Research paper

Life cycle cost estimation and environmental valuation of coal mine tailings management

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ABSTRACT

Sustainable mining management is increasingly seen as an important issue in achieving a social license to operate for mining companies. This study describes the life cycle cost (LCC) analysis and environmental valuation for several coal mine tailings management scenarios. The economic feasibility of six different options was assessed using the Net Present Value (NPV) and Benefit-Cost Analysis (BCA) methods. These options were belt press (OPT 1), tailings paste (OPT 2), thickened tailings (OPT 3), and OPT 1 with technology improvement and renewable energy sources (OPT 1A-C). The results revealed that OPT 1A (belt press technology with stack cell flotation) was the first preference in terms of LCC while OPT 1C (belt press technology with stack cell flotation and 10% wind energy) generated the highest benefits value (BCA) compared to the other options. The LCC and BCA components and the volume of GHG emissions were used to determine the best option. Normalization of these three elements resulted in the selection of Option 1C as being the most cost-effective option.

1. Introduction

Environmental management is a crucial tool for any activity that generates adverse impacts and mining is one such activity. Mining operations pose potential hazards to human health and the environment during exploration, production, and closure stages (Adiansyah, Haque, Rosano, & Biswas, 2017). These impacts, presented in Table 1, should be avoided/minimized and managed to prevent environmental disasters. Developing hazard management strategies is also necessary in order to obtain a social license to operate mines.

The first step of managing environmental impacts is to prepare a comprehensive environmental management plan. This document mainly describes potential environmental impacts and risks, environmental monitoring, measurement activities, control strategies, and environmental audits (Commonwealth of Australia, 2014). The tools that are usually employed to study the environmental impacts of different systems include life cycle assessment, life cycle costing,

net present value, and benefit-cost analysis (Ahlroth, Nilsson, Finnveden, Hjelm, & Hochschorner, 2011; Erkayaoğlu & Demirel, 2016; McLellan, Corder, Giurco, & Green, 2009). These tools can be used to determine the feasibility of the environmental management strategies for mining operations.

Tailings, categorized as mine waste, are among the materials that might contribute to environmental contamination, as presented in Table 1. In coal mining, tailings are generated from fine coal, which represents about 10—20% of the Coal Handling and Preparation Plant (CHPP) feed (Honaker, Kohmuench, & Luttrell, 2013; Kumar, Bhattacharya, Mandre, & Venugopal, 2014). There are two main arguments for considering coal mine tailings to be a critical issue in waste management. First, global coal reserves are estimated to be 860 billion tonnes (Thomas, 2013). Second, coal is listed as the second-largest energy source in the world (Energy Information Administration, 2016; Perusahaan Listrik Negara, 2015; World Nuclear Association, 2013). The International Energy Outlook 2016 report published by the U.S. Energy Information Administration predicts an increase in coal consumption between 2012 and 2040 at an average rate of 0.6% per annum (Fig. 1) (Energy Information Administration, 2016). This means that the global consumption of coal could increase from 153 quadrillion Btu in 2012 to 180 quadrillion Btu by 2040, which would cause a

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Table 1
Potential environmental impacts in a mining cycle.

Stage	Activities	Potential Environmental Impact
Exploration	Drilling or trenching, land clearing, camp and road development	- Sediment runoff and increased Total Suspended Solid (TSS) - Spills of fuels and other contaminants - Disturbance to wildlife - Habitat fragmentation
Construction	Infrastructure and facility development such as power lines, roads, tailing storage facility, water treatment plant, processing plant, and camp	- Contamination of water, and land - Declining species populations - Increasing Particulate Matter (PM) into the air - Altered patterns of drainage and runoff - Habitat fragmentation
Operation/ Production	Blasting, excavation, ore/waste transporting, milling/grinding ore, and tailing deposition/transport	- Chemical contamination of surface and ground water - Declining species populations - Toxicity impacts on organisms - Decreased water tables - Increased erosion and siltation - Mine acid drainage pollution - Tailing slurry overflow (affected to terrestrial ecosystem) - Increased greenhouse gas emissions related to energy consumption
Mine closure	Revegetation, re-contouring of stockpiles/pits and monitoring seepage	- Persistent contaminants in surface and ground waters - Expensive, long-term water treatment - Persistent toxicity to organisms - Loss of original vegetation/biodiversity - Permanent topography changes

Source: (Adiansyah et al., 2015; Bell, Bullock, Hälbich, & Lindsay, 2001; Bian et al., 2009; Franks, Brereton, & Moran, 2010; Kossoff et al., 2014; Miranda et al., 2003; Zhengfu, Hillary, John, Frank, & Sue, 2010).
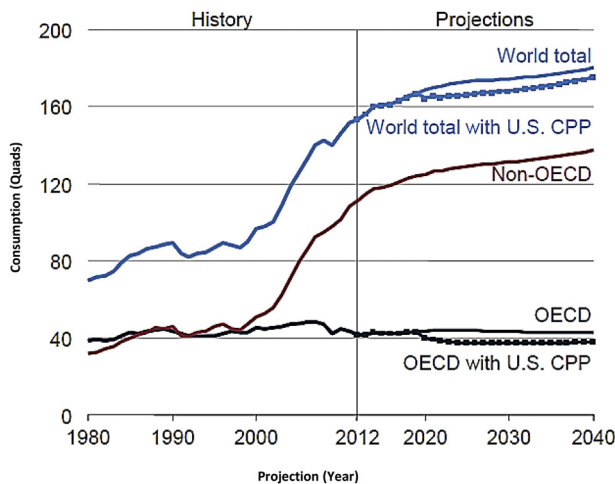
Fig. 1. World coal consumption in quadrillions Btu (Energy Information Administration, 2016).

corresponding increase in the volume of tailings.

Mining projects currently apply various types of tailings disposal strategies, including conventional tailings disposal, thickened tailings, and tailings paste (Adiansyah, Rosano, Vink, & Keir, 2015). The two most important sustainability indicators (water and energy) used for selecting the best tailings disposal method are discussed by Adiansyah, Rosano, Vink, Keir, and Stokes (2016). This study assesses the links between these indicators in order to determine the feasible scenario associated with water and energy consumption. The implementation of sustainability criteria in all mining activities has also been endorsed by the International Council of Mining and Metals (ICMM) since the organization was established in 2001. A sustainable tailings framework was introduced by Adiansyah et al. (2015) and consists of eight steps including analyzing the water-energy nexus, environmental assessment, and economic analysis. These steps enable mining companies to determine the most effective and efficient strategy for the disposal of their tailings.

Mining development also requires a large investment for capital expenditures and operating costs. For example, a copper mine in Indonesia that produces around 240 million attributable pounds of copper annually has an initial investment of approximately US $1.8 billion (Newmont, 2016; Newmont Nusa Tenggara, 2016). Other examples include the Barruecopardo project in Spain with a total capital cost of €70 million, the Hemerdon project in the United Kingdom with a total operating cost of €12.48 per tonne of ore, and the Pilbara Iron Ore project in Western Australia with a direct mine capital cost of AUS $726 million (Gordon, 2014; Sánchez et al., 2015). Therefore, cost becomes one of the critical factors when determining the feasibility of mining development projects.

Mining companies commonly conduct financial analysis at the beginning of a project, i.e. at the planning stage. Life cycle costing (LCC) and environmental valuation are two commonly used tools to assess various options necessary for mining operations including mine tailings disposal, processing technology, and power generation. These options assist decision makers in selecting the most appropriate strategy for the exploration, production, and post-mining stages.

