Case Studies

Development of Life Cycle Inventories for Electricity Grid Mixes in Japan

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Abstract. Since most industrial processes consume electricity, it is quite important to develop reliable inventory data for electricity. There is, however, a problem that only a few figures concerning emissions related to electricity have been reported. In this work, process models of power plants were developed for the Japanese situation which simulate the mass flows and estimate the missing figures of emissions dependent on technical parameters of the plants and fuels. In Japan, electricity is supplied to the various regions by 10 electric companies. Therefore, life cycle inventories for the electricity grid mixes of the 10 electric companies in 1997 were developed. The functional unit is 1 kWh of electricity distributed to electricity users in each region. The emission of CO_2, SO_2, NO_x, CH_4, CO, non-methane volatile organic compound (NMVOC), dust (all particulates) and heavy metals (Ni, V, As, Cd, Cr, Hg, Pb, Zn) from power stations as well as those from fuel production and transport were investigated. Other pollutants into air, emissions to water, solid wastes, radiation and radioactive emissions from atomic power stations were not included due to a limitation of the available data. Direct CO_2 emissions related to 1 kWh of electricity distributed by companies ranged from 0.21 to 1.0 kg/kWh (average value: 0.38 kg/kWh). Direct emissions of SO_2 and NO_x from power stations related to 1 kWh of electricity are $2.5*10^{-4}$ and $2.2*10^{-4}$ kg/kWh on the average, respectively. SO_2 emissions calculated in this work were somehow large compared with those reported by electric companies. Detailed information concerning total sulfur content in oil consumed in each oil-fired power station are required for an exact calculation of SO_2 emissions from oil-fired power stations. In addition, the ratio of sulfur that goes into slag in combustion must be investigated further. The average amounts of CO, CH_4, NMVOC and dust emissions were $5.0*10^{-5}$, $8.2*10^{-6}$, $1.8*10^{-5}$ and $6.8*10^{-6}$ kg/kWh, respectively. Heavy metal emissions from power stations were on the order of 10^{-9} to 10^{-8} kg/kWh. Detailed information concerning heavy metal content in oil and coals consumed in fossil fuel power stations are further required for an improved assessment of heavy metal emissions. Contribution of fuel production and transport to total CO_2 emission was relatively small. On the other hand, contributions of fuel production and transport to total SO_2 and NO_x emissions were relatively large. In the case of CO, NMVOC and dust, emissions in fuel production and transport were predominant to total emissions. Heavy metal emissions into air during production and transport of fuels were on the order of 10^{-8} to 10^{-9} kg/kWh.

Keywords: Air pollutants; electricity grid mixes; heavy metals; Japan; life cycle inventory

Introduction

In accordance with progress in the standardization of methodologies in the ISO-14040s, life-cycle assessment (LCA) has received much attention in Japanese industries. Most industrial processes consume electricity. It is often found that electricity consumed during use of electrical appliances predominates in the total primary energy consumption and emissions of these products' life cycles [1-2]. Thus, the results of inventory analyses of industrial products are usually sensitive to data on electricity. So, it is quite important for LCA practitioners to develop reliable life-cycle inventories (LCI) for electricity. There is, however, a problem that only a few figures concerning emissions related to electricity have been reported. One solution is to develop process models for power plants which simulate the mass flows and estimate the missing figures of emissions dependent on technical parameters of the plants and fuels. In this work, process models of power plants were developed for the Japanese situation. Data concerning technical parameters of the plants and fuels were collected.

In Japan, electricity is supplied to the various regions by 10 electric companies. They are Hokkaido Electric Co., Tohoku Electric Co., Tokyo Electric Co., Chubu Electric Co., Hokuriku Electric Co., Kansai Electric Co., Chugoku Electric Co., Shikoku Electric Co., Kyushu Electric Co. and Okinawa Electric Co. These 10 electric companies have their own power stations to generate electricity. In addition, there are some independent electric companies which generate and supply electricity to these 10 electric companies [3]. So, the electricity distributed by 10 electric companies is the mixture of electricity generated by themselves and that from independent electric companies.

In this work, life-cycle inventories (LCI) for the electricity grid mixes of these 10 electric companies in 1997 were developed.

1 Goal and Scope

The goal of this study is to develop LCIs for the electricity grid mixes of 10 electric companies in Japan in 1997. The functional unit is 1 kWh of electricity distributed to electricity users in each region.

The scope of this work is emissions of CO_2, NO_x, SO_2, CH_4, CO, non-methane volatile organic compound (NMVOC), dust (all particulates) and heavy metals (Ni, V, As, Cd, Cr, Hg, Pb, Zn). Other pollutants into air, emissions to water, solid wastes were not included in the scope of this study due to a limitation of the available data. Radiation and radioactive emissions from atomic power stations were not investigated either, which was due to a limitation of available data.

System boundaries of this work were processes in power stations, i.e. fuel combustion and abatement technologies, electric power distribution, and processes related to fuels. Coal, crude oil, natural gas mining and their transport were included. The production of heavy oil, blast furnace gas (BFG) and coke oven gas (COG) were also included. Refining of uranium for atomic power was also included. Processes related to facilities, i.e. construction of power stations, refineries, tankers, were excluded because emissions related to constructing these facilities are usually relatively negligible compared with those from operation if the average lifetime of these facilities is considered [4]. In fossil fuel power stations, fuels are burned to obtain thermal energy that is converted to electricity in succeeding processes. In the combustion of these fuels, some substances are generated and emitted. On the other hand, direct emissions from hydropower and atomic power stations are negligible compared with those from fossil fuel power stations. Therefore, direct emissions from hydropower and atomic power stations were not considered.

Direct emissions from fossil fuel power stations depend on fuel characteristics, energy conversion efficiency, inside electricity consumption, cover ratio of abatement technologies and their efficiencies in power stations. The data concerning the amount of fuels and their characteristics that most of the fossil fuel power stations in Japan consumed in 1997 were shown in the literature [3]. Net electricity production of the fossil fuel power stations in 1997 was also shown in the literature [3]. However, the literature did not contain the data concerning gas turbine power stations in 10 electric companies and that located in isolated islands. So, these power stations were not included in the scope of this work. Representativeness of fossil fuel power stations investigated in this work is shown in **Table 1**.

