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Research article

Application of a life cycle assessment to compare environmental performance in coal mine tailings management

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ABSTRACT

This study compares coal mine tailings management strategies using life cycle assessment (LCA) and land-use area metrics methods. Hybrid methods (the Australian indicator set and the ReCiPe method) were used to assess the environmental impacts of tailings management strategies. Several strategies were considered: belt filter press (OPT 1), tailings paste (OPT 2), thickened tailings (OPT 3), and variations of OPT 1 using combinations of technology improvement and renewable energy sources (OPT 1A–D). Electrical energy was found to contribute more than 90% of the environmental impacts. The magnitude of land-use impacts associated with OPT 3 (thickened tailings) were 2.3 and 1.55 times higher than OPT 1 (tailings cake) and OPT 2 (tailings paste) respectively, while OPT 1B (tailings belt filter press with technology improvement and solar energy) and 1D (tailings belt press filter with technology improvement and wind energy) had the lowest ratio of environmental impact to land-use. Further analysis of an economic cost model and reuse opportunities is required to aid decision making on sustainable tailings management and industrial symbiosis.

1. Introduction

Coal is utilized in many countries worldwide as a fossil fuel. Globally, the utilization of coal is 3.4 and 3.8 times higher than use of oil and natural gas, respectively (Osborne and Gupta, 2013). In total, coal supplied 29% of the world's primary energy in 2013 (Thomas, 2013). As illustrated in Table 1, the significant contribution of coal is at least in part due to its widespread geological distribution and to the large reserves, estimated to be around 860 billion tonnes.

These numbers indicate that coal-based industries have an important contribution to make to a country's development, not only in developed but also in developing countries. In Australia, for example, more than 64% of electricity generated comes from coal, 21.3% from natural gas, 7.2% from hydropower, and 4.4% from windpower (World Nuclear Association, 2013). In another example, Indonesia, a developing country, aims to generate 35,000 MW of electricity over the next five years, with coal-fired power plants contributing 55% of the total power generated (Perusahaan Listrik Negara, 2015). The demand for coal, currently led by the BRIC (Brazil, Russia, India, and China) economies, is predicted by Osborne and Gupta (2013) predicted to increase more than 50% between 2013 and 2030. Coal processing is needed to produce saleable coal to meet market demand, as run-of-mine (ROM) contains both coal and gangue mineral impurities. These processes, which include comminution, classification, concentration, and dewatering, take place in a coal handling and preparation plant (CHPP). An inevitable outcome of this processing is the production of tailings.

Coal tailings, also referred to as fine coal rejects, are produced from fine coal processing. The classification of fine coal is based on particle size in the range 0.15 mm–1.0 mm. Fine coal processing represents about 10–20% of the CHPP feed (Honaker et al., 2013; Kumar et al., 2014). This fine coal processing generates around 30% reject material, consisting of both coarse rejects and fine rejects (tailings). This means that 0.6–1.2 million tonnes per annum (Mtpa) of tailings are generated by coal mine sites with 20 Mtpa of ROM. Failure to manage tailings effectively can increase mining operation cost and result in severe environmental damage and human health consequences (Adiansyah et al., 2015; Kossoff et al.,

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Table 1
Distribution of proved coal reserves.

Location	Reserves (billion tonnes)	Percentage (%)
Europe/Eurasia	304.4	35.4
Asia Pacific	264.9	30.8
North America	245.1	28.5
Middle East/Africa	32.7	3.8
South America	12.9	1.5

Source: BP Statistical Review of World Energy in Thomas (2013).

2014; Zhengfu et al., 2010). Good planning is therefore required to prevent and identify impacts that might occur as a result of mine tailings management. Life Cycle Assessment (LCA) is one of the tools that could be utilized to achieve these objectives.

Although the application of LCA in mining is not as widespread as in some other fields (e.g. agriculture or food), some mining LCA studies can be found in the literature. The goals of these LCAs vary and include evaluating the environmental impact of two different alternative technologies for the disposal of mineral mine tailings (Fernandez-Iglesias et al., 2013), comparing the environmental impact of belt conveyors and off-highway trucks in surface mining (Erkayaoğlu and Demirel, 2016), identifying the environmental profile of gold production in terms of embodied energy and water, greenhouse gases, and solid waste (Norgate and Haque, 2012), reviewing the LCA methodology used in the mining industry (Awuah-Offei and Adekpedjou, 2010), underground mine development to the post-closure phase (Reid et al., 2009), and estimating land use equivalent factors in mining operations (Spitzley and Tolle, 2004). Results have been presented in the literature covering various minerals including bauxite (Bovea et al., 2007), copper (Memary et al., 2012), iron ore (Ferreira and Leite, 2015; Haque and Norgate, 2015), nickel (Mistry et al., 2016), and coal (Burchart-Korol et al., 2016; Ditsele and Awuah-Offei, 2012). Recent literature, however, has not considered LCA and land-use impacts of different coal tailings management. This study attempts to fill this gap and discover the novelty of environmental and land-use impacts in coal mine tailings management.

The aim of this study is to compare the environmental performance/impact of different mine tailings management strategies, and to evaluate the magnitude impact of land-use change. To achieve these objectives, three mine tailings strategies and five improvement strategies were selected and applied at a coal mine site located in New South Wales (NSW) Australia. The potential impacts of each of these strategies were analyzed using SimaPro with two impact methods: the Australian Indicator and ReCiPe (Simapro manual PRe Consultants, 2008). The analysis of land-use impact was based on the method developed by Spitzley and Tolle (2004) and Milà I Canals et al. (2007).

