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Life cycle GHG emission analysis of power generation systems: Japanese case

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Abstract

This study presents the results of a life cycle analysis (LCA) of greenhouse gas emissions from power generation systems in order to understand the characteristics of these systems from the perspective of global warming. Nine different types of power generation systems were examined: coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV). Life cycle greenhouse gas (GHG) emission per kW h of electricity generated was estimated for the systems using a combined method of process analysis and input–output analysis. First, average power generation systems reflecting the current status in Japan were examined as base cases. Second, the impacts of emerging and future nuclear, wind power and PV technologies were analyzed. Finally, uncertainties associated with some assumptions were examined to help clarify interpretation of the results.

1. Introduction

With growing concerns over anthropogenic climate change, an appropriate understanding of the GHG emission characteristics of various power generation systems from an environmental perspective is required. Worldwide, a large amount of life cycle analysis (LCA) studies have so far been performed analyzing greenhouse gas emissions for power generation. For example LCA studies in some countries are introduced in [1]. A great deal of effort has likewise been made on analyzing and evaluating GHG emission characteristics of power generation systems in Japan (see for example [2–7]). However, the previous studies still have some points to be more developed. Most Japanese studies

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employ data that do not necessarily reflect power generation systems in our country's current status. This requests the detailed investigation of power generation systems today in Japan. In the prior works methods to estimate materials/energy requirements and calculate GHG emissions are not sufficiently mature. So far the development of a more convincing method for estimating materials/energy requirements have little been discussed, while a few attempts to improve the estimation of GHG emissions method can be found (for example the use of input–output tables [3,7,8]). When interpreting the results, in addition, few studies sufficiently examine uncertainties associated with technological improvements and/or changes of assumptions.

The present paper gives the results of an LCA of GHG emissions from power generation systems in order to understand the characteristics of the systems from the perspective of global warming. This study employed an advanced methodology and the latest data, and developed a model for the estimation of life cycle GHG emissions. It has three advantages of (1) being based on new reliable data reflecting the current status in Japan, (2) allowing for the reasonable calculation of materials/energy requirements for various systems that have different specifications (see Section 2.2.1), and (3) calculating GHG emissions with an advanced method to combine process analysis and input–output analysis (see Section 2.2.2). Using the developed model, life cycle GHG emissions per kW h of electricity for nine different types of power generation systems were estimated: coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV).

Technologies cannot exist independent of society. In other words, the characteristics of technologies depend crucially on the characteristics of the society wherein they exist. Therefore, it is essential to clearly define the scope with regard to time and space for any technology assessment. First, average power generation systems reflecting the current status in Japan were examined as base cases. Base cases assumed (1) average level of generation technologies currently operating in Japan (e.g. thermal efficiency, efficiency of PV cell) and (2) the current status reflecting Japanese socio-economics (e.g. import share of generation fuels, technology used for the production of uranium fuels) during the second half of the 1990s. Second, the impacts of technology improvements in the future were examined as future cases. The influences of emerging and future technologies on life cycle GHG emissions per kW h were quantitatively analyzed for nuclear, wind power and PV. Furthermore, the effects on the results of uncertainties associated with changes in assumptions were examined. These additional analyses allow for a better understanding of the GHG emission characteristics of the power generation technologies.

2. Methodology

2.1. Life cycle GHG emission factor

Life cycle GHG emission factor (LCE) was used as an index to evaluate the GHG emission characteristics of the power generation technologies from the viewpoint of global warming. The amount of greenhouse gases emitted across the entire life cycle to generate net 1 kW h of electricity is defined as follows:

$$\mathrm{LCE} = \frac{\sum_i \mathrm{GWP}_i \times (E_{\mathrm{f}_i} + E_{\mathrm{c}_i} + E_{\mathrm{o}_i} + E_{\mathrm{d}_i})}{Q} \tag{1}$$

where E_f is direct emission caused by the combustion of fossil fuels in power plants. E_c is emission associated with the construction of plants required in the system studied. E_o is emission for operation and maintenance for the plants. E_d is emission by decommissioning the plants. E_c, E_o and E_d are here referred to as indirect emissions. Subscript i indicates the type of greenhouse gas (CO_2 and CH_4). GWP is the value of global warming potential factor of each greenhouse gas. Q is net output of electricity during a lifetime of a power plant. Net output is the amount of electricity supplied to the grid excluding the energy consumption for the operation of the plant.

This study focuses on CO_2 and CH_4 emissions as greenhouse gases. CO_2 emissions associated with the combustion of fuels (including wastes) and the production of cement were examined. CH_4 leakage from the extraction of coal, oil and natural gas directly burned in power plants was considered. The amount of CH_4 emissions was converted into CO_2 equivalents (CO_2-eq) using a global warming potential factor of 21.

