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Development of Life Cycle Inventory for Indonesian's
Grid Electric Generation Systems

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The life cycle inventory (LCI) of the electric power generation plays a vital role on LCIs of the industrial products. The objective of this study is to introduce life cycle assessment (LCA) method for Indonesian's electric power generation systems and to establish LCI for electricity grid mix of Indonesia, which would be databases for further LCA study. In this study, the main data are obtained from the Electricity Generating Authority of Indonesia (*Perusahaan Listrik Negara*, PLN), and the Independent Power Producers (IPPs) during fiscal year 1999 from April 1999 to March 2000. The result of this study could be useful for further LCA research on Indonesia.

Key Words: Power Plant Systems, Life Cycle Assessment, Life Cycle Inventory, Environmental Loads

Introduction

To analyze the environmental loads of any industrial activity like electric power generation, the lifecycle is clearly an essential point of view. This technique assesses the environmental aspects and potential impacts throughout a product's life (i.e. cradle to grave). This approach includes successive stages of the *goal definition*, the *inventory analysis* of energy input and output, the *environmental impact assessment*, and the *improvement analysis*. Within the inventory, the life cycle of each of products considered is defined by assembling the processes that constitute the different phases of the life cycle. These phases consist of industrial processes such as the production of materials or components, consumer processes such as the use and maintenance of products, and post-consumer processes such as waste handling and recycling.

Therefore the development of the life cycle inventory (LCI) data of the electric power generation plays a vital role on LCIs of the industrial products. However there are no formal life cycle assessment (LCA) studies in Indonesia so far due to limited number of LCA expertise and lack of sufficient databases relevant to domestic conditions. Then the aim of this study is to analyze and to investigate the environmental impacts for Indonesian power sector by the development of LCI for electricity grid mix of Indonesia.

Background on Indonesia

Indonesia is an archipelago consists of no less than 13,700 islands. The sea area is four times larger than its land area which about 1.9 million square kilometers. The sea area is about 7.9 million kilometers. The land area is generally covered with thick tropical rain forest and predominantly mountainous. The population has reached about 220 million in 2001, which is the third largest group in Asia after People's Republic of China and India. The population growth rate has declined from 2.2% per annum in the early eighties to 1.7% at present.

Figure 1 shows primary energy supply, final energy electricity consumption and GDP. In the 1970s - 1980s, the

country experienced relatively stable high economic growth of around 7.6% and 6.5% per annum respectively, mainly due to the high oil prices in the international market. In the nineties, the average economic growth rate for the 1990-1997 is about 7.8% per annum. However, when the economic crisis in 1998 and 1999, Indonesia fall to the minus economic growth of -14.9% and -2.2%, respectively. And the growth of 4.8% in 2000 is not sustainable, being attributable to favorable short-term factors, including high world oil prices, a surge in non-oil exports, and increased domestic demand for consumer durables.

The energy sector accounted for slightly over 20 % of GDP in 1999 and approximately 40 % of the export earnings. The domestic primary energy supply in 1999 was accounted around 89.5 [MTOE] after dropped in 1998, (86.8 [MTOE] in 1997 and 85.6 [MTOE] in 1998) and was dominated by oil with 41 % and biomass, as a traditional form of energy, which contributed 31 %. Natural gas supplied 18 % of the domestic consumption. The remainder was shared by coal (6%) and hydropower together with the geothermal energy (4%).

Fig. 1 Primary energy, final energy and GDP

Fig. 2 Indonesia and the distribution of electric generating facilities

Table 1 summarized the energy resource in Indonesia. The situation of the fossil energy reserves is characterized by limited oil reserves, sufficient gas reserves and abundant coal reserves. In 2000, the Minister of Mine and Energy estimated Indonesia's oil reserves to be 10.72×10^9 [barrels]. The proven and potential gas reserves are estimate at about 101.8×10^{12} [scf]. Coal is found predominantly in east and south Kalimantan, and central and south Sumatra. The total resources were estimated in 2001 at 38.31×10^9 [tons].