LCC and environmental assessment have not been studied as widely in the mining industry as in other fields, such as building and forestry. Epstein et al. (2011) discussed the LCC of coal mining in the Appalachia region of the United States. The life cycle considered in that study was extraction, transport, processing, and combustion. The cost analysis, called the "externalities cost", was based on a waste stream that created multiple impacts on human health and the environment. The authors proposed a number of recommendations including reducing the number of coal-fired

power plants, promoting clean smart grids, and ending the mountaintop removal method (MTR). The environmental and economic performance of an enhanced landfill mining (ELFM) in Belgium was assessed by Danthurebandara, Van Passel, Machiels, and Van Acker (2015) in their paper. The paper used integrated evaluation tools, LCA and LCC, and identified three factors that influenced the economic feasibility of EFLM: technology, regulations, and markets.

In the area of environmental valuation, there are some studies available in the Environmental Valuation Reference Inventory (EVRI) database. The authors of this paper found 24 out of more than 2000 studies by conducting a search in EVRI using "mining" as a keyword. Two of those studies were conducted in Australia: Colliery-New South Wales and Jarrah Forest-Western Australia. The value of environmental and social impacts was the focus of an underground coal mining project assessment in Colliery, New South Wales (Economics, 2008). That study used willingness to pay (WTA) as a research method and the results are presented in Table 2. The Western Australia study considered bauxite mines and used choice modeling as a survey method to estimate the non-market environmental value of the rehabilitation of their mines (Burton, Zahedi, & White, 2012). A total of 252 respondents completed the questionnaire and the results show that the in-situ rehabilitation was the most preferred option. Detailed monetary values of the options are presented in Table 2.

Past studies have not assessed mine tailings management strategies. Therefore, this paper aims to estimate the financial value of six different tailings disposal methods in coal mining. A comparison of cost analysis is presented to determine the most preferable option in terms of cost, benefit, and environmental impact. The estimation is based on two economic perspectives: life cycle costing and environmental valuation (Australian Government, 2014; Finnveden & Moberg, 2005; Harrison, 2010; Höjer et al., 2008). These two perspectives assess the cost of coal tailings disposal across different time scales. Life cycle costing represents the life cycle flow and depends on the functional unit, as determined in the life cycle assessment, while environmental valuation generates the cost and benefit of each disposal method during the lifetime of the mine.

To achieve the above objectives and to assess the material input and output during fine coal processing, a life cycle flow chart was created, as shown in Fig. 2. A desk study was also conducted to determine the economic value of materials involved in the processing flow. Section 2 provides a review of the previous studies on life cycle costing and the environmental valuation of mining operations. Section 3 presents the methodologies used in the data analysis, including data sensitivity based on three different discount rates. Sections 4 and 5 discuss the results of the net present value and benefit-cost analyses for each tailings management option.

2. Material and methods

Section 2.1 describes the process flow for each tailings management option. Table 3 outlines the six different scenarios considered in coal tailings management.

Technology improvement and substituting 10% of the fossil fuel energy with renewable energy are two strategies introduced for Options 1A, 1B, and 1C. Section 2.2 describes the methodologies used in this study: LCC and environmental valuation.

2.1. Case study

The case selected is an open pit coal mine located in New South Wales, Australia. The mine is projected to extract around 20 million tonnes per annum (Mtpa) of run-of-mine (ROM) coal. Three primary dewatering technologies were assessed: belt press, deep cone thickener (paste), and thickener. These technologies increase the percent solids in tailings and reduce the volume of water transported to the tailings disposal facility (Adiansyah et al., 2016).

The process flow of fine coal rejects is organized as illustrated in Fig. 2, where four processes are involved: material input, processing, products, and final values. The four products generated during the process are saleable coal, tailings, water and land conservation, and GHG reduction.

Option 1. Dewatering the tailings using belt press technology

This option requires electricity, water, and chemicals to process the fine raw coal. Overflow from the flotation tank generates saleable coal in slurry form. The underflow slurry, categorized as tailings, requires further treatment in the thickener to increase its percent solids. This process in the thickener creates two material outputs: recycled water and tailings. The recycled water is pumped into water storage tanks, and underflow tailings are fed into the belt press to achieve its final percent solid portion of 65%. This stage produces additional recycled water for belt wash purposes while tailings consisting of 65% solids are transported to the co-disposal area (coarse rejects and tailings). Chemicals also play a significant role in the segregation and dewatering process. These chemicals have three functions as collectors, frothers, and flocculants. In this case study, a coal-fired power plant supplied 100% of the energy required. The authors also introduced technological improvements in Option 1A by replacing the type of flotation technology and incorporating 10% renewable energy (solar and wind power) for Options 1B and 1C as described in Table 3.

Option 2. Dewatering the tailings using paste thickener technology

The primary inputs required for Option 2 are similar to Option 1; the difference lies in the total amount of these materials used. The fine raw coal is segregated in the flotation tank into two products: saleable coal as flotation overflow and underflow tailings. The tailings thickener receives the underflow tailings from the flotation tank and increases the percent solids of tailings by adding Sodium

Table 2
Environmental value of two mine sites.

Asset/endpoint	Financial value	Unit	Method
Stream protected from adverse affects of the mine	$4.78-$5.13	kilometer	Willingness to pay
Additional job from mining	$4.17-$4.91	year	Willingness to pay
Protect an additional upland swamp	$0.43-$0.45	hectare	Willingness to pay
Protect an additional aboriginal site from adverse affects	$0.37-$0.44	hectare	Willingness to pay
1% decrease in plant richness	$2.41 million	percent	Willingness to accept
No habitat re-creation	$77.39 million	habitat site	Willingness to accept
Decreasing population of the red-tailed black cockatoo	$7.49 million	population	Willingness to accept
Decreasing population of the Chuditch	$8.69 million	population	Willingness to accept

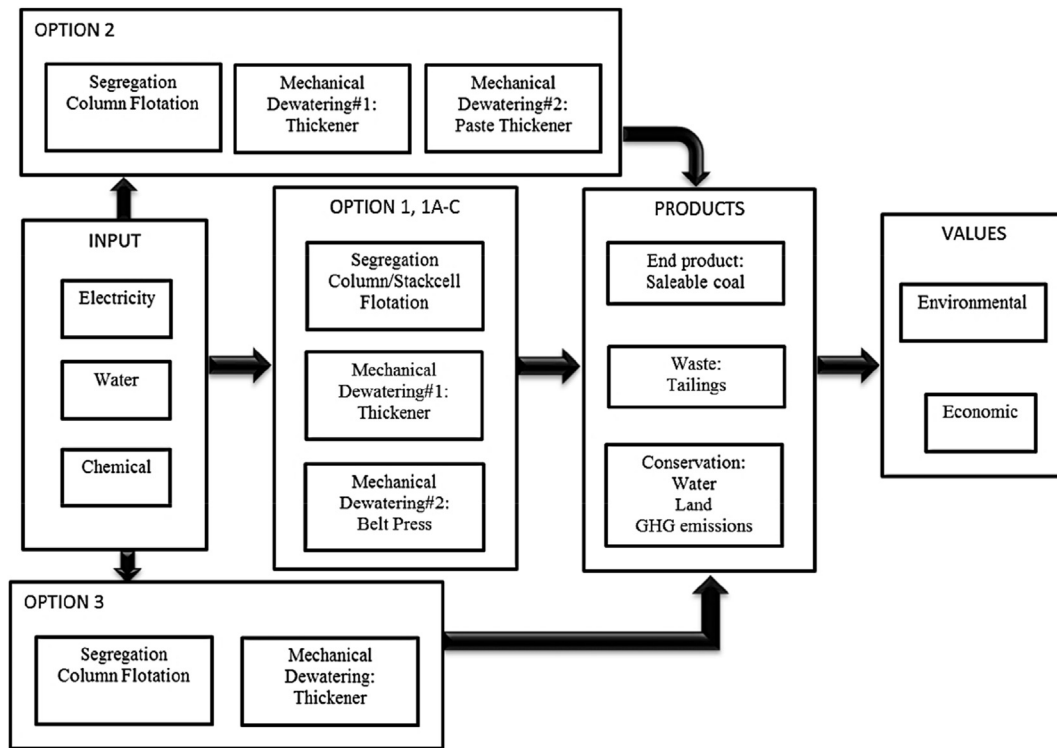Source: (Burton et al., 2012; Economics, 2008)

Fig. 2. Process flow for each tailings management option.