2.2. Method for the estimation of life cycle CO_2 emissions

Fig. 1 shows the outline of the method developed for this analysis. This method consists of two parts: estimation of energy/materials requirements and CO_2 emissions. The outline and originality of the developed methods are described in the following. The detailed description regarding this method and data can be found in reports by Hondo et al. [9,10].

2.2.1. Estimation of energy/materials requirements

This analysis used a model to estimate energy/materials requirements for each sub-system inside the system studied. In this model, energy/materials requirements for each sub-system can be calculated from parameters of power generation systems (e.g. gross output of a power plant, thermal efficiency of a power plant, distance of ocean transport, and dead weight of an oil tanker). For example, the amount of steel and concrete required for the construction of a hydropower plant was expressed as a function of

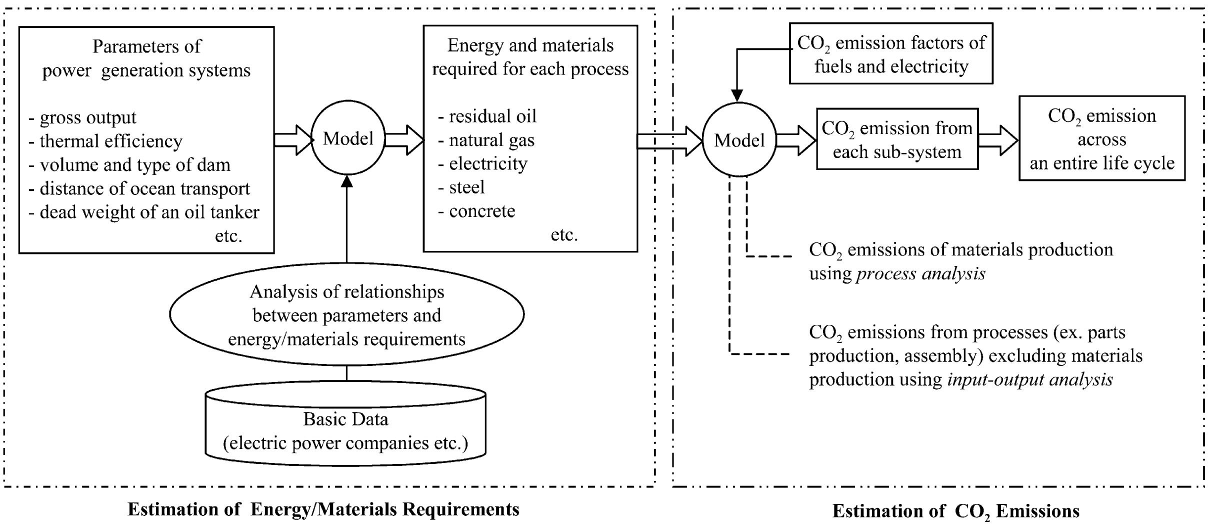

Fig. 1. Outline of estimation of life cycle CO_2 emissions.

output (MW), the maximum intake to the powerhouse (m^3/s), type and volume (m^3) of a dam, length of a pressure pipe (m), and type and length (m) of a penstock. Therefore, steel and concrete required for this sub-system can be estimated reflecting the characteristics of a particular hydropower plant. In the model, the functions representing the relationship between parameters and energy/materials requirements are prepared. These functions were derived by performing regression analysis using basic data obtained from electric power companies, energy-related companies, etc. Therefore, the developed model allows for the reasonable estimation of energy/materials requirements for any systems.

2.2.2. Estimation of CO_2 emissions from energy/materials inventories

CO_2 emissions associated with the energy requirement can be easily calculated from multiplying the amount of energy by its CO_2 emission factor. CO_2 emission factors of fuels, published by the Ministry of the Environment in Japan, were used. The CO_2 emission factor for electricity was calculated based on an average generation mix of each country. For example, for electricity required for coal mining in Australia, the CO_2 emission factor of Australian average electricity was applied.