2. Methodology

2.1. Base case and scenario definition

The case selected is an open pit mine that is projected to extract about 20 million tonnes per annum (Mtpa) of ROM coal and operate for 20 years. Four scenarios were developed in order to compare the potential impacts of different tailings management strategies, as shown in Table 2. These scenarios seek to reduce the volume of water transported in tailings by increasing the percentage of solids. Scenario 3 is the base case scenario, with the highest percentage water content. The use of tailings paste was selected for Scenario 2, with the percentage solids increasing to 50% compared to Scenario 3. Scenario 1 involves tailings cake, with the lowest percentage water content. Scenario 1 was also subject to an additional technology improvement of the flotation system, as shown in Table 2. Two systems were replaced, namely the aeration and sparging technologies that could decrease energy consumption in a flotation tank, as noted in Kohmuench et al. (2010). Altered mechanical dewatering systems were applied to achieve the final water content prior to disposal. The four scenarios are described in section 2.3.1.

2.2. Goal and scope

The objectives of this study were to develop an inventory of different tailings management scenarios, to assess and compare the environmental impacts of each tailings management scenario, and to determine the associated land-use impacts. In addition, the most sustainable management option for fine coal tailings management was also to be determined. The functional unit (FU) is defined as 1 tonne of fine coal concentrate slurry generated by flotation cells.

2.3. Life cycle inventory (LCI)

A life cycle inventory (LCI) considers the input and output of a product throughout its life cycle (ISO 14044). In this study, the product was fine coal concentrate slurry from flotation cells which also generates tailings as a by-product. This section describes the system boundary and operation of each scenario, the data sources, and some of the main assumptions of this study.

2.3.1. System boundary and description

The LCA system boundary mainly consists of three stages: segregation of fine coal, mechanical dewatering, and tailings transportation. Fig. 1 shows the life cycle stages, with each of the

Table 2
Coal tailings management strategies for each scenario.

Scenario	Segregation	Mechanical dewatering	Tailings transport
1. Tailings with 65% solids 1.A Tailings with 65% solids – flotation technology improvement	Flotation column cells with additional of frother and collector.	#1. Thickener with additional of anionic flocculant; #2. Belt press with additional anionic and cationic flocculants.	Transported by truck to the tailings disposal area.
2. Tailings with 50% solids	Flotation column cells with additional of frother and collector.	#1.Thickener with additional of anionic flocculant; #2. Paste thickener with an additional anionic flocculant.	Pumping to the tailings disposal area.
3. Tailings with 30% solids	Flotation column cells with additional frother and collector.	Thickener with additional of anionic flocculant.	Pumping to the tailings disposal area.

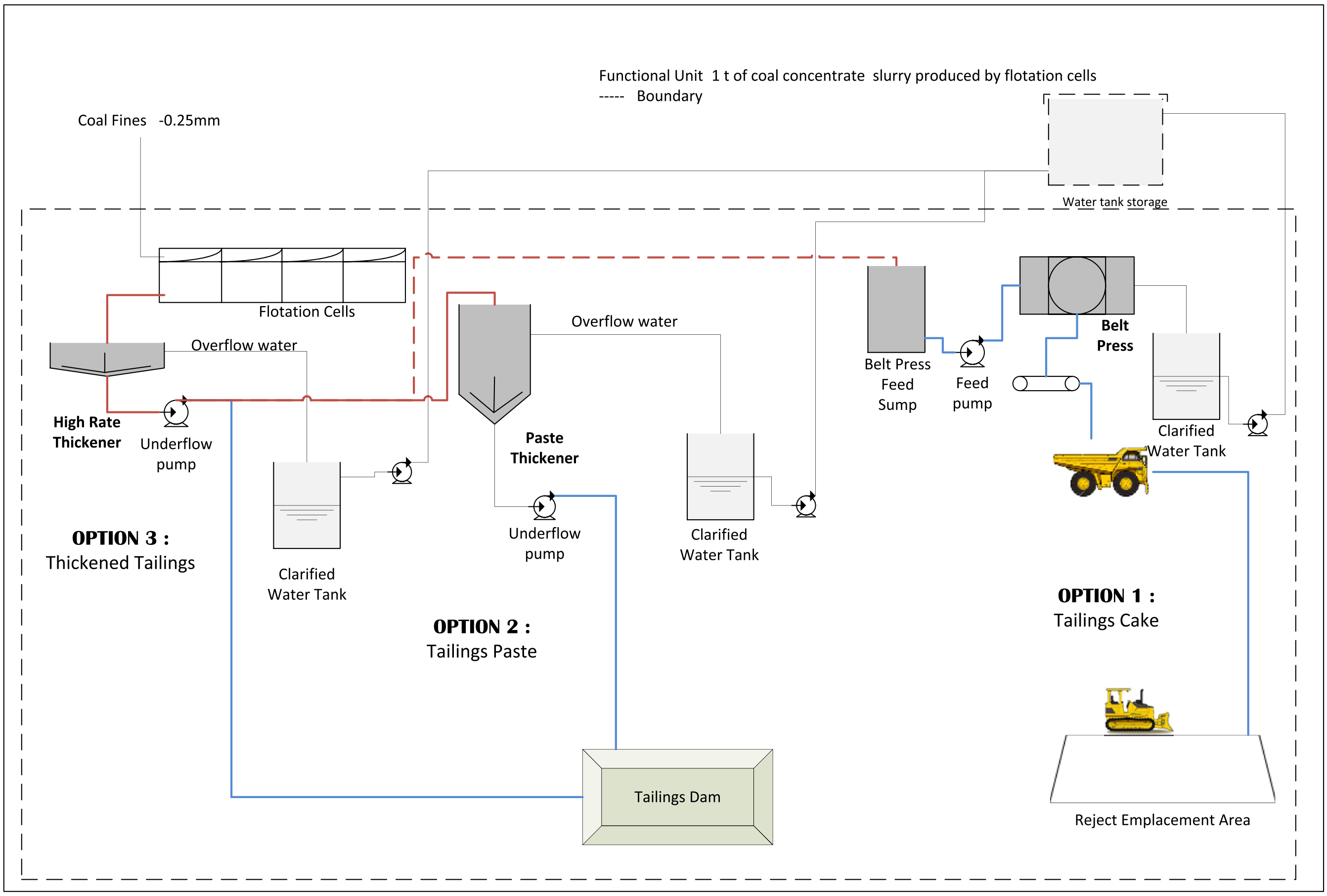

Fig. 1. Flow diagram of coal mine tailings strategies.

three scenarios consisting of several processes including segregation of coal from its impurities, chemical mixing, water and tailings pumping, and electricity usage.

