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Life cycle assessment of coal-based power plants: impacts on urban carbon footprint and externality costs

Analisis daur hidup pembangkit listrik berbasis batu bara: dampaknya terhadap jejak karbon perkotaan dan biaya eksternal

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Abstrak.
Pertumbuhan ekonomi Indonesia bertumpu pada industri di kota-kota besar yang menyebabkan tingginya permintaan energi. Sekitar 40-70% energi nasional berasal dari pembakaran batu bara, yang berkontribusi besar terhadap emisi karbon dan pemanasan global. Batu bara diprediksi tetap menjadi sumber utama energi masa depan Indonesia, terutama di kota-kota besar. Studi ini mengestimasikan emisi karbon dan biaya lingkungan (EC) dari siklus hidup pembangkit listrik menggunakan metode transfer manfaat, sembari memperhitungkan pencemaran udara dan air. Pada periode 2010-2020, biaya lingkungan akibat emisi gas rumah kaca berkisar US$ 9-19 miliar, sementara biaya akibat polusi udara mencapai US$ 1,56-5,37 miliar. Pencemaran air rata-rata tercatat sebesar 0,0027 g/TWh (fenol) dan 9,16 g/TWh (total COD), dengan penipisan air sekitar 4,9 miliar m^3/MWh. Jakarta memiliki jejak karbon sebesar 25.755 ton CO_2 dan menghasilkan biaya eksternal sebesar US$ 3.249.506. Studi ini menekankan pentingnya pengurangan emisi karbon melalui inovasi teknologi, penguatan kebijakan energi, dan peningkatan literasi energi masyarakat, dengan kota-kota sebagai penggerak utama transisi menuju energi bersih.

Kata kunci: jejak karbon, biaya eksternal, analisis daur hidup, pembangkit listrik batu bara

Abstract.
Indonesia's economic growth is strongly driven by industrial activities concentrated in large urban areas, resulting in high energy demand. Approximately 40-70% of Indonesia's energy is supplied by coal combustion, contributing significantly to carbon emissions and accelerated global warming. The coal used would still be main source in the future energy of Indonesia especially in cities. This study proposes to estimate the carbon emission and environmental cost (EC) of power plant life cycle use benefits transfer method, while also accounting air = and water pollution. The results show that during 2010-2020, the EC for GHG emission is about 9 to 19 billion US$, while EC for air pollution is about 1.56-5.37 billion US$. Water pollution averaged 0.002658049 g/TWh for phenol and 9.16425 g/TWh for total COD. Then, the total water depletion is estimated to be an average of around 4.9 billion m^3/MWh. Jakarta itself has a carbon footprint of 25,755 tons of CO_2 and produces external cost of US$ 3,249,506. This study highlights the urgency of reducing carbon emissions through technological innovation, strengthened energy policies and enhanced public energy literacy, with positioning cities as key drivers of the transition toward cleaner energy systems.

Keywords: carbon footprint, externalities cost, life cycle assessment, coal based powerplant

1. INTRODUCTION

Rising concentrations of greenhouse gases (GHGs), particularly CO_2 have exacerbated global warming and climate change. Manabe (2019) clearly explained the process of CO_2 concentration contributing to global warming, highlighting that CO_2 increases surface and stratospheric temperatures, affects the water cycle and enhances infrared opacity, thereby increasing absorption of longwave radiation. Bengtsson (1996) revealed that the most common gases in the atmosphere, oxygen and nitrogen occupying more than 99% of the total volume, are almost completely transparent to solar and terrestrial radiation, underscoring CO_2's dominant role.

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Major emitters derive from the energy sector, with the global CO_2 emissions originating from the power industry, including public and auto-producer power and heat generation plants, reached significant levels, at 0.284 t CO_2 per GDP unit and 126,635 USD in 2020 (European Commission 2021). China contributed 32.5% of world emissions, the US 12.6% and Indonesia 1.6%, with China's power generation (41%) and industrial combustion (28%) driving 508 kg CO_2 per 1000 PPP yr.