On the other hand, CO_2 emissions associated with the construction of power plants or other facilities cannot easily be calculated only from energy/materials inventories. The estimation of CO_2 emissions requires examining process chains relevant to the construction from resource extraction, materials production to manufacturing. However, detailed examinations of the process chains alone were not feasible due to constraints on data availability. Therefore, in this study, a combined method of process analysis and input–output analysis was developed and employed. CO_2 emissions associated with materials (e.g. steel, aluminum) production were estimated by process analysis. Since available data regarding materials production are relatively abundant, the estimation by process analysis was practically possible. CO_2 emissions from various manufacturing processes (e.g. parts production, assembly) after accounting for materials production were estimated using an input–output analysis. Input–output analysis is a more efficient tool to analyze complex manufacturing processes considering the number and complexity of different products (e.g. boiler, turbine, pipe) required for power generation systems. With regard to environmental stressors strongly connected with fuel combustion such as CO_2, the process of materials production was more important compared to other processes such as parts production and assembly. Therefore, it was reasonable that the CO_2 from materials production was more accurately estimated by process analysis, while the CO_2 from other processes was roughly estimated using an input–output table. This is a new approach to take advantage of both process and input–output analyses.

3. Power generation systems

3.1. Power plants studied

Nine different types of power generation systems were examined: coal-fired, oil-fired, LNG-fired, LNG combined cycle (LNGCC), nuclear, hydropower, geothermal, wind power and solar-photovoltaic (PV). Table 1 contains the key parameters for the power plants examined. Base cases assumed (1) average level of generation technology in Japan (e.g. thermal efficiency, efficiency of PV cell) and (2) the current status reflecting Japanese socio-economics (e.g. import share of generation fuels, technology used for the production of uranium fuels) during the second half of the 1990s. The power plants examined in base cases were based on the information from existing power plants in Japan.

Table 1
Power plants studied

Power plant	Case	Gross output MW	Capacity factor (%)	Net thermal efficiency ((HHV)%)	Plant lifetime years
Coal-fired		1000	70	36.8	30
Oil-fired		1000	70	36.2	30
LNG-fired		1000	70	37.2	30
LNGCC		1000	70	43.6	30
Nuclear	Base and future	1000	70	32.2	30
Hydro		10	45	–	30
Geothermal		55	60	–	30
Wind	Base	0.3	20	–	30
	Future	0.4	20	–	30
Solar-PV	Base and future	0.003	15	–	30

Future cases were also examined for nuclear, wind power and PV. Key parameters for future cases are also shown in Table 1.

3.2. Systems studied

Fig. 2 shows the systems studied as life cycle of electric power generation. The construction and operation in each stage (e.g. transportation, electricity generation) were examined. The decommissioning in each stage was excluded, except that decommissioning of the nuclear power plant was considered. Recycling of spent uranium fuels was examined as a future case of nuclear.

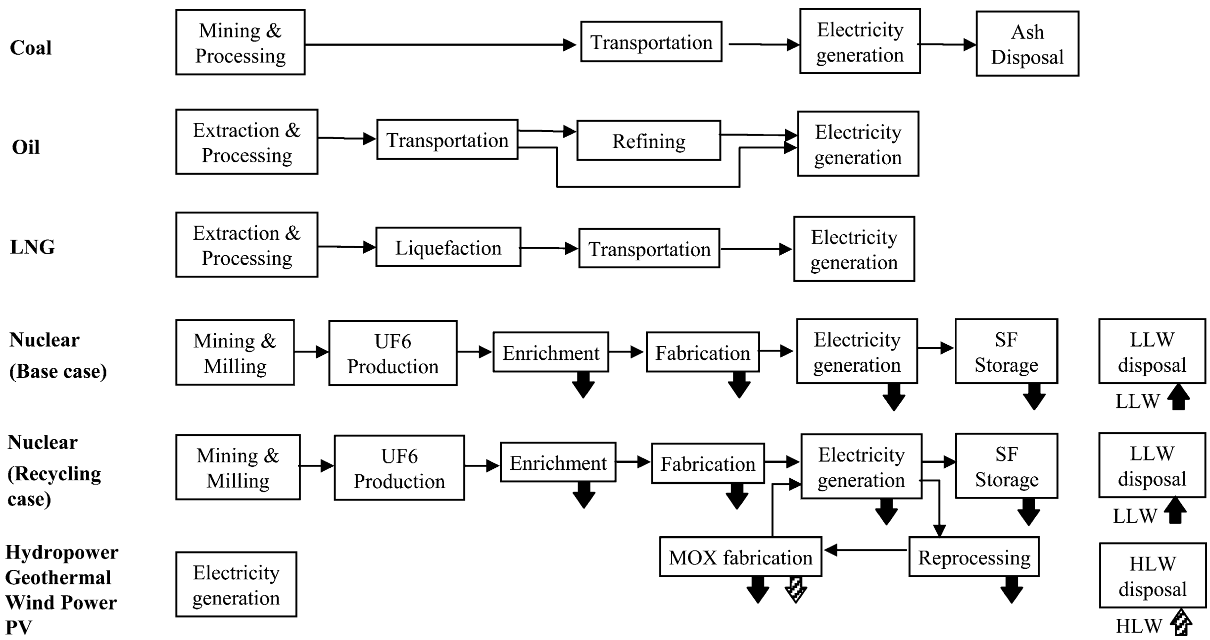

Fig. 2. Life cycle of electric power generation.