Flotation cells are fed with raw coal slurry originating from the de-sliming process in the CHPP, where raw coal particles smaller than 0.1 mm are separated. Two types of chemicals are utilized to separate coal from its impurities: methyl isobutyl carbinol (MIBC) as a frother and diesel oil as a collector. The segregation process generates two products, namely coal concentrate slurry and tailings slurry. This study is focused on comparison of three options for management of the tailings slurry generated by flotation cells. The different handling methods of coal tailings are applied when flotation cells generate tailings with 20% solids or more.

2.3.1.1. Option one: tailings cake using belt press filters. The first two steps of this option (i.e. flotation and thickening) are also used in options two and three. The thickener underflow 30% solids are pumped into a belt press feed sump and distributed to the belt press filter machine as shown in Fig. 2.

During the flocculation stage, the fine coal tailings are flocculated using two types of polymer: an anionic flocculant and a cationic coagulant. The free water in the flocculated slurry is drained by gravity through the drainage (lower) belt, leaving a mat of solids. Pressure is first applied in the wedge stage, squeezing the remaining water out of the tailings. Further dewatering occurs during the high-pressure stage when the tailings solids are compressed and sheared between belts and rollers. Tailings with 65% solids are discharged from the belt press filter and are transferred by conveyor to a transfer point, from where trucks transport the tailings cake to a disposal area (reject emplacement).

2.3.1.2. Option two: tailings paste using paste thickener. The tailings from flotation cells flow by gravity to a tailings thickener and anionic flocculant is added to the tailings thickener to assist in the settling and aggregation of tailings. Underflow tailings from the thickener with 30% solids are pumped into a paste thickener, as an extension of the normal thickening process. An anionic flocculant is added to the paste thickener to bind the fine particles together. Flocculated particles with 50% solids settled at the bottom of the paste thickener are then pumped and transported by pipeline into the tailings disposal area. The overflow water from the thickener and paste thickener flows to a clarified water tank by gravity.

2.3.1.3. Option three: thickened tailings using thickeners. The tailings from flotation cells flow by gravity to a tailings thickener and anionic flocculant is added to the tailings thickener to assist in settling and aggregation. Underflow tailings with 30% solids from the thickener are pumped and transported by pipeline into the tailings dam. The overflow water from the thickener flows to the clarified water tank by gravity.

2.3.2. Data collection and main assumptions

LCIA modelling was performed using Simapro 8.0 software. Necessary materials, energy, chemicals, and equipment were identified for each of the three tailings management options. Site-specific data were obtained from a publicly available consultant

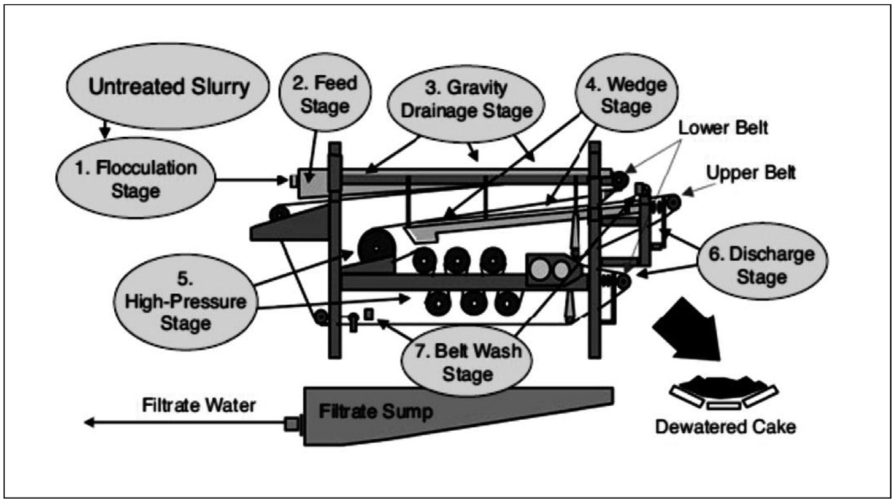

Fig. 2. Belt press filter operations (Fenzel, 2012).

report (QCC Resources Pty Ltd: 'dewatering option report'). To complete the LCI, laboratory results and information from the literature were used as supporting data. Assumptions made during the inventory analysis elaboration stage are as follows:

- The water used in the three options are from a close-cycle water system, with the reclaimed water generated from each tailings management process returned to the plant and reused.
- There are two types of disposal areas used for final tailings disposal: a tailings dam for tailings with 30% and 50% solids, and reject emplacement area for tailings with 65% solids.
- The energy consumption for underflow pumping was obtained from rheology laboratory results generated in previous research by Adiansyah et al. (2016).
- Other data related to equipment maintenance/transportation, labour, revegetation, and tailings disposal site monitoring and inspections were excluded from the study due to lack of data.

2.4. *Life cycle impact assessment (LCIA)*

As shown in Fig. 3, life cycle impact assessment (LCIA) is the third stage of LCA, after the goal and scope definition, and life cycle inventory (LCI) development. At this stage, potential impacts are assessed based on defined impact categories (goal and scope definition) and the environmental flows identified (inventory analysis).

