Does It Take to Make a Gallon of Ethanol?*", http://www.carbohydrateeconomy.org/library/admin/uploadedfiles/How_Much_Energy_Does_it_Take_to_Make_a_Gallon_.html (English)
- Mann, M.K. and P.L. Spath [1997]: "*Life Cycle Assessment of a Biomass Gasification Combined-Cycle System*", prepared under Task No. BP811030, National Renewable Energy Laboratory (NREL), U.S. DOE, NREL/TP-430-23076 (English)
- Marano, J.J and J.P. Ciferno [2001]: "*Life-Cycle Greenhouse-Gas Emissions Inventory For Fischer-Tropsch Fuels*", prepared by U.S. DOE, NETL and Energy and Environmental Solutions, LCC, Download at : http://www.netl.doe.gov/coal/gasification/pubs/pdf/GHGfinalADOBE.pdf (English)
- Marland, G. and A.F. Turhollow [1991]: "*CO2 emissions from the production and combustion of fuel ethanol from corn*", Energy Vol.16, No.11/12, pp.1307-1316 (English)
- Ministry of Economy, Trade and Industry (METI) [2002]: "*Yearbook of Production, Supply and Demand of Petroleum, Coal and Coke 2001*"
- Ministry of International Trade and Industry (MITI) [1998]: "*Yearbook of Production, Supply and Demand of Petroleum, Coal and Coke 1997*"
- Ministry of the Environment (MOE) [2002-1]: "*Heisei 14 nen-do Onshitsu-koka Gasu Haisyutsu-ryou Santei Houhou Kentou-kai Enerugii Kougyou-purosesu Bunka-kai Houkoku-sho (Nenryou)*" (report by energy and industrial process subcommittee (fuel), the panel on GHG emission calculation methodology, FY2002)
- Ministry of the Environment (MOE) [2002-2]: "*Onshitsu-koka Gasu Haisyutsu-ryou Santei ni kansuru Kentou Kekka – Dai-3-bu, Unyu Bunka-kai Houkoku-sho, Nougyou Bunka-kai Houkoku-sho, Haiki-butsu Bunka-kai Houkoku-sho*" (investigation results on GHG emission calculation, part 3: report by transport subcommittee, report by agriculture subcommittee, report by waste subcommittee), the panel on GHG emission calculation methodology
- Ministry of the Environment (MOE) [2003-1]: " '*Jidousha no Nenryou no Seijou ni kansuru Kyou Gendo oyobi Jidousha no Nenryou ni Fukumareru Bussitsu no Ryou no Kyoyou Gendo' no Ichibu Kaisei ni tsuite*" (Amendment to the Maximum Permissible Limit for the Quality of Motor Vehicle Fuel and for the Quantity of Substances in Motor Vehicle Fuel), News Release on August 25, 2003

- Ministry of the Environment (MOE) [2003-2]: "*Chuuou Kankyou Shingi-kai 'Kongo no Jidousya Haisyutsu Gasu Teigen Taisaku no arikata ni tsuite (dai 7-ji Toushin)*" (publishing the 7th report of "Future Policy for Motor Vehicle Emission Reduction" by Central Environment Council), News Release on July 29, 2003
- Mitsubishi Research Institute, Inc. (MRI), Fuji Research Institute Corporation [2002]: "*Heisei 13-nendo Shokuhin Risaikuru Kinkyuu Chousa Hukyuu Itaku Jigyou Houkoku-sho*" (report of urgent survey on food waste recycle and promotion project, FY 2001), commissioned by Food Industry Policy Division, General Food Policy Bureau, Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan
- Myburgh, Ian S., P. W. Schaberg, J. J. Botha, I. Khalek [2000]: "*Comparative Emissions Performance of Sasol Fischer-Tropsch Diesel Fuel in Current and Older Technology Heavy-Duty Engines*", SAE 2000-01-1912 (English)
- NAKAJIMA, Takeshi, Takao SAKAI [1993]: "*Topuso-hou Suijouki Kaishitsu Purosesu*" (Topsoe method for steam reforming process), PETROTECH, Vol. 16, No. 10, pp.84-85