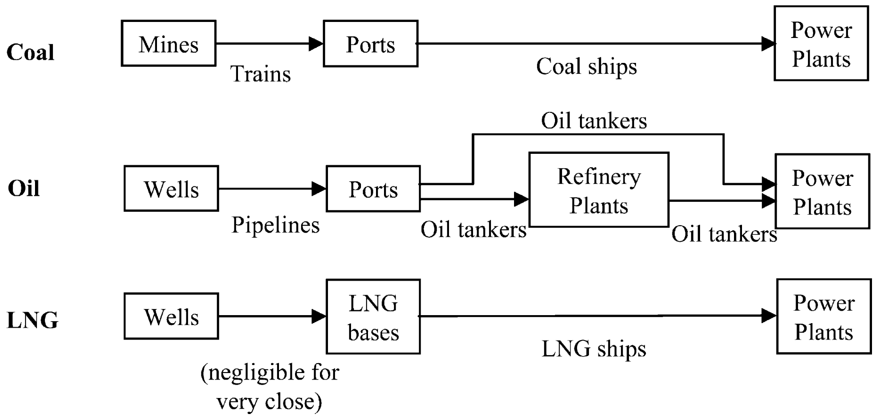

Fig. 3. Transportation of generation fuels from mines or wells to fossil fuel-fired power stations.

3.3. Fossil fuel-fired

The fossil fuel-fired systems can be divided into four stages as shown in Fig. 2. Imports of coal, crude oil and LNG required for generation were assumed to come from Australia, China, Indonesia and others. The import share was decided based on the current status in Japan. Methane leakage during the mining of coal as well as the extraction of oil and natural gas was considered. Assumptions regarding transportation of generation fuels from mines or wells to power plants are shown in Fig. 3. The coal- and oil-fired power plants were assumed to be typical Japanese plants. These use selective catalytic reduction (SCR) and flue gas desulphurization (FGD). LNG-fired and LNGCC power plants were assumed to be typical Japanese plants with SCR. Assumed thermal efficiency was an average value of all existing power plants. This analysis assumed that about half of ash generated after the combustion of coal was placed in a landfill, while the remaining ash was recycled for cement materials, etc.

3.4. Nuclear

The nuclear system can be divided into seven stages: mining, conversion, enrichment, fuel fabrication, generation, spent fuel (SF) storage and LLW disposal as shown in Fig. 2. Since direct disposal of spent fuel is not implemented in Japanese current energy policy, the base case includes stages through SF intermediate dry storage for 50 years, but excludes the SF disposal stage. The use of uranium mined in Canada and Australia was assumed. This analysis assumed that uranium was enriched using gaseous diffusion and centrifuge methods in the countries shown in Table 2. Table 2 indicates, for example, that 67% of uranium fuels (ton-U) for the studied plant is enriched using gaseous diffusion method in the United States of America. Re-conversion and fuel fabrication in Japan was assumed.

Table 2
Enrichment condition

Method	Gaseous diffusion		Centrifuge		
Country	USA	France	Japan	Netherland	UK
Share (%)	67	22	8	2	1

The power plant examined was a boiling water reactor (BWR) type with an enrichment of 3.4% and a burn-up of 40GWD/t-U. Decommissioning of the power plant was also examined. Low-level radioactive waste (LLW) associated with the operation of this system and the decommissioning of the power plant was considered. LLW was assumed to be stored without maintenance in near-surface waste disposal sites.

Recycling of spent uranium fuels were examined as a future case (Fig. 2). This analysis assumed that MOX fuel fabricated by reprocessing spent fuel was used only once. Reprocessing and MOX fabrication in Japan was assumed. High-level radioactive waste (HLW) was assumed to be disposed underground. Since a HLW disposal site cannot be identified, transportation of HLW was ignored. But the influence was negligible.

3.5. Hydropower

The hydropower plant studied was a run-of-river type with a small reservoir. The plant mainly consisted of a small concrete dam (2000 m^3 volume), a penstock (9000 m), a pressure pipe (490 m) and a powerhouse. The maximum intake to the powerhouse was 4.8 m^3/s.

3.6. Geothermal

The geothermal power plant studied was a double flash type. In addition to drilling of production wells and installing the plant, drilling of exploration wells was also considered. The analysis assumed five exploration wells dug to a depth of 1500 m. Fourteen production wells and seven re-injection wells dug to a depth of 1000 m. Failure of drilling was considered. During operation, an additional production well was drilled each year and an additional re-injection well was drilled every other year.