Table 3
Scenario for tailing management options.

Tailing management	Characteristics
Option 1	Tailing cake with belt press
Option 1A	Tailing cake belt press with technology improvement
Option 1B	Tailing cake belt press with technology improvement and 10% Solar RE
Option 1C	Tailing cake belt press with technology improvement and 10% Wind RE
Option 2	Tailing paste with paste thickener
Option 3	Thickened tailings with thickener

Acrylate ($C_3H_3NaO_2$). This acts as an anionic flocculant to the tailings slurry and the process reclaims water, which is then distributed to the water storage tank. In order to attain a final percent solid level of 50%, a flocculant is added to the tailings in the paste thickener tank. Reclaimed water is generated by this process and pumped into the water storage tank. In this option, 100% of the electricity is supplied from the coal-fired power plant.

Option 3. Dewatering tailings using thickener technology

This option creates tailings which are 30% solids and transports these tailings by a pipeline to the disposal area (a tailings dam). The first two processes in Option 3 (segregation and thickened tailings) are similar to the other two options. These processes generate recycled water which is pumped to the water storage tank. There is no renewable energy introduced in this option.

2.2. Economic assessment and environmental valuation

The authors consider economic and environmental perspectives when assessing the feasibility of each option. Both perspectives are based on the capital cost, operational cost, and benefits value. This enables the study results to provide a sufficient financial description and overview to determine the most viable option for coal tailings disposal management.

2.2.1. Life cycle costing (LCC) method

LCC is an environmental system tool used to determine the most cost-effective alternative among different available scenarios/products from a life cycle perspective (AS/NZS, 2014; Finnveden & Moberg, 2005; Höjer et al., 2008). This tool is valuable when making a range of decisions, including disposal option technologies, comparison of alternative product strategies, and long-term financial planning (Standard, 2016). There are some important economic indicators associated with LCC: net present value (NPV), internal rate of return (IRR), and discounted rate (DR) (Brealey, Myers, Allen, & Mohanty, 2012; Harrison, 2010).

To perform an LCC analysis for the options described in Section 3.1, the authors used a theoretical case study of a coal mine with a maximum production rate of 20 Mt per annum and a lifetime of 20 years. The functional unit had 1 tonne of fine coal concentrate slurry generated by flotation cells. The recovery percentage from flotation was assumed to be approximately 40%.

Capital cost and operational cost data was collected through literature review and a desk study, as presented in Table 4. Procurements and facility developments such as the thickener, the paste thickener, and belt press filters are considered capital expenses. Daily expenses such as chemical and electricity costs are listed as operational expenses. The authors found that maintenance costs varied for each mine site and ranged between 0.2% and 1.45%

Table 4
Input values used in the cash flow model.

Description	Value	Unit	Source	Normalization value (2016)
Capital Cost (CC)				
Thickener	2,000,000	$	(Bickert, 2004)	2,683,168
Paste thickener	700,000	$	(Bickert, 2004)	939,109
Belt press filter	350,000	$	(Bickert, 2004)	469,554
Column flotation	1,965,000	$	(Kohmuench, Yan, & Christodoulou, 2012)	1,561,218
Stackcell flotation	1,965,000	$	(Kohmuench et al., 2012)	1,561,218
Tailing dam	19,808,075	$	(QCC, 2013)	20,745,849
Co-disposal	2,518,519	$	(Bickert, 2004)	3,378,805
Solar PV	2,505,000	$/MW	(Jacobson, Wayder, & Franslin, 2013)	2,623,594
Wind power	3,500,000	$/MW	(Windustry, 2012)	2,081,623
Operational Cost (OC)				
Chemical	4.5	$/kg	(QCC, 2013)	4.7
Electricity	51.6	$/MW	(Australian Energy Market Operator, 2016)	51.6
Reject conveying and trucking	1.5	$/ton	(QCC, 2013)	1.6
Co-disposal	0.3	$/ton	(Bickert, 2004)	0.4
Maintenance	0.83	% of CC	(Moolman & Vietti, 2012; QCC, 2013; Wang, Shammas, & Hung, 2007)	0.83

of total capital costs. Therefore, this analysis used the median value of 0.83% of total capital costs when estimating the maintenance cost.

The value in Table 4 was normalized by using an average annual inflation rate to eliminate the value variation associated with the use of multiple sources of data. All the values have been converted to the Year 2016 (Reserve Bank of Australia, 2016a).

A central feature of LCC is the application of the net present value (NPV). The steps to measure NPV as described in Callan and Thomas (2013) are as follows:

1. Calculate the future value (FV) of the costs by dividing the current value (CV) with the inflation rate (r) for the appropriate time period (t) as shown in Equation (1).

$$FV = \frac{CV}{(1+r)^t} \quad (1)$$

2. Select the appropriate discounted rate (DR).
3. Discount the FV for each time period (t) as shown in Equation (2).

$$PV = \frac{FV}{(1+DR)^t} \quad (2)$$

4. Sum the discounted value over all t periods to find the present value (PV) of costs.
5. Monetize NPV in real dollars by adding capital cost (CC) to total PV as shown in Equation (3).

$$NPV = CC + \sum_{t=0}^{t=n} PV \quad (3)$$

The authors used NPV to compare each option for the disposal of coal mine tailings and, subsequently, to determine the most cost-effective strategy for the mine site.

2.2.2. Environmental valuation method

2.2.2.1. Valuation. A mining project evaluation is not only based on its financial profitability but also its sustainable development performance. According to Eggert (2001), sustainability is maintaining the level of environmental (e.g. water quality, air quality), economic (e.g. community income), and social parameters at their current standards. All stages of a mining project contribute to these three

parameters and so their contribution should be estimated or valued. Environmental benefit valuation utilized in this study has increasingly been considered an important tool in decision-making over the last decade (Damigos, 2006; Marre et al., 2016).

Use value and non-use value are commonly used in valuation methods. Use values consist of direct use (actual resource utilization, i.e. commercial purpose or recreation); indirect use (benefits gained from ecosystem functions, i.e. water and nutrient regulations); and option value (willingness to pay for future use of a resource as an insurance premium) (Damigos, 2006; Damigos, Menegaki, & Kalimpakos, 2016; De Groot, Wilson, & Boumans, 2002). Non-use values are associated with the non-physical consumption of goods or services. These include well-being, health, and comfortable feelings (Dlamini, 2012).

Generally, there are three categories of valuation techniques available (Damigos, Menegaki, & Kaliampakos, 2016; De Groot et al., 2002) which are as follows:

(a) direct market valuation approaches, such as market-price based and cost-based valuations, and production functions use data from the actual market;
(b) revealed preference approaches such as the Travel Cost Method (TCM) and the Hedonic Pricing Method (HPM) present an individual choice reflecting their behavior based on the market information;
(c) stated preference approaches such as the Contingent Valuation Method (CVM) and Choice Modeling (CM) undertake a social survey to obtain individual preferences concerning the changes in environmental and social goods, and services.

