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Carbon Emission Reduction using Waste Management Strategy Approach for Improving a Mine Site Environmental Performance

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The mining industry generates various types of waste that could affect environmental quality. One type of waste that is commonly managed by the mine site due to its coal-fired power plant operation is fly ash and bottom ash (FABA). The landfilling system is a worldwide common application strategy to manage FABA generated by a coal-fired power plant. The volume of coal burned for generating electricity determines the volume of coal ash managed in the landfill. This study applied a case study of a 160 MW coal-fired power plant in Indonesia that generates about 16 thousand t of coal ash annually for fulfilling mine site electricity demand. This study aims to compare the carbon emission reduction of three different management strategies associated with fly ash and bottom ash handling. Three scenarios have been developed: on-site landfilling, third-party shipment, and road-based application (internal utilisation). A life cycle assessment (LCA) was applied to compare those scenarios by using a cradle-to-gate boundary system. The functional unit (FU) used was a carbon footprint generated of 1 t of FABA managed using three different scenarios. The result showed that the lowest CO_2-eq emitted from the FABA road-based application scenario with 0.90 kg CO_2-eq, and the highest carbon footprint generated by the on-site landfilling scenario due to the life cycle of landfill facility. Compared with the on-site landfill and shipment to third party scenario, the road-based application scenario would reduce carbon footprint by about 305.70 kg CO_2-eq and 0.32 kg CO_2-eq for each t of FABA managed. Network impact analysis indicates that utilisation of diesel is the main environmental hotspot of each scenario. Further fuel efficiency studies should be conducted to create a better environmental performance.

1. Introduction

The mining industry is categorised as an energy-intensive industry where mining activities consume about 6.2 % of total global energy, including grinding, haulage, and digging (Holmberg et al., 2017). Energy consumption of each activity varies for open pit and underground mines, commonly determined by total production, type of mineral mined, and type of fuel used. One study indicated that the energy requirements of seven mine sites (four gold and three iron ore) ranged from 10,241 kWh/kt to 33,507 kWh/kt (Jeswiet and Szekeres, 2016).

The coal-fired power plant, one of the typical energy sources to fulfil mining's energy demand, would generate waste (fly ash and bottom ash) during the operational stage. One study revealed that coal-fired power plants contributed about 38 % of total power generated worldwide (Zierold and Odoh, 2020). In general, coal combustion for steam generation in coal-fired power plants would generate higher fly ash content (80 %) than bottom ash (20 %). These two types of coal-fired power plant wastes have technical differences in density, physical characteristics, and size. Fly ash has a density that ranges from 1.00 g/cm^3 to 2.50 g/cm^3 (Feng and Li, 2021), and bottom ash density ranges from 0.89 g/cm^3 to 1.06 g/cm^3 (Ullah et al., 2020). Fly ash and bottom ash (FABA) have three main similar chemical compositions, namely, calcium oxide (CaO), aluminium oxide (Al_2O_3), and silica oxide (SiO_2). By having these chemical compositions, FABA is widely used in construction projects, including concrete for reducing cement content (Maeijer et al., 2020), highway embankments for backfilling purposes (Rai et al., 2010), road stabilisation (Vestin et al., 2012), backfill material (Lee et al., 2014). Some other studies associated with FABA applications worldwide are presented in Table 1.

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Table 1: Various applications of FABA worldwide

Application	Region	Source
Reclamation uses:		
Abandoned mine reclamation	India	(Dube, 2020)
Clay mine rehabilitation	Sri Lanka	(Suloshini et al., 2020)
Soil erosion prevention	Indonesia	(Matsumoto et al., 2016)
Agricultural applications:		
Soil amendment	Australia	(Ukwattage et al., 2013)
Soil stabilisation	USA	(Anderson et al., 2004)
Manufacturing and other uses:		
Filler on asphalt	Poland	(Woszuk et al., 2019)
Cement substitution	Poland	(Rutkowska et al., 2021)
Bricks	India	(Yousuf et al., 2020)