There is some exchange of electricity between electric companies. In some companies, the amount of exchange of electricity is up to 10% of the total net electricity production of an electric company [3]. This may cause some effect on emission intensities for each electric company. However, exchange of electricity between electric companies was not investigated in this work.

2 Methodologies for Calculating Direct Emissions from each Power Station

To calculate standard emissions and heavy metal emissions from power stations, the following methodologies were used.

2.1 CO_2

CO_2 emissions from fossil fuel power stations depend on characteristics of fuels and their amount. The types of fossil fuels and their amount that were consumed to generate 1 kWh of electricity (net electricity production base) in each power station were identified with the literature [3]. CO_2 emission intensity (kg-CO_2/kWh) of each power station was calculated by the following equation:

CO_2 emission intensity (kg-CO_2/kWh) (eq. 1)
= CO_2 emission coefficient (kg-CO_2/kg-fuel) × amount of fuel consumed to produce 1 kWh of electricity (kg-fuel/kWh)

CO_2 emission coefficient for coal depends highly on the heat capacity of coal. In this work, CO_2 emission coefficients for coals were calculated with the following equation [5]:

CO_2 emission coefficient of coal (kg-CO_2/kg-coal) (eq. 2)
= 0.201 + 0.087 × net calorific value of coal (MJ/kg-coal)

CO_2 emission coefficients for other fuels, i.e. heavy oil, crude oil, liquefied natural gas (LNG), blast furnace gas (BFG), coke oven gas (COG), converter gas (MXG), were obtained in the literature [6].

2.2 SO_2

SO_2 emissions from fossil fuel power stations depend on total sulfur content of fuels, cover ratio of desulfurizers in power stations and their efficiencies.

Table 1: Net electricity production in fossil fuel power stations in 10 electric companies; actual values and those investigated in this work

Electric company	(a) Actual net electricity production (10^6kWh)	(b) Net electricity production investigated in this work (10^6kWh)	(b)/(a) (%)
Hokkaido Electric Co.	15709	15676	99.8
Tohoku Electric Co.	58180	55301	95.1
Tokyo Electric Co.	139036	133039	95.7
CHUBU Electric Co.	80464	80018	99.4
Hokuriku Electric Co.	14775	14434	97.7
Kansai Electric Co.	48483	46101	95.1
Chugoku Electric Co.	45145	43938	97.3
Shikoku Electric Co.	14819	14703	99.2
Kyushu Electric Co.	32400	29028	89.6
Okinawa Electric Co.	6434	5887	91.5

Coal, crude oil and heavy oil were the main fuel that fossil fuel power stations consumed in 1997 [3]. Thus, the total sulfur content of these three fuels was investigated in this work. Total sulfur content of coals that each coal-fired power station in Japan consumed in 1997 was calculated using information found in the literature [7-9], which is shown in **Table 2**. Total sulfur content of crude oil that each electric company consumed in 1997 was calculated from the information in the literature [3,10], which is shown in **Table 3**. Data concerning total sulfur content of heavy oil that each electric company consumed in 1997 were not available. Thus, the average value, 0.81 wt%, was used as the total sulfur content of heavy oil consumed in each fossil fuel power station according to the literature [3].

In this work, all sulfur in the fuel was assumed to be transformed to SO_2 during combustion. Then, SO_2 emission intensity (kg-SO_2/kWh) from each power station based on net electricity production was calculated using the following equation:

SO_2 emission intensity (kg-SO_2/kWh)

$$= \frac{(TFC) \times (TSC) \times (M_{SO2}/M_S) \times (1 - E_{f.SO2} \times P_{equipped} / P_{total})}{(NEP)} \quad \text{(eq. 3)}$$

TFC: Total fuel consumption in each power station in 1997 (kg), TSC: Total sulfur content of fuels that each power station consumed (wt%), M_{SO2}: molecular weight of SO_2 (32 g), M_S: molecular weight of sulfur (16 g), $E_{f.SO2}$: efficiency of desulfurizer (%), $P_{equipped}$: power of the electric generators that are equipped with desulfurizer (MW), P_{total}: total power of the electric generators in each power station, NEP: net electricity production in each power station (kWh)

Table 2: Characteristics of coals consumed in each coal-fired power station

Electric company	Coal-fired power station	Sulfur content (wt%)	Ash content (wt%)	Origin
Hokkaido	Sunagawa	0.20	26	Domestic coal
	Naie	0.22	30	Domestic coal
	Other	0.57	14	Import coal mixture
Tohoku	All	0.73	14	Import coal mixture
Chubu	Hekinan	0.66	12	Import coal mixture
Hokuriku	All	0.57	9.4	Import coal mixture
Chugoku	All	0.63	12	Import coal mixture
Shikoku	Nishijo	0.71	13	Domestic/ Import coal mixture
Kyushu	Omura	0.80	37	Domestic coal
	Others	0.63	14	Domestic/ Import coal mixture
Okinawa	Gushigawa	0.49	10	Import coal mixture
Dengenkaihatsu	Isogo	0.48	14	Domestic coal
	Takasago	1.5	20	Domestic coal
	Takehara	0.68	12	Domestic/ Import coal mixture
	Others	0.49	10	Import coal mixture
Jouban Kyodo	Nakoso	0.55	13	Domestic/ Import coal mixture
Sumitomo Kyodo	All	0.45	13	Import coal mixture
Souma Kyodo	Shinchi	0.53	10	Import coal mixture
Sakata Kyodo	Sakata	0.73	14	Import coal mixture
Toyama Kyodo	Toyama	0.62	10	Domestic/ Import coal mixture

Table 3: Total sulfur, V and Ni content in crude oil consumed in each electric company

Electric company	Total sulfur (w%)	V (ppm)	Ni (ppm)
Hokkaido	0.089	2.4	1.6
Tohoku	0.090	0.38	1.1
Tokyo	0.085	3.4	4.6
Chubu	0.079	2.5	4.8
Hokuriku	0.13	1.1	12
Kansai	0.080	4.2	2.7
Chugoku	0.15	0.53	17
Shikoku	0.17	1.1	22
Kyushu	0.11	3.2	11
Sumitomo Cooperative	0.04	0.05	0.05

Data about the efficiency of desulfurizer were obtained in the literature [11]. Powers of the electric generators that were equipped with desulfurizer were calculated with the literature [11], whereas the total powers of the electric generators in each power station were obtained in the literature [3]. Net electricity production in each power station was also obtained in the literature [3].