Indonesian national GHG emissions in 2014 were dominated by forest fires (979,422 Gg CO_2e), energy (602,458 Gg CO_2e) and agriculture (113,440 Gg CO_2e), with the energy sector increasing annually by about 5.2% (Government of Republic Indonesia 2017). Energy supply remains dominated by coal for electricity (40-70% (HEESI 2019), as Indonesia hosts vast coal resources formed by Cenozoic rift tectonics in southern Sundaland (Friederich *et al.* 2016). Coal demand in power plants rising from 90 to 150-160 million tons by 2028-2030, with coal generating 65% of electricity (140 thousand Gg Watt) in 2019, fuelled by the 35,000 MW coal-fired project (PLN 2019). Economic growth amplifies emissions, as Raihan et al. (2022) showed that a 1% increase in economic growth and fossil fuel energy use raises CO_2 by 0.36% and 0.67%, respectively, creating a dilemma with net-zero targets delayed to 2070.

Urban areas, especially dense cities like Jakarta, consume substantial electricity from fossil fuels, emitting SO_2 and NO_2 that cause acid rain and diseases, with energy use deemed wasteful (Listyarini 2012). In Indonesia, urban households consume significantly more electricity, often due to more appliances and higher living standards, leading to elevated carbon emissions from power generation. Additionally, urban transport with dense vehicle networks contributes substantially to GHG emissions. Household consumption patterns in urban settings tend to be carbon-intensive, given greater access to energy services and consumer goods, which amplifies emissions from multiple sources including transportation, electricity use and waste disposal.

Indonesia faces rising temperatures (0.01-0.06°C post-1950), altered rainfall patterns and vulnerabilities in coastal, agricultural, urban and health sectors, compounded by El Niño/La Niña (Government of Republic Indonesia 2017). Northern Java cities, like Jakarta (Surya *et al.* 2019), Semarang (Marfai and King 2008), Gresik (Handoko *et al.* 2022) and Demak (Prasetyo *et al.* 2019), risk subsidence and sea-level rise, displacing communities (Setyowati *et al.* 2017).

Environmental costs stem from resource depletion, air pollution and ecosystem degradation (Pirmana 2021) during coal's lifecycle from mining, transport to powerplant. One of the most significant impacts of underground coal mining is acid mine drainage (AMD) contamination from both past and ongoing mining activities (Ojonimi et al. 2021). Coal distribution could impact benthic flora and fauna, especially those that are vulnerable to coal dust and potential anoxic conditions by coal oxidation within a short distance (0-100 m) of the coal-loading terminal (Ryan & Bustion 2006). Coal power contributes 741-1022 g CO_2/kWh globally, worsening urban footprints in Indonesia's cities. Despite global LCA studies, Indonesia lacks comprehensive cradle-to-grave analyses linking coal power to urban carbon footprints and externalities.

This study aims (1) to estimate externality costs of coal power plants across their lifecycle (from establishment to disposal) and explore GHG reduction potentials, as well as (2) to quantify urban electricity use impacts on carbon footprints, urging independent clean energy generation in cities.

2. METHODOLOGY

2.1. Data collection

This study utilizes electricity consumption and coal-fired power generation data from the *Handbook of Energy and Economic Statistics of Indonesia* (HESSI) for the period 2000–2020. Environmental costs are estimated using a benefit transfer approach based on valuation results from existing life cycle assessment (LCA) studies of coal power plants. This approach enables the application of non-market environmental values for the study area, while LCA provides a systematic framework to assess environmental impacts across the entire life cycle of power generation.

2.2. Analysis procedure

This study focuses on two main stages: power generation and electricity use. The assessed impact categories include greenhouse gas (GHG) emissions (kg CO_2-eq), air pollutants (AP) and water pollutants (kg SO_2-eq). Total GHG emissions from coal-fired power plants were calculated by multiplying coal-based electricity generation by the emission factor per GWh. Based on Arsyad & Setiadi (2020), 1 GWh of electricity produced from coal power plant in Indonesia is equivalent to 800 tons of CO_2eq. Thus, the total of GHG emission to SCC (125 US$/t$CO_2$eq) with this **Equation 1.**

$$(EC_{GHGEM})t-n\ from\ coal\ powerplant = \Sigma electricity(Gwh) \times 800 tonne\ CO2eq \times 125\left(\frac{US\$}{tCO2}\right) \times IER \times \frac{IPIt\_n}{IPIt} \div IERt_n = ..USt\_n\$ \quad (1)$$

