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A life-cycle-based review of sulfur dioxide abatement installations in the South African platinum group metal sector

V. Munyongani[1] · **H. von Blottnitz**[1] · **J. L. Broadhurst**[1]

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Abstract In the late 2000s, several South African platinum producers retrofitted sulfur dioxide abatement technologies to smelters in the Rustenburg area. While such end-of-pipe technologies can reduce local environmental impacts, they may also increase impacts associated material and energy use. Two methodologies were fused to study how these retrofits have shifted environmental burdens, and whether such knowledge would have been useful to design decision-makers. A life cycle assessment was carried out to determine the environmental impacts associated with the key design choices of these smelter and furnace flue gas SO_2 abatement technologies, viz. technology choice and the fractional recovery of SO_2. The two technology options used by industries and investigated were i) concentrated dual-alkali srubbing and ii) a srubber feeding an acid plant. The results show that the concentrated dual-alkali process has, overall, higher environmental impacts than the scrubber with acid plant. Notably, for the former, all environmental impacts (except acidification) increase with increasing SO_2 recovery, whereas for the latter some impacts reduce with increasing recovery due to the by-product sulfuric acid that replaces acid otherwise produced. Subsequently, the results of the LCA were combined with insights from expert interviews to explore design decision-making in the minerals industry, and whether incorporating LCA in formal environmental assessment processes would be of any value to the minerals industry. Expert interviews revealed that incorporating LCA could enable the quantification of impacts for the different technology options, and help justify the chosen options. We argue that normalised results would enable more meaningful interpretation of LCA to further assist such decision-making processes.

Keywords Decision making · Life cycle assessment · Environmental impacts · Desulfurisation

Introduction

Mining has been a major driving force in the history of African colonisation. For example it has been a force of racialised repression and unequal development in the economy of South Africa, which hosts one of the world's leading mining and mineral processing industries (Giliomee and Mbenga 2007). Since the run-up to the 2002 World Summit for Sustainable Development in Johannesburg, the global and also the African mining industry have, however, sought to appreciate better their contribution to sustainable development (IIED 2001), which has also spawned significant research endeavours (Moran et al. 2014).

Mining activities are associated with significant environmental impacts. These range from atmospheric and aquatic emissions, to impacts associated with resource consumption and local environmental disruptions due to the extraction of resources (Rebitzer et al. 2004). The primary production of metals (i.e. the processing and production stages) require large amounts of energy and

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✉ V. Munyongani
mnyver002@myuct.ac.za

[1] Minerals to Metals Initiative, Department of Chemical Engineering, University of Cape Town, Rondebosch, South Africa

chemicals, and produce large amounts of (sometimes toxic) waste that is potentially harmful to the environment and society (van Berkel 2007).

South Africa is endowed with extraordinary mineral wealth. Amongst many other significant mineral commodities, it is the largest producer of platinum and platinum group metals (PGM), holding 95% of estimated global reserves and providing more than 80, 70 and 35% of the world's supply of rhodium, platinum and palladium respectively (Chamber of Mines 2017). Platinum plays a key role in environmentally-related technologies through its catalytic properties, with a strong expected growth in fuel-cell applications to help meet the environmental and technological challenges of the 21st Century (IPA 2014). The platinum industry is actively seeking to progress its commitment to sustainability principles by reducing the negative environmental impacts of mining and mineral processing (IPA 2014; Glaister and Mudd 2010). Technical innovation to improve future concentrator and smelter plant designs, as well as the development of management policies, guidelines and protocols for the efficient operation of processing plants has therefore become a strategic priority for the South African platinum industry (Anglo American 2015).

A key intervention for the drastic improvements of industrial processes lies in process design, an activity historically focused on product quality and production rate, at the lowest cost and meeting all applicable regulations (Cano-Ruiz and McRae 1998). Advanced environmental regulations and corporate sustainability strategies require new approaches to process design, if they are to result in the reduction of energy consumption and the minimisation of waste and pollution (Basson and Petrie 2001; Guma et al. 2009; Corder et al. 2010).