- NAKAMURA, Arata, Motoki SATO [2002]: "*GTL: Gasu-den Kaihatsu wo Sokushin suru Opusyon to nariuru-ka – GTL Nenryou no Shijousei to Kadai –*" (GTL: an option to accelerate gas wells development? – marketability and issues of GTL fuel –", Oil and Gas Review, November 2001, pp.10-29
- New Energy and Industrial Technology Development Organization, the (NEDO) [1992]: "*Paamu-yu kara no Yusou-you Baio-fueru Jitsuyou Kanousei Chousa*" (Research on Possibility of Utilization of Palm Methylester for Diesel Engines), NEDO-P-9213
- New Energy and Industrial Technology Development Organization, the (NEDO) [1995]: "*Heisei 6-nendo Enerugii Shiyou Gourika Syuhou Kokusai Chousa*" (international research on methodologies of increasing the efficient use of energy, FY1994)
- New Energy and Industrial Technology Development Organization, the (NEDO) [1996]: "*Chikyuu Kankyou kara Mita Sougou-teki Kaseki Nenryou Saikuru Bunseki Hyouka Syuhou no Chousa (III)*" (investigation on evaluation methodology of comprehensive fossil fuel cycle analysis from the viewpoint of global environment (III)), NEDO-GET-9507
- New Energy and Industrial Technology Development Organization, the (NEDO) [2000]: "*Suiso Riyou Kokusai Kurin Enerugi Sisutemu Gijutsu (WE-NET) Dai II-ki Kenkyu Kaihatsu Tasuku 1 Sisutemu Hyouka ni Kansuru Chousa Kenkyu*" (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 1: Surveys and Studies of System Analysis), NEDO-WE-NET-9901
- New Energy and Industrial Technology Development Organization, the (NEDO) [2001-1]: "*Suiso Riyou Kokusai Kurin Enerugi Sisutemu Gijutsu (WE-NET) Dai II ki Kenkyu Kaihatsu Tasuku 1 Sisutemu Hyouka ni Kansuru Chousa Kenkyu*" (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 1: Surveys and Studies of System Analysis), NEDO-WE-NET-0001
- New Energy and Industrial Technology Development Organization, the (NEDO) [2001-2]: "*Suiso Riyou Kokusai Kurin Enerugi Sisutemu Gijutsu (WE-NET) Dai II ki Kenkyu Kaihatsu Tasuku 7 Suiso Kyoukyu Suteshon no Kaihatsu*" (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 7: Development of Hydrogen Refueling Station), NEDO-WE-NET-0007

- New Energy and Industrial Technology Development Organization, the (NEDO) [2001-3]: "*Tennen Gasu wo Nenryou Denchi tou ni mochiita baai no Sougou Henkan Kouritsu no Santei ni kansuru Chousa*" (study on calculation of comprehensive conversion efficiency when using natural gas for fuel cells), NEDO-00
- New Energy and Industrial Technology Development Organization, the (NEDO) [2002-1]: *"Suiso Riyou Kokusai Kurin Enerugi Sisutemu Gijutsu (WE-NET) Dai II ki Kenkyu Kaihatsu Tasuku 1 Sisutemu Hyouka ni Kansuru Chousa Kenkyu"* (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 1: Surveys and Studies of System Analysis), NEDO-WE-NET-0101
- New Energy and Industrial Technology Development Organization, the (NEDO) [2002-2]: "*Suiso Riyou Kokusai Kurin Enerugi Sisutemu Gijutsu (WE-NET) Dai II ki Kenkyu Kaihatsu Tasuku 7 Suiso Kyoukyu Suteshon no Kaihatsu*" (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 7: Development of Hydrogen Refueling Station), NEDO-WE-NET-0107
- New Energy and Industrial Technology Development Organization, the (NEDO) [2003-1]: "*Suiso Riyou Kokusai Kuriin Enerugii Shisutemu Gijutsu (WE-NET) Dai II-ki Kenkyuu Kaihatsu Tasuku 1 Sisutemu Hyouka ni kansuru Chousa, Kenkyuu*" (International Clean Energy Network Using Hydrogen (WE-NET), Phase II – Task 1: Surveys and Studies of System Analysis), NEDO-WE-NET-0201