Table 1. Energy reserves compared to utilization in 2001

	Crude Oil [Bbl]	Natural gas [Tscf]	Coal [BT]	Hydro power [GW]	Geo-thermal [GW]
Java	1.32	12.4	0.06	4.2	7.8
Sumatra	8.32	64.1	24.78	15.6	4.9
Kalimantan	1.00	24.4	9.36	21.6	-
Other islands	0.08	68.9	4.11	34.2	3.4
Totals	10.72	101.8	38.31	75.6	16.1
Production	0.5	2.4	0.07	-	-
Installed	-	-	-	3.4	0.3

Source: ACE ESSPA, January 2001

Considering the current energy reserves and utilization situation, the general feeling that within 20 years, Indonesia will have to be a net oil importer to satisfy its demand. Natural gas and coal may become the dominant energy supply. For the past five years the production and use of coal has been accelerating. With increasing environmental actions, the use of natural gas also is expected to grow at a steadily increasing pace.

As shown in Table 1 that most of the energy resources are located out of Java, but the demand of energy is concentrated in Java. Therefore the regional transportation of energy will be an important factor for the future energy demand-supply projection.

The present level of energy consumption in Indonesia is still very low and it is expected to continue to increase, as in most developing countries. Figure 1 also clarifies the trend of Indonesian final energy consumption. The industrial sector has the highest share of commercial energy consumption. For the

last 10 years, the commercial energy consumption in industrial sector increased by 3.6%. In transportation sector increased by 5% and the other sectors that includes household, government and commerce sub-sector, increased by 4.9%.

Figure 2 shows the distribution of power generating capacity. Despite the possession of a broad array of energy resources, oil has been the main source for power generation in Indonesia. Oil's share of power generation hit a peak of 77% in 1982, and declining ever since due to various efforts from the government to free up as much of the domestic oil supply for export and industrial feed stock purposes as possible. Nonetheless, the role of oil in the electricity sector in 1999 was 49% is still high (from the national installed electric generation capacity stand point). For coal, natural gas, hydropower and geothermal, their share in the power generation are 11%, 27%, 12% and 1% respectively.

System Boundary of LCI

Principally, we have investigated the direct and indirect emissions of the Indonesian's grid electric generation systems during the life cycle. Figure 3 shows the system boundary for fossil fueled power plants and renewable energy power plants that evaluated in this study.

Fig. 3 System Boundary of LCI

Due to the unavailable data and data quality of water and solid waste emissions, this study did not include these emissions. Transportation, production of fuels and construction of power plants was calculated based on the Japanese data (which is used in the MieLCA software). For the calculation of air pollution emissions from power plants in Indonesia, the measured data and the following equations are used;

CO₂

Carbon dioxide emissions from power generation system depend on characteristic of fuels and amount of fuels used for the generations. Carbon dioxide emission intensity, $EI_{CO_2}^{Elec}$, [kg-CO₂/kWh] of electricity consumed by customers was calculated by the following equations:

$$EI_{CO_2}^{Elec} = \frac{\sum F_{CO_2,i} \times H_i \times G_i}{E_{Customer}^{Elec}} \quad (1)$$

where:

- $F_{CO_2,i}$ = CO₂ emissions factor of fuel i [kg-CO₂/MJ]
- H_i = Heating value of fuel i [MJ/kg]
- G_i = Total amount of fuel used [kg]
- $EI_{Customer}^{Elec}$ = Total electricity consumed by customers [kWh]

SO₂

Sulfur oxides emissions from fossil fuel power stations strongly depend on sulfur contained in the fuel, cover ratio of desulfurizers in the power stations and their efficiencies. Sulfur oxides emissions from combustion systems are predominantly in the form of sulfur dioxides (SO₂). In this study, all sulfur content in the fuels is assumed to transform to sulfur dioxide during combustion process. Sulfur dioxide emission intensity, $EI_{SO_2}^{Elec}$, [kg-SO₂/kWh] of electricity consumed by customers, is calculated by the following equation;

$$EI_{SO_2}^{Elec} = \frac{\sum C_{S,i} \times \left(\frac{M_{SO_4}}{M_S}\right) \times (1 - \eta_{DeSO_2}) \times \left(\frac{P_{DeSO_2}}{P_{Total}}\right) \times G_i}{E_{Customer}^{Elec}} \quad (2)$$

where:

- $C_{S,i}$ = Sulfur content of fuel i [-]
- M_{SO_4} = Molecular weight of sulfur dioxide (64)
- M_S = Molecular weight of sulfur (32)
- η_{DeSO_2} = Efficiency of desulfurizer (fraction)
- P_{DeSO_2} = Capacity equipped with De-SO₂ [MW]
- P_{Total} = Total generating capacity [MW]
- G_i = Total amount of fuel used [kg]
- $EI_{Customer}^{Elec}$ = Total electricity consumed by customers [kWh]

NO_x

Nitrogen oxides formed in combustion process due either to thermal fixation of atmospheric nitrogen in the combustion air or to the conversion of chemically bond nitrogen in fuel. These emissions depend on nitrogen content of fuels, temperature inside the boilers, cover ratio of NO_x removal filters and their efficiency. The NO_x emission intensity, $EI_{NO_x}^{Elec}$, [kg-NO_x/kWh] was calculated by the following equations:

$$EI_{NO_x}^{Elec} = \frac{\sum F_{NO_x,i} \times H_i \times (1 - \eta_{DeNO_x}) \times \left(\frac{P_{DeNO_x}}{P_{Total}}\right) \times G_i}{E_{Customer}^{Elec}} \quad (3)$$

where:

- $F_{NO_x,i}$ = NO_x emissions factor of fuel i [kg-NO_x/MJ]
- H_i = Heating value of fuel i [MJ/kg]
- η_{DeNO_x} = Efficiency of NO_x removal (fraction)
- P_{DeNO_x} = Capacity equipped with De-NO_x [MW]
- P_{Total} = Total generating capacity [MW]

G_i = Total amount of fuel used [kg]

$EI_{Customer}^{Elec}$ = Total electricity consumed by customers [kWh]

Dust and Heavy Metals

Dust (suspended particulate matter/SPM) and heavy metals emissions depend on substances content on fuel, cover ratio of filter (ESP, electrostatic precipitators), cover ratio of de-SO_x and their efficiency. Dust and heavy metals emission intensity, $EI_{DHM,j}^{Elec}$, [kg-substance/kWh] of electricity consumed by customers was calculated by the following equations:

$$EI_{DHM,j}^{Elec} = \frac{\sum C_{j,i} \times (1 - \eta_{Filter}) \times \left(\frac{P_{Filter}}{P_{Total}}\right) \times (1 - \eta_{DeSO_2}) \times \left(\frac{P_{DeSO_2}}{P_{Total}}\right) \times G_i}{E_{Customer}^{Elec}}$$

where:

- $C_{j,i}$ = Substance j content of fuel i [-]
- η_{Filter} = Efficiency of dust filters (fraction)
- η_{DeSO_2} = Efficiency of desulfurizer (fraction)
- P_{Filter} = Capacity equipped with filters [MW]
- P_{DeSO_2} = Capacity equipped with De-SO₂ [MW]
- P_{Total} = Total generating capacity [MW]
- G_i = Total amount of fuel used [kg]
- $EI_{Customer}^{Elec}$ = Total electricity consumed by customers [kWh]

N₂O, NMHC, CH₄ and CO

The emission factors of N₂O, NMHC (non-methane hydro carbon), CH₄ and CO used in this work were obtained from literature. These emission intensities, EI_j^{Elec} , [kg-substance/kWh] of electricity consumed by customers was calculated by the following equations:

$$EI_j^{Elec} = \frac{\sum F_{j,i} \times H_i \times G_i}{E_{Customer}^{Elec}} \quad (5)$$

where:

- $F_{j,i}$ = Emissions factor for j of fuel i [kg/MJ]
- H_i = Heating value of fuel i [MJ/kg]
- G_i = Total amount of fuel used [kg]
- $EI_{Customer}^{Elec}$ = Total electricity consumed by customers [kWh]

Results and Discussions

Table 2 shows the national, PLN generating capacity and PLN's electricity production. In 1999/2000 the capacity of the Indonesian power system was 29,188 [MW], consisting of the installed PLN power system 15,912 [MW] (54.5%), non-PLN 12,875 [MW] (44.1%), and private sector 402 [MW] (1.4%). The supply of electricity was 66,501 [GWh] consisting of PLN's self-production 64,817 [GWh] (97.5%) and purchase of 1,683 [GWh] (2.5%). The consumed electricity was 57,998 [GWh].

