Application of a Life Cycle Impact Assessment framework to evaluate and compare environmental performances with economic values of supplied coal products

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Abstract

The South African economy is strongly based on coal as a mined resource, and various grades of coal are supplied to local and international customers. However, the environmental impacts associated with the preparation and production of different coal grades from Run of Mine (RoM) or raw coal are variable; specifically, the different mining methods used for coal extraction – opencast or underground mining – have different environmental impacts. The entire life cycles of the grades of coal must therefore be evaluated in order to compare environmental performances with supplied economic values. In this paper, a Life Cycle Impact Assessment (LCIA) methodology, based on the ISO 14040 standard, is applied for this purpose. Four cases are considered in South Africa: typical high-grade and low-grade coals from opencast and underground mines.

Article Outline

1. Introduction

Coal has been, and currently still is, the cornerstone of the South African energy economy. It provides 75% of South Africa's primary energy requirements. Approximately 90% of the electricity in South Africa is generated from coal, and it is the third largest mined resource export earner after the platinum group metals and gold [1].

Suppliers of coal (i.e. coalmines or collieries) sell various grades to a variety of consumers. Local petrochemical and energy industries rely heavily on low-grade coal as feedstock. High-grade coal, in turn, is exported to developed countries and is therefore an important contribution to the influx of foreign currency. The preparation and production of the various grades of coal differ. Apart from the normal crushing and screening processes, washing of the Run of Mine (RoM) or raw coal is required to produce high-grade coals. The environmental impacts associated with coal preparation and production are subsequently variable, as the mining methods used to extract coal – opencast of underground techniques – result in different environmental impacts. The environmental profiles or performances of the supply chains of coal products (i.e. specific grades) in relation to the associated economic values of these products have subsequently been questioned [2].

2. Environmental impacts of coal production

Due to its nature, the mining and coupled processing of coal has the potential to cause a number of ambient environmental burdens if proper planning and management practices are not in place [3]. In the South African context, the impacts must specifically be addressed in terms of four natural resource groups: land resources, water resources, air resources, and mined abiotic resources [4] and [5]. The *South African Constitution of 1996* (Act 108) stipulates in Section 24 that the quantity and quality of these natural resources must be maintained for society (human health and welfare) and ecology in general (ecosystem quality) for present and future generations [6].

2.1. Impacts of coal production on land resources

Mining implies the extraction of ore with the subsequent disturbance of land surfaces, which is dependent on the type of mining operation or method deployed. Surface or opencast mining is practised where coal seams are nearly horizontal and covered with a relatively thin overburden, and where the surface topography is of low relief. Opencast coal mining is essentially an earth-moving operation, which typically includes the blasting of the overburden, and using draglines, shovels, and dump trucks [7]. Although mining companies are obliged to rehabilitate the land to (approximately) its pre-mining state [8], the topography is affected; this may lead to erosion, as the potential productivity of the soil (for plant growth) may be reduced after mining [9].

Underground mining methods are generally utilised when the coal is deeply embedded [7]. The major impact of underground mining to the topography of the land surface is subsidence. This can result from the caving of underground roof materials following the removal of coal, which often induces collapse of the overlying rock strata. Subsidence is dependent on the mining situation and geological setting and hence has different impacts on land surfaces. The impacts include, but are not limited to, a lowering of the topography, deep pit cracks and fissures, as well as troughs and steep offsets [9]. Subsidence may render the land unusable due to the safety hazard associated with it.

The dumping of the discard material or waste during the mining operation also affects the land in the vicinity of the operation. For example, the overburden and the material discarded from the processing plant may contain soluble salts, which may dissolve during the rainy seasons and deposit into the soil, thus causing acidification and contamination.

2.2. Impacts of coal production on water resources

Land surfaces disturbed from mining are prone to erosion, which, in turn, may increase sediment loading to surface waters [3]. The areas with high erosion potential include tailings piles, discard dumps, roadways, product stockpiles, and other land areas disturbed during, and shortly after, the construction phase of a mining operation [7]. Sediment loading may be aggravated by uncontrolled storm water from the aforementioned areas. Depending on the end use of the water, sediment loading can have adverse effects on the water quality due to an increase in total suspended solids, which can be of danger to human, animal and aquatic life [10].

Of particular importance and concern to the global coal mining industry is acid mine drainage (AMD) [9] and [11]. This is caused by the oxidation of pyritic sulphur due to exposure of pyrite (FeS_2) to air and water; this can cause acidity (or decrease in the pH of water) and subsequent elevated concentrations of metals that are associated with sulphide mineralogy (i.e. iron, sulphate and other metals such as copper, mercury, lead, arsenic, molybdenum, antimony, cobalt, zinc and nickel). Pyrite is generally found in the coal, coal discards and overburden.

The acidity dissolves carbonate minerals and other acid-consuming minerals, which may be present in the rock or soils, whereby additional metals such as magnesium, aluminium, manganese and calcium are added to the AMD. Moreover, as the AMD is released into the environment, neutralisation reactions occur between acidic water and the carbonate minerals (e.g. calcite in the sediment and surface water to release calcium which precipitates as gypsum, such as calcium sulphate). Because mining can open the flow paths for water, AMD and the consequent contamination of surface waters and groundwater reserves depend on the permeability of the rock.

Another hydrological effect of mining is the leaching of metals, which can occur with precipitation through the coal or discard dump. The leaching of metals is dependent on the chemical character of the water leaching through the solid material and the form of the metals in the solid matrix. In areas experiencing problems with acid rain and where oxidation of sulphide minerals occurs, leaching can be excessive.

Water consumption is also of importance in coal mining and processing. It is even more so in South Africa, where water is a scarce commodity [12]. Water in coal mining is mainly used in the (coal) preparation or washing process. The coal preparation plants in South Africa are reportedly using half a tonne of water per tonne of high-grade coal washed [13]. Consumption, however, varies with the amount of water returned to the plant from the slurry. Low-grade coal preparation plants, which utilise only simple crushing and screening preparation methods, use less water. Additional consumption of water can occur due to the evaporation from dust suppression activities, irrigation of reclaimed land and slurry ponds [7].

2.3. Impacts of coal production on air resources

Air pollution, with local, regional and global effects, is an environmental impact associated with mining. The pollutants that are of chief concern are particulates, sulphur oxides (SO_x), nitrous oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), methane, lead and other hazardous metallic [7].

Of all the abovementioned air pollutants, particulates, particularly in the form of dust, are by far the major concern for the mining industry [7]. The typical impacts are, among other things, chronic respiratory illnesses, reduced visibility, irritation of the eyes and throat, etc. Particulates are emitted in large amounts during all aspects of mining operations, particularly the earth-moving processes of surface mining (as discussed in Section 2.1), and gravel roads that are used to access the mining sites. Significant amounts of dust are also emitted during the transportation and storage of the coal products due to wind erosion. For example, during processing operations, fine coal dust is typically generated from conveyor belts, whereby large areas of land can be contaminated. Applying water sprays and dust bonding agents such as surfactants reduces dust emissions from transportation routes and stockpiles. In underground mining especially, water sprays diminish ambient dust emissions to a minimum.

SO_x, NO_x, CO and VOCs are mainly emitted during the combustion of coal and/or other fossil fuels. In coal mining operations, these environmental impacts are rather limited, although spontaneous combustion may occur in the peat and the discard dumps. Spontaneous combustion of the discard dumps has, however, largely been solved through the exclusion of oxygen by compaction and encapsulation of the dumps with soil. The major source is the emissions from transportation vehicles and machinery that are used for extracting coal [7]. The impacts of these pollutants on the environment include acid precipitation, particularly from SO_x and NO_x, respiratory tract illnesses, and production of smog [3].