To account for annual variability in US dollar values, price adjustments were incorporated using the Indonesia Price Index (IPI) and Indonesia Exchange Rate (IER) for the period 2011-2020, as summarized in **Table 1**. Air pollutant emissions from coal-fired power plants were estimated based on Widiyanto *et al.* (2003), who quantified emissions per 1 kWh of electricity generation, including SO_2 (0.00417 kg/kWh), NO_x (0.00429 kg/kWh), suspended particulate matter/SPM (0.000641 kg/kWh) and CO (0.00014 kg/kWh). Then, we estimate the cost by **Equation 2**.

Table 1. Indonesia price index and Indonesia exchange rate during years 2011-2020.

Years	Indonesia Price Index	Indonesia Exchange Rate	Years	Indonesia Price Index	Indonesia Exchange Rate
2011	105.4	8,770	2016	137	13,308
2012	109.9	9,386	2017	142.2	13,380
2013	116.9	10,461	2018	146.7	14,236
2014	124.4	11,865	2019	151.2	14,147
2015	132.3	13,389	2020	154.1	14,582

Source: World Bank (2021).

$$(EC_A P)_{t-n}\ \text{from coal powerplant} = \text{Total Electricity (kWh)} \times \text{AP (kg (AP)}_2\text{eq)} \div 1000 \times \text{AP cost}\left(\frac{\text{US\$}}{\text{kg AP}}\right) \times \text{IER}_t \times \frac{IPI_{t-n}}{IPI_t} \div \text{IER}_{t-n} = \text{US}_{t-n}\$ \quad (2)$$

Another method used to provide emission images generated from cities in Indonesia. We focus on the most densely populated cities in Indonesia that is DKI Jakarta. By using secondary data issued by BPS with a range of 2020 to 2022. Also, it will be supported by journals, documents and city government reports. Finally, the calculation will use the **Equation 1**.

3. RESULT AND DISCUSSION

3.1. GHG emission and external cost from powerplant

Accompanying economic growth and population, coal usage in power plants increased annually, from about 34 million tonnes in 2010 to 104 million in 2020. This data was highly echoed by the report of Ministry of Environment and Forestry that primarily sources of GHG emission in Indonesia come from coal powerplant. Indonesia‘s coal powerplant use two different technologies.

There are 1) subcritical coal-fired power plants (CF-SUB) that use sub-bituminous coal as fuel with a share of 59% and 2) Supercritical coal-fired power plant (CF-SUPERs) that use more brown coal or lignite, with share of 41 % (Nugroho *et al*. 2022). However, some of them only calculate lifecycles of powerplant processes. Some calculated more than the life cycle but also calculated social cost or damage that community will receive, such as the impact of GHG emission or non-GHG emission, landscape and noise impact, ecosystem and biodiversity impact another coal can release hazardous elements that negatively impact the environment (Tozsin 2014; Samadi 2017).

The coal consumption for powerplant showed a consistent upward trend, from about 45 in 2011 to 112 million tonnes in 2021 and coal consumption increases by about 10 million tonnes for every year, which was synchronous with uptrend of total electricity produced. The higher the coal consumption, the more considerable amount of CO2eq. in 2020, the highest amount of CO2eq was about 144 million tonnes and the external cost was about 18 billion US$ (see **Table 2**).

Table 2. Amount of coal burning in power plant and its EC in Indonesia 2011-2021.

Years	Total Amount (tonne)	Total Electricity Production (GWh)	Total CO2eq (tonne)	Total EC GHG (US$)
2011	45,118,519	81,090	64,872,000	9.3
2012	52,815,519	102,166	81,732,800	11.3
2013	61,860,000	111,252	89,001,600	11.7
2014	63,054,000	119,532	95,625,600	11.8
2015	70,080,000	124,657	99,725,600	11.6
2016	75,400,000	135,381	108304800	13.1
2017	83,000,000	147,964	118,371,200	14.8
2018	91,140,000	160,013	128,010,400	15.6
2019	98,550,260	174,493	139,594,400	17.6
2020	104,829,892	180,869	144,695,200	18.0

Source: this research estimations.