3.7. Wind power

A 300 kW type wind power plant was examined in the base case. This analysis assumed the wind power plant was installed at the relatively windy sites in Japan. In addition, a more sophisticated 400 kW type wind power plant was examined as a future case. This analysis assumed that both 300 and 400 kW types of wind turbines were installed in a small wind park with only a few wind turbines

This analysis assumed that electricity generated in wind power and PV plants can be delivered to the utility grid.

3.8. Solar-photovoltaic (PV)

Rooftop type PV (3 kW) systems were studied in both base and future cases. The base case assumed that PV cells use solar-grade (SOG) polycrystalline silicon. The assumed cell and system efficiencies are 17.0 and 10.0%, respectively. The reference yearly production rate of PV modules was assumed to be 10 MW/year. In addition to the base case, two future cases were examined. Future case 1 assumed that PV cells use the same SOG polycrystalline silicon as the base case and the production rate of PV cells was 1 GW/year. Future case 2 assumed that SOG amorphous silicon (a-Si) was used (system efficiency: 8.6%) and the production rate of a-Si cells was 1 GW/year.

4. Results

4.1. Fossil fuel-fired

Tables 3–5 show life cycle GHG emission factors (LCEs) and their breakdowns for coal-fired, oil-fired and LNG-fired and LNGCC generation, respectively. The vast majority of the CO_2 is emitted directly from the power plant when the fossil fuel is combusted. The direct emissions account for 91, 95 and 79% of the total emissions for coal-fired, oil-fired and LNG-fired (LNGCC), respectively. The share of indirect emission for LNG-fired (LNGCC) is relatively larger because of the three following reasons. First, a considerable amount of energy is required for liquefaction of natural gas. Since the ocean separates Japan from other countries, natural gas needs to be transported in the form of liquefied natural gas (LNG). Second, CO_2 included inherently in crude natural gas (NG) is released to the air when crude NG is refined. For example, crude NG extracted from gas wells in Indonesia includes a considerable amount of CO_2 (11 mol%). Third, CO_2 emissions from ocean transport for LNG are greater than for coal and oil transport. Since the speed of LNG ship is about 1.3 times faster than a coal ship or an oil tanker, the energy consumed for transport of LNG is greater.

Table 3
LCE for coal-fired power generation

	g-CO_2/kW h	Share (%)
Fuel combustion	886.8	90.9
Construction	3.6	0.4
Operation	32.0	3.3
Mining	9.7	1.0
Transport	15.6	1.6
Generation	6.7	0.7
Ash disposal	0.0	0.0
Methane leakage	52.9	5.4
Total	975.2	100.0

Table 4
LCE for oil-fired generation

	g-CO_2/kW h	Share (%)
Fuel combustion	704.3	94.9
Construction	2.3	0.3
Operation	35.2	4.7
Extraction	11.1	1.5
Fuel	6.7	0.9
Flare	4.4	0.6
Transport	6.7	0.9
Refinery	12.6	1.7
Generation	4.8	0.6
Methane leakage	0.3	0.0
Total	742.1	100.0

Table 5
LCEs for LNG-fired and LNGCC power generation

	LNG-fired		LNGCC	
	g-CO_2/kW h	Share (%)	g-CO_2/kW h	Share (%)
Fuel combustion	477.9	78.7	407.5	78.5
Construction	2.9	0.5	2.7	0.5
Operation	117.7	19.4	100.9	19.5
LNG production				
Fuel	67.6	11.1	57.7	11.1
CO_2 in Crude NG	26.2	4.3	22.3	4.3
Transport	19.4	3.2	16.5	3.2
Generation	4.5	0.7	4.5	0.9
Methane leakage	9.1	1.5	7.7	1.5
LNG production	9.1	1.5	7.7	1.5
Total	607.6	100.0	518.8	100.0

4.2. Nuclear

As shown in Table 6, enrichment accounts for 62% of the total emissions from nuclear in the base case. 67% of uranium fuel used in Japan is enriched using the gaseous diffusion method in the USA (Table 2). The gaseous diffusion method requires a considerable amount of electricity for enrichment of uranium. In addition, since coal has a large share of utility power generation in the USA, the CO_2 emission factor of average electricity in the USA is relatively larger compared with other countries. Therefore, the CO_2 emissions from the enrichment process are dominant.