Global warming can be attributed to certain pollutants that are emitted during coal mining. Methane and CO_2 are known to contribute significantly to global warming or the greenhouse effect [14] and [15]. Methane (and minor quantities of CO_2) is released during the extraction of coal, which is ventilated (in underground mines) to the atmosphere to prevent explosions, thereby ensuring the safety of mining employees.

2.4. Impacts of coal production on mined abiotic resources

Extraction of coal implies the depletion of non-renewable energy reserves. The Minerals Bureau estimates a South African coal reserve of 34.3 billion tonnes [16], based on previous studies [17] and the production rates between 1982 and 2002. However, the amount of extractable South African coal reserves for future use is currently not well defined. South Africa's reliance on coal as a primary source of energy and source of foreign revenue from exports is therefore uncertain. However, the South African Department of Minerals and Energy (DME) is currently undertaking a study on national coal resources and reserves; accurate figures should be obtainable in the near future.

Although coal is a non-renewable resource, South Africa, for macro-economic reasons, cannot cease to extract this material in trying to preserve it. In addition, globally, coal is likely to remain a significant source of affordable energy into the foreseeable future [18]. The major challenge facing the coal industry is environmental acceptability.

2.5. Objectives of the paper

The objectives of this paper are to evaluate the environmental performances or profiles of specific coalmines that use different mining and beneficiation methods, and to compare the environmental performances with the economic values of different grades of coal produced at the investigated mines. The paper thereby attempts to identify the most appropriate (economic and environmental) coal mining methodologies for application in the South African context. The results of the proposed study could assist the South African coal mining industry in making decisions regarding priorities for environmental management.

Risk or environmental performance indicators are calculated for the life cycles of coal products from four collieries in South Africa that:

• Utilise opencast mining and produce low-grade coal for South African customers,

• Utilise opencast mining and produce beneficiated high-grade coal for the export market,

• Utilise underground mining and produce low-grade coal for South African customers, and

• Utilise underground mining and produce beneficiated high-grade coal for the export market.

Thereafter, the performance indicators are compared with the economic values of the supplied coal from the investigated mines.

3. The product life cycles of the four collieries as case studies

Life Cycle Assessment (LCA) uses a "cradle to grave" approach to assess and obtain an environmental profile of the life cycles of products [19]. However, this paper does not consider the full "cradle to grave" life cycle, as it only covers raw material extraction or Run of Mine (RoM) production, beneficiation (screening and washing) as well as distribution and transportation (rail and conveyor belt) to customers: a "cradle to gate" assessment. Auxiliary processes, such as electricity and water requirements, are also included in the boundaries of the investigated life cycles. The life cycle value chains of the investigated South African coal products are presented in Fig. 1 [20]. In terms of exported high-grade coal, the basis of sales is limited to Free on Board (FoB), where the supplier bears all costs, from the production up to the onboard (sea) vessel. In Fig. 1, 'Electy' (or the electricity generation sector) and 'Sasol' (a large petrochemical manufacturing industry) reflects the market offset points for the low-grade coal.

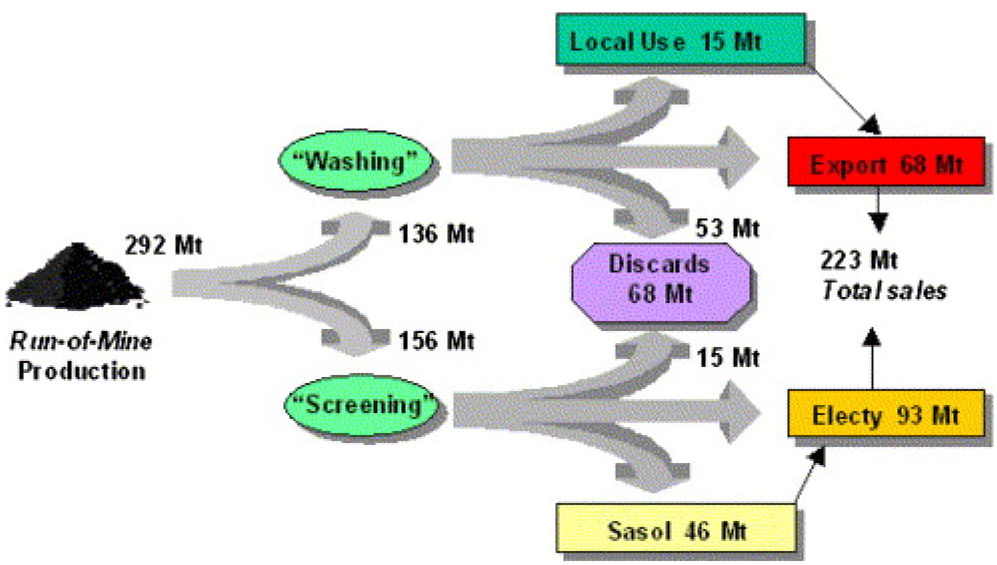

Fig. 1. The South African coal value chain [20].

The functional unit of the life cycles, for which all life cycle inventory constituents or Life Cycle Inventories (LCIs) [19] are determined, is a "tonne of delivered coal product", based on an annual (2002) production rate. In the case of low-grade coal, the economic value of the product (grade D coal) is approximately US$ 10 per tonne, and for high-grade coal, US$ 40 per tonne of supplied product (B grade steam coal). The methods used for data collection to compile the LCIs per tonne of product, included interviews, publications, as well as personal observations in the coal mining industry. The LCI data that were available from the mines and gathered for this study included the annual tonnages sold, methane and CO_2 emissions, water use, dust fallout, energy use, land use and water quality impacts in terms of sulphates and pH.

The characteristics of the four case studies are as follows:

• *Mine* $A_{open\text{-}low}$: opencast mining methods are used to produce low-grade (D) coal that is crushed, screened and transported with a conveyor belt to a nearby electricity generation utility.

• *Mine* $B_{open\text{-}high}$: opencast mining methods are also used, but coal beneficiation is utilised to produce high-grade (B) coal that is supplied to the export market, via the northeast coast of South Africa (Richards Bay).

• *Mine* $C_{under\text{-}high}$: underground mining methods are used with beneficiation to supply high-grade (B) coal to the export market, also through the port of Richards Bay.

• *Mine* $D_{under\text{-}low}$: underground mining methods are used to produce low-grade (D) coal, which is again crushed, screened and transported with a conveyor belt to a nearby electricity generation utility.

4. Life Cycle Impact Assessment (LCIA) to evaluate environmental performance

The Life Cycle Impact Assessment (LCIA) phase of LCAs defines the methodology used to obtain quantitative indicators, or environmental profiles, of product life cycle systems [21]. The LCIA phase is divided into [22]:

• Classification, whereby the results of the Life Cycle Inventory (LCI) analysis (i.e. input and output constituents) are categorized or grouped into classified impact categories;

• Characterisation, which determines the contribution of the inventory data to each impact category (i.e. a characterisation value is assigned for each LCI constituent); and

• Valuation, whereby the different impacts are normalised and weighed against each other.

Fig. 2 illustrates that all LCIA methods must include the two elements of classification and characterisation. The ISO 14042 standard stipulates the considerations that need to be taken into account when executing these two obligatory elements [21]. Problem-oriented (midpoint) or damage-oriented (endpoint) approaches are followed in LCIA methods to define the impact categories [23]. For example, considering a global warming impact category, characterisation values can either be assigned as CO_2 equivalence values (midpoint), or as disappeared fraction of certain plant species, expressed as a percentage (endpoint).