The Environmental Impact Assessment (EIA) is a frontline assessment done when a new production site is planned, or an existing one modified. EIA ensures the identification, forecasting, interpretation and measurement of the environmental consequences of projects to be carried out (Morero et al. 2015). According to the International Association of Impact Assessment (IAIA 2016) the main purpose of conducting an EIA is to ensure that the decision-making process concerning activities that may have a significant influence on the environment takes into account the environmental aspects related to the decision. The EIA also helps to establish the terms and conditions for project implementation. This then ensures that diversity of species is maintained and there is no harm done to the quality of life. EIAs are widely used in the mining industry and in many jurisdictions, also in Africa, a mining may not commence without an environmental authorisation (AMLA 2017).

EIA is often regarded as a synonym for local, point source-oriented evaluation of the environmental impacts, which takes into account time-related aspects and the existing background pressures on the environment (Tukker 2000). The key element of an EIA is to provide a comparison of the proposed activity to the most environmentally-friendly option and a 'business as usual case'. Therefore, this means that an EIA is not just a tool but is also intended to provide a framework for organising the decision-making process (Tukker 2000). The site-specific focus of EIA processes has, however, for some time been recognised to be a limitation to understanding remote impacts caused by the production of materials (or utilities needed by a process), or by the use and ultimate disposal of the products themselves (e.g. Manuilova et al. 2009).

Increasingly, designers of metal-based products (e.g. in the automotive sector) aim to make design decisions, which will result in the reduction of environmental impacts occurring across all stages of the product's life cycle. Life cycle assessment (LCA) was developed as a tool to identify and quantify such impacts and, thus, provide a basis for environmental system optimisation (Hellweg and Milà-i-Canals 2014). In a sense, both LCA and EIA have the same basic purpose of supporting environmental decision-making (Manuilova et al. 2009). Tukker (2000) points out that the major difference between LCAs and EIAs is that LCAs provide a time- and location-independent assessment of the potential impacts in relation to an entire production system. It has long been suggested that if the two assessments were to be merged the differences between the two can be used to complement one another, providing a much stronger assessment tool (Tukker 2000). Studies have shown that when EIAs and LCAs are merged, then LCAs can indeed complement and add value to EIA processes (Manuilova et al. 2009). This would mean that while the EIA process would be specific to a particular project, the LCA would then comprehensively compare available alternatives and take into account all the important aspects that are usually not present when only studying one project (Morero et al. 2015). When LCA is used to assist decision-making, it provides highly detailed and well defined data that can be directly mapped onto the decision cycle (Stewart 2001) (see Figure S1 in the Supplementary Electronic Material).

LCA has been widely applied in the minerals processing industry since the mid-to-late 1990s with the majority of the initial work having been focused on the development of Life Cycle Inventories for metal production processes (Durucan et al. 2006). This then developed into actually carrying out LCAs for the study of consumer products through design and beyond the production process (Dubreuil 2005). The LCA perspective can bring powerful insights into addressing sustainable mineral resource development by evaluating the environmental impacts that all stages of the life cycle of the process have and aims to minimise them while increasing the economic output

(UNEP 2009). A limitation of using LCA in isolation is that it is mainly focused on environmental damage (Hellweg and Milà-i-Canals 2014), and does not balance this with any of the positive aspects of development, both social and economic. In that sense, LCA needs to be complemented with other tools so that other significant concerns of developing countries, such as employment rates and poverty eradication, are duly considered.

There has been a growing demand for mining companies to utilize sustainability frameworks that equally address environmental, economic and social benefits and damages (Lodhia and Hess 2014). LCA-based approaches such as Social Life Cycle Assessments (S-LCA) and Life Cycle Sustainability Analysis (LCSA) hold promise towards this end, with UNEP's guide on LCSA already including the case of Coltan mining in the Democratic Republic of the Congo (UNEP 2009). Up to now LCA studies have been performed for various mining processes such as copper production, the iron and steel industry, and other basic metals (Durucan et al. 2006). LCAs have also been performed for the platinum industry, with results obtained from this study used to inform clients (e.g. companies that manufacture hydrogen fuel cells and/or catalytic convertors) on how the actual extraction process is performed (IPA 2014).