Table 6 also shows the result of the recycling case. The LCE for the recycling case is almost same as the base case despite the fact that the four following processes are added within

Table 6
LCEs for nuclear power generation (base and recycling cases)

	Base case		Recycling case	
	g-CO_2/kW h	Share (%)	g-CO_2/kW h	Share (%)
Construction	2.8	11.7	3.2	14.3
Operation	20.9	86.6	18.5	83.7
Mining and Milling	1.1	4.5	0.9	4.0
Conversion	0.2	0.9	0.2	0.9
Enrichment	15.0	61.9	12.4	55.8
Fuel fabrication	0.7	2.8	0.6	2.8
Reprocessing	–	–	0.7	3.2
MOX fabrication	–	–	0.0	0.2
Fuel transport	0.0	0.2	0.0	0.2
Generation	3.2	13.1	3.2	14.3
Spent fuel storage	0.7	2.9	0.2	1.0
LLW transport and dispoal	0.1	0.3	0.1	0.4
HLW storage and disposal	–	–	0.2	1.0
Decommissioning	0.4	1.8	0.5	2.0
Total	24.2	100.0	22.2	100.0

Table 7
LCE for hydropower generation

	g-CO_2/kW h	Share (%)
Construction	9.3	82.8
Machinery	0.9	8.0
Dam	0.5	4.5
Penstock	4.5	39.8
Other foundations	2.4	21.0
Site construction	1.1	9.6
Operation	1.9	17.2
Total	11.3	100.0

the system: reprocessing, MOX fabrication, HLW storage and HLW disposal. CO_2 emissions from these additional processes account for 6.4% (1.9, 4.4 and 0.1% for the construction, operation and decommissioning, respectively) of the total emissions. On the other hand, since uranium and plutonium extracted from spent fuels can be used, the necessary amount of primary uranium fuels decrease. As a result, the decrease of CO_2 emissions from the enrichment process is slightly larger than the increase from additional processes.

4.3. Hydro, Geothermal, wind, PV

Tables 7–10 indicate LCEs and their breakdowns for hydro, geothermal, wind power and PV, respectively. The construction of these power plants accounts for approximately 70–80% of total emissions except for geothermal. CO_2 emissions associated with the production of steel and concrete for the foundations are dominant with regard to hydro and wind power. More than half of the total emissions for PV is generated by the production of the PV panel. For geothermal, a greater amount of CO_2 is emitted during operation compared to construction. This is because considerable CO_2 emissions are associated with digging additional wells and with manufacturing and replacing hot water heat exchanger pipes.

Table 9 also shows the results of the future case for wind assuming the use of a sophisticated 400 kW type. The LCE for the 400 kW type is smaller by 28% than the base case, primarily because the per kW h quantity of materials required for each power plant is almost the same, although the outputs are different.

Table 8
LCE for geothermal power generation

	g-CO_2/kW h	Share (%)
Construction	5.3	35.3
Foundations	2.0	13.2
Machinery	3.2	21.2
Exploration	0.1	0.9
Operation	9.7	64.7
Drilling of additional wells	2.9	19.6
General maintenance	2.3	15.1
Exchange of equipment	4.5	30.0
Total	15.0	100.0

Table 9
LCEs for wind power generation (base and future cases)

	Base case		Future case	
	g-CO_2/kW h	Share (%)	g-CO_2/kW h	Share (%)
Construction	21.2	71.9	14.2	69.8
Foundations	7.4	25.1	4.0	19.4
Blades	1.4	4.8	1.3	6.3
Nacelle	5.9	20.0	3.3	16.3
Tower	3.4	11.7	3.7	18.1
Turbine, etc.	3.0	10.3	2.0	9.7
Operation	8.3	28.1	6.1	30.2
Total	29.5	100.0	20.3	100.0

Table 10 also indicates the results of two PV future cases. In the case that the production rate of PV cells is 1 GW/year, the LCE is smaller by 18% compared to the base case. Large-scale production could decrease the amount of energy and materials required per unit of PV cells. The LCE for the second future case, assuming the use of a-Si cell, is 26 g-CO_2/kW h. The CO_2 emissions from PV panels greatly decrease compared to the base case, since the amount of silicon required for a PV cell using a-Si is much less than a PV cell using p-Si.

4.4. Life cycle CO_2 emission factors for different types of power generation systems

Fig. 4 summarizes life cycle GHG emission factors for different types of power generation systems. It is shown that GHG emissions using fossil fuel are significantly greater than GHG emissions using nuclear or renewable from a life cycle perspective. When comparing among non-fossil systems, however, the effect of changes to assumptions on LCEs should be analyzed. In Section 4.5, uncertainty analysis on changes to assumptions will be performed for an appropriate interpretation of the reference values shown in Fig. 4.