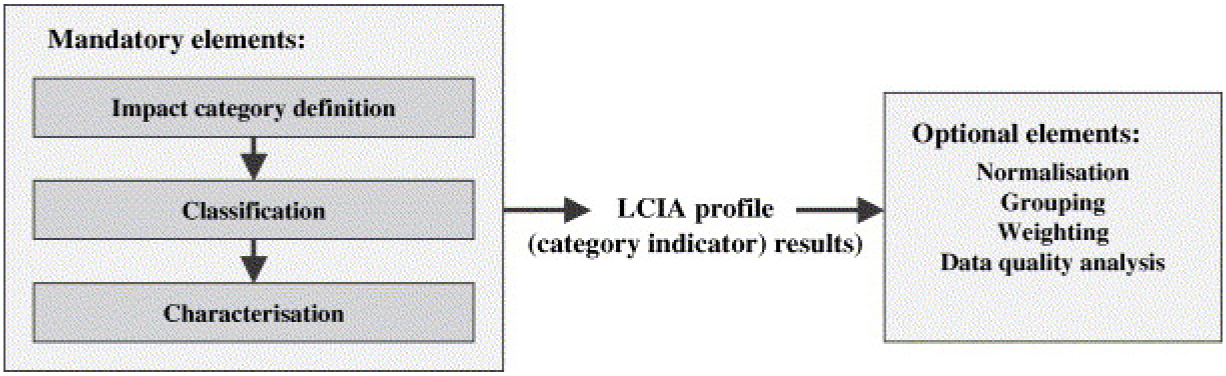

Fig. 2. Life Cycle Impact Assessment (LCIA) according to ISO 14042 [21].

In terms of the optional elements of a LCIA, normalisation is usually incorporated in order to compare the impacts of a system on the different categories [23]. Normalisation typically considers the current environmental burden of society on the classified impact categories (e.g. an estimate of the total release of global warming gases into the atmosphere). In some LCIA methods, a single scoring mechanism is also an option [23], which requires the LCIA method to include a procedure to determine weighting values for the classified impact categories.

A LCIA procedure has been introduced [4], [5] and [24], which follows the ISO 14040 standard, and whereby the environmental impacts and performances of these life cycle systems can be determined in the South African context. Thereby, Resource Impact Indicators (RIIs) are calculated for the four natural resource groups: land resources, water resources, air resources, and mined abiotic resources (as specified in Section 2). These calculations are based on the ambient distance-to-target approach for established [15] and introduced midpoint impact categories [4] and [5]. Fig. 3 illustrates the framework on which the RII calculation procedure is based, as well as examples of inventory constituents of a life cycle system that may be considered in the calculation. Through the RII procedure, region-specific impact indicators are calculated for four regions in South Africa (see Fig. 4) [4], [5] and [24]. The four collieries (of the case studies) are all situated in the southern-central part of SALCA Region 3. The Richards Bay port, which is used to export the high-grade coal, is situated in SALCA Region 2. However, in order to simplify the case studies, the rail transportation impacts are assumed to be attributable to the required electricity, which is also primarily generated in SALCA Region 3 [25].

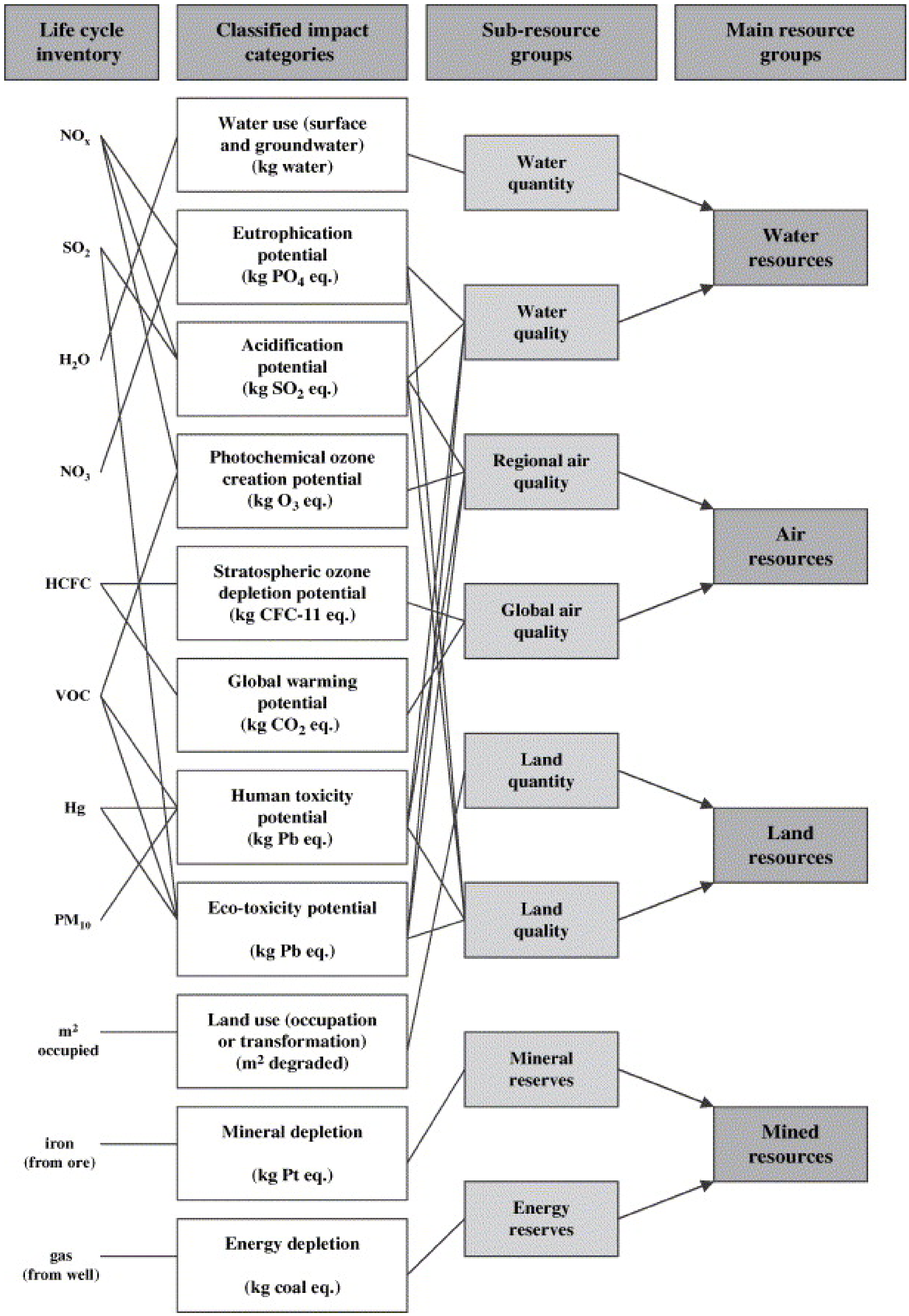
Life cycle inventory
Classified impact categories
Sub-resource groups
Main resource groups
NOx
SO2
H2O
NO3
HCFC
VOC
Hg
PM10
m² occupied
iron (from ore)
gas (from well)
Water use (surface and groundwater) (kg water)
Eutrophication potential (kg PO4 eq.)
Acidification potential (kg SO2 eq.)
Photochemical ozone creation potential (kg O3 eq.)
Stratospheric ozone depletion potential (kg CFC-11 eq.)
Global warming potential (kg CO2 eq.)
Human toxicity potential (kg Pb eq.)
Eco-toxicity potential (kg Pb eq.)
Land use (occupation or transformation) (m² degraded)
Mineral depletion (kg Pt eq.)
Energy depletion (kg coal eq.)
Water quantity
Water quality
Regional air quality
Global air quality
Land quantity
Land quality
Mineral reserves
Energy reserves
Water resources
Air resources
Land resources
Mined resources

Fig. 3. Proposed framework for a South African LCIA procedure [4] and [5].