The utilisation of FABA, a by-product of pulverised coal in a thermal power plant, is currently also applied in the mining industry. Some applications include soil remediation for reducing soil acidity in minerals mines, road-based material for the mining access road, and concrete for structural and non-structural purposes in the mining area. These applications would assist mining industries in reducing their potential environmental impacts, such as climate change (Adiansyah, 2019), soil and water contamination (Haddaway et al., 2019), and depletion of soil nutrients (Emmanuel et al., 2018). One of the tools that could be used to estimate the environmental impact of activity through its life cycle is life cycle assessment (LCA). A study revealed that three primary commodities (coal, aggregates, and copper ores) were dominating the LCA study in mining (Segura-Salazar et al., 2019). Some studies associated with fly ash utilisation were also found, including fly ash as geopolymer material (Tang et al., 2021), fly ash for partial replacement of cement in concrete (Dandautiya and Singh, 2020), and fly ash carbonation process (Margallo et al., 2018). None of the studies discusses fly ash and bottom ash for road-based mining areas. This study aimed to compare the carbon emission reduction of three different management strategies of fly ash and bottom ash handling using a life cycle assessment approach. A mine site in Indonesia that applies those strategies was taken as a case study.

2. Methods

The life cycle assessment (LCA) was applied to estimate the carbon emission of three different coal ash management strategies. Those three coal ash management strategies are landfilling on-site, shipping to the third party for further treatment, and road-based application, as presented in Figure 1. Based on the ISO standard on life cycle management, there are four stages required: 1) goal and scope, 2) inventory analysis, 3) impact assessment, 4) interpretation (ISO, 2006), where SimaPro 9.3.03 (Mark et al., 2016) was used for calculating the environmental impact.

2.1 Case study

A mine site that operates a 160 MW coal-fired power plant is taken as a case study where the coal-fired power plant generates two types of waste, namely, fly ash and bottom ash that would be dumped on a dedicated landfill (known as coal ash landfill). Fly ash and bottom ash (FABA) are generated from the combustion of coal in coal grinding equipment (pulverizer). The fine coal is delivered to the furnace by primary air using a pipeline, and burned coal will generate a solid residue (ash). Two pollution management tools are applied to prevent contamination due to coal-fired power plant FABA. These tools are bag-house for collecting the fly ash and submerged chain conveyor for storing the bottom ash.

FABA (waste) generated by an internal coal-fired power plant is about 10,000 t/y and is currently managed by operating a landfill and conducting a regular shipment to the third-party that has a permit from the Government of Indonesia for managing the FABA. These management methods are known as business as usual scenarios, as presented in Figure 1 (Scenario 1 and Scenario 2), and more than 60 % of FABA generated were shipped regularly to the third-party. The third scenario is utilising FABA as road-based material in the mining area that aims to apply the reduce, reuse and recycle concepts. Utilising FABA will also reduce mine road maintenance costs and external treatment or management costs of FABA.

2.2 Goal and scope

This study aimed to determine the carbon footprint of three different FABA management strategies. In this comparison, the volume of one shipment (8,000 t of FABA) is used as the parameter for collecting the operational data. The functional unit (FU) was 1 t of FABA, and cradle to gate system boundary was applied, as illustrated in Figure 1. The life cycle impact that estimated base on the operational data of 8,000 t of FABA would be transformed into 1 t of FABA as discussed in sub-section 3.1.