2.4.1. *Potential environmental impacts*

The method employed to analyse the potential environmental impacts of each scenario was the Australian indicator set methods version 2.01. This method is composed of 12 impact categories (midpoint): global warming (GW), eutrophication (EU), land-use (LU), water use (WU), solid waste (SW), fossil fuels (FF), minerals (MN), human toxicity (HT_C and $_{NC}$) (carcinogenetic and non-carcinogenetic), aquatic ecotoxicity (AE_{FW} and $_{MA}$) (freshwater and marine aquatic). However, only seven impact categories are typically considered to be associated with mining activities: global warming (GW), human toxicity, freshwater aquatic ecotoxicity, eutrophication, land use, water use, and energy use (Awuah-Offei and Adekpedjou, 2010; Mistry et al., 2016; Santero and Hendry, 2016). In addition, this method only considers one factor (global warming) in its weighting calculation and the single score generated from this method refers to the number (tonnes) of carbon

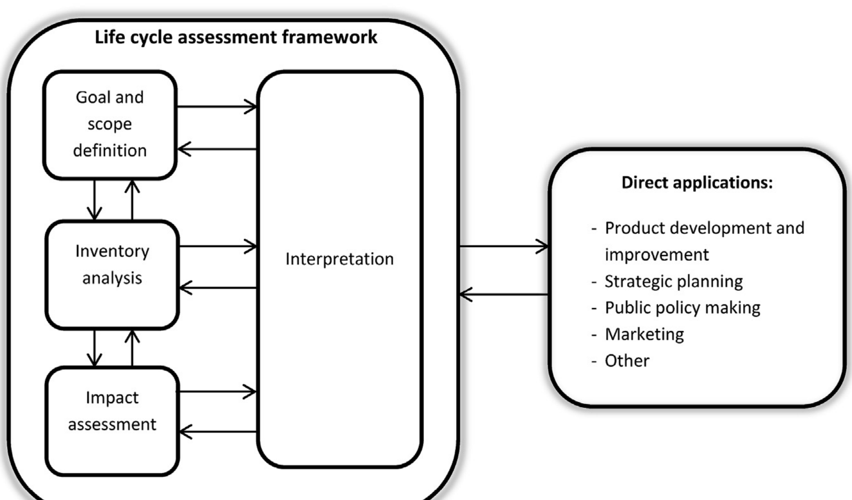

Fig. 3. Life cycle assessment framework (International Organization for Standardisation, 2006).

dioxide equivalent ($tCO_{2\text{-}eq}$) released. As one of the steps required in LCIA, the weighting factor has an important role as a variable to integrate various environmental impacts and to contribute in environmental impact interpretation (Itsubo et al., 2015). This is an obvious limitation of the Australian indicator set methods.

In order to address this limitation, the authors opted to also use the ReCiPe method as well to calculate the environmental endpoints. This method was developed by a number of institutions including RIVM and Radbound University, Institute of Environmental Sciences (CML) at Leiden University, and PRe Consultants. Three types of endpoint categories are included, as shown in Table 3: damage to human health (HH), damage to ecosystem diversity (ED), and damage to resource availability (RA).

2.4.2. Land-use impacts

Two land-use elementary flows are land occupation and land transformation, with the differences between the two associated with the land occupation type and period (Koellner et al., 2013; Milà I Canals et al., 2007). Koellner et al. (2013) defined the terms as follows: land transformation aims to modify the current land use to align with an intended use, such as mine revegetation to help establish grazing areas, whilst land occupation is utilized for production purposes and requires ongoing maintenance such as land use during mining operations.

Currently, there are challenges related to land use modelling using biodiversity indicators. Souza et al. (2015) noted several limitations including the absence of functional and population effects and the oversimplification of the real dynamics and complexity of species interactions. On this basis, the authors decided to use the surface area occupation method to evaluate land-use impacts. Here, land occupation impact (LOI) is the function of three variables: Area (A), Time (t), and Quality (Q) (Lindeijer, 2000) as presented in Equation (1).

$$\text{LOI} = \text{Area}\ (A) \times \text{Time}\ (t) \times \text{Quality}\ (Q) \tag{1}$$

The use of land to support mining operations results in a number of environmental impacts. These impacts are mainly caused by functional changes in the land prior to and during mine operations. Mining companies are required to revegetate to restore the land function to its original condition. In this study, the authors assumed that the pre-mining and post-mining land quality would be similar ($Q = 1$). However, this assumption does not apply when permanent degradation has occurred.

3. Results and discussion

3.1. Inventory analysis

The four mine tailings disposal scenarios were assessed in terms of material and energy inputs as shown in Table 4. The paste tailings strategy generated the highest energy consumption, mainly from two sources: column flotation contributed 85% and the paste thickener contributed 13% of total energy use. The energy consumed by the paste thickener to produce 50% mass solids was 4.1 kWh/t, while use of the belt-press to increase the solids content in tailings to 65% required around 1.9 kWh/t (QCC, 2013).

The different levels of energy consumption associated with each scenario were mainly due to the differences in energy use by the installed dewatering technology. For example, the belt press used to produce tailings with higher mass percent solids than the paste thickener required 10% less energy and generated 19% fewer tailings by weight. This means that using the belt press provided two advantages (lower energy use and higher tailings solids production) over use of the paste thickener. In addition, producing higher tailings solids also means less land required for tailings disposal, as shown in Table 4.

The introduction of new technology into the base case scenario could reduce energy use. Technological improvement during aeration and sparging in option 1A (belt press with upgraded technology) resulted in a decrease in energy consumption by more than 45% of the total energy usage. As a result, option 1A had the lowest energy use compared to other scenarios. However, this scenario then had the highest level of chemical input including MIBC, anionic and cationic flocculant used in the flotation and belt press system.

These data were assessed by life cycle impact assessment to estimate their contribution to environmental impacts, as presented in Section 3.2 and 3.3. Detailed inventory data (input materials, energy and machines) for all scenarios are presented in the supplementary information.

3.2. Impact evaluation analysis

Data presented in Section 3.1 shows that energy has been identified as one of the main contributors to the environmental impacts associated with tailings management. The energy source plays an important role in determining the magnitude of the environmental impact. In this case study, a coal-fired power plant was the main energy source used by the mine site. As clearly shown in Table 5, the environmental impact hotspots indicate that the electricity generated by the coal-fired power plant contributed more than 90% of the total environmental impact.

Improvement strategies were introduced to reduce the environmental impact (hotspots percentage), as follows: 1) Technology improvement in column flotation by replacing the aeration supply system and sparging method. The aeration supply uses a blower instead of a compressor, and the agitator method is used to replace the recycle pump system; 2) Introducing renewable energy to change the current mine site energy mix. Two types of renewable energy (solar and wind) were considered in this study, with these being the two main sources of renewable electricity generation in New South Wales (NSW) after snowy hydropower (Haylen, 2014; NSW Government, 2015; The Climate Institute, 2011). The use of renewable energy creates variations in tailings management options, as shown in Table 6. The authors focused only on improvement strategies (i.e. Options 1, 1A, 1B, 1C, 1D, and 1E) because these scenarios generate more tailings solids and require less land compared to other options.

