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Research Article

Carbon emission and environmental cost from coal production in Indonesia

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Abstract

Indonesia primarily exports coal, with an average annual quantity of over 421 million tonnes in the past decades (2011-2020), reaching its peak at 616 million tonnes in 2019. Despite its economic benefits, coal production carries hidden costs. This research delves into using life cycle assessment (LCA) to gauge the environmental impact of coal production and estimate external cost (EC) related to Greenhouse gases (GHG) and air pollutants (AP). The study applied the benefit transfer method to make these estimations, focusing on coal mining and international transport processes. The findings revealed that over the past decades, per tonne coal mining contributed an estimated EC of $12.54-15.26 for GHG and $3,439-5,250 for AP, while transport abroad per-tonne-km coal incurred an EC of $19.98-23.94 for GHG and $19.58-23.30 for AP. Moreover, coal mining contributes to water pollution and substantial water depletion. Despite the coal production in Indonesia generating around $40 billion in revenue in 2020, the study shows that the total EC from GHG and AP is up to $2,131 billion, which is 53 times the revenue, posing serious health and ecological risks to Indonesians and exacerbating global climate change. Notably, these estimates exclude EC from water pollution (WP) and water depletion. With the global push towards 'net zero emissions', the coal industry as a whole faces an urgent need to curb its GHG and AP emissions from its.

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Introduction

Indonesia has experienced significant economic growth in recent decades, emerging as a newly industrialized nation and a member of the G20, collaborating on global economic challenges. Indonesia was the 10th largest economy in terms of purchasing power parity, ranked 16th globally (World Bank, 2022) and 1st in Southeast Asia (Asia Fund Managers, 2022). This economic development has been supported by Indonesia's government policy, Indonesia's endowment of natural resources, and growing labor forces (Elias and Noone, 2011). Also, trade openness, the real exchange rate depreciation, and changes in the external term of trade contributed to the economic growth in Indonesia between 1966 and 2003 (Hossain, 2006). In 2022, economic growth was caused by positive terms of trade, including exports and a recovery in private consumption (World Bank, 2023). Exports and imports have actively played a vital role in Indonesia's economic growth. Indonesia classifies its export products into two categories: 'oil and gas' and 'non-oil and gas'. 'Non-oil and gas' means raw materials and industrial products, excluding forms of oil and gas, such as industry, mining, and agriculture. Non-oil and gas exports have consistently been the largest contributors to Indonesia's exports, reaching a peak of over $219.362 billion in 2021. Specifically, the highest value of non-oil and gas exports in 2021 was approximately $179.201 billion. The top five industry products contributing to this value were fat and vegetable oil (12.61%), iron and steel (10.19%), machinery and electrical equipment (5.15%), vehicles and equipment (3.77%), and rubber and related products (2.52%) (Ministry of Trade of Indonesia, 2021). Mining has also been a significant export sector, with fluctuating values peaking at $64.127 billion in 2012. Agriculture, on the other hand, has consistently maintained the lowest export value with stable figures. As for 'oil and gas' exports, they reached a peak of about $36.977 billion in 2012 and a low of about $8.251 billion in 2020 (Ministry of Trade of Indonesia, 2021).

Coal mining is a prominent industry in Indonesia, characterized by increasing production over the past twelve years, averaging about 421 million tonnes annually and peaking at 616 million tonnes in 2019 (Ministry of Energy and Mineral Resources of Indonesia, 2020). Indonesia's coal resources and reserves are distributed across various provinces. As of December 2020, the largest coal reserves are found in East Kalimantan, totaling over 59,691 million tonnes, followed by South Sumatra with over 43,852 million tonnes, with additional reserves scattered across 21 other provinces. In 2020, 47% and 30% of coal production originated from East Kalimantan and South Kalimantan, respectively. Notably, a significant portion of coal, around 70-80%, is intended for export, while domestic consumption accounts for only 15-20% over the twelve-year period. The Indonesian government actively encourages foreign investment in the mining sector, sustaining the coal and natural resources industries (Ministry of Investment of Indonesia, 2021). However, the extraction of these resources has resulted in environmental damage within the production regions. Activities associated with resource extraction, including exploration (road construction, explosives, land clearance, and restoration), raw material acquisition (topsoil removal, drilling and blasting, overburden removal, dumping, coal extraction, hauling, and stockpiling), and coal processing (crushing, washing), contribute to air, water, and noise pollution.

Indonesia has significantly contributed to deforestation and carbon loss in Southeast Asia due to activities like oil palm plantations, logging, fiber plantations, and mining. These industries collectively accounted for 44.7% or 6.6 million hectares of forest loss in Kalimantan, Sumatra, Papua, Sulawesi, and Maluku over the past decade (Abood et al., 2015). Peatland in Malaysia, Sumatra, and Kalimantan reduced significantly from 76% in 1990 to 29% in 2015, and industrial plantations have nearly doubled their extent since 2007, about 15% to 27% (Miettinen et al., 2016). Thus, Indonesia was ranked fourth globally in greenhouse gas emissions (Chrysolite et al., 2020).