2.3 NO_x

NO_x emissions from fossil fuel power stations consist of fuel NO_x and thermal NO_x [12]. NO_x emissions from fossil fuel power stations depend on nitrogen content of fuels, temperature inside the boilers in power stations, cover ratio of denitrification facilities in power stations and their efficiencies. Since data concerning nitrogen content of fuels and temperature inside the boilers in power stations were not available, the literature values for NO_x formation factors in the boilers in each type of fossil fuel power station were adopted in this work [13]. These values indicated the amount of NO_x formation per total (lower) heating value of the fuels that were consumed in boilers in European power stations. Thus, these NO_x formation factors might not necessarily reflect the actual condition of boilers in Japanese power stations.

NO_x emission intensity (kg - NO_x /kWh) from each power station was calculated by the following equation:

NO_x emission intensity (kg - NO_x /kWh)

$$= \frac{(TLHF)\times(NOxFC) \times (1 - E_{f.Nox} \times P_{equipped} / P_{total})}{(NEP)} \qquad \text{(eq. 4)}$$

TLHF: total net heating value of the fuels that were consumed in each power station in 1997, NO_xFC: NO_x formation factor in the boilers in each type of power station, $E_{f.NOx}$: efficiency of denitrification facilities (%), $P_{equipped}$: power of the electric generators that are equipped with denitrification facilities (MW), P_{total}: total power of the electric generators in each power station, NEP: net electricity production in each power station (kWh)

Total net heating values of the fuels that were consumed in each power station in 1997 were calculated using information found in the literature [3]. Powers of the electric generators that were equipped with denitrification facilities were calculated using information found in the literature [11], whereas the total powers of the electric generators in each power station were obtained in the literature [3]. The efficiency of denitrification facilities was assumed as 80% according to the literature [12]. Net electricity production in each power station was also obtained in the literature [3].

2.4 Non-methane volatile organic compound (NMVOC), CH_4, CO

The literature values for NMVOC, CH_4 and CO emission factors from each type of fossil fuel power station were adopted in this work [14-16]. These values indicated the emissions of these substances per total (net) heating value of the fuels that were consumed in European fossil fuel power stations, which are shown in **Table 4**. These emission factors might not necessarily reflect the actual condition of boilers in Japanese power stations. As they are shown in Table 4, these emission factors vary to some extent. Thus, average values as well as minimum and maximum values were adopted in this work to show the variability of the emissions.

Table 4: Emission factors for non-methane hydrocarbon (NMHC), CH_4 and CO in each fired power plant (kg/TJ)

Power plant	NMVOC	CH_4	CO
Coal fired power plant	0.4–4 (2)	0.04–2 (1)	3–20 (13)
Oil fired power plant	3–8 (3.5)	3–8 (3.5)	4–20 (15)
LNG fired power plant	2–8 (4)	0.04–2 (1)	1.5–80 (5)
Top-gas fired power plant	2–8 (4)	0.04–2 (1)	1.5–80 (5)

*) Values in ( ) are average values

Emission intensity for NMVOC, CH_4 and CO (kg substance / kWh) from each power station based on net electricity production was calculated by the following equation:

Emission intensity (kg substance /kWh) (eq. 5)
= (emission factor (kg/TJ)) × (Total net heating values of the fuels that were consumed in each power station (TJ)) / (Net electricity production of each power station)

Total net heating values of the fuels that were consumed in each power station in 1997 were calculated using information found in the literature [3]. Net electricity production in each power station was also obtained using information found in the literature [3].

2.5 Dust (all particulates)

Dust emissions from coal-fired power stations and oil-fired power stations were investigated in this work. Dust emissions from LNG-fired power stations, BFG-fired power stations, COG-fired power stations and MXG-fired power stations are usually negligible, which were not investigated in this work. Dust formations in oil-fired power stations were correlated with total sulfur content in oil consumed in oil-fired power stations, which is shown in the following equation [17]:

Dust formation (g /liter-oil consumed in oil power station) (eq. 6)
= 0.38 + 1.25 × (sulfur content in oil (wt%))

According to this equation, dust formations from oil-fired power stations were calculated. Concerning total sulfur content of heavy oil consumed in each oil-fired power station, the average value, 0.81 wt%, was used [3]. Total sulfur content of crude oil that each electric company consumed in 1997 is shown in **Table 3**.

Electrostatic precipitators are equipped in most oil-fired power stations in Japan to reduce dust emissions. The efficiency of electrostatic precipitators that were equipped in oil-fired power stations was considered as 80% [18]. In addition, some of the oil-fired power stations are equipped with desulfurizer. Dust emissions would be further reduced with desulfurizer. The reduction rate of dust emissions by desulfurizer was assumed to be 90% according to the literature [19]. Thus, dust emission intensity in oil-fired power stations were calculated with the following equation:

Dust emission intensity in oil-fired power stations (g-dust / kWh), in cases where power station is not equipped with desulfurizer

$$= \frac{1.25 \times (SCO) \times (TOC) \times (1\text{-}0.8)}{(NEP)} \qquad \text{(eq. 7)}$$

Dust emission intensity in oil-fired power stations (g-dust / kWh), in case power station is equipped with desulfurizer

$$= \frac{1.25 \times (SCO) \times (TOC) \times (1\text{-}0.8) \times (1\text{-}0.9)}{(NEP)} \quad \text{(eq. 8)}$$

SCO: total sulfur content in oil consumed in each oil-fired power station (wt%), TOC: total oil consumption in each oil-fired power station (liter), NEP: net electricity production in each power station (kWh)

Total oil consumption in each oil-fired power station, net electricity production in each power station and cover ratio of desulfurizer in power stations were obtained in the literature [3,11].