4.5. Uncertainties

4.5.1. Fossil fuel-fired

Both an increase and a decrease in thermal efficiency were examined. Thermal efficiencies for coal-, oil-, LNG-fired and LNGCC were 39.6, 38.4, 38.9 and 44.6% in the base case, respectively.

Table 10
LCEs for PV power generation (base and future cases)

	Base case		Future case 1		Future case 2	
	g-CO_2/kW h	Share (%)	g-CO_2/kW h	Share (%)	g-CO_2/kW h	Share (%)
Construction	41.1	76.9	33.7	76.9	20.0	76.9
PV panel	28.3	53.0	21.0	47.8	6.8	26.2
Support	9.8	18.3	9.8	22.3	10.2	39.3
Others	3.0	5.6	3.0	6.8	3.0	11.4
Operation	12.3	23.1	10.1	23.1	6.0	23.1
Total	53.4	100.0	43.9	100.0	26.0	100.0

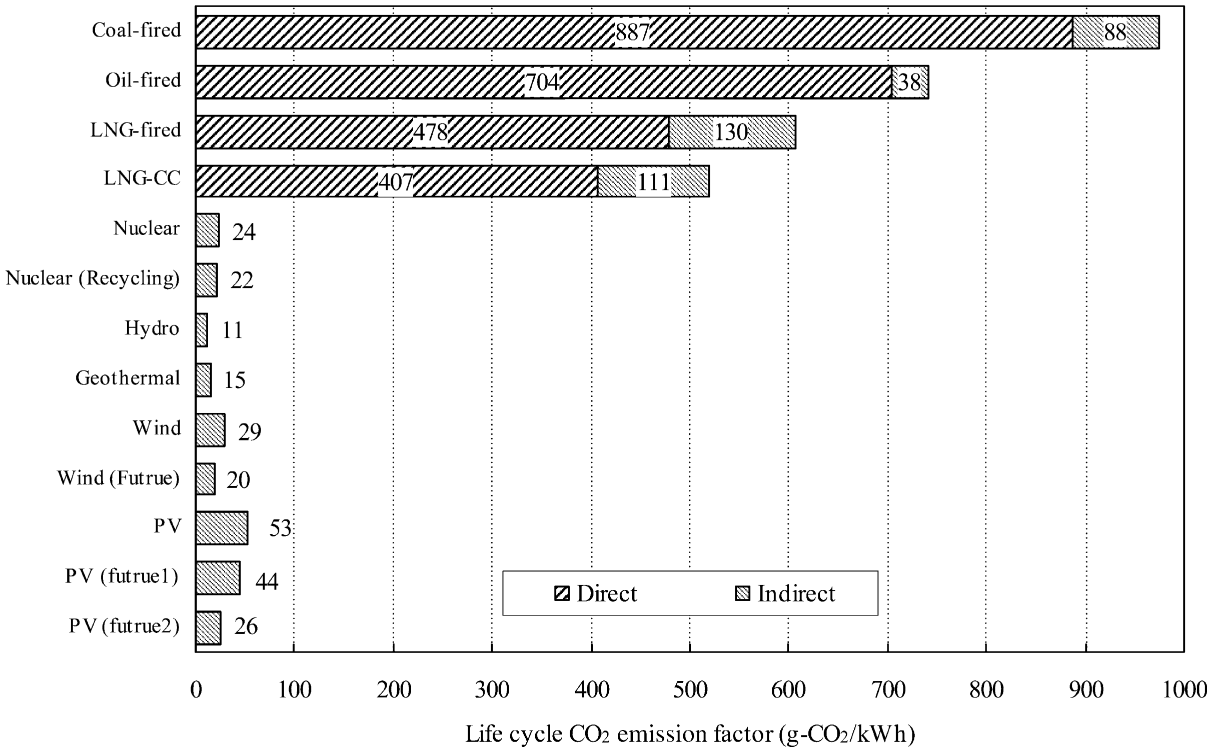

Fig. 4. Life cycle CO_2 emission factors for different types of power generation systems.

Table 11 gives the results when thermal efficiency varies from −3 to +3 points to the above values. Real variations of thermal efficiency do not change the order of coal-, oil-, and LNG-fired plant emissions as shown in Fig. 4. Likewise, real variations of CO_2 emission factors for fossil fuels (coal, oil, LNG) as well as a change in the assumed fossil fuel market share of any importing country does not influence the order.