Mining activities have notably reduced forested areas, particularly evident in East Kalimantan Province, where approximately 9.33 million hectares, or 78% of its land area, is allocated for forestry, agriculture, and mining activities under concession permits. Specifically, coal mining permits cover around 4 million hectares in East Kalimantan (Mining Advocacy Network, 2019). Abandoned and unreclaimed mining pits have filled with water, leaving scars on the province's landscape and posing dangers, with reports of 32 children drowning in these open mining pits, water-filled voids, often located close to residential areas (Toumbourou et al., 2020). Communities residing near mining areas bear the cost of environmental degradation. Some regions in Kalimantan Island grapple with flooding caused by extensive land conversion and severe weather conditions. South Kalimantan experienced 289 flooding incidents between 2019 and 2021, with 2021 being particularly severe due to heavy rainfall (Pratama et al., 2021). This flooding directly affected approximately 24,379 households and 39,549 residents (National Disaster Management Agency of Indonesia, 2021). Regarding economic impact, according to a study by Syahrir et al. (2020), mining activities in the Singkep Island case initially brought economic benefits but eventually led to economic collapse and long-term losses.

Indonesia also confronts challenges stemming from unsustainable practices in natural resource extraction, leading to high pollution and environmental deterioration. The extractive sector, notably coal mining, is dominated and controlled by Indonesia's oligarchs (Hadiz and Robison, 2013). The coal industry is primarily controlled by national companies and affluent investors in Indonesia. There exists a symbiotic relationship between political actors and wealthy business investors to secure government contracts and mining concessions (Berenschot, 2018).

The overarching goal of this study was fourfold: 1) to quantify the carbon emissions from coal mining and transportation abroad, 2) to estimate the ecological costs associated with coal mining and transportation, 3) to identify areas for improvement within the extraction industries and Indonesia's economy, and 4) to recommend government actions to address carbon emissions in Indonesia. Assessing the environmental costs of one of Indonesia's largest economic sectors, the extraction industry contributes to the literature on achieving sustainable socioe-conomic development (Pirnama et al., 2020). It provides insights for policymakers to reconsider economic growth strategies reliant on natural resources.

Methods

Life cycle assessment

This research encompassed the entire coal production of Indonesia, with over 47% originating from East Kalimantan, 30% from South Kalimantan, and 9% from South Sumatra and other regions. The study period spanned from 2011 to 2021, with data on total coal production and exports sourced from the Handbook of Energy and Economic Statistics in Indonesia (HESSI), excluding coal imports from the analysis. Due to incomplete data for 2021 across provinces, some calculations relied on available data from 2010-2020 or 2011-2020.

This research aimed to estimate the external cost of coal production in Indonesia. The estimations of environmental impact used the life cycle assessment (LCA). The LCA is a methodology to evaluate and examine the environmental consequences of products or activities in their life cycles. The journey starts with extraction, process, transport to users, usage, and final disposal. Therefore, LCA is often called cradle-to-grave assessment (ISO, 2004). According to the International Standard Organization (ISO), there are four steps to conduct LCA, including (1) goal and scope statement, (2) inventory analysis, (3) impact assessment, (4) interpretation (ISO, 2004). The scope of the study boundaries includes all life cycles of coal mining and coal transport. The inventory analysis is related to study boundaries, and the following diagram explains the detailed process of coal production, from raw material exploitation to coal transport (see Figure 1). The Impact assessment includes four chosen impact categories, such as GHG emissions, air pollutants, water pollution, and water depletion. The parameters have two groups: a) Physical parameters for heat content (per GJ), GHG Emission (tonne CO_2eq), Air Pollutants (kg SO_2eq, kg NO_xeq, kg PM_{10}, kg $PM_{2.5}$), b) Water pollutants (kg SO_2eq, g N-eq, g PO_{43}eq), c) Water depletion (L and m^3), and d) Parameters related to the external cost of GHG emission and air pollutants referred to valuation studies.

This study utilized benefit transfer (BT) to estimate the external cost of the above environmental impacts. BT is a method that transfers the current valuation of non-market values from the original (primary) study to a new research location known as a secondary site.