Dust from coal-fired power station mainly consists of fly ash that is formed from coal ash during combustion [12]. Ash content in coal consumed in coal-fired power stations was calculated using information found in the literature, which is shown in **Table 2** [3,7-9]. In this work, dust formations form coal-fired power stations were calculated with the assumption that 50% of coal ash would go into fly ash and the rest of coal ash would remain in slag [12].

Electrostatic precipitators are equipped in most coal-fired power stations in Japan to reduce dust emissions. The efficiency of electrostatic precipitators in coal-fired power stations was considered as 99.5% according to the literature [18]. In addition, some of the coal-fired power stations were equipped with desulfurizer. Dust emissions will be further reduced with desulfurizer. The reduction rate of dust emissions by desulfurizer was assumed as 90% according with literature [19]. Thus, dust emission intensity in coal-fired power stations were calculated with the following equation:

Dust emission intensity in coal-fired power stations (kg-dust /kWh), in case power station is not equipped with desulfurizer

$$= \frac{(AshC) \times (TCC) \times 0.5 \times (1\text{-}0.995)}{(NEP)} \quad \text{(eq. 9)}$$

Dust emission intensity in coal-fired power stations (kg-dust /kWh), in case power station is equipped with desulfurizer

$$= \frac{(AshC) \times (TCC) \times 0.5 \times (1\text{-}0.995) \times (1\text{-}0.9)}{(NEP)} \quad \text{(eq. 10)}$$

AshC: ash content in coal consumed in each coal-fired power station (wt%), TCC: total coal consumption consumed in each coal-fired power station (kg), NEP: net electricity production in each power station (kWh)

2.6 Heavy metals

Heavy metal emissions from coal-fired power stations and oil-fired power stations were investigated in this work. Heavy metal emissions from LNG-fired power stations were not investigated. Natural gas usually contains small amounts of mercury that is corrosive to certain metals. Mercury in natural gas is removed with sulfur-impregnated activated carbon before it goes into the liquefaction process to avoid the corrosion of the facilities. So, the mercury in LNG could be considered as negligible [20]. Heavy metal emissions from BFG-fired power stations, COG-fired power stations and MXG-fired power stations were also not investigated due to a lack of information.

Heavy metal emissions from fossil fuel power station depend on the amount of fuel consumed in power stations and their heavy metal contents. Data concerning heavy metal (Ni, V, As, Cd, Cr, Hg, Pb, Zn) contents in coals in various countries were obtained from the literature [21]. According to the literature, heavy metal contents in coals usually vary significantly even in the same coal [21,22]. Thus, mean values of heavy metal contents in coals were used in this work. They are shown in **Table 5**. Country share rate of coals that coal fired power stations consumed in 1997 were calculated using information found in the literature, which is shown in **Table 6** [3,7,8]. Then, heavy metal content in coals consumed in coal-fired power stations was calculated.

Table 5: Heavy metals in coals (ppm)

Country	As	Cd	Cr	Hg	Ni	Pb	V	Zn
Australia	2	0.1	10	0.1	10	10	20	20
Canada	10	0.5	20	0.1	20	30	40	50
China	5	0.5	30	0.1	50	40	50	50
Indonesia	10	0.5	20	0.1	20	40	40	50
Japan	10	0.5	20	0.1	20	40	40	50
U. S. A.	15	0.5	20	0.2	20	15	35	20
Republic of South Africa	3	0.01	100	0.2	20	10	50	30
Russia	10	0.5	20	0.1	20	40	40	50

Concerning the data about heavy metal contents in crude oil consumed oil-fired power stations, only Ni and V could be obtained from the literature [10]. According with the country share rate of crude oil that electric company imported in 1997, heavy metal contents in crude oil were calculated [3].

In the combustion of fuel, heavy metals in fuel would be transferred to exhaust gas from boilers. Some of the heavy metals in exhaust gas would be trapped by electrostatic precipitators and desulfurizers. Then, the rest of heavy metals would be emitted into air. Trap ratio of heavy metals in electrostatic precipitators and desulfurizers were obtained from the literature, which are shown in **Table 7** [19,22,23]. Cover ratio of desulfurizers in power stations were obtained from the literature [11]. Then, heavy metal emission intensity from power stations was calculated with heavy metal contents in fuel, fuel consumption per 1 kWh of electricity in each power station and trap ratio of heavy metals.

3 Emissions During Fuel Production and Transport

Emissions during fuel production and transport were investigated by authors [20]. Coal, crude oil, natural gas mining and their transport were included. Refining of uranium for atomic power was also investigated. The country share rate of each fuel that electric companies imported was reflected. This work will be submitted to this journal in the near future.

Table 6: Country share rate of coals consumed in each coal-fired power station

Electric company	Coal-fired power station	Country share (%)							
		Japan	Australia	Canada	China	Republic of South Africa	U.S.A.	Russia	Indonesia
Hokkaido	Sunagawa	100	0	0	0	0	0	0	0
	Naie	100	0	0	0	0	0	0	0
	Others	0	65	11	5.2	3.1	0	16	0
Tohoku	All	0	68	10	16	0	6.4	0	0
Chubu	Hekinan	0	51	11	21	0	9.4	0	6.7
Hokuriku	All	0	46	0	0	18	0	0	37
Chugoku	All	0	55	17	13	9.8	3.6	0	1.8
Shikoku	Nishijo	10	74	0	0	0	0	0	16
Kyushu	Omura	100	0	0	0	0	0	0	0
	Others	5.7	62	9.8	13	0	9.8	0	0
Okinawa	Gushigawa	0	77	0	8.0	11	4.3	0	0
Dengenkaihatsu	Isogo	100	0	0	0	0	0	0	0
	Takasago	100	0	0	0	0	0	0	0
	Takehara	19	62	0	6.4	8.8	3.5	0	0
	Matsuhima	0	77	0	8.0	11	4.3	0	0
	Others	0	77	0	8.0	11	4.3	0	0
Jouban Kyodo	Nakoso	32	68	0	0	0	0	0	0
Sumitomo Kyodo	All	0	100	0	0	0	0	0	0
Souma Kyodo	Shinchi	0	36	0	0	0	64		0
Sakata Kyodo	Sakata	0	68	10	16	0	6.4	0	0
Toyama Kyodo	Toyama	6.5	43	0	0	17	0	0	34