From comparable, a study of external cost of one of the coal power plants in Indonesia, namely Suralaya powerplant by Sugiyono (2005) revealed that resulting exterior prices are 0.18-2.34 percent $/kWh. This cost does not include maintenance, investment and fuel cost but health cost that community needs because of the dangerous pollutant water produced. Moreover, because of these external costs, generating electricity will increase the cost by 15 percent. Wijaya and Limmeechokchai

(2010) applied life cycle assessment and first calculated the external cost of electricity fossil fuel by various types of powerplant technology. The result was the environmental cost of energy in Indonesia was about 11.6 billion US and will increase to 42 billion US$ 2025.

Moreover, Karkour *et al*. (2020) appraised the current external charge of electricity production in G20 nations by employing a global life cycle assessment (LCIA) based on final point modeling (LIME3). This research indicated that India and Indonesia have top external values about 0,172 $/kWh and 0,135 $/kWh respectively. So, If Indonesia consumed about 264.028.912 kWh in 2020 from coal. The external expense would be over 543 million US$. Study from Wang *et al* 2015, coal power-plant in Northeast China produced external cost 0.072 US $/kWh. Still, in China, the externalities of coal in Southwestern China are estimated at USD 73.5 billion or 284.3 USD/t (Wang *et al*. 2020).

3.2. Air pollutant and external cost from coal powerplant

The amounts and the external cost of air pollutants emitted from Indonesia's domestic coal power plants during 2010-2020 are calculated by **Equation 2**. The estimations shows that the total emissions produced in the last ten years are around 1,56-5,37 million US$ and in 2019 and 2020 has the highest coal about 5,24 and 5,37 million US$ due to electricity produced increase (**Table 3** and **Table 4**). For SO_2 about 0.06-1.34, NO_x about 1.19-3.02, for SPM about 0.31-0.79 and CO about 0.00029-0,00073 million US$ (**Table 4**). Other study revealed that when pulverized coal is burned, most of the mercury (Hg) vaporizes, some are captured by fly ash, while almost none was retained in the bottom ash. Hg was released into the atmosphere primarily as a gas and, to a lesser extent, as solid-phase pollutants (Yudovich & Ketris 2005).

The total external cost of GHG emission and air pollutant from coal powerplant has 84 to over 100% from total revenue of electricity sales in the last ten years (PLN 2019), and it does not include the water pollutions cost. Indonesia has an economic and population growth year by year, so electricity consumption will also increase. Electricity consumption in Indonesia is divided into four: household, industry, business and others. This increase in electricity consumption is supported by a government program that will realize electricity target of 35,000 MW for all Indonesia.

Table 3. Air pollutants emitted from domestic coal power plants in Indonesia 2010-2020.

Years	Total Electricity Production (kWh)	SO_2 kg/kWh	NO_x kg/kWh	SPM kg/kWh	CO kg/kWh
2010	6.8477E+10	28,554,909	293,766,330	43,893,757	9,586,780
2011	8.1090E+10	338,145,300	347,876,100	51,978,690	11,352,600
2012	1.02166E+11	426,032,220	438,292,140	65,488,406	14,303,240
2013	1.11252E+11	463,920,840	477,271,080	71,312,532	15,575,280
2014	1.19532E+11	498,448,440	512,792,280	76,620,012	16,734,480
2015	1.24657E+11	519,819,690	534,778,530	79,905,137	17,451,980
2016	1.35381E+11	564,538,770	580,784,490	86,779,221	18,953,340
2017	1.47964E+11	617,009,880	634,765,560	94,844,924	20,714,960
2018	1.60013E+11	667,254,210	686,455,770	102,568,333	22,401,820
2019	1.74493E+11	727,635,810	748,574,970	111,850,013	24,429,020
2020	1.80869E+11	754,223,730	775,928,010	115,937,029	25,321,660

Source: this research estimates.