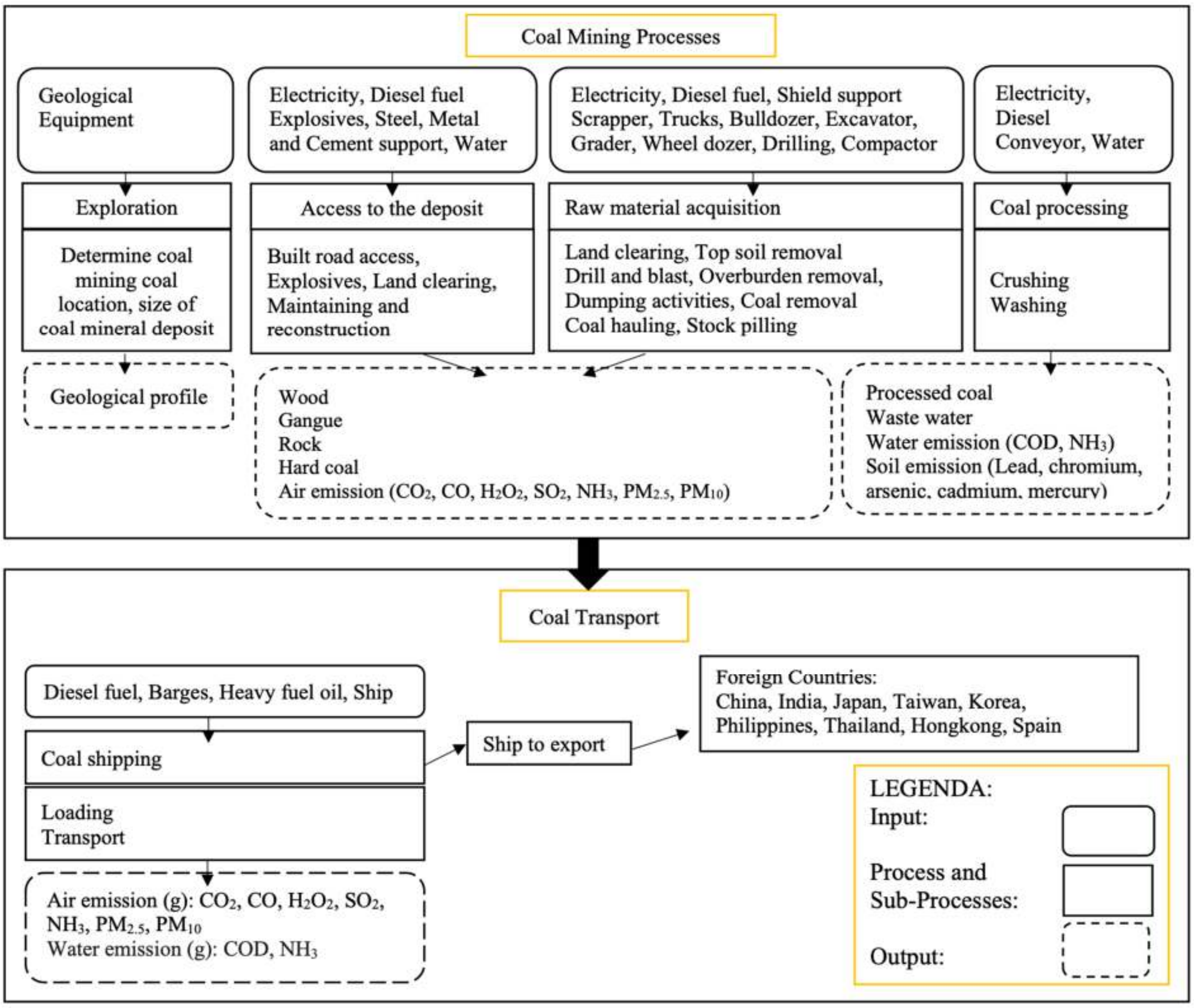

Figure 1. The study boundaries.

Calculating GHG emission and air pollutant (AP) from coal mining and its external cost

Regarding coal mining processes, GHG included in this study are fugitive CO_2, N_2O, and CH_4 emitted from fossil fuel on-site combustion, energy input, material input, mine surface, and post-mining stage. Aguirre-Villegas and Benson (2017) pointed out that coal mining with a heat content of 1 GJ produced 4,021 g CO_2eq. The average heat content of coal produced in East Kalimantan is 26.69 GJ/tonne and emits 107.32 kg CO_2eq. The moderate heat content of coal produced in Indonesia was collected and calculated from available literature studies of every producing coal region (see Table 1).

Table 1. Heat content in every province.

Provinces	Weighted average heat content (GJ/tonne)	GHGEM (kg CO_2eq/tonne coal)
East Kalimantan	26.69	107.32
South Kalimantan	22.6	90.87
South Sumatra	27.9	112.19
North Kalimantan	12.2	49.06
Central Kalimantan	39.73	159.75
Others	30.91	124.29

GHG emission from producing one tonne of coal (GHGEM) was calculated with equation (1). The total amount of GHG emission from Indonesia's coal mining industries in each year (T_GHGEM_t) is equal to GHGEM times the total coal production in tonnes for t year (TP_t) as equation (2).

$$\mathrm{GHGEM\ (kg\ CO_2eq/tonne)} = 26.69\mathrm{(GJ/tonne)} \times 4{,}021\ \mathrm{(kg\ CO_2eq/GJ)} \times \frac{1}{1000}\mathrm{(kg/g)}$$
$$= 107.32\mathrm{(kg\ CO_2eq\ /tonne)} \qquad (1)$$

$$\mathrm{T\_GHGEM_t(tonne\ CO_2eq\ )} = \mathrm{GHGEM(kg\ CO_2eq/tonne)} \times \mathrm{TP_t\ (tonne)} \times \frac{1}{1000}\mathrm{(tonne/kg)}$$
$$= 107.32\mathrm{(kg\ CO_2eq\ /tonne)} \times \mathrm{TP_t\ (tonne)} \times \frac{1}{1000}\mathrm{(tonne/kg)} \qquad (2)$$

Regarding the external cost of air pollutants in this study, Pirmana et al. (2021) researched the environmental costs of all economic activities in Indonesia. They showed that the total environmental cost of air pollution damages in Indonesia was about 348.35 trillion (Rp) in 2010, and they also revealed the EC of per kg air pollutants and total EC per air pollutant categories (see Table 2).