- New Energy and Industrial Technology Development Organization, the (NEDO) [2003-2]: "*Kokusai Enerugii Siyou Gourika tou Taisaku Jigyou, Kokusai Enerugii Shouhi Kouritsu-ka tou Moderu Jigyou, Paamu-yu Riyou Baio-diizeru Nenryou Seizou Moderu Jigyou Jisshi Kanousei Chousa*" (feasibility study of the model project for bio-diesel fuel manufacturing from palm oil, international model project of increasing the efficiency of energy use, International Projects for Increasing the Efficient Use of Energy.), NEDO-IC-02EF09
- Norton, P., K. Vertin, B. Bailey, N. N. Clark, D. W. Lyons, S. Goguen, and J. Eberhardt [1998]: "*Emissions from Trucks using Fischer-Tropsch Diesel Fuel*", SAE 982526 (English)
- OGAWA, Yoshiki, Sung Yee YOON [1998]: "*Saikutsu kara Nensyou made Guroobaru ni mita kaku-Kaseki Enerugii-gen no Onshitsu-koka no Hikaku*" (Comparison of Total Green House Effects of Each Fossil Energy Examining at the Global Viewpoint from Mining to Combustion), Energy Economics, 24 (5), pp.30-55
- OGAWA, Yukimasa, Masanori FUJITA, Yoshiteru NAKAGAWA [2003]: "*Fun-nyou Shokuhin Zansa no Metan Hakkou Shisetsu ni okeru Unten Deta no Kaiseki*" (Analysis of the Operation Data of a Methane Fermentation Facility that Treats Manure and Tofu Refuse), Journal of the Japan Society of Waste Management Experts, Vol.14, No.5, pp.258-267
- OKAMURA, Tomohito, Michinobu FURUKAWA, Shinichi TADA, Hisashi ISHITANI [2004]: "*LNG oyobi Toshi Gasu no LCCO2 Bunseki ni okeru Chuutou Purojekuto no Inpakuto Hyouka*" (Impact Analysis of LNG Project in the Middle East in Life Cycle CO2 Analysis of LNG and City Gas), Proceedings of the 20th Conference on Energy, Economy, and Environment

- OHKI, Yuichi, Koichi SASAKI, Hiroki KUDO [2002]: "*Mokushitsu Baiomasu Hatsuden Dounyuu no tameno Kadai Chousa*" (feasibility study for introduction of woody biomass power generation), R&D report May 2002, environment group of 2nd research division, The Institute of Energy Economics, Japan. (IEEJ), Download at : http://eneken.ieej.or.jp/data/pdf/404.pdf
- Organization of the Petroleum Exporting Countries (OPEC) [2001]: "*OPEC Annual Statistical Bulletin 2001*" (English)
- Organization for the Promotion of Low Emission Vehicles [2003]: "*Tennen Gasu Jidousya no Shin-gijutsu Kaihatsu Joukyou Chousa Houkoku-sho*" (report on a status of technological development of natural gas vehicles), research project for FY2002 commissioned by Ministry of Land, Infrastructure and Transport
- Osaka Gas Co., Ltd., Tokyo Gas Co., Ltd. [2003]: "*Kyuuchaku-zai wo mochiita Shinki-na Tennen Gasu Chozou Gijutsu Kaihatsu Seika Houkoku-sho*" (Report on Development of New Natural Gas Storage System using an Absorbent), commissioned by the New Energy and Industrial Technology Development Organization, "Development of Immediately Effective and Innovative Technology for Energy and Environment" project, FY2002
- Peter Ahlvik and Åke Brandberg, Ecotraffic R&D^3 AB [2001]: "*Well-To-Wheel Efficiency for alternative fuels from natural gas or biomass*", Publication number: 2001: 85, ISSN: 1401-9612, Download at : http://www.vv.se/publ_blank/bokhylla/miljo/2001_85/2001-85.pdf (English)
- Peter Ahlvik and Åke Brandberg, Ecotraffic R&D^3 AB [2002]: "*Sustainable fuels, Introduction of biomass*", Publication number: 2002: 144, ISSN: 1401-9612, Download at : http://www.vv.se/publ_blank/bokhylla/miljo/2002_144/2002-144.pdf (English)
- Petroleum Association of Japan [2000]: "*Keidanren Kankyou Jisyu Koudou Keikaku Forou-appu Siryou*" (follow-up material for Keidanren Voluntary Action Plan on the Environment)