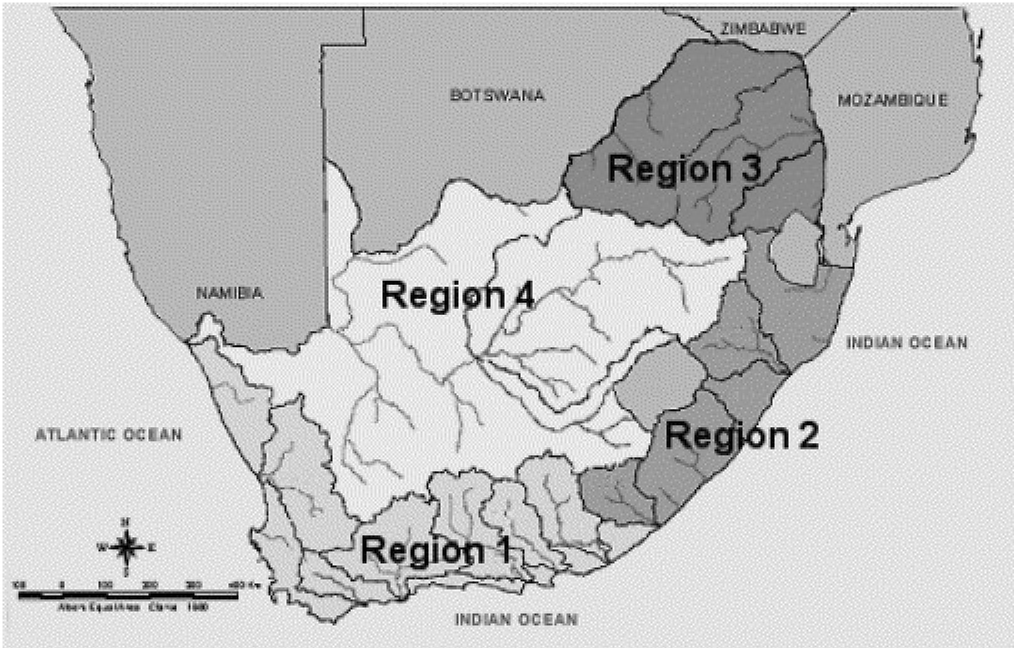

Fig. 4. SALCA Regions for South Africa to determine ambient environmental impacts [4], [5] and [24].

5. Results of the cases studies and discussion

5.1. Mine $A_{open\text{-}low}$ case study

The Life Cycle Inventory (LCI) data that was obtained for Mine $A_{open\text{-}low}$ (per supplied coal product) and converted to suite the units of the Resource Impact Indicator (RII) framework (see Fig. 3) are shown in Table 1. The Life Cycle Impact Assessment (LCIA) results for the midpoint categories of Fig. 3 are shown in Table 2. The subsequently calculated RIIs for the four natural resource groups are depicted in Fig. 5.

Table 1.

Life Cycle Inventory (LCI) data for Mine $A_{open\text{-}low}$

Aspects	**Inventory constituent**	**Value**	**Converted unit**	**Value**
Production	Annual RoM coal produced (t)	11080327	tonne	1.11×10^7
	Saleable coal produced (t)	11003141		1.10×10^7
Land resources	Land under company charge (ha)	16821	m^2	1.68×10^8
	Land altered for mineral extraction activities (ha)	2027		2.03×10^7
	Land rehabilitated to agricultural use (ha)	565		5.65×10^6
	Land fully rehabilitated (ha)	629		6.29×10^6
Water resources	Water used for primary activities (1000 m^3)	561	tonne	5.61×10^5
	Potable water from an external source (1000 m m^3)	699		6.99×10^5
	Non-potable water from an external source (1000 m^3)	0		0.00
	Surface water used (1000 m^3)	0		0.00
	Ground water used (1000 m^3)	0		0.00
	Water used for non-primary activities (1000 m^3)	138		1.38×10^5
	Water recycled in processes (1000 m^3)	187		1.87×10^5
	Total water consumption (1000 m^3)	1398		1.40×10^6
	Total water used (1000 m^3)	1585		1.59×10^6

Aspects	Inventory constituent	Value	Converted unit	Value
	pH of effluents	5.9		–
	Sulphates in effluents (mg/l)	1340		2.12×10^3
Air resources	Total CO_2 equivalent emissions (t CO_2 eq.)	93343	tonne	9.33×10^4
	Dust fallout (mg/m^2/day) – Internal	313		1.92×10^4
Mined abiotic resources	Total energy used (GJ)	514227	tonne	1.75×10^4

Table 2.

Life Cycle Impact Assessment (LCIA) results for Mine $A_{open\text{-}low}$

Resource group	Midpoint category[a]	Unit	Characterisation value	Normalisation value[b]
Land resources	Acidification potential	kg H_2SO_4 equivalence	2.124×10^6	5.72×10^1
	Human toxicity potential	kg Pb equivalence	4.796×10^3	6.44×10^{-3}
	Terrestrial toxicity potential	kg Pb equivalence	0.00	0.00
	Land use (occupied)	m^2 a natural degraded equivalence	1.68×10^8	2.09×10^4
	Land use (transformed)	m^2 natural degraded equivalence	4.27×10^7	1.18×10^4
Water resources	Water use	kg available reserves	1.40×10^6	4.43×10^1

Resource group	**Midpoint category**[a]	**Unit**	**Characterisation value**	**Normalisation value**[b]
		equivalence		
	Eutrophication potential	kg PO_4^{3-} equivalent	0.00	0.00
	Acidification potential	kg H_2SO_4 equivalence	2.12×10^6	5.72×10^1
	Human toxicity potential	kg Pb equivalence	1.28×10^6	2.56×10^5
	Aquatic toxicity potential	kg Pb equivalence	0.00	0.00
Air resources	Acidification potential	kg SO_2 equivalence	0.00	0.00
	Ozone creation potential	kg O_3 formed	0.00	0.00
	Ozone depletion potential	kg CFC-11 equivalence	0.00	0.00
	Global warming potential	kg CO_2 equivalence	9.33×10^4	6.68×10^{-8}
	Human toxicity potential	kg Pb equivalence	1.28×10^6	1.80×10^2
Mined abiotic resources	Mineral reserves depletion	kg platinum equivalence	0.00	0.00
	Energy reserves depletion	kg coal (RSA) equivalence	1.11×10^{10}	3.99×10^4

[a] Midpoint categories as defined by the South African LCIA procedure [4], [5] and [22].
[b] Normalisation is based on distance-to-target ambient values for SALCA Region 3, except for mined abiotic resource categories, where South African values are used.