Table 2. External cost of air pollutants.

No	Air Pollutant	External cost* (Rp/kg in 2010)	External cost** (US$/kg in 2010)	Total external cost (billion Rp in 2010)*
1	SO_x	19,500	2.15	6,583
2	NO_x	36,820	4.05	1,605
3	TSP	35,560	3.91	2,896
4	PM_{10}	66,180	7.20	2,247
5	$PM_{2.5}$	96,290	10.5	869

Note: *Pirmana et al. (2021). **this study.

Carleton and Greenstone (2021) estimated the social cost per tonne of carbon (SCC), the damage caused by each additional tonne of carbon emissions to the global, as 125 US dollars. Thus, the total external cost of GHG, emission in (t-n) years ($\mathrm{EC\_GHGEM_{t-n}}$) was calculated with equation (3). This research adopted Indonesia Price Index (IPI) and Indonesia Exchange Rate (IER) in 2011-2020 (World Bank, 2024). After knowing the external cost in (t-n) year of coal mining activities (EC_{t-n}), we need to multiply the ratio of IER (IER_t/IER_{t-n}) and the ratio of IPI (IPI_{t-n}/IPI_t) to transfer money value from t year (2010) to (t-n) year (2011~2021).

$$\mathrm{EC\_GHGEM_{t-n}(tonne\ CO_2eq\ )} = \mathrm{T\_GHGEM_{t-n}(tonne\ CO_2eq\ )}$$
$$\times 125\mathrm{(US\$/tonneCO_2eq)} \times \frac{\mathrm{IER_t}}{\mathrm{IER_{t-n}}} \times \frac{\mathrm{IPI_{t-n}}}{\mathrm{IPI_t}}$$
$$\mathrm{EC_{t-n}} \times \frac{\mathrm{IER_t}}{\mathrm{IER_{t-n}}} \times \frac{\mathrm{IPI_{t-n}}}{\mathrm{IPI_t}} \qquad (3)$$

Calculating GHG emission, air pollutant (AP) from coal transport and its external cost

The EC of coal transport of g GHG emission was calculated by multiplying the distance from Indonesia to the destination country (D), total coal export in t year (TCE*t*), GHG emission from 1-tonne km transported ship to run with HFO, SCC price, and then calculated with IPI and IER for the US$ adjustment. The length distances were derived from www.Indonesia distantworld.com (see equation 4), while for EC the air pollutant also had a nearly similar equation (see Equation 5), except we also multiplied by AP cost from the existed study (Table 2).

$$\mathrm{EC\_GHGEM}_{\mathrm{t-n\&country}} = \mathrm{D} \times \mathrm{TCEt(tonne)} \times \mathrm{GHG\ (g\ CO_2eq)} \div 1{,}000{,}000\mathrm{(tonne／g)} \times 125\left(\frac{\mathrm{US\$}}{\mathrm{tCO_2}}\right) \times \frac{\mathrm{IER_t}}{\mathrm{IER_{t-n}}} \times \frac{\mathrm{IPI_{t-n}}}{\mathrm{IPI_t}} = \mathrm{US_{t-n}\$} \qquad (4)$$

$$\mathrm{EC}_{\mathrm{AP}_{\mathrm{t-n\&country}}} = \mathrm{D} \times \mathrm{TECt(tonne)} \times \mathrm{AP\ (g\ CO_2eq)} \div\ 1{,}000{,}000\left(\frac{\mathrm{tonne}}{\mathrm{g}}\right) \times \mathrm{AP\ Cost}\left(\frac{\mathrm{US\$}}{\mathrm{kg\ AP}}\right) \times \mathrm{IER_t} \times \frac{\mathrm{IPI_{t-n}}}{\mathrm{IPI_t}} \div \mathrm{IER_{t-n}} = \mathrm{US_{t-n}\$} \qquad (5)$$

Calculating water pollution and water depletion

Regarding the water pollution from coal production, this research utilizes the estimates from existing studies. Burchart-Korol et al. (2016) stated that coal mining produced water pollutants such as $Cl + SO_2$ was 0.6425 kg per Mg of processed coal. Tao et al. (2022) applied LCA to estimate 1 tonne of coal-produced emissions to water, such as COD (chemical oxygen demand) and ammonia N, about 8.87 g and 0.42 g, respectively. Regarding water consumption, this study cited Aguirre-Villegas and Benson (2017) who estimated water consumption for coal (1 GJ) in 3 ways consist of (1) water directly used on site: 41.5 L/GJ, (2) total water withdrawal (consumption + water waste): 267 L/GJ, (3) Total withdrawal less water treated and returned to environment: 2 L/GJ (Aguirre-Villegas and Benson, 2017). Based on their study, the coal production per year in South Kalimantan (SK) was 56,000,000 tonnes or equal to 1092 million GJ, which means that the average heat content of sub-bituminous coal is 0.195 GJ/kg. Thus, 1 tonne of sub-bituminous coal in SK is 0.195 GJ/kg times 1,000 = 195 GJ/tonne. Formulas for estimating water consumption:

1. Water directly used: 1 tonne coal: 195 (GJ/tonne) x 41.5 L/GJ = 8,092.5 (L/GJ) x Total Production (GJ)
2. Consumption + water waste: 1 tonne coal: 195 (GJ/tonne) x 267 (L/GJ) = 50,115 (L/GJ) x Total coal production
3. Water treated – returned to the environment = 1 tonne coal: 195 (GJ/tonne) x 2 (L/GJ) = 390 (L/GJ) x total production (GJ)

Results and Discussion

GHG Emission and external cost of coal mining

The absorption and release of radiant energy by greenhouse gases, which include water vapor, carbon dioxide, methane, nitrous oxide, and ozone, contribute to global warming. According to Guimarães da Silva et al. (2018), coal mining results in direct and indirect emissions throughout coal production and transportation processes, with methane emissions accounting for 98.3% of surface mining and post-mining activities such as coal crushing and handling. To calculate the total cost of GHG emissions, there are three methods for pricing CO_2eq: (1) the reduction cost of CO_2eq, (2) the trading price of CO_2eq, and (3) SCC of CO_2eq. Method (3) is renowned for its accuracy but is complex because it comprehensively considers GHG leads to climate change and has great impacts on social, economic, agricultural, and coastal damages across the carbon life cycle. As atmospheric CO_2eq concentrations increase, climate-related disasters impose increasing social costs on global populations. Nordhaus (2017) estimated the SCC to be \$31 per tonne of CO_2eq, whereas Carleton and Greenstone (2021) argued for an SCC of \$125 per tonne of CO_2eq, incorporating a 2% discount rate and emphasizing the importance of updating SCC calculations to include factors like climate damage, global and domestic impacts, socio-economic considerations, emission projections, uncertainty values, and equity assessments.

Looking at Table 3, the result of the calculation of total GHG emission and its external cost, it is evident that higher coal production correlates with increased greenhouse gas (GHG) emissions. From 2011 to 2020, CO_2 equivalent emissions rose from 40-60 million tonnes annually, reaching a peak of 63 million tonnes in 2019. East Kalimantan and South Kalimantan stand out as the highest contributors to emissions, averaging 25 million and 14 million tonnes of CO_2 equivalent per year, respectively. The external costs also peaked at \$8 billion in 2019 and \$7 billion in 2020, reflecting the impact of total coal production. The lowest external cost was observed in 2015 due to reduced production that year, while other years remained around \$5-6 billion.

In 2019, the mining industry contributed 5-8% to Indonesia's GDP over the past decade, with approximately 80% of this contribution coming from the coal industry (Arinaldo et al., 2019). The data clearly indicates a surge in foreign demand for coal in 2019, with exports to China totaling 144,415 thousand tonnes and to India totaling 116,949 thousand tonnes - an increase from 63,429 and 49,967 tonnes, respectively, in 2018. This marks the culmination of total exports over the last 10 years (Ministry of Energy and Mineral Resources, 2020).

Apart from GHG emissions, a study from Yuniarto and Amalia (2022) revealed the impact of coal mining in the Berau coal mining site in East Kalimantan; one tonne of coal generates a global warming impact 30.861kg CO_2eq, eutrophication 0.034kg PO_4eq, and acidification 33.097kg SO_2eq.

GHG emission and external cost from coal transport

Looking broadly at Indonesian coal consumers, most are located in Southeast and South Asia, spanning distances ranging from approximately 1,794 to 4,821 km from Indonesia via shipping routes.

Table 3. The external cost of GHG emission from coal mining during 2011-2020

Years	Total production (tonne) 2011-2020 (Ministry of Energy and Mineral Resources (2020)	Total GHGEM (CO_2eq)	Total external cost (billion US$)
2011	379,082,834	40,683,170	5.8
2012	450,918,456	48,392,569	6.7
2013	456,141,531	48,953,109	6.5
2014	432,500,000	46,415,900	5.8
2015	404,043,038	43,361,899	5.1
2016	431,871,750	46,348,476	5.7
2017	461,440,000	49,521,741	6.3
2018	512,575,182	55,009,568	6.8
2019	619,159,594	66,448,208	8.4
2020	560,741,894	60,178,820	7.5

Spain stands as the farthest coal consumer, situated approximately 12,368 km away. In terms of coal import volumes, India and China are notable for purchasing substantial quantities compared to other countries, followed by Japan and Korea. As international trade activity increases between countries, marine transportation contributes significantly to emissions and pollution from fuel use. Various marine fuels are utilized, including Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), Liquefied Natural Gas (LNG), and GTL (Gas-To-Liquid), with HFO commonly used in sea transport, including Indonesian transoceanic coal-exporting ships ranging in capacity from 55,000 to 170,000 tonne (Aguirre-Villegas and Benson, 2017). Research by Bengtsson et al. (2011) indicated that running a 1-tonne-kilometers of ship transport using HFO caused approximately 42 grams CO_2eq GHG emissions. Utilizing equation (4), Table 4 shows the result of EC calculation of GHG from coal transport. It indicated that the highest coal transport external cost is in 2019 and 2020, about 11 and 10 billion US$, respectively, and for the rest of the years 2011-2020, it is about 6-8 billion US$.

Table 4. The external cost of GHG emissions from coal transport abroad.