Table 4. The external cost of AP from domestic coal power plants in Indonesia 2010-2020 (million US$).

Years	External cost SO_2	External cost NO_x	External cost SPM	External cost CO	Total external cost of air pollutants
2010	0.06	1.19	0.31	0.00029	1.56
2011	0.79	1.54	0.40	0.00037	2.74
2012	0.97	1.89	0.50	0.00046	3.36
2013	1.01	1.96	0.52	0.00047	3.49
2014	1.02	1.98	0.52	0.00048	3.52
2015	1.00	1.95	0.51	0.00047	3.46
2016	1.14	2.20	0.58	0.00053	3.92
2017	1.28	2.48	0.65	0.00060	4.42
2018	1.34	2.60	0.68	0.00063	4.63
2019	1.52	2.95	0.77	0.00071	5.24
2020	1.56	3.02	0.79	0.00073	5.37

Source: this research estimates.

For consumption in the industrial sector, coal will be an alternative fuel that is cheap and widely available in Indonesia while oil and gas fuel prices are getting more expensive, therefore, electricity consumption in the household sector is not much different from the amount consumed by industry (Ministry of Energy and Mineral Resources 2020). In the industrial sector, 90% of coal is consumed by cement factories. As for coal imports have so far been very small because they are only used for special purposes such as reducing agents in the metallurgical industry (Ministry of Energy and Mineral Resources 2016).

3.3. Water pollution and consumption from coal powerplant

A study by Widiawaty *et al* (2020) stated that two powerplants in Cirebon Regency, Indonesia affected the water quality in Mundu Bay, where the concentration of total suspended solids (TSS) and sea surface temperatures (SST) values increased. Water consumption depends significantly on the powerplant technology needed in the coal power plant process. The power plant also produces water which contains many pollutants and it returns to the environment. A study from Dincă *et al* (2010) revealed that combustion of coal has polluted the water such as phenol about 0.000019143 g/TWh and COD about 0.066 g/TWh.

An LCA study of water use and wastewater from coal-fired power plants in China show the water footprint of electricity generation is approximately 6.60 m^3/MWh. From the total, blue water footprint contributes 24.8%, while the grey water footprint represents the dominant share at 75.2% (Zhu et al 2020). Sabubu (2020) states that the effect of wastewater from this coal powerplant caused the temperature of sea water around the coast to rise and causes fisherman around the coast to have fish far away to find fish, in other word, hot waste water causes ecosystem in water to be disrupted and even extinct. **Table 5** showed the estimations result of the water pollution and water depletion of coal power plants.

Table 5. Total water pollution and depletion from coal powerplant.

Years	Total Electricity Production (GWh)	Total Phenol g/TWh	Total COD g/TWh	Total water depletion m^3/MWh
2011	81,090	0.001552306	5.35194	2,890,047,600
2012	102,166	0.001955764	6.742956	3,641,196,240
2013	111,252	0.002129697	7.342632	3,965,021,280
2014	119,532	0.002288201	7.889112	4,260,120,480
2015	124,657	0.002386309	8.227362	4,442,775,480
2016	135,381	0.002591598	8.935146	4,824,978,840
2017	147,964	0.002832475	9.765624	5,273,436,960
2018	160,013	0.003063129	10.560858	5,702,863,320
2019	174,493	0.003340319	11.516538	6,218,930,520
2020	180,869	0.003462375	11.937354	6,446,171,160

Source: this research estimates.

From the estimations results, water pollution has an average of 0.002658049 g/TWh for phenol and 9.16425 g/TWh for total COD. Then, the total water depletion is estimated to be an average of around 4.9 billion m3/MWh.

3.4. Urban electricity consumption

This research selects Jakarta as a representative of electricity consumption in highly populated urban areas. **Table 6** presents the estimated external cost data from electricity consumption in Jakarta for three years, from 2020 to 2022. This data included total electricity production in kilowatt-hours (KWh) and gigawatt-hours (GWh), total carbon dioxide (CO2e) emissions in tons and total environmental costs in millions of US dollars. Electricity consumption is divided into six categories: social, household, enterprise, industry, office and others.