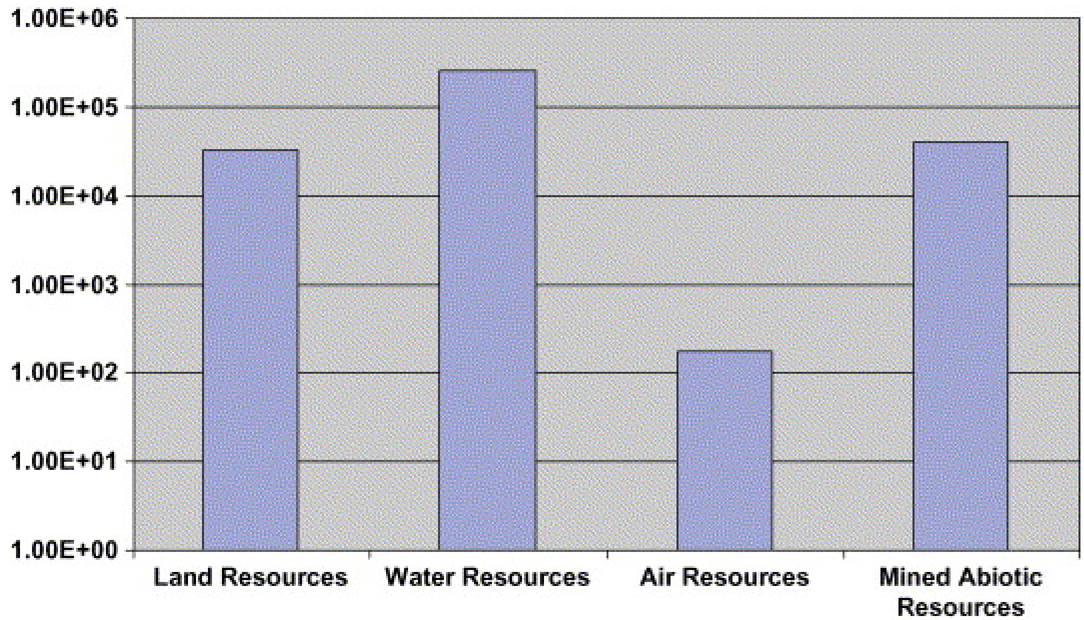

Fig. 5. Resource Impact Indicator (RII) results for Mine $A_{open-low}$.

The RII for the water resource group is the highest. This is mainly due to the high normalisation value of the human toxicity potential category, and the high sulphate content of water releases. Priority in terms of environmental management should therefore be given to the water resource group.

The next highest RIIs are for the mined abiotic resource and land resource groups. This is not unexpected since the coal mining operations involve earth-moving operations and the extraction of ore (i.e. coal). Although the high RIIs for both the mined abiotic and land resources are not unexpected, the operations should be done in a more responsible manner in line with sustainable development. The contribution of the energy that is used in the life cycle to the mined abiotic resource group is negligible when compared to the actual coal that is extracted (i.e. energy requirements contribute less than 1% to the mined abiotic resource group). Therefore, if the environmental burden associated with the depletion of non-renewable coal reserves is excluded from the analysis, the RII for this resource group would be lowest.

However, by including the extracted ore in the analysis, the RII for the air resources is the lowest. Nevertheless, environmental risks are associated with air pollution, particularly in terms of dust emissions, which can have adverse effects on the health of the internal workforce in the mine, as well as surrounding communities. Mitigation procedures should therefore be considered in the strategies associated with environmental management of the mining operations.

5.2. Mine $B_{open-high}$ case study

The LCI data for the Mine $B_{open-high}$ case study are presented in Table 3. The LCIA results are given in Table 4 with the subsequent calculated RII values illustrated in Fig. 6.

Table 3.

Life Cycle Inventory (LCI) data for Mine $B_{open\text{-}high}$

Aspects	**Inventory constituent**	**Value**	**Converted unit**	**Value**
Production	Annual RoM coal produced (t)	7662361	tonne	7.66×10^6
	Saleable coal produced (t)	4381113		4.38×10^6
Land resources	Land under company charge (ha)	7139	m^2	7.14×10^7
	Land altered for mineral extraction activities (ha)	2377		2.38×10^7
	Land rehabilitated to agricultural use (ha)	1009		1.80×10^7
Water resources	Water used for primary activities (1000 m^3)	204	tonne	2.04×10^5
	Potable water from an external source (1000 m m^3)	5		4.65×10^3
	Non-potable water from an external source (1000 m^3)	280		2.80×10^5
	Surface water used (1000 m^3)	184		1.84×10^5
	Ground water used (1000 m^3)	810		8.10×10^5
	Water recycled in processes (1000 m^3)	2878		2.88×10^6
	Total water consumption (1000 m^3)	1483		1.48×10^6
	Total water used (1000 m^3)	4361		4.36×10^6
	pH of effluents	4.7		–
	Sulphates in effluents (mg/l)	2491		1.09×10^7

Aspects	Inventory constituent	Value	Converted unit	Value
Air resources	Total CO_2 equivalent emissions (t CO_2 eq.)	150507	tonne	1.51×10^5
	Dust fallout ($mg/m^2/day$) – Internal	489		1.27×10^4
Mined abiotic resources	Total energy used (GJ)	961093	tonne	3.28×10^4

Table 4.

Life Cycle Impact Assessment (LCIA) results for Mine $B_{open\text{-}high}$

Resource group	Midpoint category[a]	Unit	Characterisation value	Normalisation value[b]
Land resources	Acidification potential	kg H_2SO_4 equivalence	1.09×10^7	2.93×10^2
	Human toxicity potential	kg Pb equivalence	3.19×10^3	4.28×10^{-3}
	Terrestrial toxicity potential	kg Pb equivalence	0.00	0.00
	Land use (occupied)	m^2 a natural degraded equivalence	7.14×10^7	8.89×10^3
	Land use (transformed)	m^2 natural degraded equivalence	4.16×10^7	1.15×10^4
Water resources	Water use	kg available reserves equivalence	1.48×10^6	4.69×10^1
	Eutrophication potential	kg PO_4^{3-} equivalent	0.00	0.00

Resource group	**Midpoint category**[a]	**Unit**	**Characterisation value**	**Normalisation value**[b]
	Acidification potential	kg H_2SO_4 equivalence	1.09×10^7	2.93×10^2
	Human toxicity potential	kg Pb equivalence	8.52×10^5	1.70×10^5
	Aquatic toxicity potential	kg Pb equivalence	0.00	0.00
Air resources	Acidification potential	kg SO_2 equivalence	0.00	0.00
	Ozone creation potential	kg O_3 formed	0.00	0.00
	Ozone depletion potential	kg CFC-11 equivalence	0.00	0.00
	Global warming potential	kg CO_2 equivalence	1.51×10^5	1.08×10^{-7}
	Human toxicity potential	kg Pb equivalence	8.52×10^5	1.20×10^2
Mined abiotic resources	Mineral reserves depletion	kg platinum equivalence	0.00	0.00
	Energy reserves depletion	kg coal (RSA) equivalence	773×10^9	2.78×10^4

[a] Midpoint categories as defined by the South African LCIA procedure [4], [5] and [22].
[b] Normalisation is based on distance-to-target ambient values for SALCA Region 3, except for mined abiotic resource categories, where South African values are used.

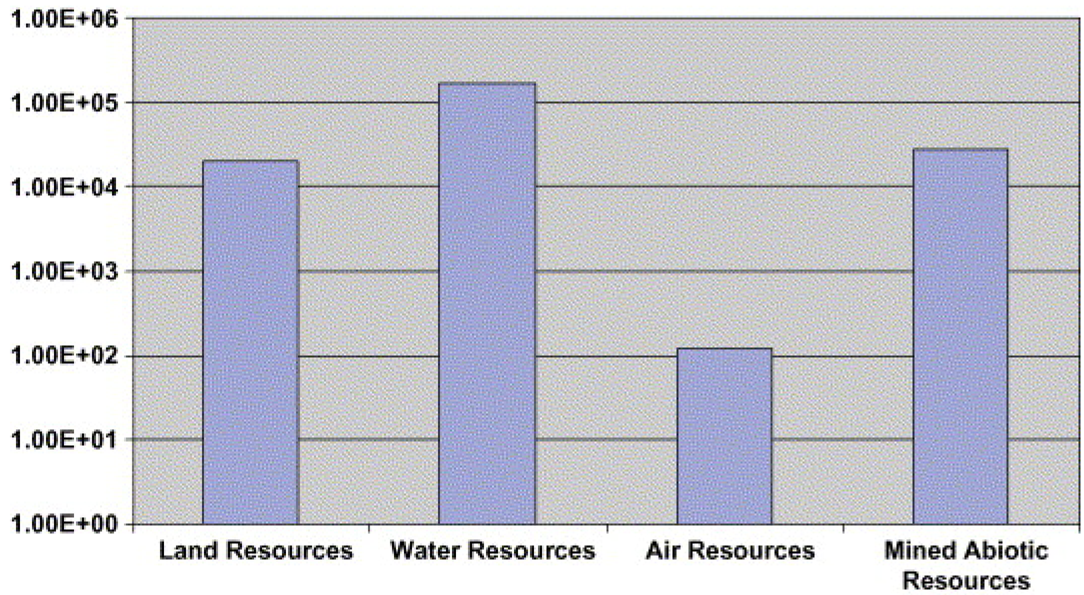

Fig. 6. Resource Impact Indicator (RII) results for Mine $B_{open\text{-}high}$.