Years	EC of GHG from coal transport abroad (billion US$)
2011	7
2012	8.6
2013	7.6
2014	8.1
2015	6.7
2016	7.2
2017	7.3
2018	8
2019	11
2020	10

In addition, when coal production exceeds immediate demand, stockpiles or temporary storage areas must be created. Coal can remain in temporary stockpiles for extended periods, sometimes exceeding six months. Prolonged coal storage in these conditions can lead to self-ignition or spontaneous combustion, with temperatures reaching up to 1,742°C and emissions reaching 117,120 ppm (Yusuf, 2023). Zhang et al. (2021) explored the impact of shipping-induced air emissions on marine environments, revealing that ship-induced nitrogen deposition can enhance phytoplankton growth on the sea surface and contribute to atmospheric nitrogen deposition by about 43%. Besides marine fuel type, factors like vessel variety and engine type (slow and high-speed diesel engines) influence emission levels (Wu et al., 2021).

Air pollutants from coal mining

Air pollutants can have direct or indirect effects on the environment. Major pollutants from coal mining areas include particulate matter (PM), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and heavy metals. The heavy metal concentrations in PM include iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), lead (Pb), chromium (Cr), cadmium (Cd), and nickel (Ni) (Pandey et al., 2014). These pollutants degrade air quality and directly impact human health and the surrounding flora and fauna near coal mining sites (Singh et al., 1991). This study refers to Pirmana et al. (2021), who investigated the environmental costs of all economic activities in Indonesia, including the external costs associated with coal mining. Their findings revealed that coal mining contributes significantly to sulfur dioxide (SO_2) emissions, with an external cost of about 6,583 trillion Indonesian rupiah (Rp). Other notable external costs from air pollutant damages include total suspended particulates (TSP), PM_{10}, and nitrogen oxides (NO_x), amounting to approximately 2,896 trillion Rp, 2,247 trillion Rp, and 1,605 trillion Rp, respectively, in the year 2010. After quantifying the external costs of air pollutants, the next step is to calculate the annual external cost of coal mining activities by multiplying the external cost of each air pollutant (AP) by the Indonesia Price Index (IPI) and dividing it by the Indonesia Exchange Rate (IER) for each year.

Table 5 presents the external cost of air pollutants from coal mining in Indonesia. Over the past decade, the total external cost for all air pollutants from coal mining ranged from approximately 1,563 to 2,129 billion US$ broken down as follows: SO_x 724~1,068 billion US$, NO_x 177~261 billion US$, TSP 319~ 471 billion US$, PM_{10} (particulate matter with diameter ≤10 micrometers) 247~336 billion US$, $PM_{2.5}$ (particulate matter with diameter≤2.5 micrometers) 96~142 billion US$.

Air pollutants and external cost of coal transport

According to Bengtsson et al. (2011), marine fuel with high air pollutant emissions potential, particularly in terms of SO_2eq, is Heavy Fuel Oil (HFO), emitting approximately 0.83 g of SO_2eq 1-tonne-kilometer transported (consisting of 0.57 g of SO_x and 0.26 g of NO_x). In comparison, other marine fuels such as Gas-to-Liquid (GTL) emit 0.59 grams of SO_2eq, Marine Gas Oil (MGO) emits 0.58 grams of SO_2eq, and Liquefied Natural Gas (LNG) emits 0.09 grams of SO_2eq. Additionally, HFO emits approximately 0.45 grams PM_{10}. To calculate the environmental impact, we employed equation (5), multiplying the distance (D) by the total amount of coal exported (CE) and the emissions of 1 tonne-kilometer for a ship running with HFO. This result is then further calculated with the Indonesia Price Index (IPI) and Indonesia Exchange Rate (IER) over the course of a year. This approach provides a comprehensive assessment of the environmental impact associated with transporting coal using HFO-fueled ships.

Table 5. EC of air pollutants from coal mining 2010-2020 (unit billion US$).

Years	EC SO_x	EC NO_x	EC TSP	EC PM_{10}	EC $PM_{2.5}$	Total AP
2010	724	177	319	247	96	1,563
2011	922	225	406	314	122	1,990
2012	1,068	261	471	364	142	2,306
2013	1,031	252	454	352	137	2,226
2014	967	237	426	330	128	2,089
2015	912	223	402	311	121	1,968
2016	950	232	419	324	126	2,051
2017	981	240	432	335	130	2,117
2018	951	232	419	324	126	2,053
2019	986	241	435	336	131	2,129
2020	975	238	431	333	129	2,105

Table 6 presents the external costs of air pollutants from the calculations associated with coal transportation abroad, ranging from approximately 5.36 to 9.75 billion US$. Among these pollutants, PM_{10} incurs the highest external cost, estimated at 3.15 to 5.73 billion US$, while SO_x and NO_x contribute about 1 to 2 billion US$ each. The highest external cost was recorded in 2019, reaching 9.75 billion US$. In fact, polluting the ocean-atmosphere during transportation, coal shipping in Indonesia involves stopping at Jakarta port in North Jakarta for loading and unloading. Studies have indicated that particulate matter or coal flying ash from these operations has caused health issues, such as corneal illness, among residents in the Marunda District of North Jakarta (Djajatmadja and Wisnuwardhani, 2022). It is important to note that these estimates only pertain to coal transported abroad, excluding domestic transport. For domestic consumption, coal is delivered to power plants scattered throughout Indonesia. Most of these power plants are located on Java Island due to its large population and high energy demand. Indonesia has 126 coal-fired power plants, with approximately 80 units located outside Java Island and 43 units within Java Island.