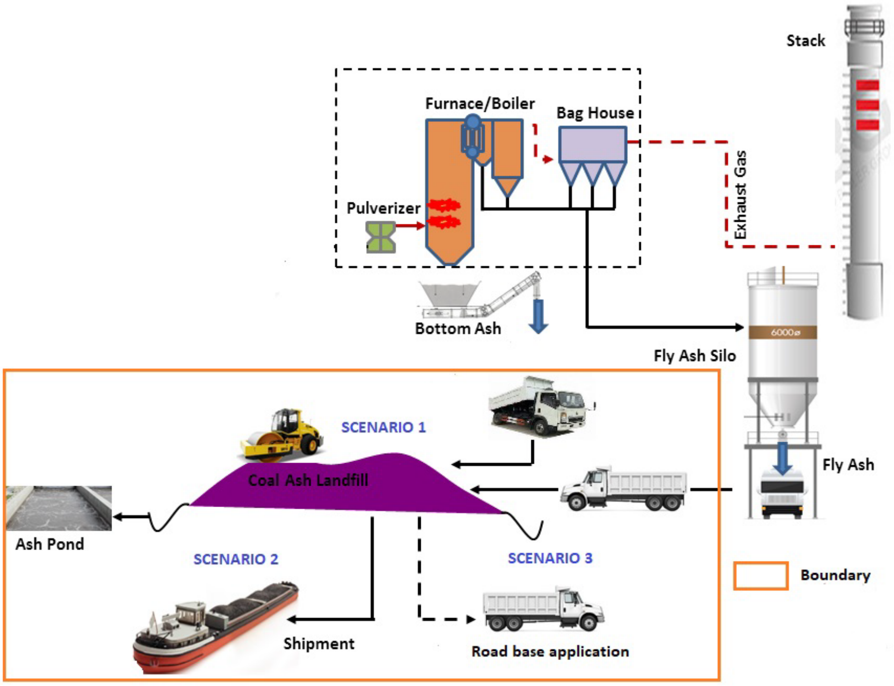

Figure 1: System boundaries

2.3 Inventory analysis (LCI)

The three FABA management scenarios, namely, landfilling on-site, shipping to the third party for further treatment, and road-based application, are summarised in Table 2 – Table 4.

The first scenario, as presented in Table 2, covers some activities: transportation of FABA from a coal-fired power plant to a disposal area (landfill), landfill re-contouring, and leaching water treatment. Coal bottom ash collected from a submerged chain conveyor was transported to a landfill using a dump truck with a load capacity of 5 t. A dump truck with a load capacity of 10 t was used for transporting fly ash from the fly ash silo to the disposal area (landfill). Beside diesel fuels, chemicals (sulphuric acid), water, and electricity for the dosing pump are required in the FABA landfill scenario.

Table 2: Data inventory – FABA landfill on-site scenario

Main activities	Sub-activities	Total material input	Unit
Transporting bottom ash to landfill	Diesel for dump truck	272	kg
Landfill re-contouring	Diesel for dozer	3,188	kg
	Water for dust suppression	3.5	m^3
Transporting fly ash to landfill	Diesel for dump truck	194	kg
Landfill re-contouring	Diesel for dozer	3,188	kg
	Water for dust suppression	3.5	m^3
Wastewater treatment	Dosing sulphuric acid	1,472	kg
	Dosing pump	200	kWh

Database approach (ecoinvent database) was used in landfill on-site scenario to estimate the impact of FABA landfill facility. Based on the government of Indonesia regulation, FABA is categorised as a waste that shall be managed properly. One of the strategies is transporting to the third party with a hazardous waste management license. Therefore, the second management strategy is shipping the FABA to other company that has hazardous waste management facility. The third party company is located about 350 nautical miles from where FABA is generated. There are four activities within the scope of the second scenario: FABA transporting and handling, tug-boat services, and shipment process, as presented in Table 3. Fossil fuel consumption (diesel) for loading and hauling activity is the main material input of the second scenario. A small volume of water is required for dust suppression during the barge's FABA handling.