Table 7: Heavy metal trap ratio at dust filter and desulfurizer in coal-fired and oil-fired power plants

	As	Cd	Cr	Hg	Ni	Pb	V	Zn
Desulfurizer[19)]	75	75	85	60	85	75	85	75
Dust filter (coal-fired)[22, 23)]	98	97	99	0	99	98	99	98
Dust filter (oil-fired)[22, 23)]	-	-	-	-	60	-	60	-

1) - : not investigated in this work

2) Heavy metal trap ratio at dust filter was calculated with the dust filter efficiency: 99.5% for coal-fired power plants and 80% for oil-fired power plants.

Data concerning emissions in refineries were obtained in literature [24]. Data for emissions related to blast furnace gas and coke oven gas were obtained using information found in the LCA software 'Gabi ver. 3' [16]. Emissions from coke oven gas were allocated based on heating values, and those from blast furnace products were based on market values. Table 8 (a) and (b) show the summary of emissions into air during the production and transport of each fuel.

Table 8 (a): Summary of emissions into air during production and transport of each fuel

		CO_2 (kg/kWh)	SO_2 (kg/kWh)	NO_x (kg/kWh)	CO (kg/kWh)	Methane (kg/kWh)	NMVOC (kg/kWh)	Dust (kg/kWh)
Coal	1 kg	7.73E-02	7.36E-04	1.22E-03	1.88E-04	4.45E-03	1.96E-04	3.24E-04
Heavy oil	1 kg	3.13E-01	1.50E-03	2.39E-03	4.26E-04	2.65E-03	7.45E-03	1.20E-04
Crude oil	1 kg	2.73E-01	9.63E-04	2.05E-03	4.83E-04	2.54E-03	7.00E-03	1.32E-04
LNG	1 kg	6.61E-01	9.26E-04	1.29E-03	4.91E-04	6.71E-03	3.23E-04	3.01E-05
BFG	1 MJ	1.47E-02	3.07E-05	2.76E-05	2.59E-04	1.33E-04	4.82E-07	7.23E-07
COG	1 MJ	3.09E-02	8.95E-05	9.62E-05	1.01E-04	6.04E-04	2.96E-06	1.18E-05
Enriched Uranium	For 1 kWh of electricity	7.17E-02	3.08E-04	3.10E-04	1.48E-05	8.65E-05	2.29E-05	3.17E-05

Table 8 (b): Summary of emissions into air during production and transport of each fuel (continued)

		Ni (kg/kWh)	V (kg/kWh)	As (kg/kWh)	Cd (kg/kWh)	Cr (kg/kWh)	Hg (kg/kWh)	Pb (kg/kWh)	Zn (kg/kWh)
Coal	1 kg	3.92E-08	7.35E-08	3.35E-09	1.09E-09	4.66E-09	9.94E-10	1.18E-08	9.71E-09
Heavy oil	1 kg	1.57E-07	6.29E-07	3.17E-09	8.01E-09	4.00E-09	7.12E-10	1.40E-08	9.96E-09
Crude oil	1 kg	1.63E-07	6.50E-07	3.27E-09	8.28E-09	4.12E-09	8.18E-10	1.44E-08	1.03E-08
LNG	1 kg	2.14E-07	8.56E-07	4.29E-09	1.09E-08	5.32E-09	1.59E-08	1.89E-08	1.33E-08
Enriched Uranium	For 1 kWh of electricity	4.05E-08	2.18E-08	1.27E-08	8.60E-10	1.86E-08	4.36E-09	4.51E-08	3.72E-08

*) Heavy metal emissions into air by BFG and COG were not included in this work

4 Development of LCIS for Electricity Grid Mixes in each Electric Company

The electric companies, i.e. Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu, and Okinawa electric companies, distribute electricity to different regions. The electricity grid mix of each electric company consists of electricity generated by each power station. The emission intensity of each substance for the electricity grid mix of each electric company based on net electricity production was calculated according to the share rate of each power station to total net electricity production. Then, the emission intensity of each substance based on net electricity distributed to customers by each electric company was calculated with the following equation:

$$EID = \frac{(EIP) \times (NEP)}{((NEP) - (LP) - (LT)) \times (1 - (LD/100))}$$

EID: emission intensity of each substance based on net electricity distributed to customers by each electric company (kg/kWh), EIP: emission intensity of each substance based on net electricity production (kg/kWh), NEP: net electricity production in each power station (kWh), LP: loss of electricity in pumping (kWh), LT: loss of electricity in transformer (kWh), LD: distribution loss (%).

Values to calculate EID are shown in **Table 9** [3].

Table 9: Net electricity production, electricity consumption for pumping, electricity consumption in transformer substation and distribution loss in Japanese electric power companies in 1997

Electric company	Net electricity production (10^6kWh)	Electricity consumption (10^6kWh)		Distribution loss (%)
		For pumping	In transformer substation	
Hokkaido Electric Co.	25815	142	61	7.0
From other local company	2950			
Total	**28765**			
Tohoku Electric Co.	61196	329	82	6.3
From other local company	17254			
Total	**78450**			
Tokyo Electric Co.	246097	9817	413	5.3
From other local company	29336			
Total	**275433**			
Chubu Electric Co.	113544	2040	132	4.9
From other local company	7930			
Total	**121474**			
Hokuriku Electric Co.	21150	78	27	4.8
From other local company	8423			
Total	**29573**			
Kansai Electric Co.	127986	2944	187	5.4
From other local company	7929			
Total	**135915**			
Chugoku Electric Co.	40154	643	56	5.9
From other local company	17753			
Total	**57906**			
Shikoku Electric Co.	27197	238	28	7.6
From other local company	4511			
Total	**31708**			
Kyushu Electric Co.	62694	656	76	5.7
From other local company	9184			
Total	**71878**			
Okinawa Electric Co.	3947	0	4	4.9
From other local company	1945			
Total	**5893**			