4.5.2. Nuclear

The changes of enrichment conditions greatly influence LCEs for nuclear generation. Both base and recycling cases assume the enrichment condition as shown in Table 2. When all uranium fuels are enriched using gaseous diffusion method in the USA, the LCEs for base and recycling cases increase to 30 and 27 g-CO_2/kW h, respectively (Table 12). On the other hand, when all uranium fuels are enriched

Table 11
Effects of thermal efficiencies on LCEs (g-CO_2/kW h)

	−3 pts	−2 pts	−1 pt	Reference	+1 pt	+2 pts	+3 pts
Coal	1061	1031	1002	975	950	925	902
Oil	809	785	763	742	722	704	686
LNG	660	642	624	608	592	577	563
LNFCC	557	543	531	519	507	496	486

Table 12
Effects of enrichment conditions on LCEs (g-CO_2/kW h)

	Reference (Table 6)	Centrifuge Japan	Gas diffusion USA
Base case	24	10	30
Recycling case	22	11	27

Table 13
Effects of intermediate storage and final disposal of spent fuels on LCEs (g-CO_2/kW h)

	50 years (reference)	50 years + final disposal	200 years	200 years + final disposal
Base case	24.2	24.4	26.6	26.9
Recycling case	22.2	22.3	23.0	23.1

using the centrifuge method in Japan, the LCEs for base and recycling cases decrease to 10 and 11 g-CO_2/kW h, respectively (Table 12).

Both base and recycling cases assume that spent fuel (SF) is stored for 50 years. Final disposal was not considered in the both cases, reflecting Japanese energy policy. Table 13 shows the influence of long-term intermediate storage and final disposal on the LCEs. Final disposal of SF has little effect on LCEs. On the other hand, when SF is stored for 200 years and then the final disposal of SF is implemented, the LCEs become greater by about 10% than the reference values. The primary factor of this change is the increase of electricity consumption associated with extending intermediate storage.

4.5.3. Renewables

The LCEs for renewables generation depend greatly on the assumption of lifetimes and capacity factors. Table 14 shows the influences of lifetimes on the LCEs for hydropower, geothermal, wind power and PV generations. Table 15 shows the effects of capacity factors on the LCEs.

Additionally, the influence of the surrounding topography on LCE for hydropower generation was examined. LCE significantly varies depending on the location and type of a power plant. These factors greatly influence the amount of steel and concrete required for construction. LCEs for existing 369 plants

Table 14
Effects of lifetimes on LCEs (g-CO_2/kW h)

Lifetime (year)	Reference				
	10	20	30	50	100
Hydropower	30	16	11	8	5
Geothermal	26	18	15	13	11
Wind power (base)	72	40	29	21	15
Wind power (future)	49	27	20	15	10
PV (base)	136	74	53	37	25
PV (future 1)	111	61	44	30	20
PV (future 2)	66	36	26	18	12

Table 15
Effects of capacity factors on LCEs (g-CO_2/kW h)

Capacity factors	−10 pts	−5 pts	Reference	+5 pts	+10 pts
Hydropower	14	13	11	10	9
Geothermal	18	16	15	14	13
Capacity factors	−5 pts	−3 pts	Reference	+3 pts	+5 pts
Wind power (base)	39	35	29	26	24
Wind power (future)	27	24	20	18	16
PV (base)	80	67	53	45	40
PV (future 1)	66	55	44	37	33
PV (future 2)	39	32	26	22	19

(10–100 MW) in Japan were calculated using the developed model (plant life: 30 years; capacity factor: 45%). As a result, it was found that LCEs for 92% of the studied plants varied from 6 to 30 g-CO_2/kW h.

When a hydro reservoir is constructed, the newly flooded biomass will decay and the decomposition of this biomass will gradually produce some greenhouse gases. The present analysis did not consider the GHG emission associated with this process. Gagnon and van de Vate [11] discuss that the GHG emission may significantly influence LCEs for hydropower with reservoirs. According to [11], for examples, the two research programmes in Finland and Canada report that the emissions from decaying flooded biomass are 65–72 and 34 g-CO_2 equivalent/kW h, respectively. The amount of GHG emission associated with the decomposition of flooded biomass is site-specific and would have a great deal of uncertainty.

5. Conclusions

The present paper gives the results of greenhouse gas emission analyses on nine different power generation technologies from a life cycle perspective. The GHG emission characteristics of each technology from the perspective of global warming can be discerned from this analysis. Additional analyses on the impacts of emerging and future technologies as well as the influences of changes of various assumptions are helpful for a better understanding. When comparing between technologies, it is especially important to interpret the results while considering the effects associated with these uncertainties. The results obtained by this study could provide valuable information to select power generation technologies in the future. But it should be noted that the results show the characteristics only from the viewpoint of global warming. Further analysis is required to evaluate the power generation technologies from other environmental as well as economic and safety aspects.

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