As already mentioned South Africa is a key player in the PGM industry. Currently the maximum allowable sulfur dioxide (SO_2) emissions from smelters is regulated through the Air Quality Act of 2004. All mining companies in the Rustenburg area (a mining town located in the North West Province) had to develop and deploy SO_2 abatement technologies to comply with the legal limits. In particular, between 2002 and 2008, three PGM-producing companies in this area selected, designed and commissioned new SO_2 scrubbing processes. These companies had a choice between various wet scrubbing technologies and chose either the concentrated dual-alkali process or the scrubbing plant with acid production process, which both result in very high SO_2 removal efficiencies.

Literature suggests that some companies opted for the concentrated dual-alkali process due to the characteristics of the off-gas that had to be treated, the composition of which varied between 0.5 and 6% SO_2 by volume (Bezuidenhout et al. 2012a, b; Eksteen et al. 2011; Jones 2005). Pure lime-based processes were deemed inadequate for off-gas with higher SO_2 concentration, whereas acid plant processes were deemed unfit for off-gas with lower SO_2 concentrations (Eksteen et al. 2011). Therefore, the concentrated dual-alkali scrubber was the technology of choice for some companies as it could handle both off-gas with high SO_2 concentrations and the swings in the off-gas SO_2 concentrations. Bezuidenhout et al. (2012a, b) pointed out that the dual-alkali technology could overcome the disadvantages that are inherent to lime and limestone scrubbing such as scaling and low reactivity, and also had very low energy requirements. However, currently the $CaSO_x$ product is not of saleable quality and hence it is disposed of as waste, while there is no large market for gypsum. Therefore, if $CaSO_x$ were to be produced as a by-product of SO_2 mitigation processes, it would not be of much value to companies.

Other companies decided to adopt acid production processes for SO_2 mitigation (Davenport et al. 2006; Hundermark et al. 2011; Sichone 2009). One of the companies motivated this choice by considering capital expenditure (CAPEX), operating expenses (OPEX) and "operability and ease of expansion" (Kruger 2004). Therefore, this means that apart from merely treating the off-gas, the company is able to make a saleable product. Daum (2009) suggests that the production of sulfuric acid is the most viable option of sulfur recovery from smelter off-gas.

Whilst the adoption of clean-up process retrofit installations described above undoubtedly helped to reduce local environmental impacts, it also requires additional material and energy consumption and in some cases generates waste. Thus, in an effort to improve the local environment, burdens may thus have been shifted unintentionally. LCA is an appropriate tool to study such effects given its ability to identify burden-shifting, as described above. The objective of this study is to present to the sustainability science community how the environmental analysis tool LCA could have provided additional value to project design decision-makers in the mining sector.

Methodology

This study adopts a two-step methodology to determine "how" and "how strongly" the installation of SO_2 abatement technologies in the Rustenburg area induced burden-shifting, and whether knowledge of such effects would have been of use to stakeholders that had to make technology and design choices. First, the impacts of the different technology options were quantitatively studied using an LCA. This involved technical process modelling on ASPEN Plus to generate foreground system mass and energy data, followed by LCA modelling on SimaPro (v7.2) using ecoinvent (v2) background datasets. Subsequently, design and environmental management experts with involvement in the platinum industry and the retrofit projects were interviewed, to understand their approach to environmental considerations and, upon being confronted with the LCA findings to identify whether LCA could have provided useful additional information to the design team.

Life cycle assessment of SO_2 abatement options

Goal definition and scope

The goal of the LCA reported in this paper is to identify how key design decisions induced environmental burden shifting when platinum smelters in the Rustenburg area added SO_2 abatement technologies to their processes. Furthermore, it identifies whether these burdens could have been reduced had the LCA perspective been taken into account.

The two major technologies adopted by platinum mining companies, as way of reducing SO_2 emissions compared in this LCA are (a) sulfur fixation using a dual-alkali scrubber, and (b) the combination of a scrubber with an acid generation plant. The two main variables for the analysis are (a) technology choice, and (b) the specified sulfur removal efficiencies. The three removal efficiencies analysed in this LCA are 92, 96 and 99%, all of which have been determined to achieve the regulatory limits of the operations (Fig. 1). Between them they represent six different scenarios studied quantitatively by LCA in this paper.