Table 3: Data inventory – FABA shipment to the third-party scenario

Main activities	Sub-activities	Total material input	Unit
Transporting FABA to barge	Diesel for dump truck	217.60	kg
	Diesel for loader	446.25	kg
FABA handling at the barge	Diesel for dozer	1,062.5	
	Diesel for excavator	807.5	kg
	Water for dust suppression	2.0	m^3
Tug-boat services	Diesel for two tug-boats	1,275	kg
Shipment to the third-party	Diesel for tug-boat 1200 HP	13,458.90	kg

The internal data record showed that more than 50 % of the total FABA generated was transported to the third party from the Year 2010 to the Year 2017. FABA utilisation scenario is proposed for increasing the volume of FABA utilisation internally. A total of 8,000 t FABA is mixed with 8,000 t of mine soil or 50 % FABA and 50 % mine soil composition. The mixture materials are spread out into five layers with 40 cm height for each layer as road-based in the mining area. There are four activities involved in road-based work, namely, transportation, FABA mixing and spreading, and compacting road-based layers. These all activities consume fossil fuel (diesel) as the main input material, as presented in Table 4.

Table 4: Data inventory – FABA road-based application scenario

Main activities	Sub-activities	Total material input	Unit
Transporting FABA for site application	Diesel for dump truck	2,992	kg
	Diesel for loader	446	kg
FABA mixing with soil	Diesel for excavator	1,857	kg
	Diesel for loader	1,466	kg
Spreading of mixed material	Diesel for dozer	1,594	kg
	Diesel for grader	842	kg
Compacting	Vibrator compactor	238	kg

3. Results and discussion

3.1 Life cycle impact assessment (LCIA)

Life cycle impact assessment applied ReCiPe midpoint methods and Hierarchist version where global warming as the impact category focused. Table 5 compares the CO_2 equivalent (CO_2-eq) emissions that were released from handling 1 t of FABA material for each scenario. It can be seen from Table 5 that the lowest CO_2-eq emitted from the FABA handling with 0.90 kg CO_2-eq is the road-based application strategy, and the highest carbon footprint is generated by the landfilling on-site scenario. Compared with the first and second scenarios, the road-based application strategy would reduce carbon footprint by about 305.70 kg CO_2-eq and 0.32 kg CO_2-eq for each t of FABA managed.

Table 5: Global warming of 1 t FABA – based on scenario applied

Impact Category	Unit	Scenario 1	Scenario 2	Scenario 3
Global Warming	kg CO_2-eq	306.60	1.22	0.90

Figure 2 shows that utilisation of diesel is the main environmental hotspot of each scenario. On-site landfill scenario generated the highest environmental hotspot (99.8 %) from the life cycle of the landfill facility, as seen in Figure 2a. The FABA shipment scenario (see Figure 2b) shows that diesel consumption of vessels that transport FABA to the third party contributes 77.9 % of the total carbon footprint. Scenario 3 for FABA on-site application, as seen in Figure 2c, shows that more than 50 % of the total carbon is emitted by FABA mixing activity.

There are also other impact categories such as terrestrial acidification, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, and water consumption that compare each scenario's environmental impact magnitude. The highest environmental impact of all impact categories would be the on-site landfill scenario, where most of the lowest environmental impacts are generated by applying a road-based scenario.