Goods or services are considered to determine the type of evaluation method, but most valuation studies require significant resources (time, labour, and money) to produce reliable estimates. These constraints on the valuation research can be overcome by using the Benefit Transfer (BT) method. BT is typically used to estimate the environmental benefits of a project based on the available information from previous studies and, therefore, it does not require as much time or money as the original valuation studies. The two main approaches in BT are value transfer and function transfer techniques (Damigos, 2006). The transfer occurs between the 'study site' (the original research site) and the 'policy site' (where the value is assigned). In this study, the market-price based approach and BT (value transfer) approach were used to estimate the value of the coal mine tailings management based on time and resource limitations. The values shown in Table 5 represent the base input data for the benefit-cost

Table 5
Direct use value.

Description	Value	Unit	Sources	Normalization value (2016)
Operational Cost				
Chemical	4.5	$/kg	(QCC, 2013)	4.7
Electricity	51.6	$/MW	(Australian Energy Market Operator, 2016)	51.6
Reject conveying and trucking	1.5	$/ton	(QCC, 2013)	1.6
Co-disposal	0.3	$/ton	(Bickert, 2004)	0.4
Tailing dam	1.2	$/ton	(Bickert, 2004)	1.6
Reclamation cost:				
- Tailing dam	100,000	$/ha	(Fenzel, 2012)	104,081
- Co-disposal	50,000	$/ha	(Fenzel, 2012)	52,041
Reclamation bond	1038	$/ha	(Qugley, 2017)	1038
Benefit Value				
Market:				
Saleable coal	88.35	$/ton	(Index, 2017)	88.35
Water conservation	2000	$/ML	(Gillespie, 2012)	2146
Land conservation	5172.4	$/Ha	(Gillespie, 2012)	5550
Non-market:				
GHG reduction	10.8	$/t CO_2-e	(World Bank and Ecofys, 2016)	10.8

analysis (BCA) to compare each mine tailings option, from an economic perspective.

The value in Table 5 was normalized by using an average annual inflation rate to eliminate the value variation associated with the use of multiple sources of data. All the values were converted to Year 2016 (Reserve Bank of Australia, 2016a).

2.2.2.2. Benefit-cost analysis (BCA). BCA aims to improve decision making by providing information about costs and benefits in present value dollar terms (Australian Government, 2016; Harrison, 2010). There are a number of advantages of BCA implementation including assistance when identifying cost-effective options, maximizing net benefits to the community, and providing quantitative and qualitative information for decision-makers (Australian Government, 2016).

The Australian Government (2016) introduced the following eights steps for preparing a full BCA:

(1) Specify the set of possible options.
(2) Calculate or measure the cost and benefits of the project, i.e. capital cost, operational cost, and benefit value. This study uses BT and market-price based methods to value the benefits;
(3) Identify the impacts of each option.
(4) Predict the impact period. In this study the impact period was different for each mine tailings management option ranging between 22 and 25 years.
(5) Monetize (assign a dollar value) to the impacts. This study focuses on three environmental impacts: water conservation, land use, and GHG emissions, as explained in Section 3.2.2.1.
(6) Calculate the present value by considering the discount rate of benefit and cost flows, as shown in Equation (4).

$$NPV = \sum_{t=0}^{t=n} \frac{B_t - C_t}{(1 + DR)^t} \qquad (4)$$

where B_t = the benefit at t period; C_t = the cost at t period; DR = the discount rate; t = the year.

If the (*PVB-PVC*) value for a particular option is greater than 0, the choice is considered feasible (Callan & Thomas, 2013).

(7) Conduct a sensitivity analysis to identify the effect of variable changes to the overall costs and benefits of a project including discount rates and time horizons.

2.3. Limitations of the study

One of the biggest challenges facing research in the mining field is the limited amount of publicly available data due to disclosure policies (Haque & Norgate, 2015). Because of the lack of available information, assumptions are made for some parameters including the percent recovery from flotation tanks, the rehabilitation period for each scenario, and maintenance costs.

Another constraint is the requirement of significant resources, i.e. time and money, when conducting environmental valuation studies (Damigos, 2006). Researchers in this field use methodologies which involve a substantial number of respondents. Such methods include the Contingent Valuation Method (CVM), Travel Cost Method (TCM), and Hedonic Pricing Method (HPM). For example, Burton et al. (2012) used the choice modeling method in their study and this required 252 respondents to assess the environmental valuation of a bauxite mine site in Western Australia. Studies with such a large number of interviewees require significant time, and human and financial resources. To cope with limited resources, some studies suggested using the Benefit Transfer Method (BTM), which has two types of approaches: value transfer and function transfer (Damigos, 2006; Mazzotta, Wainger, Sifleet, Petty, & Rashleigh, 2015). The BTM is allowed to transfer available information (value) from studies completed in another location or context. This study uses the BTM combined with the market-price based approach.

This study focuses on three environmental issues: water use, land use, and greenhouse gas (GHG) emissions. The volume of the tailings produced and the run-of-mine (ROM) data are two primary parameters for estimating the level of water conservation. Estimating the total land area required for disposing of the tailings depends on these two parameters as well as the density of the tailings. Three different tailings densities used in this study were from two coal mines in Australia (GHD, 2013; New Hope Group, 2014). A life cycle assessment was conducted using SimaPro software to estimate the GHG emissions.

3. Results and discussion

3.1. Estimating life cycle costing

The estimated total quantity of materials required to generate 1 tonne of fine-coal concentrate slurry is shown in Table 6. The option which consumed the largest amount of electricity was OPT 2 which used paste thickener technology, while the belt press technology of

Table 6
Amount of input into the process flow.

Materials	Unit	Technology				Source
		Belt press (OPT 1)	Belt press (upgrade)[a]	Paste thickener (OPT 2)	Thickener (OPT 3)	
Total Energy	kWh	918.3	509	1016.6	887.2	(Adiansyah et al., 2016; Kohmuench et al., 2012; QCC, 2013)
Flotation		864.5	455.3	864.5	864.5	
Thickener		20.75	20.75	20.75	20.75	
Underflow pump thickener		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	(Fawell, Adkins, & Costine, 2015; Owen, 1989; QCC, 2013)

[a] Upgrade to stack cell flotation (OPT 1A-C).

OPT 1 (OPT 1A-C) used higher amounts of chemicals compared to the other options.

The capital value (*CV*) of material inputs was calculated by multiplying the operating cost (*OC*) input (Table 4) with quantity of materials (Table 6). Incorporating an inflation rate of 3% per year (Reserve Bank of Australia, 2016b) resulted in the total future values (*FV*) over the lifetime of the mine as shown in Table 7. Discounting the CV with a 7% discount rate (Australian Government, 2016, 2014) generated the highest present value (*PV*) for Option 2 followed by Option 3, Option 1B, Option 1C, Option 1, and Option 1A. There was a significant difference (226%) between the highest and the lowest values. The capital costs associated with the construction of the disposal area resulted in *NPVs* 10 times higher than the *PVs*, as presented in Table 7.

The three keys factors at this stage are the type of technology applied, market price, and consumption pattern. The combination of these factors can be observed in Option 2 with the highest *NPV* of $28,271,186 making it the least preferred option. The authors also calculated the *NPV* using the discount rates of 3% and 10% (Fig. 3). Fig. 3 shows that there is a consistency in the *NPV* analysis outputs, despite the changes in the discount rate. Option 1A, using belt press technology with stack cell flotation and 10% renewable energy, was found to be the most economically feasible option.

Additionally, the *NPVs* of Option 1 and Option 1A-C differed only by 0.1%. This means that the ultimate decision to determine the optimal option will be influenced by other factors such as the benefits value (as discussed in Section 4.2).

3.2. Environmental valuation

This section compares the benefits of implementing different mine tailings management strategies. The authors focus on three environmental benefits: water conservation, land conservation, and GHG reduction. These environmental parameters are also mentioned by Adiansyah et al. (2015, 2016) as the main indicators of the sustainability of tailings management.