Table 6. Estimation of external cost from electricity consumption in Jakarta.

Years	Categories	Total Electricity Production (KWh)	Total Electricity Production (GWh)	Total CO2e (tonne)	Total External Cost GHG (million US$)
2020	Social	1.221.742.008	1,22	977,393	123.313
	Household	14.604.749.545	14,60	11.683,799	1.474.093
	Business	10.525.716.850	10,53	8.420,573	1.062.386
	Industry	3.831.806.986	3,83	3.065,445	386.754
	Offices	1.550.620.228	1,55	1.240,496	156.508
	Others	460.232.131	0,46	368,185	46.452
	Total	**32.194.867.748**	**32,19**	**25755,894**	**3.249.506**
2021	Social	1.286.813.881	1,29	1.029,451	134.518
	Household	14.724.520.787	14,72	11.779,616	1.539.234
	Business	10.583.416.787	10,58	8.466,733	1.106.342
	Industry	4.184.303.379	4,18	3.347,442	437.408
	Offices	1.519.119.920	1,52	1.215,295	158.802
	Others	1.482.916.704	0,41	328,903	42.978
	Total	**32.709.304.744**	**32,71**	**26167,443**	**3.419.281**
2022	Social	1.482.916.704	1,48	1.186,333	148.292
	Household	14.823.996.394	14,82	11.859,197	1.482.400
	Business	12.085.066.135	12,09	9.668,052	1.208.507
	Industry	4.140.339.703	4,14	3.312,271	414.034
	Offices	1.591.810.878	1,59	1.273,448	159.181
	Others	454.161.897	0,45	363,329	45.416
	Total	**34.578.291.711**	**34,58**	**27662,633**	**3.457.829**

Source: this research estimates.

In 2020, total electricity production in Jakarta reached 32.19 GWh, resulting in CO2e emissions of 25.755 tonnes, with total environmental costs reaching 3.249.506 million US dollars. And it is clear that the leading sources of emission are from household and businesses in all given years. The household sector was the largest contributor to electricity consumption, followed by the enterprise and industry sectors. In 2021, there was an increase in total electricity production to 32.71 GWh with CO2e emissions of 26.167 tonnes and total environmental costs of 3.419.281 million US dollars. This increase indicated growth in electricity consumption in Jakarta year over year. In 2022, total electricity production reached 34.58 GWh, with CO2e emissions of 27.662 tonnes and total environmental costs of 3.457.829 million US dollars. Overall, the data showed an increasing trend in electricity consumption and CO2e emissions in Jakarta from 2020 to 2022. This indicates the need for efforts to reduce energy consumption and greenhouse gas emissions in densely populated urban areas such as Jakarta.

4. CONCLUSION AND RECOMMENDATION

This study estimates the external costs of coal-fired power plants in Indonesia and their implications for environmental economics. The results show that coal power generation imposes substantial and increasing external costs across its life cycle. The external cost of GHG emissions increased from about 9 billion US$ in 2011 to 18 billion US$ in 2020. External costs from air pollutants ranged from 1.56 to 5.37 billion US$, with NOx, SPM, and SO_2 as the main contributors. While in 2015 total external costs were nearly equal to electricity revenue, since 2016 these costs have risen significantly relative to profits.

Coal power plants also contribute to water pollution and high water consumption. Average phenol and COD concentrations were 0.00265 g/TWh and 9.16425 g/TWh, respectively, while total water depletion reached around 4 billion m^3 over the past decade. Overall, external electricity costs ranged between 3.2 and 3.4 million US$, with household and business sectors experiencing the highest impacts and a consistent upward trend.

These findings indicate the need for stronger energy policies to reduce emissions from coal-based power generation in line with Indonesia’s net-zero target for 2060. Emission reduction efforts should focus on cleaner power plant technologies, increased renewable energy shares (particularly in urban areas), and improved energy efficiency. At the community level, clean energy awareness and energy-saving practices can further support the transition toward low-carbon electricity.

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