A key difference between the two technologies is that one produces sulfuric acid as a useful by-product, whereas the other merely transforms the bulk of the harmful sulfur emissions into a solid waste for contained disposal. When a second product is made, the LCA has to consider how the environmental burdens are to be allocated between the different products. LCA applications to metallurgical operations have been confronted with the sulfuric acid question for some time (Dubreuil 2005). The ISO 14044 standard for LCA recommends avoiding the allocation problem by system expansion, when possible. When the different recoveries for the scrubber with acid plant option were investigated, a systems expansion was thus applied to keep the comparison valid for options in which different quantities of the useful by-product arise. This was carried out by adding the conventional production of some sulfuric acid (ecoinvent v2 dataset Sulfuric Acid production), specifically the difference in acid produced by the 92% or the 96% option to that of the 99% recovery. By so doing, all the three processes then produce the same amount of sulfuric acid. The dual-alkali options were initially analysed as is (i.e. uni-functional), with systems expansion only incorporated once the comparison between the two technologies was being done.

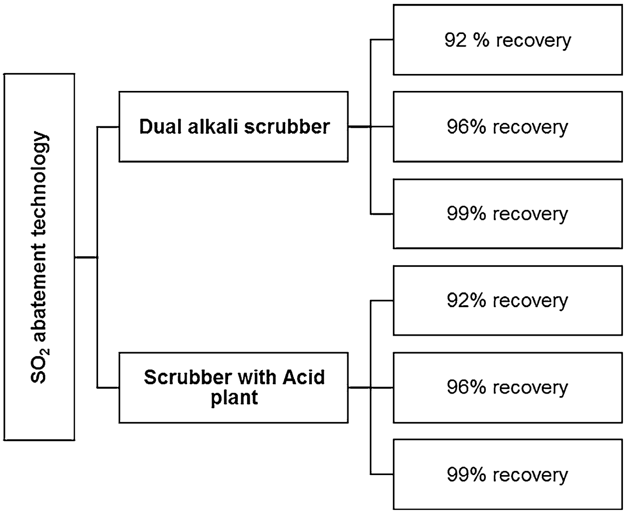

Fig. 1 Schematic of the SO_2 abatement technologies and sulfur removal efficiencies analysed

Functional unit and reference flow Since the LCA aims to compare the environmental burdens of different sulfur removal technologies and configurations that could have been chosen to enable continued operation of platinum smelters, the functional unit specified for this study is the legally compliant treatment of off-gas produced by a smelter in one year. Thus the basis for comparison was set as the smelting of 1.08 Mt of PGM concentrate.

The reference flow for the system analysis is the annual quantity of SO_2 present in the smelter off-gas, presented as an SO_2 concentration relative to an off-gas flow rate, and determined to be 90,000 t. No more than 23 t/day of this is allowed to be emitted.

Definition of the object of analysis and system boundaries While in most LCAs the objects of analysis are products, in this paper they are process options as described in the previous section (see Figures S2, S3 in the Supplementary Electronic Material). Figures 2 and 3 show the system boundary for the LCAs, with all inputs and outputs being "elementary" flows (e.g. residual SO_2 released to air from the foreground process, SO_2/CO_2 released to air from the electricity generation process). Figures 2 and 3 also show how the system expansion was made on the first option so that it would include the sulfuric acid production process, so that comparison with the second process would be possible. Therefore, this ensures that both case studies have sulfuric acid as the main product.

Data sources and modelling The mass and energy balance data were obtained by modelling the six different scenarios (see Fig. 1) using Aspen Plus software. The data used for the Aspen simulation were mainly based on secondary data collected from the literature (Bezuidenhout et al. 2012a, b; Sichone 2009; Westcott et al. 2007), supplemented by process data obtained from company publications and interviews done with experts from companies running similar processes (see next section). The completed mass and energy balances (Tables S1, S2,