3.2.1. Water conservation

Water reclamation took place in every stage, including the segregation process in flotation cells and the thickening process within the thickener tank. The initial raw fine coal slurry, which was fed into the flotation cell, consisted of 10% solids, whereas the final mass percent of solids for Option 1, Option 2, and Option 3 was 65%, 50%, and 30%, respectively. Total water used and reclaimed is linearly correlated with the percentage of solids in the tailings.

Option 1, which used a belt press, resulted in the highest level of water conservation. By taking a water tariff assumption of $2.97 per unit of water used (NSW Government, 2016), this option had 220% and 476% greater cost-savings compared to Option 2 and Option 3, respectively (see supplementary data). Option 2, using the paste thickener, created 80% higher cost-savings compared to Option 3, which used the thickener method. All recycled water was fed into a closed-cycle system and was supplied back to the processing plant as processing water.

3.2.2. Land conservation

One of the critical components of tailings management is the land availability for the tailings disposal area. Total land use for each option during the lifetime of the mine has been discussed in Adiansyah et al. (2016), and Option 3 was found to require the greatest disposal area. The authors in this study used Option 3 as a base case to compare the land conservation values with other options.

Calculated using the BT method, the land value is $5550 per hectare (see Table 5). This value was multiplied by the total disposal area to produce the cost value for every hectare of land required during the tailings disposal process. As a reference scenario, the cost value of Option 3 was used to deduct from the other values in all scenarios. Table 8 presents the results in which Option 1 and 1A generated the highest land conservation value of $3.1 million during the lifetime of mine.

The introduction of 10% renewable energy in Option 1B and 1C increased the land use requirement for a renewable energy facility. On the other hand, the total land value of these options decreased by approximately 2% (Option 1B) and 1% (Option 1C) compared to Option 1.

3.2.3. GHG reduction

Electricity is the main contributor to each kilogram of carbon

Table 7
Net Present Value with 7% discount rate.

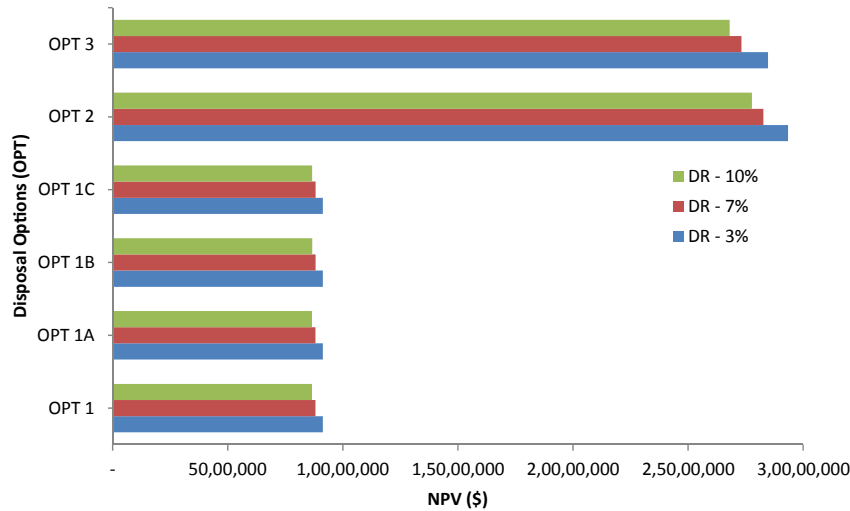| Total Economic value ($)	Mine tailings management Option					
	OPT 1	OPT 1A	OPT 1B	OPT 1C	OPT 2	OPT 3
Future Value (*FV*)	1,066,474	1,066,137	1,066,827	1,066,676	3,518,714	3,590,956
Present Value (*PV*)	718,642	718,415	718,880	718,778	2,341,843	2,333,216
Net Present Value (*NPV*)	8,811,388	8,811,161	8,817,190	8,815,939	28,271,186	27,323,451
Preference	2	1	4	3	6	5

Fig. 3. The influence of discount rate on *NPV*.

Table 8
Total land conservation value.

Tailing management	Total land value ($)	Additional information
OPT 1	3,055,393	column flotation
OPT 1A	3,055,393	stack cell flotation
OPT 1B	2,989,857	renewable energy
OPT 1C	3,028,323	renewable energy
OPT 2	1,594,172	column flotation
OPT 3	–	reference scenario

dioxide equivalent (CO_2-e) produced by the process flow. Consumption of electricity is strongly influenced by the type of technology used, for example stack cell flotation utilized less electricity compared to the column flotation. Table 9 presents the LCA results in which Option 1A-C generated less CO_2-e compared to the reference scenario (OPT 3). These scenarios generated 39.5%, 45.2%, and 45.2% less CO_2-e, respectively.

The authors also used Option 3 as a reference scenario when calculating the value of carbon reduction. The calculation of the reduction value used a carbon market price of $10.8 per tonne CO_2-e (World Bank and Ecofys, 2016). The results displayed in Table 9 indicate that Options 1A-C generated positive values, while Option 1 and 2 generated negative values. The negative values reflect the higher amount of carbon equivalent produced by those options as compared to the reference scenario. Options 1A-C contributed positive values in the range of $2646 to $3028 (referring to the carbon market mechanism), and BCA discussed in Section 4.3 considers this value to be a benefit.

Table 9
Total GHG reduction value.

Tailing management	Global warming[a] (kg CO_2-e)	Total GHG value ($)
OPT 1	920	−426
OPT 1A	523	2646
OPT 1B	474	3028
OPT 1C	474	3028
OPT 2	1104	−1859
OPT 3	865	reference scenario

[a] Life cycle assessment supplement data.

3.3. Benefits cost analysis (BCA)

Tailings are a by-product of fine raw coal processing, where the main product is saleable coal. These two products contribute to the financial flow of a mining company. Therefore, it is essential to identify the incremental costs and benefits for each option to determine the most cost-effective one.

This study focuses on four components considered to have benefit value: (1) coal product generated from the fine raw coal processing, (2) water reclaimed from the segregation and dewatering process, (3) land conservation for the tailings disposal area, and (4) GHG reductions from renewable energy technology and application. These elements play a significant role in improving the sustainability level of the tailings management practices. The sum of these components represents the benefit value of each scenario and is used to determine the feasibility of each tailings disposal method. The benefits and costs of each option were evaluated based on a time horizon. The lifetime of mining operation, excluding post-mine closure, is estimated to be 20 years. One of the critical factors that determines the total time horizon of the tailings management is land rehabilitation. The average time required to reclaim the disposal area, including the drying time and the reclamation process, was two years for Option 1, three years for Option 2, and five years for Option 3 (EMGA Mitchell McLennan, 2012; Jones & Watkins, 2015).

The cost value of each option was calculated using the values from Tables 4 and 5 and shown in Table 10. Option 1C had the lowest total cost value compared to the other options. The deep cone thickener (paste) technology with the tailings dam method applied in Option 2 provided a total cost which was 20% higher than that of Option 1C. This difference was mainly due to the low operational costs of the co-disposal operation (Table 5). The operational cost-saving using Option 1C was $1.2 per tonne compared to Option 2. Another option that used thickener technology with tailings dam facility generated a total cost which was 45% higher than Option 1C. This result is primarily affected by the amount of solids in the tailings slurry where the solids content in Option 1C was 35% greater than Option 3.

In contrast to the total cost, the total net benefits presented in Table 10 showed that Option 1C produced the greatest benefits ($996 million) compared to all other options. The three components contributing to these results were water conservation, land conservation, and GHG reductions, as discussed in Section 4.2.

Table 10
Net Present Value (NPV) with 7% discount rate.