Table 6. EC from AP of coal transport in Indonesia 2010-2020 (unit: billion US$).

Years	EC SOx	EC NOx	EC PM10	Total EC of AP
2010	1.19	1.02	3.15	5.36
2011	1.56	1.34	4.11	7.0
2012	1.84	1.65	5.07	8.59
2013	1.84	1.58	4.88	8.3
2014	1.68	1.44	4.44	7.56
2015	1.41	1.22	3.74	6.37
2016	1.57	1.33	4.08	6.98
2017	1.69	1.43	4.62	7.74
2018	1.8	1.61	4.77	8.19
2019	2.17	1.86	5.73	9.75
2020	1.86	1.6	4.93	8.4

Polluted water and water depletion of coal mining

Coal mining in Kalimantan Island contributes to water pollution, which is especially evident in the Lati River in East Kalimantan. Research by Marganingrum and Noviardi (2010) found that the surface water in the Lati River exhibits high acidity, likely resulting from its proximity to coal mining operations, particularly those of PT Bureau Coal. Additionally, Subagiyo et al. (2019) classified the water quality in this area as polluted due to various factors, including domestic waste, agricultural runoff, mining activities (such as coal mining), deforestation, and forest fires. These activities collectively contribute to the deterioration of water quality in the region, impacting the ecological health of the Lati River and surrounding areas. Dewi (2021) studied mining activities in Aceh Province, which disturb the ocean's ecosystem and cause the flow of coal water waste. The results of estimation presented in Table 7 highlight significant loads of chloride (Cl) and sulfate (SO_4) in water, averaging around 2 quadrillion g, along with chemical oxygen demand (COD) of around 2 million g, and ammonia of around 192 thousand g.

Water consumption plays a crucial role in coal mining, particularly when washing coal to separate it from other substances in the mixture. In the Kalimantan region, water used for mining operations is often sourced from rivers, although some mining companies may have recycling facilities that treat and return water to the environment. According to Aguirre-Villegas and Benson (2017), a mining site in South Kalimantan operates a treatment facility capable of processing water waste totaling approximately 802,500 m^3 from coal operations, crushing activities, and nearby community settlements. Given the importance of water usage in coal mining, it is essential to closely monitor the environmental impact of water depletion to ensure sustainable water management practices. Based on the estimates provided in Table 8 by the occupied water consumption equation, the average water directly used on-site amounts to 3 trillion liters, with water consumption including water waste plus water treated and returned to the environment totaling 2 trillion liters.

Table 7. Polluted water from coal mining activities.

Years	Total production 2011-2020*	Load of Cl + SO_4 in water (kg)	COD	Ammonia (kg)
2010	325,325,793	2.03003E+14	1,909,662	136,637
2011	379,082,834	2.36548E+14	2,225,216	159,215
2012	450,918,456	2.81373E+14	2,646,891	189,386
2013	456,141,531	2.84632E+14	2,677,550	191,579
2014	432,500,000	2.6988E+14	2,538,775	181,650
2015	404,043,038	2.52123E+14	2,371,732	169,698
2016	431,871,750	2.69488E+14	2,535,087	181,386
2017	461,440,000	2.87939E+14	2,708,652	193,804
2018	512,575,182	3.19847E+14	3,008,816	215,281
2019	619,159,594	3.86356E+14	3,634,466	260,048
2020	560,741,894	3.49903E+14	3,291,554	235,512

Source: *Ministry of Energy and Mineral Resources (2020).

Table 8. Water consumption in coal mining.

Years	Water directly used on-site (L/GJ)	Consumption + water waste (L/GJ)	Water treated returned to the environment (L/GJ)
2010	2.63254E+12	1.63037E+13	1.26877E+11
2011	3.06754E+12	1.89977E+13	1.47842E+11
2012	3.54883E+12	2.25978E+13	1.75858E+11
2013	3.6911E+12	2.28595E+13	1.77895E+11
2014	3.49979E+12	2.16747E+13	1.68675E+11
2015	3.26952E+12	2.02486E+13	1.57577E+11
2016	3.49471E+12	2.16433E+13	1.6843E+11
2017	3.73397E+12	2.31251E+12	1.79962E+11
2018	4.14776E+12	2.56877E+12	1.99904E+11
2019	5.01024E+12	3.10292E+13	2.41472E+11
2020	4.53752E+12	2.81016E+13	2.18689E+11

Analyzing Figures 2 and 3 reveals the disparity in external costs versus revenue percentage from the coal industry, encompassing both coal mining and coal transportation abroad.