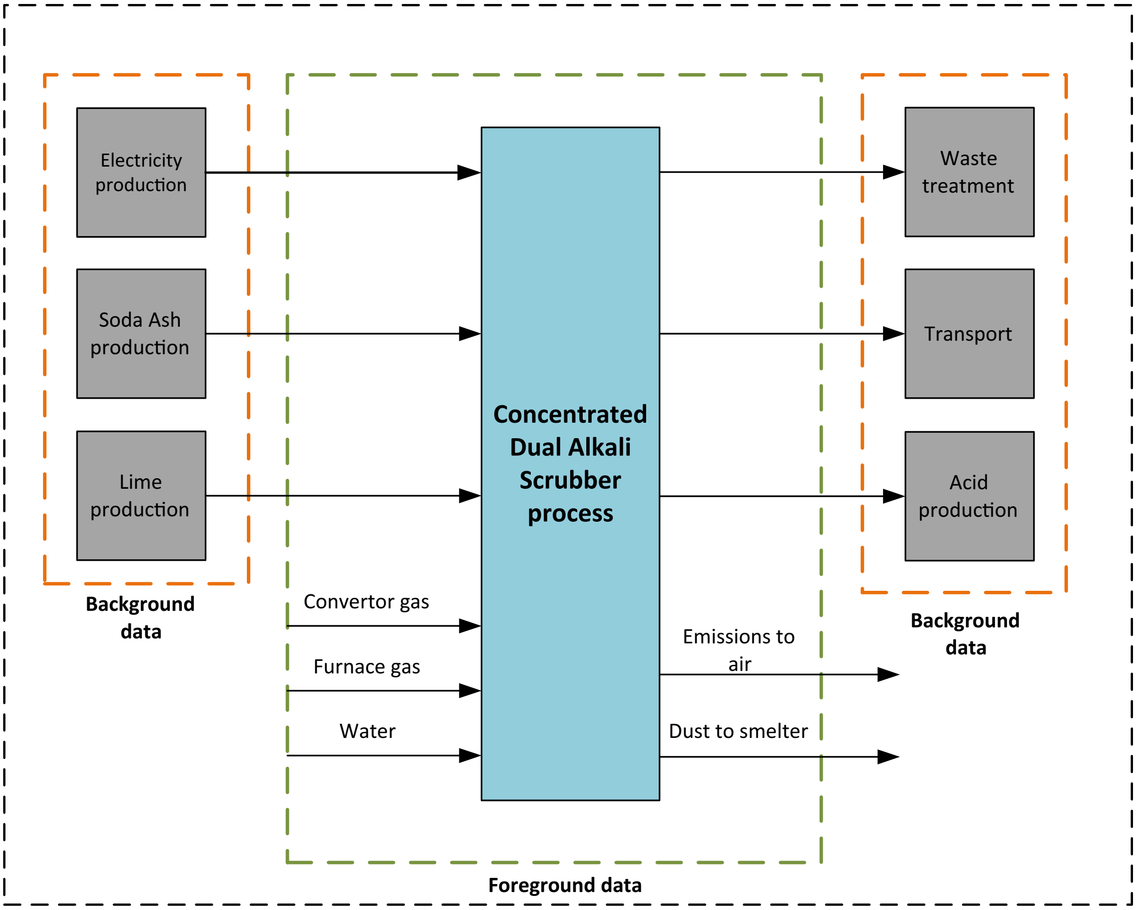

Fig. 2 LCA system boundary for concentrated dual-alkali process

Supplementary Electronic Material) were then used to construct life cycle models using SimaPro v7.2 software. Suitable processes were selected from the ecoinvent v2 database to represent the background datasets (Tables S3, S4, Supplementary Electronic Material). Electricity generation was represented by the SA fuel mix available in ecoinvent.

The differences in potential environmental impacts based on the two key variables were then quantified and analysed by means of life cycle impact assessment (LCIA). In keeping with general practice in comparing different process options by LCA (e.g. Fernandez-Torres et al. 2012; Broadhurst et al. 2015), in this study we consider mid-point rather than end-point indicators of potential environmental impacts. Six impacts are identified as being of particular relevance to the potential burden-shifting induced by the SO_2 scrubbing process (Table 1), including:

- Human toxicity: The scrubbers remove SO_2 and particulate matter. Their main function is to protect human health around the plant. However, scrubbers use electric power, which may transfer human health impacts to people living around power stations.
- Climate change: Though the SO_2 abatement technologies reduce the amount of sulfur dioxide that is released into the atmosphere, they also tend to be energy intensive. In the South African context where most electricity supply is coal-based, this may lead to significant greenhouse gases (GHG) emissions from coal-burning, which is a major cause of anthropogenic climate change.
- Depletion of abiotic resources: The scrubbing process in the acid plant generates sulfuric acid as a by-product. This means that the sulfuric acid produced can be used in other processes that require it as an input, thereby eliminating the acid production process. This means that this reduces the need for such companies to produce sulfuric acid from mined resources. The dual-alkali process, on the other hand, relies on the mining of alkali material to be added to the scrubber, thus increasing resource depletion.
- Water use: Both types of SO_2 scrubbers considered in this study use water for cooling the gas stream. In view of the high importance of freshwater availability in South Africa, water use is an important indicator.