5 Results

Tables 10 (a) and (b) show the direct emissions into air from power stations related to 1 kWh of electricity distributed by each electric company in Japan. Average emissions of 9 electric companies, Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies, are also shown. Most electric companies reported the amount of direct CO_2, SO_2 and NO_x emissions per 1 kWh of electricity generated in the year of 1997 [25-33]. They are shown in **Table 11**. Since they reported emissions on the basis of gross electricity production, these values were modified to emission values based on net electricity distributed to users. CO_2 emissions of each electric company calculated in this work deviates up to 27% from those reported by electric companies. In this work, the exchange of electricity between electric companies was not investigated. On the other hand, exchange of electricity was considered in CO_2 intensities reported by electric companies. This might account for the difference between calculated values in this work and reported values.

As it is shown in **Table 10** (a), direct CO_2 emissions related to 1 kWh of electricity distributed by companies ranged from 0.21 to 1.0 kg/kWh (average value: 0.38 kg/kWh). CO_2 emissions of Kansai Electric Co. are 0.21 kg/kWh, which were the smallest among those of 10 electric companies. CO_2 emissions of Okinawa Electric Co. and Chugoku Electric Co. were relatively large, the values of which were 1.0 and 0.71, respectively. The share rate of powers, i.e. fossil fuel power, hydropower and atomic power to total net electricity production in each company is shown in **Fig. 1**. As it is shown in Fig. 1, 66% of electricity in grid mixes was generated by hydropower and atomic power in Kansai Electric Co., leading to small CO_2 emissions. On the other hand, the share rate of fossil fuel power to total net electricity production was 76% in Chugoku Electric Co. and 99.9% in Okinawa Electric Co., respectively. These high share rates of fossil fuel power caused large CO_2 emissions in these companies.

Table 10 (a): Direct emissions into air related to 1 kWh of electricity distributed by each Electric Power Company

Electric company	CO_2 (10^{-1}kg /kWh)	SO_2 (10^{-4}kg/kWh)	NO_x (10^{-4}kg/kWh)	CO (10^{-5}kg/kWh)	Methane (10^{-4}kg/kWh)	NMVOC (10^{-5}kg/kWh)	Dust (10^{-6}kg/kWh)
Hokkaido Electric Co.	5.0	8.9	5.6 (±30%)	8.1 (±65%)	12(±100%)	1.6(±100%)	49
Tohoku Electric Co.	5.6	4.1	3.6 (±90%)	7.5 (±300%)	9.4(±110%)	2.1 (±110%)	7.9
Tokyo Electric Co.	3.0	2.4	1.9 (±50%)	3.7(±790%)	7.1(±110%)	1.9(±110%)	4.6
Chubu Electric Co.	4.2	2.2	1.6 (±170%)	5.7 (±530%)	9.9 (±110%)	2.3(±110%)	6.3
Hokuriku Electric Co.	4.6	2.9	2.2 (±160%)	7.1(±80%)	9.6(±120%)	1.3(±110%)	6.9
Kansai Electric Co.	2.1	1.0	0.93 (±120%)	3.0 (±610%)	6.3 (±120%)	1.3 (±110%)	2.8
Chugoku Electric Co.	7.1	3.2	4.0 (±80%)	9.3 (±170%)	12(±110%)	2.1 (±110%)	8.6
Shikoku Electric Co.	4.0	4.0	3.5 (±50%)	7.2 (±80%)	13(±120%)	1.5 (±120%)	9.9
Kyushu Electric Co.	3.3	1.0	1.8 (±80%)	3.8 (±460%)	5.0 (±110%)	1.3(±100%)	2.9
Okinawa Electric Co.	10	17	9.4 (±60%)	15(±80%)	20(±120%)	2.7 (±110%)	31
Average of 9 Electric Co.*	3.8	2.5	2.2 (±80%)	5.0 (±440%)	8.2 (±110%)	1.8(±110%)	6.8

*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

Table 10 (b): Direct emissions into air related to 1 kWh of electricity distributed by each Electric Power Company (continued)

Electric company	Ni (10^{-8}kg/kWh)	V (10^{-8}kg/kWh)	As (10^{-9}kg/kWh)	Cd (10^{-10}kg/kWh)	Cr (10^{-9}kg/kWh)	Hg (10^{-9}kg/kWh)	Pb (10^{-9}kg/kWh)	Zn (10^{-8}kg/kWh)
Hokkaido Electric Co.	10	9	10	8	10	8	50	7
Tohoku Electric Co.	5	3	4	3	3	6	10	2
Tokyo Electric Co.	6	3	0.8	0.4	0.4	0.9	2	0.3
Chubu Electric Co.	7	4	2	1	1	2	6	1
Hokuriku Electric Co.	10	3	4	2	5	5	10	2
Kansai Electric Co.	3	3	0.4	0.2	0.2	0.2	1	0.2
Chugoku Electric Co.	10	3	4	2	5	6	10	3
Shikoku Electric Co.	20	5	1	0.8	1	2	4	0.9
Kyushu Electric Co.	2	0.8	2	1	2	3	5	1
Okinawa Electric Co.	30	20	5	3	8	10	20	4
Average of 9 Electric Co.*	7	3	2	1	2	2	6	1

*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

Table 11: Reported values of CO_2, SO_2 and NO_x emissions in 9 electric companies

Electric company	CO_2 (10^{-1}kg/kWh)	SO_2 (10^{-4}kg/kWh)	NO_x (10^{-4}kg/kWh)
Hokkaido Electric Co.	4.7	7.9	5.6
Tohoku Electric Co.	4.1	1.9	3.0
Tokyo Electric Co.	3.3	0.91	1.4
Chubu Electric Co.	4.3	0.8	1.1
Hokuriku Electric Co.	3.8	2.0	1.7
Kansai Electric Co.	2.5	0.37 [1)]	0.64 [1)]
Chugoku Electric Co. [1)]	5.4	1.2 [2)]	1.9 [2)]
Shikoku Electric Co. [2)]	3.0	-	-
Kyushu Electric Co.	3.1	1.2 [2)]	0.85 [2)]
Average	3.6	1.0	1.1