Tailing management	Total cost ($)	Total benefits ($)	Total net benefits ($)	NPV ($)	Preference
OPT 1	371,328,738	995,812,427	624,483,690	307,376,828	4
OPT 1A	356,171,019	995,815,499	639,644,480	314,880,435	3
OPT 1B	354,291,359	995,750,345	641,458,986	315,775,687	2
OPT 1C	354,290,210	995,788,811	641,498,602	315,795,875	1
OPT 2	425,987,452	932,621,493	506,634,041	247,168,814	5
OPT 3	514,839,246	918,558,821	403,719,575	205,308,234	6

The total net benefits resulting from the quantification of costs and benefits during mine tailings operations were then discounted at a rate of 7% per year (Australian Government, 2016, 2014). This calculation presented in Equation (4) provided an NPV for each mine tailings management option. The highest NPV was for Option 1C, which uses belt press technology with stack cell flotation instead of column flotation and 10% of fossil fuels substituted with wind energy.

The NPV results for every five years also showed that Option 1C was the most preferred scenario for this mine site (Fig. 4). The average percent difference in the NPV for all options in Year 5, 10, 15, and 20 was 29%. It means that the discount rate of 7% contributed to NPV reduction by more than a quarter of its original value in every five years. Table 10 and Fig. 4 indicate that all options have higher Present Benefit Values (PBV) than the Present Cost Values (PCV). In other words, all options are considered feasible for this mining site (PBV-PCV > 0).

3.3.1. Sensitivity analysis

A sensitivity analysis is undertaken in a BCA to assess the data uncertainty that would affect the overall costs and benefits of the mine tailings scenario. In this study, the sensitivities to the lifespan and the discount rate were analyzed.

The discount rate in the BCA was analyzed by changing the rate from 7% to 3% and 10%. The NPV results for the three discount rates and four lifespans are shown in Fig. 5. The results revealed that NPV increases as the discount rate decreases, as predicted. Changes in the discount rate contributed significantly to the total NPV, total operational cost, and total benefit value. A significant increase in NPV, by 47%, occurred when the discount rate was decreased from

7% to 3%. The increase in NPV was greater than 80% when the discount rate was reduced by 7% (from 10% to 3%).

Overall, BCA was significantly affected by the changes in the discount rate, as the discount rate contributed to the future operational cost and benefits value. Therefore, BCA is considered to be sensitive to the discount rate and any differences in the rate should be considered when comparing the results with the other BCA studies.

3.4. Selection the feasible scenario

The most feasible scenario out of the six available options for tailings management was determined using a normalization approach where LCC, BCA, and GHG emissions were the main parameters. These parameters have different units (i.e. AU$, kilogram CO_2-e) and scales, therefore the value of these parameters was divided by their ideal values to provide the normalized results (Azapagic, 1999; Huppes & Ishikawa, 2005; Islam, Jollands, Setunge, Ahmed, & Haque, 2014; Mangan & Oral, 2016). The results are presented in Fig. 6 and the most feasible option was indicated as the one with a normalized value close to unity.

The best scenario (Option 1C) is belt press operation with stack cell flotation and 10% fossil fuel substituted with wind power (detailed points as follows: GHG = 1, LCC 3%−10% ≈ 1.001 and, BCA 3%−10% = 1). Option 1B and Option 1A also have values close to the most preferred scenario (Fig. 6). Option 1B has similar characteristics to Option 1C except for the type of renewable energy introduced to the system: solar power (PV) versus wind power. The utilization of PV generates a land conservation value which is 1.3% lower than for wind power. The third feasible option (Option 1A) is
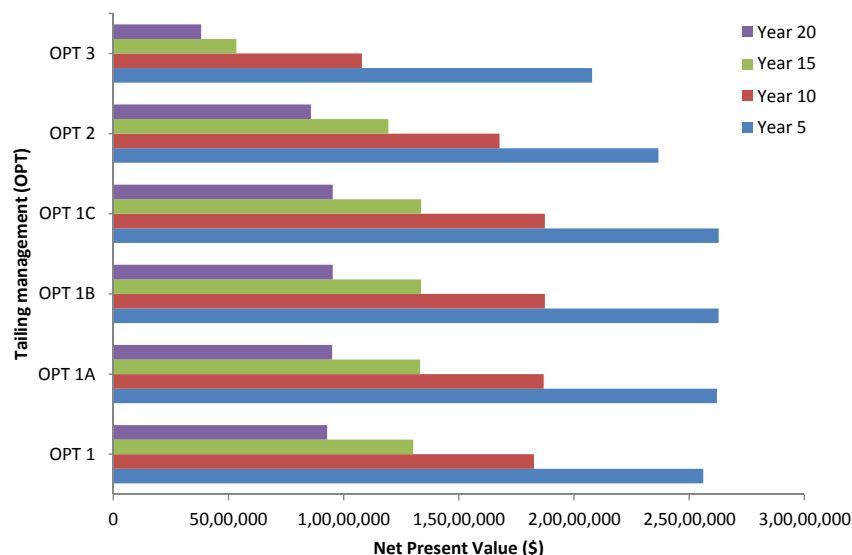
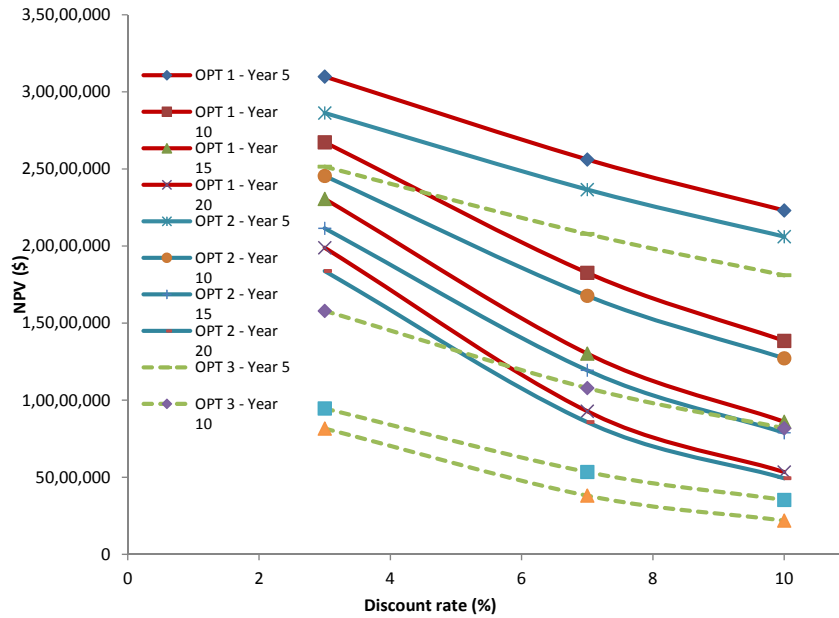Fig. 4. NPV of tailing management option in different time horizon.