3.2.1. Comparison of midpoint categories

A total of eight mine tailings management scenarios were

Table 3
Endpoint categories of ReCipe Method.

Impact category name	abbr.	Indicator name	Unit
damage to human health	HH	disability-adjusted life years	DALY
damage to ecosystem diversity	ED	loss of species during a year	species.yr
damage to resources availability	RA	increased cost	$

Adapted from (Goedkoop et al., 2013).

Table 4
Material input for different tailings management options.

Material	Unit	Dewatering options			
		1	1A	2	3
		Tailings cake (belt press)	Tailings cake (belt press with upgrade technology)	Paste tailings (paste thickener)	Thickened tailings (thickener)
Total Energy	kWh	918.3	509	1016.6	887.2
Column flotation		864.5	455.3	864.5	864.5
Thickener		20.75	20.75	20.75	20.75
Underflow pump		0.2	0.2	0.2	1.9
Belt press		32.9	32.9	–	–
Paste thickener		–	–	131.2	–
Chemical	kg	16.1	16.1	8.3	5.8
Machine: Truck and Dozer	lt	49.3	49.3	–	–
Land use	ha.m	0.00155	0.00155	0.00249	0.00352

Table 5
Environmental impact hotspots.

Environmental Impact	Hotspots		
	OPT1: Belt Press	OPT2: Paste Thickener	OPT3: Thickener
Global Warming (GW)	Electricity, black coal, 96.4%	Electricity, black coal, 98.4%	Electricity, black coal, 98.6%
Eutrophication (EUT)	Electricity, black coal, 92.5%	Electricity, black coal, 96.6%	Electricity, black coal, 97%
Land use (LU)	Electricity, 98%	Electricity, 99.5%	Electricity, 99.8%
Solid waste (SW)	Electricity, black coal, generate fly ash, 1.10 m^3	Electricity, black coal, generate fly ash, 1.45 m^3	Electricity, black coal, generate fly ash, 1.14 m^3
Cumulative Energy Demand (CED)	Black coal mine operations, 91.1%	Black coal mine operations, 94.2%	Black coal mine operations, 94%
Human toxicity- non cariogenic (HT)	Electricity, black coal, 97.5%	Electricity, black coal, 99.2%	Electricity, black coal, 99.4%
Human toxicity-cariogenic (HT)	Electricity, black coal, 96.3%	Electricity, black coal, 98.9%	Electricity, black coal, 99.3%
Freshwater aquatic-ecotoxicity (FWAE)	Electricity, black coal, 66.5%	Electricity, black coal, 89.4%	Electricity, black coal, 93.8%

Table 6
Scenario improvement options.

Tailings management	Types
Option 1	Tailings cake with belt press
Option 1A	Tailings cake belt press with technology improvement
Option 1B	Tailings cake belt press with technology improvement and 100% Solar RE
Option 1C	Tailings cake belt press with technology improvement and 10% Solar RE
Option 1D	Tailings cake belt press with technology improvement and 100% Wind RE
Option 1E	Tailings cake belt press with technology improvement and 10% Wind RE

assessed during the impact evaluation stage, as shown in Fig. 4. For ease of presentation, each scenario was normalized by dividing with the scenario that generates the highest impact in each category. However, this does not mean that the impacts from different categories can be compared against one another because they are not expressed using the same units.

The mine tailings management option that generated the highest environmental impact in most of the impact categories was Option 2 – thickener paste. All categories (GW, EUT, LU, SW, CED, and HT) were largely dominated by the operation of the flotation tank and paste thickener which consumed a large amount of energy. The highest water use was Option 1 which required 2.8 m^3 water per tonne solids (QCC, 2013) for belt press operations. The higher water usage of this option resulted in higher results for two impact categories (WU and FWAE) compared to other options. Different conditions were also applied for Option 1 with technology improvement and renewable energy installation. The introduction of technology and renewable energy contributed to reducing the impacts of WU and FWAE because less water was used to generate energy. It was estimated that energy consumption declined by approximately 45% compared to Option 1 (OPT 1) and 43% compared to Option 3 (OPT 3).

The authors provide an example of the comparison between energy use and global warming impact to give an overview of the impact of technology and renewable energy for each option as shown in Fig. 5. Six Option 1 scenarios (OPT: 1, 1A, 1B, 1C, 1D, and 1E) were examined with results showing that technology improvement contributed 43% GW reduction; this impact reduction increased by up to 97% when technology improvement and renewable energy were combined.

3.3. *Lifecycle damage categories*

Fig. 6 provides a global overview of impacts associated with Human Health (HH), Ecosystem Diversity (ED), and Resources Availability (RA) for each option.

As mentioned in the ReCiPe methodology (Goedkoop et al., 2013), environmental issues were addressed via three damage scores (known as endpoints): 1) HH, covering climate change, ozone depletion, toxicity, and human health associated with PM_{10} and ozone; 2) ED, covering climate change, acidification, toxicity, and land-use; 3. RA, covering mineral resource depletion, and fossil fuel depletion.

Option 1 shows a higher score compared with option 3 for all damage categories. This impact score reduces significantly when technology and renewable energy (Option 1B and 1D) are introduced as shown in Fig. 6. Option 1B generates the lowest impact score (4.2), especially compared to Option 2 (106.4), which had the highest impact score in all damage categories.