- Petroleum Energy Center (PEC) [1997]: "*Sekiyu Seihin no Raifu Saikuru Inbentorii no Sakusei ni Kansuru Chousa Houkoku-sho*" (report on development of life cycle inventory of petroleum products), fundamental research project for petroleum refining rationalization, FY1996, PEC-1996R-09
- Petroleum Energy Center (PEC) [1998]: "*Yusou dankai wo hukumeta Sekiyu Seihin no Raifu Saikuru Inbentorii no Sakusei ni kansuru Chousa Houkoku-sho*" (report of a study on development of life cycle inventory for petroleum products, including transport phase), research project of a rationalization basis of petroleum refinery systems, FY1997, PEC-1997R-12
- Petroleum Energy Center (PEC) [2000]: "*Sekiyu Seihin Yushu betsu LCI Sakusei to Sekiyu Seihin Kankyou Eikyou Hyouka Chousa Houkoku-sho*" (report on LCI development by type of petroleum products and the environmental impact analysis of petroleum products), research project of a rationalization basis of petroleum refinery systems, FY1999, PEC-1999R-13
- Petroleum Energy Center (PEC) [2002-1]: "*Shin Nenryou-yu no waga Kuni e no Dounyuu Kanousei Chousa"* (feasibility study for introducing new fuel oil to Japan), PEC- 2001L-02

- Petroleum Energy Center (PEC) [2002-2]: "*Yusou-you Nenryou Raihu Saikkuru Inbentorii ni kansuru Chousa Houkoku-sho – Nenryou Jidousya to Kizon Jidousha no Hikaku –*" (report for the study on life cycle inventory for transport fuels – a comparison between fuel cell and conventional vehicles), project of a basis for technological development in petroleum industry, FY2001, PEC-2001L-04
- Petroleum Energy Center (PEC) [2003]: "*Suiso Syakai ni okeru Suiso Kyoukyuu-sya no Bijinesu Moderu to Sekiyu Sangyou no Ichi-zuke ni kansuru Chousa Houkoku-sho*" (report on business model of hydrogen suppliers and status of petroleum industry in hydrogen society), research project related on environmentally-friendly petroleum, FY 2002, PEC-2002P-04
- Plastic Waste Management Institute [1993]: "*Purasuchikku Seihin no Shiyou-ryou Zouka ga Chikyuu Kankyou ni Oyobosu Eikyou Hyouka Houkoku-sho (Kaitei-ban)*" (Life Cycle Assessment of Plastic Packaging (revised edition))
- PricewaterhouseCoopers [2003]: "*Shell Middle Distillate Synthesis (SMDS) Update of a Life Cycle Approach to Assess the Environmental Inputs and Outputs, and Associated Environmental Impacts, of Production and Use of Distillates from a Complex Refinery and SMDS Route*", Technical Report v 3.1 (English)
- SAKA, Shiro [2001]: "*Baiomasu Enerugii Kankyou*" (biomass, energy and the environment)、ISBN 4-901493-13-2 C3043
- SATO, Motoki [2001]: "*Tennen Gasu no Ekitai Nenryou-ka Gijutsu (GTL) to Sekai no Saishin Doukou*" (GTL technologies and current trend of the world), PETROTECH、Vol. 24, No. 7, pp.543-548
- Science and Technology Agency [1992]: "*Ajia no Enerugii Riyou to Chikyuu Kankyou*" (energy use in Asia and global environment), compiled by Science and Technology Policy Research Institute, Science and Technology Agency. Published by Printing Bureau, Ministry of Finance
- Sheehan, J., V. Camobreco, J. Duffield, M. Graboski, H. Shapouri [1998]: "*Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*", Final Report, prepared by U.S. Department of Agriculture and U.S. Department of Energy, NREL/SR-580-24089 UC Category 1503, Down-load at : http://www.nrel.gov/docs/legosti/fy98/24089.pdf (English)