Fuel used by PLN for electrical power generation in 1999/2000 comprised 2,727,573 [kilo liters] oil fuel (of which 2,247,988 [kilo liter] of HSD, 7,591 [Kℓ] of IDO, 471,984 [Kℓ] of MFO), 7,546,106 [tons] of coal and 21,730,445 [thousand mscf] of natural gas. PLN produced 12,453,171.27 [MWh] by using 2,727,573 [Kℓ] of oil. This means for each [kWh], 0.29 [ℓ] (11.1 [MJ/kWh]) of oil is needed. PLN coal based production in the amount of 16,670,606.58 [MWh] has consumed 7,546,108 [tons] of coal. It means to produce 1 [kWh] of electricity, 0.45 [kg] (11.6 [MJ/kWh]) of coal is needed. The PLN natural gas based production in the amount

of 28,232,657,74 [MWh] has consumed 21,730,455 [thousand Mscf]. It means that 1 [kWh] of electricity needs 0.0077 [Mscf] (8.6 [MJ/kWh]) of natural gas.

Table 3 shows a measured data form selected power plant of the emission coefficient (direct emissions) for Sulfur dioxide (SO₂), Nitrogen oxides (NO_x), Suspended Particulate Matter (SPM/dust) and Non Methane Hydro Carbon (NMHC). Table 4 presents the emission factors for N₂O, NMHC, CH₄ and CO.

Table 2 National, PLN capacity and PLN produced electricity

Power Plant	National Capacity		PLN Capacity		PLN Generated Electricity	
	[GW]	[%]	[GW]	[%]	[TWh]	[%]
Hydropower	3.37	11.5	2.18	13.7	4.81	7.4
Fossil fuel fired	25.52	87.4	13.42	84.4	57.46	88.6
Combined Cycle	4.42	15.2	4.42	27.8	24.65	38.0
Steam Turbine	7.58	26.0	5.37	33.8	25.90	40.0
Gas Turbine	3.30	11.3	1.04	6.5	1.33	2.1
Diesel	10.22	35.0	2.59	16.3	5.58	8.6
Geothermal	0.31	1.1	0.31	1.9	2.55	3.9
Total	29.19	100.0	15.91	100.0	64.82	100.0

Table 3 Measured specific direct emissions of fossil fuel PP

Power Plant	SO ₂ [kg/kWh]	NO _x [kg/kWh]	SPM [kg/kWh]	NMHC [kg/kWh]
Coal Fired ^{1a)}	4.36×10 ⁻³	4.39×10 ⁻³	6.70×10 ⁻⁴	3.20×10 ⁻⁵
Coal Fired ^{1b)}	3.99×10 ⁻³	4.19×10 ⁻³	6.12×10 ⁻⁴	3.20×10 ⁻⁵
Oil Fired ²⁾	1.17×10 ⁻²	2.32×10 ⁻³	2.88×10 ⁻⁴	9.40×10 ⁻⁵
LNG Fired ³⁾	negligible	2.26×10 ⁻³	negligible	1.37×10 ⁻⁴
LNG-CC ³⁾	negligible	1.79×10 ⁻³	negligible	1.08×10 ⁻⁴
Gas Turbine (NG) ³⁾	negligible	2.67×10 ⁻³	negligible	2.81×10 ⁻⁴
Gas Turbine (Diesel) ⁴⁾	2.46×10 ⁻³	4.56×10 ⁻³	1.04×10 ⁻⁴	2.45×10 ⁻⁴
Diesel Generators ⁴⁾	2.01×10 ⁻³	8.64×10 ⁻³	3.24×10 ⁻⁴	4.68×10 ⁻⁴

Note: 1a) use Bukit Asam (Sumatra) coal (in a 600 MW coal fired PP)

1b) use Kalimantan coal (in a 600 MW coal fired PP)