1) 1: data in 1996, 2: data in 1998
2) -: Data were not available

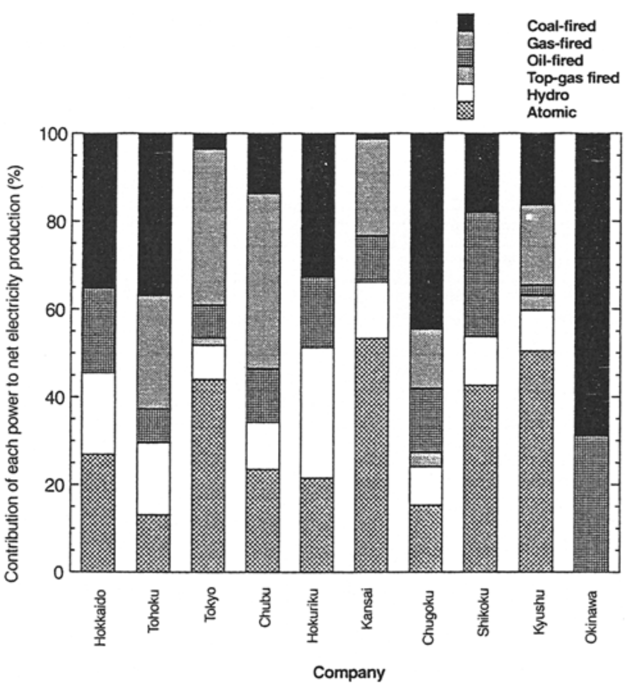

Fig. 1: Share rate of fossil fuel power, hydropower and atomic power to total net electricity production in each company in 1997

SO_2 emissions of most electric companies calculated in this work were relatively large compared with those reported by electric companies. In this work, the total sulfur content in crude oil consumed in oil-fired power stations was assumed to be the same for each electric company. Total sulfur content in heavy oil was also assumed to be the same for all fossil fuel power stations. Actually, it is likely that each electric company consumed oil with less sulfur content in power stations equipped without desulfurizers, and consumed oil with high sulfur content in power stations equipped with desulfurizers. In that case, SO_2 emissions for electricity grid mix of each electric company reduced to some extent. In addition, all sulfur in the fuel was assumed to be transformed to SO_2 during combustion. Actually, some of the sulfur in coal would go into slag, which might also reduce SO_2 emissions. Detailed information concerning total sulfur content in oil consumed in each oil-fired power station are required for an exact calculation of SO_2 emissions from oil-fired power stations. In addition, the ratio of sulfur that goes into slag in combustion must be investigated further.

NO_x emissions for each company calculated in this work were almost similar with those reported by electric companies. The average amounts of CO, CH_4, NMVOC and dust emissions were $5.0*10^{-5}$, $8.2*10^{-6}$, $1.8*10^{-5}$ and $6.8*10^{-6}$ kg/kWh, respectively.

Table 10 (b) shows heavy metal emissions into air from power stations related to 1 kWh of electricity distributed by each electric company in Japan. All heavy metal emissions were on the order of 10^{-8} to 10^{-9} kg/kWh. Detailed information concerning heavy metal content in oil and coals consumed in fossil fuel power stations are further required for an improved assessment of the calculation of heavy metal emissions.

Tables 12 (a) and (b) show emissions into air during production and transport of fuels related to 1 kWh of electricity distributed by each electric company. **Tables 13** (a) and (b) show total emissions into air related to 1 kWh of electricity distributed by each electric company. Contribution of fuel production and transport to total CO_2 emission was relatively small, 4 to 26% . In Tokyo and Kansai Electric Co., contribution of fuel production and transport to total CO_2 emission was 22% and 26%, respectively. As mentioned above, direct CO_2 emissions from power stations per 1 kWh of electricity in these companies were small due to a large share of atomic power and hydropower. Among fossil fuel power, gas (LNG)-fired power had high share in these companies. To transport natural gas, a liquefaction of natural gas is required. Energy consumption in natural gas liquefaction is relatively large, leading to large CO_2 emissions. This accounts for a relatively high contribution of fuel production and transport to total CO_2 emission in Tokyo and Kansai Electric Co.

On the other hand, contributions of fuel production and transport to total SO_2 and NO_x emissions were relatively large, 50% and 60% on average, respectively. Electric companies in Japan have made a great effort to reduce direct SO_2 and NO_x emissions from power stations to meet regulations. It is for this reason that contributions of SO_2 and NO_x emissions in fuel production and transport have become relatively large to total emissions. In the case of CO, NMVOC and dust, emissions in fuel production and transport were predominant to total emissions. Coal mining was the predominant source of methane emission.

As it is shown in **Table 12** (b), heavy metal emissions into air during the production and transport of fuels were in the order of 10^{-8} to 10^{-9} kg/kWh, which were the same order of direct emissions from power stations in most cases.