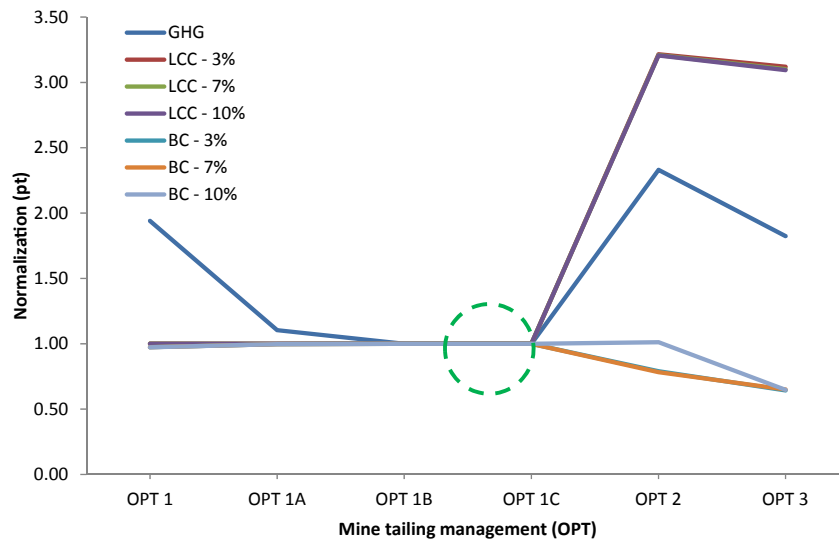**Fig. 5.** *NPV with various discount rates.*

Fig. 6. Normalized GHG, LCC, and BCA results.

a scenario that uses the belt press as the main dewatering process to increase the mass percent of the solids in tailings up to 65% and uses stack cell flotation in the segregation process. In Option 1A, the electricity was supplied by a coal-fired power plant that amplified the GHG emissions to 10% higher than Option 1C. The utilization of fossil fuel energy as the electricity source decreases the LCC value by 0.1% and benefits value by 0.3% when compared to the most feasible scenario (Option 1C).

4. Conclusions

This paper discusses the economic value of coal mine tailings management activities. The economic value analysis is required to assist the stakeholders including mining companies and the government in determining the most feasible option from various available scenarios in terms of financial considerations and

environmental sustainability.

The study compares six options that use three different dewatering technologies: belt press, paste thickener, and tailings thickener. These technologies affect the water conservation volume, chemical use, and electricity consumption. Changes in the use of raw fine coal segregation technology (column flotation to stack cell flotation) in Options 1A-C resulted in decreased electricity consumption when compared to other scenarios. The introduction of the renewable energy in Options 1B–C also increases the carbon reduction level in these two scenarios. In summary, Option 1C was found to be the most preferable scenario generating benefit values of 0.01%–54% higher and LCC values of −0.1% to 221% lower, compared to the other scenarios. By having higher benefit values and LCC values, option 1C could contribute more to the sustainability level improvement of coal tailings management in four aspects: coal production, water reclamation, land conservation, and

GHG reduction. Therefore, this study also indicates the importance of considering the economic analysis aspects as part of sustainable consideration prior to selecting a tailings disposal method.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jsm.2017.10.004.

References

Adiansyah, J. S., Haque, N., Rosano, M., & Biswas, W. (2017). Application of life cycle assessment to compare environmental performance in coal mine tailings management. *Journal of Environmental Management, 199*, 181–191.

Adiansyah, J. S., Rosano, M., Vink, S., & Keir, G. (2015). A framework for a sustainable approach to mine tailings management: Disposal strategies. *Journal of Cleaner Production, 108*, 1050–1062.

Adiansyah, J. S., Rosano, M., Vink, S., Keir, G., & Stokes, J. R. (2016). Synergising water and energy requirements to improve sustainability performance in mine tailings management. *Journal of Cleaner Production, 133*, 5–17.

Ahlroth, S., Nilsson, M., Finnveden, G., Hjelm, O., & Hochschorner, E. (2011). Weighting and valuation in selected environmental system analysis tools – suggestions for further developments. *Journal of Cleaner Production, 19*(2), 145–156.

AS/NZS. (2014). *Life cycle costing – an application guide*.

Australian Energy Market Operator. (2016). *Average price tables*. Retrieved August 1, 2017 from http://www.aemo.com.au/Electricity/Data/Price-and-Demand/Average-Price-Tables.

Australian Government. (2014). *Research Report: Environmental valuation and uncertainty (report)*. Canberra: Australian Government, Department of the Prime Minister and Cabinet.

Australian Government. (2016). *Guidance note: Cost-benefit analysis*. Canberra: Australian Government, Department of the Prime Minister and Cabinet.

Azapagic, A. (1999). Life cycle assessment and its application to process selection, design and optimisation. *Chemical Engineering Journal, 73*(1), 1–21.

Bell, F. G., Bullock, S. E. T., Hälbich, T. F. J., & Lindsay, P. (2001). Environmental impacts associated with an abandoned mine in the Witbank Coalfield, South Africa. *International Journal of Coal Geology, 45*(2), 195–216.

Bian, Z., Dong, J., Lei, S., Leng, H., Mu, S., & Wang, H. (2009). The impact of disposal and treatment of coal mining wastes on environment and farmland. *Environmental Geology, 58*(3), 625–634.

Bickert, G. (2004). *Review of tailings dewatering technologies for Australian coal processing plants*. Project number 14012. Brisbane: ACARP.

Brealey, R. A., Myers, S. C., Allen, F., & Mohanty, P. (2012). *Principles of corporate finance*. New York: Tata McGraw-Hill Education.

Burton, M., Zahedi, S. J., & White, B. (2012). Public preferences for timeliness and quality of mine site rehabilitation. The case of bauxite mining in Western Australia. *Resources Policy, 37*(1), 1–9.

Callan, S. J., & Thomas, J. M. (2013). *Environmental economics and management: Theory, policy, and applications*. Boston: Cengage Learning.

Commonwealth of Australia. (2014). *Environmental management plan guidelines*. Canberra: Department of the Environment.

Damigos, D. (2006). An overview of environmental valuation methods for the mining industry. *Journal of Cleaner Production, 14*, 234–247.

Damigos, D., Menegaki, M., & Kaliampakos, D. (2016). Monetizing the social benefits of landfill mining: Evidence from a Contingent Valuation survey in a rural area in Greece. *Waste Management, 51*, 119–129.

Danthurebandara, M., Van Passel, S., Machiels, L., & Van Acker, K. (2015). Valorization of thermal treatment residues in enhanced landfill mining: Environmental and economic evaluation. *Journal of Cleaner Production, 99*, 275–285.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics, 41*(3), 393–408.

Dlamini, C. S. (2012). Types of values and valuation methods for environmental resources: Highlights of key aspects, concepts and approaches in the economic valuation of forest goods and services. *Journal of Horticulture and Forestry, 4*(12), 181–189.

Economics, G. (2008). *Managing the impacts of a mine in the southern coalfield: A survey of community attitudes*. Sydney: Helensburgh Coal Pty Ltd.

Eggert, R. G. (2001). *Mining and economic sustainability: National economies and local communities*. London: IIED.

EMGA Mitchell McLennan. (2012). *Cobbora Coal: Project description (report)*. St Leonards: EMGA Mitchell McLennan.

Energy Information Administration. (2016). *International energy Outlook 2016 (report)*. Washington, DC: U.S. Energy Information Administration.

Epstein, P. R., Buonocore, J. J., Eckerle, K., Hendryx, M., Stout Iii, B. M., Heinberg, R., et al. (2011). Full cost accounting for the life cycle of coal. *Annals of the New York Academy of Sciences, 1219*(1), 73–98.

Erkayaoğlu, M., & Demirel, N. (2016). A comparative life cycle assessment of material handling systems for sustainable mining. *Journal of Environmental Management, 174*, 1–6.

Fawell, P., Adkins, S., & Costine, A. (2015). Reagents. In R. J. Jewell, & A. B. Fourie (Eds.), *Paste and thickened tailings – a guide* (pp. 87–108). Crawley: Australian Centre for Geomechanics.

Fenzel, M. S. (2012). Belt filter press in coal tailings dewatering – a comprehensive economic, design, and process analysis. In M. S. Klima, B. J. Arnold, & P. J. Bethell (Eds.), *Challenges in fine Coal: Processing, dewatering, and disposal* (pp. 309–327). Colorado, USA: SME.

Finnveden, G., & Moberg, Å. (2005). Environmental systems analysis tools – an overview. *Journal of Cleaner Production, 13*, 1165–1173.