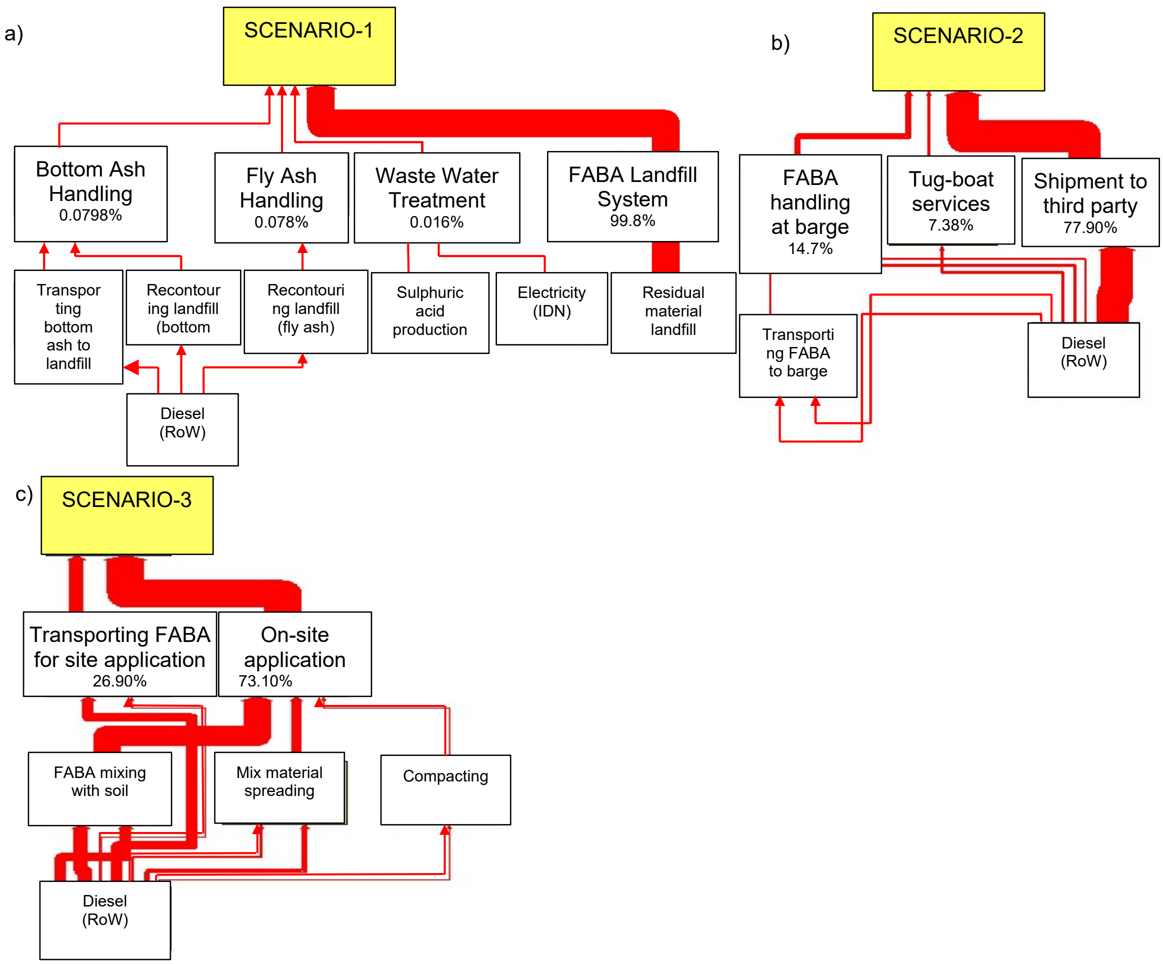

Figure 2: Network impact analysis of (a) on-site landfill scenario, (b) shipment to third part scenario, (c) on-site application scenario

3.2 Limitations

The availability of a local database would create a less reliable and accurate result for life cycle impact assessment. Some assumptions about fuel consumption have been made due to the limitation of data access. Database reference applies due to a lack of field data availability. The LCA analysis was limited to the impact categories associated with the selected method (ReCiPe).

4. Conclusions

A coal-fired power plant is currently the main energy source that supports mining activities in Indonesia. The coal combustion process would generate waste, namely, fly ash and bottom ash. These coal-fired power plant by-products should be managed properly based on the government of Indonesia's regulations. Some commonly applied management strategies are on-site landfilling, third-party handling, and internal utilisation. Each strategy generates carbon emissions mainly emitted by operational equipment, including dump trucks, dozers, excavators, and vessels. The application of on-site landfilling strategy generates the highest carbon emission for 1 t of FABA handling compared to other management strategies. The FABA utilisation strategy through road-based application indicates as the lowest carbon footprint with 305.70 kg CO_2-eq lower than on-site landfill scenario and 0.32 kg CO_2-eq lower than shipment to Scenario 3. The environmental hotspot of those three strategies indicates that the efficiency of diesel fuel usage should be considered to reduce the current carbon footprint. Further fuel efficiency studies should be conducted to create a better environmental performance.

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