Table 12(a): Emissions into air during production and transport of fuels related to 1 kWh of electricity distributed by each Electric Power Company

Electric company	CO_2 (10^{-2}kg/kWh)	SO_2 (10^{-4}kg/kWh)	NO_x (10^{-4}kg/kWh)	CO (10^{-6}kg/kWh)	Methane (10^{-4}kg/kWh)	NMVOC (10^{-4}kg/kWh)	Dust (10^{-5}kg/kWh)
Hokkaido Electric Co.	4.9	2.7	3.9	5.4	7.6	4.6	5.8
Tohoku Electric Co.	6.0	2.2	3.3	6.2	9.9	2.2	5.2
Tokyo Electric Co.	8.5	2.5	3.1	7.4	6.0	2.1	2.5
Chubu Electric Co.	7.4	2.2	3.0	6.0	7.8	2.7	3.1
Hokuriku Electric Co.	3.7	2.1	3.1	4.4	6.6	3.2	5.1
Kansai Electric Co.	7.6	2.5	2.9	4.8	4.3	2.0	2.5
Chugoku Electric Co.	5.7	2.7	4.0	1.3	12	3.1	7.1
Shikoku Electric Co.	5.6	2.7	3.6	4.7	5.3	4.3	4.7
Kyushu Electric Co.	5.5	2.4	2.9	7.7	4.8	0.79	4.1
Okinawa Electric Co.	4.7	3.3	5.3	8.6	15	6.5	10
Average of 9 Electric Co.*	7.2	2.5	3.2	7.1	6.8	2.4	3.6

*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

Table 12(b): Emissions into air during production and transport of fuels related to 1 kWh of electricity distributed by each Electric Power Company

Electric company	Ni (10^{-8}kg/kWh)	V (10^{-8}kg/kWh)	As (10^{-9}kg/kWh)	Cd (10^{-9}kg/kWh)	Cr (10^{-9}kg/kWh)	Hg (10^{-9}kg/kWh)	Pb (10^{-8}kg/kWh)	Zn (10^{-8}kg/kWh)
Hokkaido Electric Co.	3	5	4	0.9	6	1	2	1
Tohoku Electric Co.	2	7	3	1	4	2	0.9	0.7
Tokyo Electric Co.	4	8	6	1	9	3	2	2
Chubu Electric Co.	3	9	4	1	5	2	1	1
Hokuriku Electric Co.	2	4	3	0.6	5	1	1	1
Kansai Electric Co.	4	7	8	1	10	3	3	2
Chugoku Electric Co.	2	6	3	0.9	4	1	1	0.9
Shikoku Electric Co.	3	5	6	0.9	9	2	2	2
Kyushu Electric Co.	3	3	7	0.7	10	3	3	2
Okinawa Electric Co.	2	7	1	0.9	2	0.3	0.4	0.4
Average of 9 Electric Co.*	3	7	6	1	8	3	2	2

*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

Table 13 (a): Emissions into air related to 1 kWh of electricity distributed by each Electric Power Company

Electric company	CO_2 (10^{-1}kg/kWh)	SO_2 (10^{-4}kg/kWh)	NO_x (10^{-4}kg/kWh)	CO (10^{-4}kg/kWh)	Methane (10^{-4}kg/kWh)	NMVOC (10^{-4}kg/kWh)	Dust (10^{-5}kg/kWh)
Hokkaido Electric Co.	5.5	12	9.5	1.4	7.7	4.8	11
Tohoku Electric Co.	6.2	6.3	6.9	1.4	10.0	2.4	6.0
Tokyo Electric Co.	3.9	4.9	5.0	1.1	6.1	2.3	3.0
Chubu Electric Co.	4.9	4.4	4.6	1.2	7.9	2.9	3.7
Hokuriku Electric Co.	5.0	5.0	5.3	1.2	6.7	3.3	5.8
Kansai Electric Co.	2.9	3.5	3.8	0.78	4.4	2.1	2.8
Chugoku Electric Co.	7.7	5.9	8.0	1.1	12	3.3	8.0
Shikoku Electric Co.	4.6	6.7	7.1	1.2	5.4	4.5	5.7
Kyushu Electric Co.	3.9	3.4	4.7	1.2	4.9	0.9	4.4
Okinawa Electric Co.	11	20	15	2.4	15	6.8	13
Average of 9 Electric Co.*	4.5	5.0	5.4	1.2	6.9	2.6	4.3

1) Emissions of CO_2, SO_2 and NO_x were based on calculated values
2) Emissions of NO_x, CO, methane and NMHC were calculated with average values
*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

Table 13 (b): Emissions into air related to 1 kWh of electricity distributed by each Electric Power Company (continued)

Electric company	Ni (10^{-7}kg/kWh)	V (10^{-7}kg/kWh)	As (10^{-9}kg/kWh)	Cd (10^{-9}kg/kWh)	Cr (10^{-8}kg/kWh)	Hg (10^{-9}kg/kWh)	Pb (10^{-8}kg/kWh)	Zn (10^{-8}kg/kWh)
Hokkaido Electric Co.	1	1	14	2	2	9	7	8
Tohoku Electric Co.	0.7	1	7	1	0.7	8	2	3
Tokyo Electric Co.	1	1	7	1	0.9	4	2	2
Chubu Electric Co.	1	1	6	1	0.6	4	2	2
Hokuriku Electric Co.	1	0.7	7	0.8	1	6	2	3
Kansai Electric Co.	0.7	1	8	1	1	3	3	2
Chugoku Electric Co.	1	0.9	7	1	0.9	7	2	4
Shikoku Electric Co.	2	1	7	1	1	4	2	3
Kyushu Electric Co.	0.5	0.4	9	0.8	1.2	6	4	3
Okinawa Electric Co.	3	3	6	1	1	10	2	4
Average of 9 Electric Co.[*]	1	1	8	1	1	5	3	3

*) Average emissions of Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyushu electric companies

6 Conclusion

Process models of power plants were developed for the Japanese situation, which simulate the mass flows and estimate the missing figures of emissions dependent on technical parameters of the plants and fuels. The methodologies to calculate CO_2, SO_2, NO_x, CH_4, CO, NMVOC, dust (all particulates) and heavy metal emissions from power stations were presented. Then, life-cycle inventories for the electricity grid mixes of the 10 major electricity companies in Japan were developed. The methodologies presented in this paper are helpful for LCI studies because they bring a large spectrum of environmental relevance and may be specified and replaced in the future. It should be noticed that calculated flows differ in their level of confidence. The following work should be conducted further:

1. Other environmental interventions, such as pollutants into air, emissions to water, solid wastes, land use, radiation and radioactive emissions from atomic power stations should be investigated.
2. The work should be continued together with electric companies to close relevant data gaps and improve the model quality.

Finally, the authors should like to mention that methodologies presented here can also be applied to other countries where few figures concerning emissions related to electricity have been reported.

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