The highest water consumption occurred in 2019 at 5 trillion liters, while the lowest was recorded in 2010 at 2 trillion liters. The entire life cycle of coal production, from mining to transport abroad, generates a substantial external cost (EC) due to environmental impacts such as GHG emissions, air pollutants (AP), water pollution, and water depletion. Although coal companies do not directly bear this EC, all Indonesians are affected greatly by the EC of GHG and AP. The most significant contributors to external pollution costs are GHG and AP emissions. Furthermore, coal production involves substantial water consumption and leads to water. When compared to the study by Wang et al. (2023) in Southwestern China, the results indicate that the estimates of external costs for the two studies are different due to the research scope, research method, focused impact categories, and parameters are all different (see Table 9). However, both studies all point out the external cost of coal production is quite significant.

Table 9. Brief conclusion and relevant study.

Author/years	Focus area	Average coal production/yr	EC of GHG/tonne	EC of AP/tonne
Wang et al. (2023)	Coal production Southwestern, China	101 million tonnes (in 2018)		
	Coal mining		-	-
	Coal transport domestic		-	Dust pollution: US$ 214.3/tonne
	Coal combustion		30 US$ /tonne	Air pollutants: US$ 52/tonne
This Study (2023)	Coal production in Indonesia	421 million tonnes (in average 2010-2020)		
	Coal mining		12.54-15.26 US$/tonne	3,439-5,250 US$/tonne
	Coal transport abroad		19.98-23.94 US$/tonne-km	19.58-23.30 US$/tonne-km

Figure 2 illustrates that in year 2020, coal mining generated revenue of approximately 35 billion US$ (constituting 2% of the total) while simultaneously incurring a substantial external cost of 2,154 billion US$ (98%). The breakdown of this external cost includes SO_x accounting for 45%, TSP 20%, PM_{10} 16%, NO_x 11%, $PM_{2.5}$ 6%, and GHG 0.3 %. In other words, for every 1 US$ earned from coal mining revenue, there is an associated external cost of 49 US$.

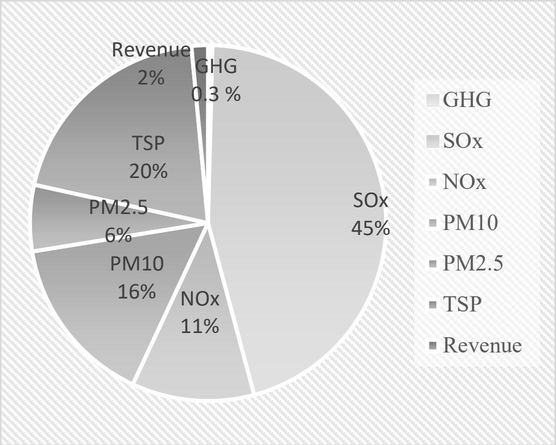

Figure 2. The percentage of revenue and external cost from coal mining.

It is important to note that coal revenue is estimated by multiplying the total production by the coal price in 2000. This significant imbalance highlights the substantial external costs associated with coal mining activities.

Examining Figure 3, it is evident that coal transportation abroad generated 63% of the revenue while contributing to 37% of the external costs, with GHG emissions accounting for 20% and AP 17% of the total external costs. This indicates that for every 1 US$ earned from coal transportation revenue, there is an associated external cost of 0.59 US$. The breakdown of these figures highlights the economic and environmental impact of coal transportation activities, with a significant portion of revenue being offset by the corresponding external costs, particularly related to GHG emissions and air pollutants.

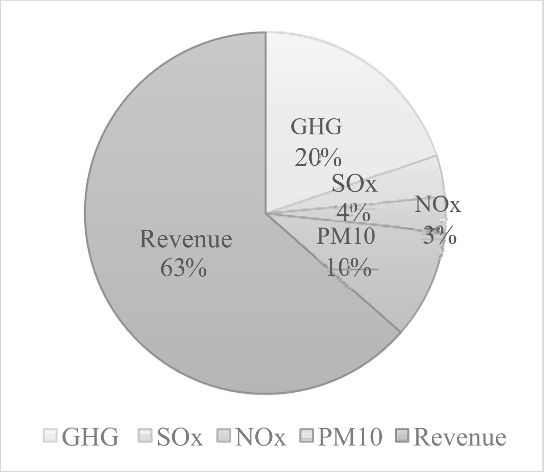

Figure 3. The percentage of revenue and external cost from coal transport.

Conclusion

To summarize, this study conducted the estimates of external costs from coal mining in Indonesia using the benefit transfer method, aiming to investigate the magnitude of GHG and AP and their associated external costs. In essence, despite substantial revenue generated by coal production, such as around 40 billion US$ in 2020, the total external costs of GHGs and air pollutants amounted to 2,154 billion US$, 53 times the revenue. This highlights a significant discrepancy where environmental damages far exceed economic gains, affecting all people in Indonesia. The study highlights the upward trend in coal production from 2010 to 2020 and emphasizes the need to address carbon emissions and air pollutants to mitigate environmental impacts. The recommendations include reducing GHG emissions and AP in coal mining activities, reconsidering coal as a primary export and energy resource, and aligning with global efforts towards achieving net-zero emissions. Furthermore, strengthening regulatory frameworks for extractive industries and recognizing indigenous peoples' rights over forested areas are crucial for sustainable resource management. Countries must prioritize sustainability and environmental conservation to safeguard against future catastrophes in light of recent climate change impacts and associated costs. Indonesia, in particular, should focus on holistic approaches to address environmental challenges and promote sustainable development.

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