Section 2.2 indicated that the coal preparation plants in South Africa are reportedly using half a tonne of water per tonne of coal washed. However, the LCIA normalised results show that water use, due to a fair amount of water recycling, is lower compared to that of the human toxicity potential and acidification potential categories. The high RII for the water resource group is mainly attributable to the high-normalised value for the human toxicity potential category, which is aggravated by the high sulphate content of the released water, as well as the dust emissions, which can increase the quantity of dispersed solids in the surface waters in close vicinity to the mining operations. Water must therefore be given priority in terms of strategies for environmental management, although the concerns are, to some extent, less for the higher-grade coal in comparison with the low-grade coal (see Section 5.1).

Similar to the water resources categories, the burdens associated with the higher-grade coal product are somewhat lower for the mined abiotic, land and air resource groups.

5.3. Mine $C_{under\text{-}high}$ case study

Table 5 summarises the LCI data for high-grade coal products from underground mining operations. The LCIA results for these products are given in Table 6, and the overall RIIs for the natural resource groups are illustrated in Fig. 7.

Table 5.

Life Cycle Inventory (LCI) data for Mine $C_{under\text{-}high}$

Aspects	Inventory constituent	Value	Converted unit	Value
Production	Annual RoM coal produced (t)	7946260	tonne	7.95×10^6
	Saleable coal produced (t)	5961548		5.96×10^6
Land resources	Land under company charge (ha)	6589	m^2	6.59×10^7
	Land altered for mineral extraction activities (ha)	1233		1.23×10^7
	Land rehabilitated to agricultural use (ha)	170		1.70×10^6
Water resources	Water used for primary activities (1000 m^3)	818	tonne	8.18×10^5
	Potable water from an external source (1000 m m^3)	1961		1.96×10^6
	Non-potable water from an external source (1000 m^3)	0		0.00
	Surface water used (1000 m^3)	140		1.40×10^5
	Ground water used (1000 m^3)	1135		1.14×10^6
	Water recycled in processes (1000 m^3)	803		8.03×10^5
	Total water consumption (1000 m^3)	4055		4.06×10^6
	Total water used (1000 m^3)	4858		4.86×10^6
	pH of effluents	6.97		–
	Sulphates in effluents (mg/l)	1140		5.54×10^6

Aspects	Inventory constituent	Value	Converted unit	Value
Air resources	Total CO_2 equivalent emissions (t CO_2 eq.)	149734	tonne	1.50×10^5
	Dust fallout ($mg/m^2/day$) – Internal	266		6.39×10^3
Mined abiotic resources	Total energy used (GJ)	643256	tonne	2.19×10^5

Table 6.

Life Cycle Impact Assessment (LCIA) results for Mine $C_{under\text{-}high}$

Resource group	Midpoint category[a]	Unit	Characterisation value	Normalisation value[b]
Land resources	Acidification potential	kg H_2SO_4 equivalence	1.60×10^3	2.15×10^{-3}
	Human toxicity potential	kg Pb equivalence	5.54×10^6	1.49×10^2
	Terrestrial toxicity potential	kg Pb equivalence	0.00	0.00
	Land use (occupied)	m^2 a natural degraded equivalence	6.59×10^7	8.20×10^3
	Land use (transformed)	m^2 natural degraded equivalence	2.33×10^7	6.43×10^3
Water resources	Water use	kg available reserves equivalence	4.06×10^6	1.28×10^2
	Eutrophication potential	kg PO_4^{3-} equivalent	0.00	0.00
	Acidification	kg H_2SO_4	4.27×10^5	8.51×10^4

Resource group	**Midpoint category**[a]	**Unit**	**Characterisation value**	**Normalisation value**[b]
	potential	equivalence		
	Human toxicity potential	kg Pb equivalence	5.54×10^{6}	1.49×10^{2}
	Aquatic toxicity potential	kg Pb equivalence	0.00	0.00
Air resources	Acidification potential	kg SO_2 equivalence	0.00	0.00
	Ozone creation potential	kg O_3 formed	0.00	0.00
	Ozone depletion potential	kg CFC-11 equivalence	0.00	0.00
	Global warming potential	kg CO_2 equivalence	1.50×10^{5}	1.07×10^{-7}
	Human toxicity potential	kg Pb equivalence	4.27×10^{5}	5.99×10^{1}
Mined abiotic resources	Mineral reserves depletion	kg platinum equivalence	0.00	0.00
	Energy reserves depletion	kg coal (RSA) equivalence	7.99×10^{9}	2.88×10^{5}

[a] Midpoint categories as defined by the South African LCIA procedure [4], [5] and [22].
[b] Normalisation is based on distance-to-target ambient values for SALCA Region 3, except for mined abiotic resource categories, where South African values are used.

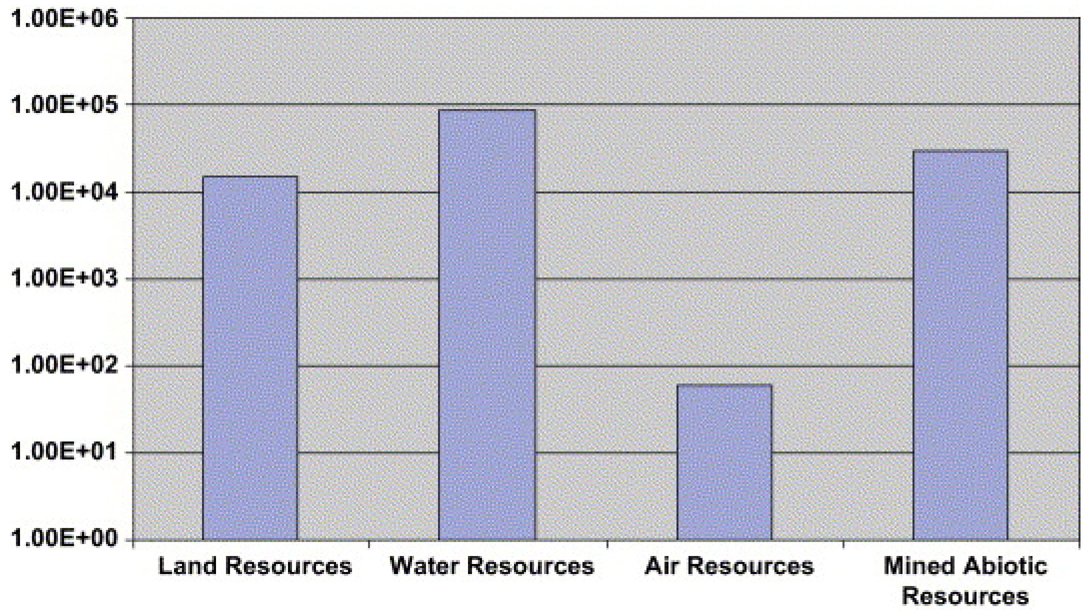

Fig. 7. Resource Impact Indicator (RII) results for Mine $C_{under\text{-}high}$.