Franks, D. M., Brereton, D., & Moran, C. J. (2010). Managing the cumulative impacts of coal mining on regional communities and environments in Australia. *Impact Assessment and Project Appraisal, 28*(4), 299–312.

GHD. (2013). *Report for mine waste management Strategy: Carmichael coal mine and rail project SEIS (report)*. Brisbane: GHD Pty Ltd.

Gillespie, E. (2012). *Cobbora coal Project: Appendix r – economic assessment (report)*. Melbourne: Economists at Large Pty Ltd.

Gordon, I. (2014). *Updated capital cost estimate for PIOP*. Washington: U. S. department of Energy.

Haque, N., & Norgate, T. (2015). Life cycle assessment of iron ore mining and processing. In L. Lu (Ed.), *Iron Ore: Mineralogy, processing and environmental sustainability* (pp. 615–630). Amsterdam: Elsevier.

Harrison, M. (2010). *Valuing the future: The social discount rate in cost-benefit analysis*. Canberra: Productivity Commission.

Höjer, M., Ahlroth, S., Dreborg, K.-H., Ekvall, T., Finnveden, G., Hjelm, O., et al. (2008). Scenarios in selected tools for environmental systems analysis. *Journal of Cleaner Production, 16*, 1958–1970.

Honaker, R., Kohmuench, J., & Luttrell, G. (2013). Cleaning of fine and ultrafine coal. In D. Osborne (Ed.), *The coal Handbook: Toward cleaner production*. Oxford, Cambridge, Philadelphia, New Delhi: Woodhead Publishing.

Huppes, G., & Ishikawa, M. (2005). A framework for quantified eco-efficiency analysis. *Journal of Industrial Ecology, 9*(4), 25–41.

Index, M. (2016). *Coal: Australian thermal coal monthly price*. Retrieved August 1, 2017 from http://www.indexmundi.com/commodities/?commodity=coal-australian&months=60&currency=aud.

Islam, H., Jollands, M., Setunge, S., Ahmed, I., & Haque, N. (2014). Life cycle assessment and life cycle cost implications of wall assemblages designs. *Energy and Buildings, 84*, 33–45.

Jacobson, N., Wayder, J., & Franslin, S. (2013). *Solar farm feasibility study (report)*. Turner: IT Power (Australia) Pty Limited.

Jones, H., & Watkins, R. (2015). Closure considerations. In R. J. Jewell, & A. B. Fourie (Eds.), *Paste and thickened tailings – a guide* (pp. 259–279). Crawley: Australian Centre for Geomechanics.

Kohmuench, J. N., Yan, E. S., & Christodoulou, L. (2012). Column and non-conventional flotation for coal recovery: Circuitry, methods, and considerations. In M. S. Klima, A. J. Barbara, & P. J. Bethell (Eds.), *Challenges in fine Coal: Processing, dewatering, and disposal* (pp. 187–209). Colorado, USA: SME.

Kossoff, D., Dubbin, W. E., Alfredsson, M., Edwards, S. J., Macklin, M. G., & Hudson-Edwards, K. A. (2014). Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry, 51*, 229–245.

Kumar, S., Bhattacharya, S., Mandre, N. R., & Venugopal, R. (2014). Present challenges in the performance of coal fines dewatering circuit. *International Journal of Engineering Research and Science & Technology, 3*(2), 172–179.

Mangan, S. D., & Oral, G. K. (2016). Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency. *Energy and Buildings, 110*, 362–376.

Marre, J.-B., Thébaud, O., Pascoe, S., Jennings, S., Boncoeur, J., & Coglan, L. (2016). Is economic valuation of ecosystem services useful to decision-makers? Lessons learned from Australian coastal and marine management. *Journal of Environmental Management, 178*, 52–62.

Mazzotta, M., Wainger, L., Sifleet, S., Petty, J. T., & Rashleigh, B. (2015). Benefit transfer with limited data: An application to recreational fishing losses from surface mining. *Ecological Economics, 119*, 384–398.

McLellan, B. C., Corder, G. D., Giurco, D., & Green, S. (2009). Incorporating sustainable development in the design of mineral processing operations – review and analysis of current approaches. *Journal of Cleaner Production, 17*(16), 1414–1425.

Miranda, M., Burris, P., Bingcang, J. F., Shearman, P., Briones, J. O., La Vina, A., et al. (2003). *Mining and critical Ecosystems: Mapping the risks*. Washington, DC: World Resources Institute.

Moolman, P. L., & Vietti, A. (2012). Tailings Disposal: An approach to optimize water and energy efficiency. In *5th International Platinum Conference, 17–21 September 2012 Sun City* (pp. 767–779). Johannesburg: The Southern African Institute of Mining and Metallurgy.

New Hope Group. (2014). *Appendix J: In-pit tailings storage facility management plan (report)*. Ipswich: New Hope Group – New Auckland Coal Mine.

Newmont. (2016). *Operation facts*. Retrieved August 1, 2017 from http://www.newmont.com/operations-and-projects/asia/batu-hijau-indonesia/operation-facts/default.aspx.

Newmont Nusa Tenggara. (2016). *Tentang PT Newmont Nusa Tenggara*. Retrieved August 1, 2017 from http://www.ptnnt.co.id/id/sejarah.aspx.

NSW Government. (2016). *Water management fees and charges*. Retrieved August 1, 2017 from http://www.water.nsw.gov.au/water-management/fees-and-charges.

Owen, M. J. (1989). Enhancement of mechanical dewatering of fine coal by surface-active additives. In G. D. Botsaris (Ed.), *Interfacial phenomena coal technology* (pp. 157–195). New York: CRC Press.

Perusahaan Listrik Negara. (2015). *35.000 MW untuk Indonesia*.

QCC. (2013). *Appendix C: Dewatering options report — comparison of options for tailings dewatering (report)*. Hexham: QCC Resources Pty Ltd.

Qugley, J. (2016). *Notices: Bond rate guidelines for the calculation of land reclamation bonds on coal mining operations*. Retrieved August 1, 2017 from http://www.pabulletin.com/secure/data/vol46/46-10/374.html.

Reserve Bank of Australia. (2016a). *Inflation calculator*. Retrieved August 1, 2017 from http://www.rba.gov.au/calculator/annualDecimal.html.

Reserve Bank of Australia. (2016b). *Inflation target*. Retrieved August 1, 2017 from http://www.rba.gov.au/monetary-policy/inflation-target.html.

Sánchez, A. S., Krzemień, A., Fernández, P. R., Rodríguez, F. J. I., Lasheras, F. S., & de Cos Juez, F. J. (2015). Investment in new tungsten mining projects. *Resources Policy, 46*, 177—190.

Standard. (2016). *AS IEC 60300.3.3—2005: Dependability management — Part 3.3: Application guide— Life cycle costing*.

Thomas, L. P. (2013). Coal resources and reserves. In D. Osborne (Ed.), *The coal Handbook: Toward cleaner production*. Oxford, Cambridge, Philadelphia, New Delhi: Woodhead Publishing.

Wang, L. K., Shammas, N. K., & Hung, Y.-T. (2007). *Biosolids treatment processes*. Totowa, New Jersey: Humana Press.

Windusty. (2012). *How much do wind turbines cost?*. Retrieved August 1, 2017 from http://www.windustry.org/how_much_do_wind_turbines_cost.

World Bank and Ecofys. (2016). *Carbon pricing watch 2016*. London: Ecofys.

World Nuclear Association. (2013). *Australia's Electricity*. Retrived August 1, 2017 from http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/Appendices/Australia-s-Electricity/.

Zhengfu, B., Hillary, I., John, L. D., Frank, O., & Sue, S. (2010). Environmental issues from coal mining and their solutions. *Mining Science and Technology (China), 20*(2), 215—223.