- Shell Gas & Power [2002]: "*Gas to Liquids: Shell Middle Distillate Synthesis and the Environment*" (English)
- SHIGETA, Jun [1990]: "*Kaseki Nenryou Riyou no tame no Nisankatanso Haisyutsu-ryou no Teiryou-teki Hyouka*" (quantitative evaluation of CO2 emissions for fossil fuel use), IAE Review Quarterly, Vol.13, No.3
- SUZUKI, Shin'ichi [2001]: "*Mikaihatsu Gasu-den wo Shijo ni Michibiku Sekiyu-koudan GTL Gijutsu Kaihatsu*" (leading undeveloped gas wells to the market -- GTL technological development conducted by Japan National Oil Corporation), Oil and Gas Review, November 2001, pp.10-30
- TABATA, Takeshi [2002]: "*Osaka Gasu ni okeru Katei-you PEFC-you Nenryou Kaishitsu Gijutsu no Kaihatsu*" (fuel reforming technology development for household PEFC conducted by Osaka Gas), Fuel Cell journal, Vol.2, No.2, pp.11-13

- TAKI, Masato [1997]: “*Chou-juushitsu-yu Gasu-ka Konbaindo Hatsuden Gijutsu Kaihatsu*” (Development of Ultra-Heavy Oil Gasification Combined Power Generation Technology), techology development news Vol. 73, Research and Development Division, CHUBU Electric Power Co., Inc.
- TAMURA, Itaru, Toshimasa KAGAJO, Shigeru KUWAHARA, Tomoyuki YOSHIOKA, Takahiro NAGATA, Kazuhiro KURAHASHI, Hisashi ISHITANI [1999]: “*Toshi Gasu oyobi LNG no Raihu Saikuru CO2 Bunseki,*”, (life cycle CO2 analysis of city gas and LNG), collected papers of 15th Energy System / Economics / Environment Conference, pp.419-424, Proceedings of the 15th Conference on Energy, Economy, and Environment, pp.419-424
- Tijmensen, M.JA. [2000]: “*The Production of Fischer Tropsch liquids and power through biomass gasification*”, Science Technology Society, Universiteit Utrecht, NWS-E-2000-29, ISBN 90-73958-62-8 (English)
- Transport Policy Bureau, Ministry of Transport (MOT) [1999]: “*Heisei 10-nen ban Un’yu Kankei Enerugii Youran*” (The survey on transport energy, 1998)
- Turhollow, A.F. and R.D. Perlack [1991]: “*Emission of CO2 from Energy Crop Production*”, Biomass and Bioenergy Vol.1, No.3, pp.129 (English)
- Wang, M.Q. [2001]: “*Assessment of Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Fischer-Tropsch Diesel*”, Center for Transportation Research, Argonne National Laboratory (ANL), prepared for U.S. DOE, Download at : http://www.ott.doe.gov/epact/pdfs/greenhouse_gas.pdf (English)
- Wang, M.Q. and H.-S. Huang [1999]: “*A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from National Gas*”, Center for Transportation Research, Argonne National Laboratory (ANL), ANL/ESD-40,
  Download at : http://www.transportation.anl.gov/pdfs/TA/13.pdf (English)
- Waste Treatment Technology, Research Group of Recyclable Resources Assessment, Graduate School of Engineering, Hokkaido University [1998]: “*Toshi Gomi no Sougou Kanri wo Shien suru Hyoka Keisan Sisutemu no Kaihatsu ni kansuru Kenkyuu*” (study on development of evaluation calculating system for supporting integrated management of solid waste).
- Williams, R.H, E.D. Larson, R.E. Katofsky, and J. Chen [1995]: “*Methanol and hydrogen from bio-mass for transportation*”, Energy for Sustainable Development, Vol. 1, No. 5, pp.18-34 (English)
- YAMAJI, Kenji (compiler/author), Hiromi YAMAMOTO, Jun’ichi FUJINO (co-authors) [2000]: “*Baio Enerugii*” (Bioenergy), Myosin publishing Co., Ltd., ISBN 4-88701-861-4 C0030
- YUASA, Toshiaki, Masaru TAKAHASHI [1991]: “*Chikyuu Kankyou Mondai to Dengen Kousei*” (global environment issues and power generation mix), Energy Economics Vol.17 (8), pp.27-39