2) use fuel oil, Indonesian crude

3) use Indonesian natural gas

4) use diesel oil, Indonesian crude

Table 4 Emission factors for N₂O, NMHC, CH₄ and CO

Power Plant	N ₂ O [kg/TJ]	NMHC [kg/TJ]	CH ₄ [kg/TJ]	CO [kg/TJ]
Coal fired	1-5 (4)	0.4-4 (2)	0.04-2 (1)	3-20 (13)
Oil fired	1-5 (2)	3-8 (3.5)	3-8 (3.5)	4-20 (15)
Natural gas fired	0.3-1.5 (0.5)	2-8 (4)	0.04-2 (1)	1.5-80 (5)
Top gas fired	0.3-1.5 (0.5)	2-8 (4)	0.04-2 (1)	1.5-80 (5)

Tables 5 (a), (b) and (c) show the result of LCI for Indonesian grid system. In these tables, the average emission into air related to 1[kWh] of electricity distributed to consumer in Indonesia is compared to Japan. It can be seen that, the environmental load due to emissions to air of Indonesian grid mix for CO₂, SO₂, NO_x, CO, CH₄, NMHC, N₂O, Dust (SPM) is 167%, 615%, 714%, 92%, 321%, 218%, 209%, 1000%, respectively that of Japan. As for Heavy metals emissions, compared with Japan, these values are about 489% to 3258%.

Figure 4 shows the comparison of Indonesia grid system and Japan grid system. As shown in this figure, the main reason of these results is that the power supply composition of the two countries is quite different. Especially, as for Japan have the nuclear power plants, with the composition ratio of

37 % from total. However, for Indonesian grid mix system, the composition ratio of oil fired-, coal fired-, natural gas fired-, hydro power station and geothermal, are 19.3%, 25.8%, 43.6%, 7.4% and 3.9%, respectively. Furthermore, the losses and own use for Indonesia in 1999, account for 21% (in which about 13% for transmission loss) of the gross generation.

Fig. 5 Power supply composition of Indonesia & Japan

Table 5(a) LCI results for Indonesian Grid System

Type	CO ₂ [kg/kWh]	SO ₂ [kg/kWh]	NO _x [kg/kWh]	CO [kg/kWh]	CH ₄ [kg/kWh]	NMHC [kg/kWh]	N ₂ O [kg/kWh]	SPM [kg/kWh]
Direct emissions	7.0E-1	2.3E-3	2.9E-3	9.4E-5	1.5E-5	3.0E-5	1.9E-5	2.3E-4
Indirect emissions	1.9E-2	1.0E-4	9.1E-5	2.5E-5	4.5E-3	6.9E-4	3.6E-6	2.7E-5
Total Indonesia	7.2E-1	2.4E-3	3.0E-3	1.2E-4	4.5E-3	7.2E-4	2.3E-5	2.7E-4

Table 5(b) LCI results for Japan Grid System

Type	CO ₂ [kg/kWh]	SO ₂ [kg/kWh]	NO _x [kg/kWh]	CO [kg/kWh]	CH ₄ [kg/kWh]	NMHC [kg/kWh]	N ₂ O [kg/kWh]	SPM [kg/kWh]
Direct emissions	4.0E-1	1.9E-4	1.9E-4	5.8E-5	9.9E-6	1.9E-5	1.1E-5	1.2E-5
Indirect emissions	3.8E-2	2.0E-4	2.4E-4	7.5E-5	1.4E-3	3.1E-4	3.7E-8	1.3E-5
Total Japan	4.3E-1	3.9E-4	4.2E-4	1.3E-4	1.4E-3	3.3E-4	1.1E-5	2.6E-5

Table 5(c) LCI results for heavy metal emissions

Type	Ni [kg/kWh]	V [kg/kWh]	As [kg/kWh]	Cd [kg/kWh]	Cr [kg/kWh]	Hg [kg/kWh]	Pb [kg/kWh]	Zn [kg/kWh]
Direct Indonesia	7E-4	1E-3	1E-5	5E-7	1E-5	1E-5	3E-5	5E-5
Direct Japan	7E-5	3E-5	2E-6	1E-7	2E-6	2E-6	6E-6	1E-5

Concluding Remarks

In this study, the life cycle inventory (LCI) for electricity grid system in Indonesia was developed for the first time. The emissions of CO₂, SO₂, NO_x, CO, CH₄, NMHC, N₂O, Dust (SPM) and heavy metals are evaluated. The result of this study could be useful for further LCA research on Indonesia.

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