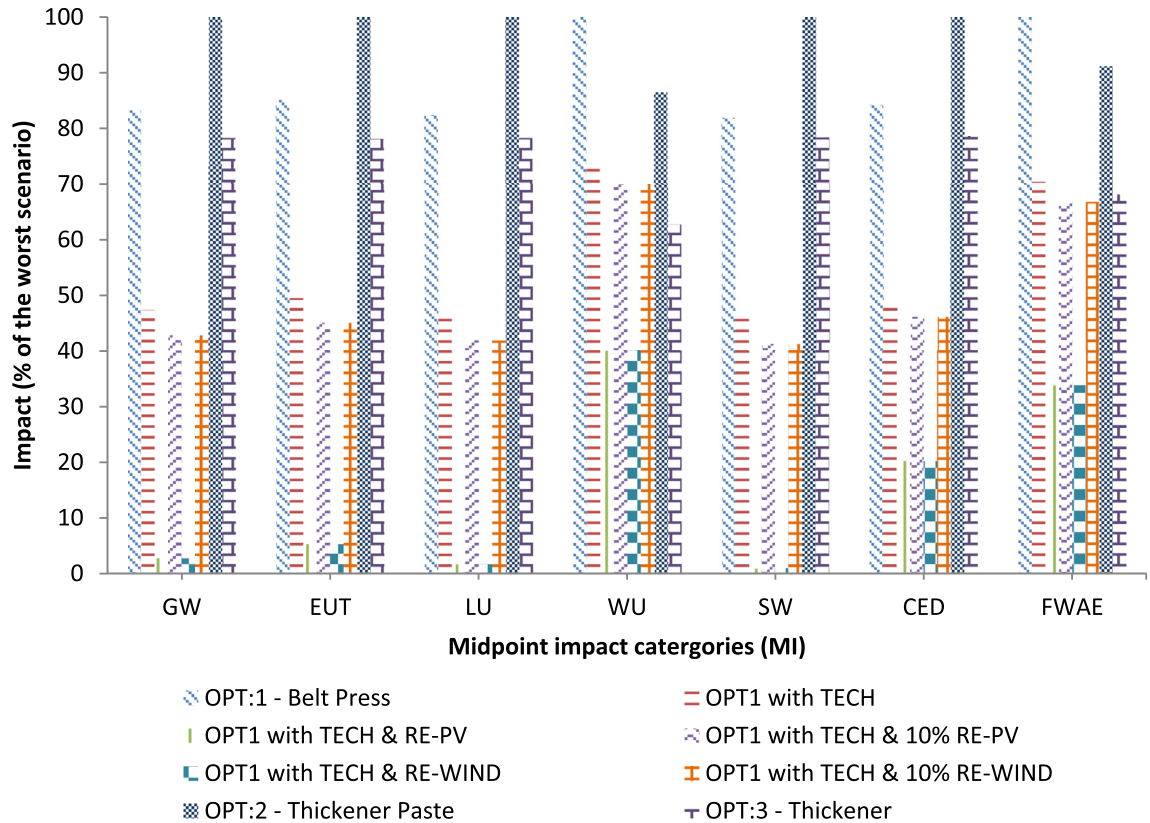

Fig. 4. Environmental impacts – midpoint result.

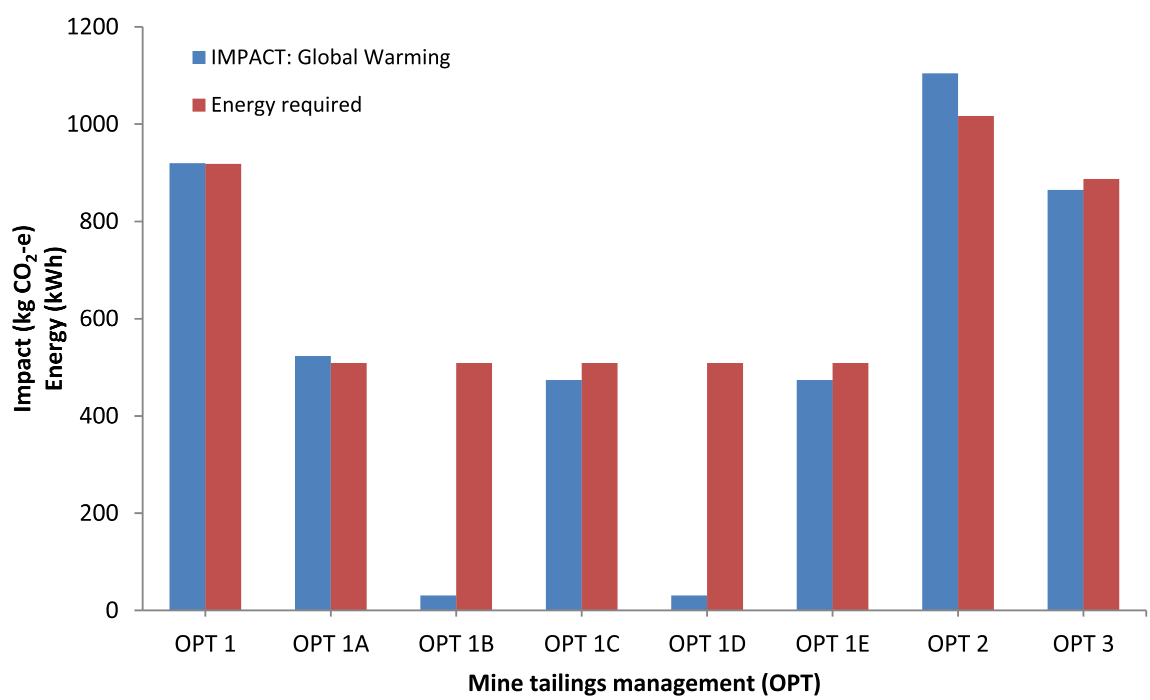

Fig. 5. Global warming impact for each option.