Compared to the two coal products produced from opencast mining operations, the RII for the water resource group is lower for the Mine $C_{under\text{-}high}$ case study. This is also true for the other natural resource groups. The LCI constituents that contribute to the different LCIA categories are similar between this and the discussed case studies in Sections Sections 5.1 and 5.2.

5.4. Mine $D_{under\text{-}low}$ case study

The LCI profile for a low-grade coal product produced and supplied from an underground operation is given in Table 7. The impact results are summarised in Table 8 and Fig. 8.

Table 7.

Life Cycle Inventory (LCI) data for Mine $D_{under\text{-}low}$

Aspects	**Inventory constituent**	**Value**	**Converted unit**	**Value**
Production	Annual RoM coal produced (t)	4317446	tonne	4.32×10^5
	Saleable coal produced (t)	4317446		4.32×10^5
Land resources	Land under company charge (ha)	27262	m^2	2.73×10^8

Aspects	**Inventory constituent**	**Value**	**Converted unit**	**Value**
	Land altered for mineral extraction activities (ha)	3426		3.43×10^7
	Land rehabilitated to agricultural use (ha)	0		0.00
Water resources	Water used for primary activities (1000 m^3)	334	tonne	3.34×10^5
	Potable water from an external source (1000 m m^3)	932		9.32×10^5
	Non-potable water from an external source (1000 m^3)	0		0.00
	Surface water used (1000 m^3)	0		0.00
	Ground water used (1000 m^3)	607		6.07×10^5
	Water recycled in processes (1000 m^3)	0		0.00
	Total water consumption (1000 m^3)	1874		1.87×10^6
	Total water used (1000 m^3)	1874		1.87×10^6
	pH of effluents	8.3		–
	Sulphates in effluents (mg/l)	1630		3.06×10^6
Air resources	Total CO_2 equivalent emissions (t CO_2 eq.)	139120	tonne	1.39×10^5
	Dust fallout (mg/m^2/day) - Internal	0[a]		0[a]
Mined abiotic resources	Total energy used (GJ)	365528	tonne	1.25×10^4

[a] Fully underground operation and all associated infrastructure is concreted or under dust suppression.

Table 8.

Life Cycle Impact Assessment (LCIA) results for Mine $D_{under-low}$

Resource group	**Midpoint category**[a]	**Unit**	**Characterisation value**	**Normalisation value**[b]
Land resources	Acidification potential	kg H_2SO_4 equivalence	0.00	0.00
	Human toxicity potential	kg Pb equivalence	3.06×10^6	8.23×10^1
	Terrestrial toxicity potential	kg Pb equivalence	0.00	0.00
	Land use (occupied)	m^2 a natural degraded equivalence	2.73×10^8	3.39×10^4
	Land use (transformed)	m^2 natural degraded equivalence	6.00×10^7	1.66×10^4
Water resources	Water use	kg available reserves equivalence	1.87×10^6	5.93×10^1
	Eutrophication potential	kg PO_4^{3-} equivalent	0.00	0.00
	Acidification potential	kg H_2SO_4 equivalence	3.06×10^6	8.23×10^1
	Human toxicity potential	kg Pb equivalence	0.00	0.00
	Aquatic toxicity potential	kg Pb equivalence	0.00	0.00
Air resources	Acidification potential	kg SO_2 equivalence	0.00	0.00
	Ozone creation potential	kg O_3 formed	0.00	0.00

Resource group	**Midpoint category**[a]	**Unit**	**Characterisation value**	**Normalisation value**[b]
	Ozone depletion potential	kg CFC-11 equivalence	0.00	0.00
	Global warming potential	kg CO_2 equivalence	1.39×10^5	9.96×10^{-8}
	Human toxicity potential	kg Pb equivalence	0.00	0.00
Mined abiotic resources	Mineral reserves depletion	kg platinum equivalence	0.00	0.00
	Energy reserves depletion	kg coal (RSA) equivalence	4.34×10^9	1.56×10^4

[a] Midpoint categories as defined by the South African LCIA procedure [4], [5] and [22].
[b] Normalisation is based on distance-to-target ambient values for SALCA Region 3, except for mined abiotic resource categories, where South African values are used.

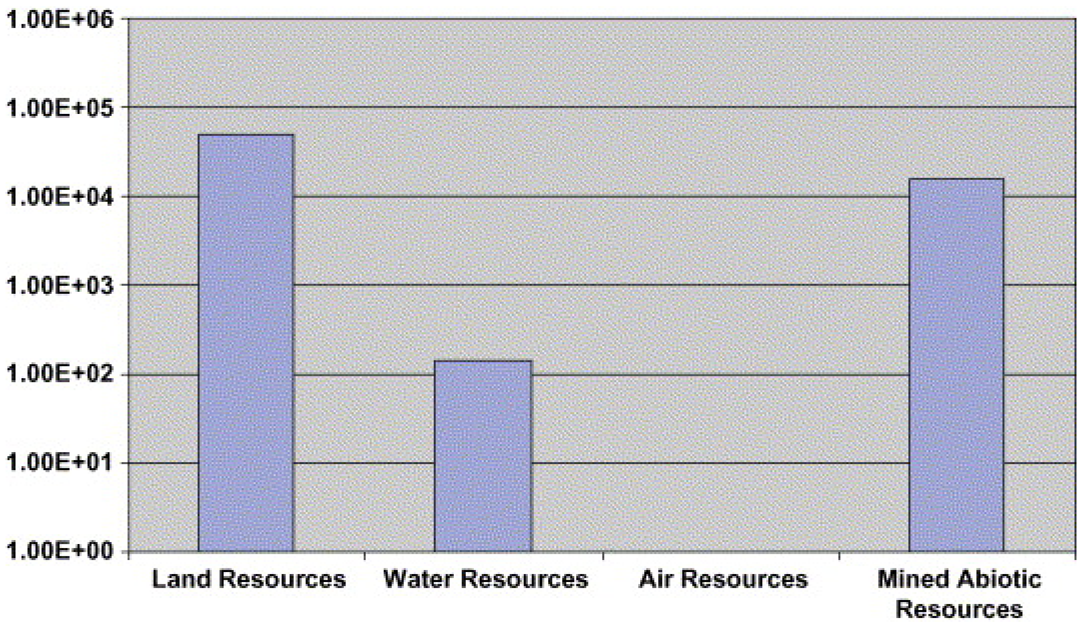

Fig. 8. Resource Impact Indicator (RII) results for Mine $D_{under\text{-}low}$.

The environmental profile of the low-grade coal product that is supplied from the underground mining operation is dissimilar from the previously-discussed case studies. Due to better environmental practices, water use, and especially the release of contaminants to water resources, as well as air emissions (due to very efficient dust management), are much reduced. For this case study, land use is the most important LCI constituent, followed by the extraction of the coal resource. The unavailability of data on rehabilitation at the mine may be the reason for the relatively high RII of the land resource group. Therefore, attention must be given to the land resource group in order to improve its environmental performance even more.