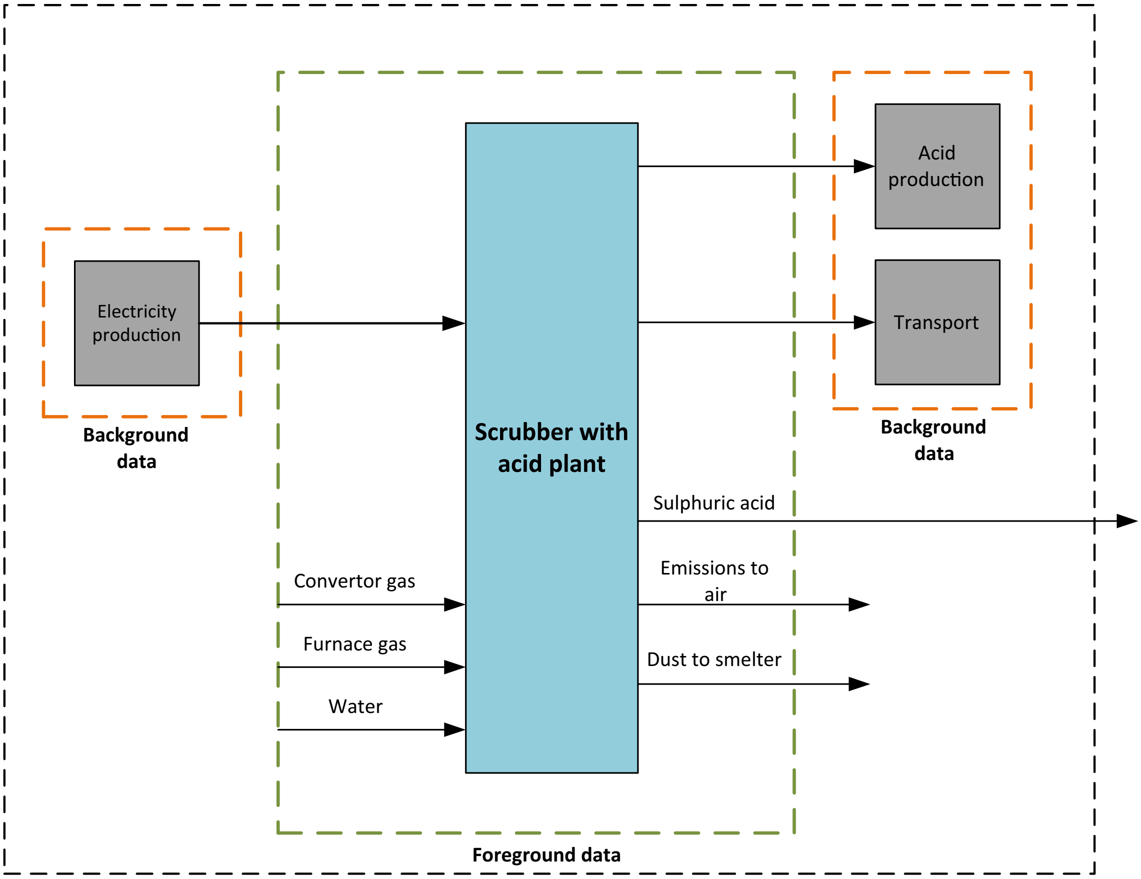

Fig. 3 LCA system boundary for scrubber with acid plant

Table 1 Life cycle impact assessment categories used in the study

Impact category	Scale	Method	Units
Abiotic resource depletion	Global	CML	kg Sb eq
Acidification	Regional	Recipe	kg SO_2 eq
Fossil fuel depletion	Global	Recipe	kg oil eq
Global warming	Global	CML	kg CO_2 eq
Human toxicity	Regional	Usetox	CTUh/kg
Water depletion	Local	Recipe	m^3