3.4. Land use

Land use change associated with mining operations can lead to substantial impacts including wildlife habitat loss, contamination of water and land, chemical contamination of surface and ground water, and lowering of the water table (Milà I Canals et al., 2007; Miranda et al., 2003). Mining operators prepare a mine plan document, addressing management of land change to avoid or prevent

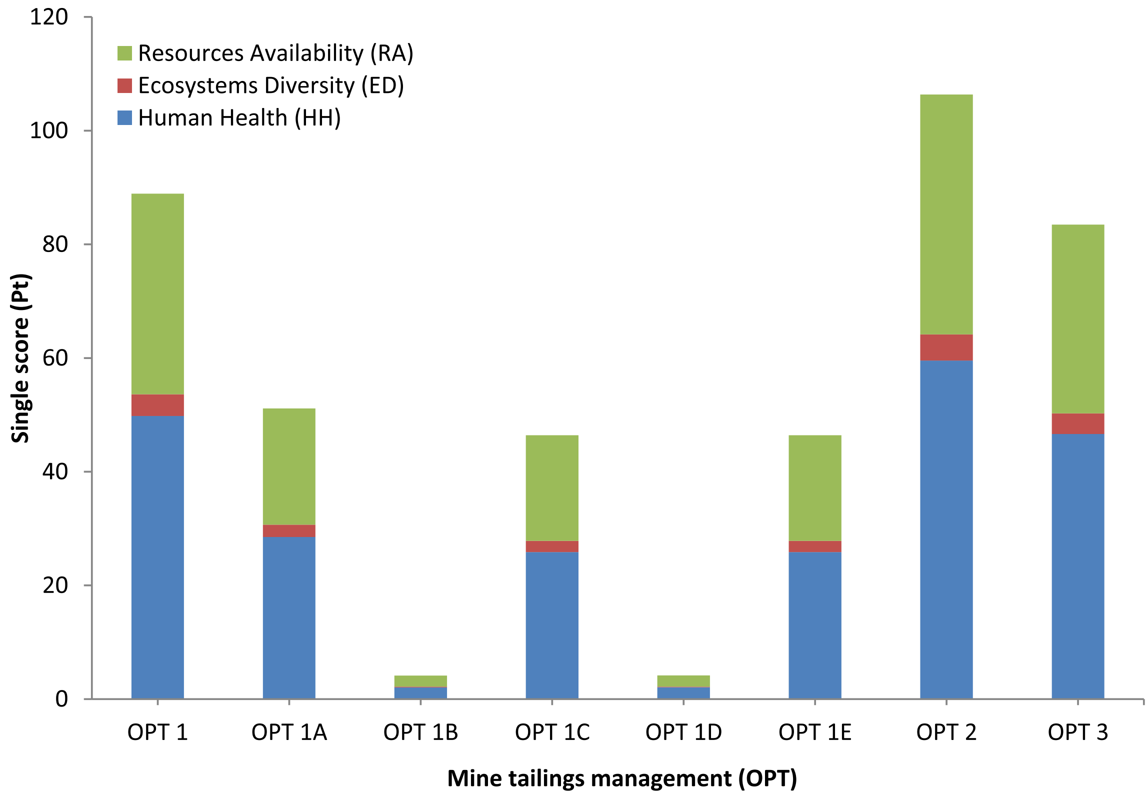

Fig. 6. Endpoint impact (Single score) for each option.

these substantial impacts throughout the life of mine. Two classifications of land are generally used: disturbed land and non-disturbed land. Disturbed land is allocated to mine operation activities and companies have an obligation to rehabilitate these areas.

3.4.1. *Land use impact evaluation*

As noted above, the case study open pit coal mine is located in New South Wales (NSW) Australia with production rate up to 20 Mtpa. ROM coal is cleaned to produce coal with an ash content of around 24%. ROM extracted from the open pit is processed in the CHPP to produce 70% coal (product) and 30% waste coal (rejects). Coal rejects consist of 25% fine reject/tailings and 75% coarse rejects. The total tailings generated range from 0.1 Mt dry/yr in the early exploitation stage to 9.6 Mt dry/yr from the fifth year until the end of mine life. Tailings are disposed of at a Tailings Storage Facility (TSF). Three disposal options were assessed in this study, as shown in Table 7, to estimate the land use equivalent factor for each tailings management option.

Pre-mining land use is mostly classified as class IV to VI (grazing land). The mine rehabilitation strategy indicates that post-mining land use will be dominated (more than 50%) by woodland use normally associated with rural land capacity class IV to VI (GSS Environmental, 2012). The total disturbed land varies, depending on the strategy used for tailings management. Option 1 results in the lowest land area affected (432.3 ha), generating 26.3-t tailings per 50.9-t coal slurry processed in a flotation tank. Implementation of Options 2 and 3 increased the area of land disturbed for tailings disposal to 61% and 41%, respectively. Based on the total average amount of tailings production of 35 Mt over the mine life, this equal to 0.000021 ha-yr/t of tailings. Results indicate that the land-use magnitude impacts of using Option 3 as a tailings management strategy are 2.3 and 1.6 times higher than when using Option 1 and Option 2.

3.4.2. *Land use and energy requirements*

The estimation of land-use presented in Section 3.4.1 shows that Option 1 uses less land compared with the other two options (Option 2 and Option 3). On the other hand, the energy consumption of Option 1 is higher than of Option 3, as discussed in Section 3.1. This contributes directly to the magnitude of the environmental impacts generated.

Introducing renewable energy in Option 1B-1E reduces the magnitude of their environmental impacts. However, this strategy also increases the area of land required for renewable energy production. Table 8 compares the land occupied by various types of energy generation technologies.

Based on the area (m^2) of land required to generate 1 GWh of energy presented in Table 8, the authors estimate that the greatest additional land (6.5 ha) that would need to be occupied by renewable energy would be required for Option 1B, as shown in Table 9. The land requirement increases gradually, depending on the mining production rate, and peaking initially during the fifth year of mining operations.

The choice of renewable energy technology significantly affects the land requirement. The land required for wind energy sources to generate 100% and 10% of 20 GWh energy is 2.7 ha and 0.27 ha respectively. Wind energy sources required 59% less land compared to a solar-PV energy source.

3.5. *Scenario comparison*

Mine tailings management options provide a wide range of opportunities for mining companies to determine the best tailings disposal option based on their mining characteristics. For this case study, eight scenarios were developed and are shown in Table 10. The introduction of technology and renewable energy sources significantly reduced the environmental impact points (ENV). The

Table 7
Land use equivalent factor.