5.5. Comparison of the overall environmental performances of the case studies

Subjective weighting values for the four natural resource groups have been introduced from the perspective of the South African process industry [22]. These are:

• Water resources – 0.475

• Air resources – 0.120

• Land resources – 0.200

• Mined abiotic resources – 0.205

An overall Environmental Performance Resource Impact Indicator (EPRII) can be calculated (through summation) for each coal product by multiplying the life cycle RIIs for the different coal products [22] by the aforementioned weighting values. Fig. 9 compares the EPRIIs per tonne of product supplied for the four case studies. The result suggests that opencast mining operations, in general, have a higher environmental burden in the South African context, compared to underground mining operations per tonne of product supplied. For these case studies, the environmental performance results imply that low-grade coal products have a higher environmental burden than high-grade coal products for opencast mining scenarios, which is the reverse for underground mining scenarios. However, this is most probably due to the more advanced environmental management practices of the mining operations for the Mine $D_{under\text{-}low}$ case study. It is expected that low-grade coal products would have an inferior environmental performance (in the developing country context) with typical mining practices.

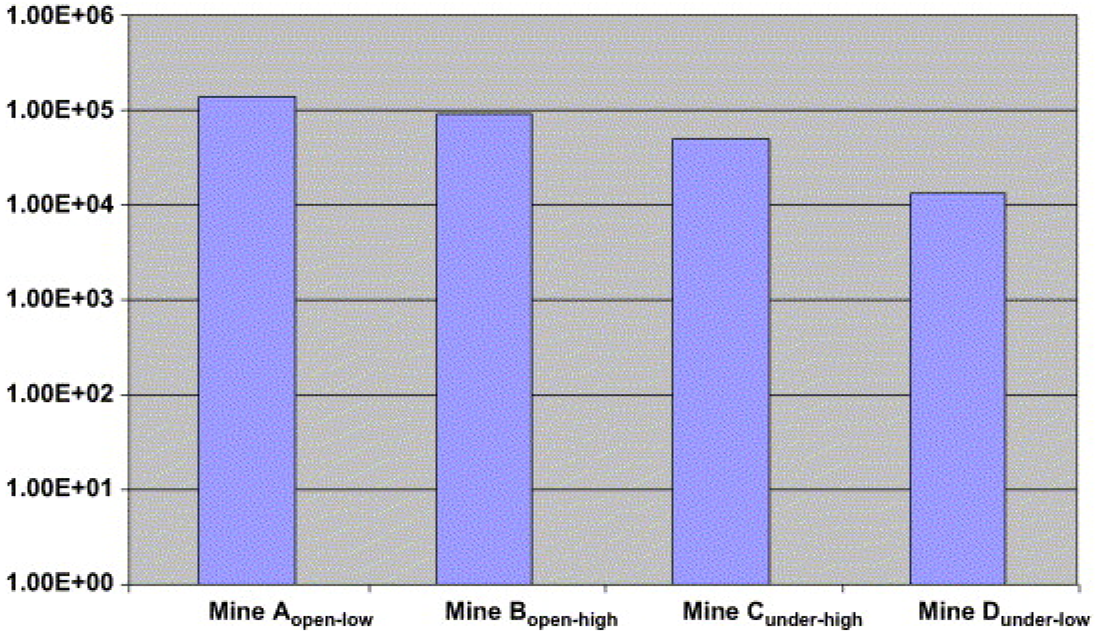

Fig. 9. Total Environmental Performance Resource Impact Indicators (EPRIIs) for the coal products.

Fig. 10 highlights that, per economic value of supplied product (or per US$), high-grade coal products have an improved environmental performance or profile if compared to low-grade coal products regardless of mining method (if similar mining practices are followed). The better practices associated with producing the higher-grade coal therefore appears to offset the additional unit processes that are required in the life cycle, i.e. beneficiation and longer distance transportation.

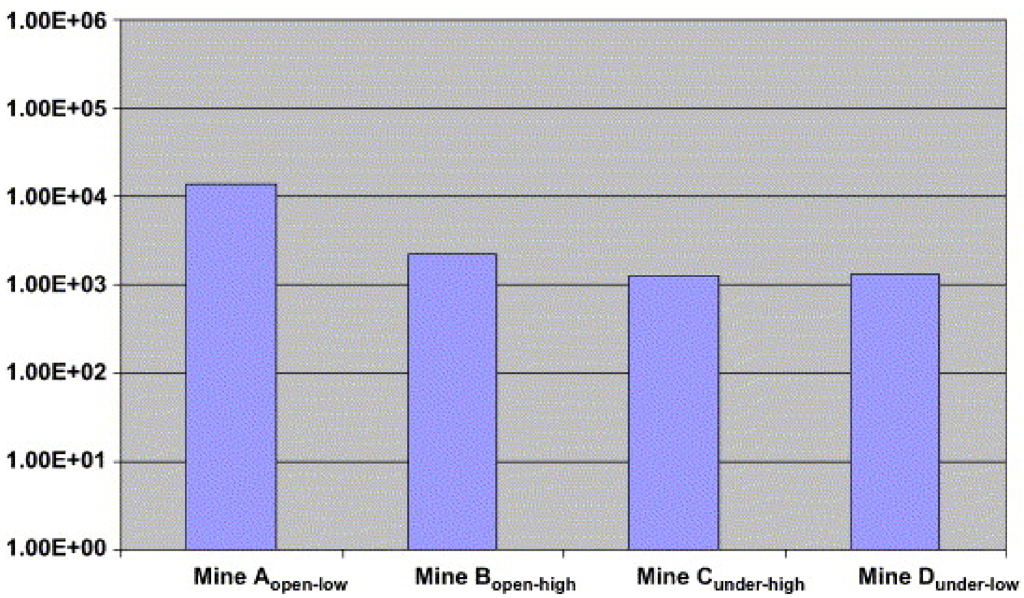

Fig. 10. Total EPRIIs for the coal products per economic value (US$).

6. Conclusions

The following conclusions are reached with respect to the four coal product life cycle scenarios, and in terms of the data provided by the specific collieries:

• In general, the impacts on water resources are the most significant from a coal mining perspective in the South African context. However, water use is not the most important factor, but rather the impact on the human toxicity potential category from sulphate releases. Impacts on air resources are of lesser importance, although dust emissions are always significant in these types of operations. However, responsible environmental management practices can improve environmental performances with respect to these impacts.

• The RII for the mined abiotic resource group is highly influenced by the amount of the RoM coal produced. However, for the mining industry, the high RII for mined abiotic is an advantage as it indicates high productivity. Production can therefore not be compromised for the reduction of the RII for the mined abiotic resource group. An efficient use of energy, which also influences the RII for the mined abiotic resource group, can reduce its value – albeit to a lesser extent. It is therefore recommended that the RoM tonnage be excluded from the calculations when evaluating the environmental performance of coal mining using the RII method.

• Except for proper rehabilitation, coal mining operations cannot address the high RII for the land resource group to a large extent, because of the inherent nature of the industry. Moreover, the occupation of a large piece of land is attributed to the geology of the coal and hence the mineral rights. Thus, with regard to the land resource group in the four mines investigated, the information generated by the RII method may be of an insignificant value to the mining industry.

With respect to the latter, the RII method can be a useful tool to evaluate the environmental performances of mining operations, and the information generated can be used together with other data for decision-making (e.g. mining, economic, geotechnical, etc). However, for the method to be even more suitable for such applications in the mining industry, it is recommended that noise, which is a major environmental hazard at sites, be included in the framework.

Furthermore, the RII method should not be a substitute for other, more detailed environmental assessments such as the Environmental Impact Assessment (EIA) tool, but serve as a complement to these where (less costly) environmental performance information is required. Most importantly, the involvement of the stakeholders, including community participation, is excluded when applying a LCIA procedure such as the RII method.

The decision as to whether to employ either opencast or underground mining is dependent on many factors such as the geology of the ore and cost of production.

However, apart from the higher price associated with beneficiated coal products, improved environmental performance may also be expected.

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