Mine tailings dewatering method	Total years of deferred land use	Cumulative land disturbed	Cumulative tailings production	Equivalent factor
	(yr)	(ha)	(t)	(ha-yr/t)
OPT 1: Belt press (tailings cake)	22			
Year 5		67.0	25,230,952.6	0.000019
Year 10		188.8	38,816,850.2	0.000022
Year 15		310.5	38,816,850.2	0.000022
Year 20		432.3	38,816,850.2	0.000022
OPT 2: Paste thickener (tailings paste)	23			
Year 5		107.8	31,044,337.4	0.000028
Year 10		303.7	47,760,519.1	0.000033
Year 15		499.7	47,760,519.1	0.000033
Year 20		695.6	47,760,519.1	0.000033
OPT 2: Thickener (thickened tailings)	25			
Year 5		152.3	38,802,546.2	0.000043
Year 10		429.1	59,696,224.9	0.000051
Year 15		706.0	59,696,224.9	0.000051
Year 20		982.8	59,696,224.9	0.000051

Table 8
Land occupied for electricity generation.

Technology	Land use (m^2/GWh)
Coal	3642
Solar Thermal	3561
Photo Voltaic (PV)	3237
Wind	1335

Source: Australian Wind Energy Association (2016).

Table 9
Additional land required for renewable energy.

Options		Land required (ha)			
		Year 1	Year 2	Year 3–4	Year 5–20
OPT 1B	100% Solar-PV	0.32	3.24	5.50	6.47
OPT 1C	10% Solar-PV	0.03	0.32	0.55	0.65
OPT 1D	100% Wind	0.13	1.34	2.27	2.70
OPT 1E	10% Wind	0.01	0.13	0.23	0.27

average percentage reductions of the environmental impact points in Option 1, 2, and 3 were 66%, 71%, and 64%, respectively. However, the land requirement for these Options increased. The average percentage increase in land-use due to inclusion of renewable energy facilities was 6%.

The advantages of technology improvement and renewable energy utilization are also demonstrated by the percentage ratio of environmental impact to land-use as presented in Table 10. The implementation of these two strategies contributes to a change in the Option 1A-1E average ratio which is 1.5%–13% lower compared to other options.

3.6. Limitations of the study

The application of ReCiPe, a European method, to calculate endpoint environmental impact in an Australian mining context has some limitations. Nevertheless, this approach was assumed to be the best available at the time, as the Australian method has even more limitations. For example in the Australian endpoint method, some of the impact categories including eutrophication, and land-use were not operational with regional normalization and weighting factors. In addition, this method only sets the greenhouse impact category as a single score. As a result, the authors opted to use ReCiPe (worldwide) for the endpoint method because it integrates normalization and weighting factors into all impact categories. However, the limitations of this approach nevertheless need to be borne in mind, as there are significant differences between Australia and European environmental impact contexts.

Another challenge of this study related to data availability because these data are limited publicly. The data used were gathered from various sources including consultant reports, books, and research papers. In some cases, reasonable assumptions were also made where applicable. This might create a problem with the accuracy of results generated. For instance, the authors did not consider the quality of coal mined during the operation period. The volume of coal produced depends on the quality of the coal mined. For example, higher impurities in coal lower the amount of coal (product) generated and this may also increase water and energy consumption during processing.

Finally, it should be noted that this study is specific to an open pit coal mine in NSW, Australia. Application of the method to another mine could lead to different results because of the specific characteristics of each mine. The same applies to the fact that the

Table 10
Ratio between environmental impact and land use.

Options	Total Environmental Impact (ENV)	Land use (LND)			Ratio (ENV/LND)
		Land use for tailings disposal	Additional land for RE	Total land use	
	(Pt)	(ha)	(ha)	(ha)	(%)
OPT 1	88.9	432.3	–	432.3	20.6
OPT 1A	51.1	432.3	–	432.3	11.8
OPT 1B-Solar (100%)	4.1	432.3	6.47	438.8	0.93
OPT 1C-Solar (10%)	46.4	432.3	0.65	432.9	10.7
OPT 1D-Wind (100%)	4.2	432.3	2.70	435.0	0.97
OPT 1E-Wind (10%)	46.4	432.3	0.27	432.6	10.7
OPT 2	106.4	695.6	–	695.6	15.3
OPT 3	83.5	982.8	–	982.8	8.5

electricity grid mix in NSW has a very high percentage of fossil fuel energy (black coal) which might substantially increase impacts related to electricity production.

4. Conclusions

Coal mine tailings can be transported in various forms including wet or dry. Wet methods usually involve use of a pipeline to transport tailings from CHPP to TSF. Dry methods, including belt press methods, seek to reduce the water content in tailings slurry to form tailings cake. Tailings cake generated by the belt press method is then disposed of. Some coal mine sites implement a co-tailings disposal method, in which the tailings cake is disposed of together with coarse coal. Alternative disposal methods provide an opportunity for mine sites to select a method that is suited to their site characteristics. Environmental impacts and land-use variables can be used as parameters to determine the feasibility of different tailings disposal methods that increasing the sustainability performance of mining waste management.

The results of this study indicated that thickened tailings (Option 3) generated the lowest environmental impact compared to the belt press (Option 1) and paste thickener (Option 2) methods. However, in terms of land-use, Option 3 occupied the highest land, close to 1000 ha. This highest land-use makes this option as an unattractive proposition compared to the other two options (Option 1 and Option 2). Two strategies (technology improvement and renewable energy sources) were introduced into the belt press option that required the least area of land. These measures can significantly reduce the overall environmental impact. The two lowest ratios of environmental impacts to land-use were generated by Option 1B (0.93%) and Option 1D (0.97%). Option 1D requires less land (1.0%) than does Option 1B.

This study also indicates the importance of considering the environmental impact and land use aspects of coal mine sites prior to selecting a tailings disposal method. Further analysis of economic aspects and reuse opportunities is also required for comprehensive discussion of sustainable tailings management and industrial symbiosis.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2017.05.050.

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