- Acidification: SO_2 scrubbing processes can reduce or shift the deposition of acidifying pollutants on soil, ground/surface water, and ecosystems (mainly due to acid rain). Since the major acidifying pollutants are SO_2 and NO_x, it is important to evaluate by how much the acidification potential of the process is reduced through the use of scrubbers, and to what extent burdens may be shifted to coal-fired power plants which also emit the same acidifying pollutants.
- Fossil fuel depletion: The two SO_2 abatement technologies are energy intensive. In the South African context, the electricity that is used is coal-based, hence it is important to investigate the depletion of fossil fuels due to the increasing energy demand for the operation of the scrubbers.

Expert interviews and analysis

After the completion of the LCA process, we conducted a set of in-depth expert interviews to determine whether LCA could help inform process design decision-making in the minerals industry. Seven in-depth interviews were conducted to obtain as much detailed insights as possible from experts who participated in the decision-making process when most of the SO_2 abatements projects were implemented. The interviewees were mainly expert design engineers from each of the three platinum producers operating a smelter, and contracted expert consultants (Table 2).

The expert interviews were semi-structured, were conducted in person and lasted for approximately 1 h each. Informed consent was obtained for recording the interviews, while interviewees were notified about the anonymity and confidentiality of the information gathered through the interview. The first part of the interview

Table 2 Overview of people interviewed

Participant(s)	Type of company	Position
ME-SC	Minerals processing and metallurgical engineering company	Specialist consultant
PC1-VP and PC1-LM	Platinum company 1	Vice president of the company and lead metallurgist
CF-C	Consulting firm	Consultant
PC2-PL1 and PC2-PL2	Platinum company 2	Process leads at a platinum mining company
PC3-TS	Platinum company 3	Technical superintendent
ECC-GC	Engineering consulting company	Consultant for gas cleaning processes
PC4-TS	Platinum company 4	Lead technical services

focused mainly on decision-making in the minerals industry, with the researcher asking for clarifications where needed, but refraining from guiding the interviewee on how to answer the question. Subsequently, the results of the LCA were presented to each expert, who was thereafter asked to comment on whether they believed that incorporating LCA into the specific process design they were involved in (and more generally into minerals processing design decision-making), would be useful.

On two occasions, interviews were followed up with site visits in plants that ran similar processes to the ones analysed through LCA. This allowed for the better understanding of how the processes work and linking theoretical information to the practical. The site visits also gave an opportunity to clarify some of the assumptions that were made in the Aspen simulation and determine the precision of the conceptual models.

Finally, the interviews were analysed through a thematic analysis approach (see Braun and Clarke 2006). The recorded interviews were transcribed in order to conduct the thematic analysis and identify common patterns and recurring themes among the design experts.

Results

The scrubber with acid production requires more energy than the dual-alkali process. For both processes, energy consumption increases exponentially as the removal of SO_2 increases from 92 to 96% and 99%[1]. For the dual-alkali process, in five of the six impact categories studied, the environmentally ideal operation point would be a recovery that just meets the legal limits, which in this case would be 92% (see footnote 1). In this scenario, acidification is the only impact category that would reduce with increasing SO_2 removal. In cases where a useful by-product is produced (i.e. H_2SO_4), the lowest life cycle impacts would occur for most impact categories for the 99% recovery option. Figure 4 shows a comparison of the best performing recovery scenarios for each technology options. It is clear that in terms of the six environmental impacts explored, the option to scrub and produce acid outperforms the dual-alkali process in all categories except water use.

As discussed in the previous sections, the key purpose of the explored technological options is the reduction of SO_2 emissions. In terms of LCA, this should result in reduced acidification potential, and possibly also in reduced human toxicity impacts. Emissions related to acidification were evaluated for the different recoveries and presented in kg SO_2 equivalent. Figure 5 shows that indeed, with increasing SO_2 removal, the acidification potential decreases almost equally for both processes. There are small differences, however, caused by the differential emission of other substances with acidification potential, due to the production and transportation of raw materials, and the energy utilised during the scrubbing processes (Fig. 6).

While the reduction of SO_2 emissions at the smelters should have positive effect on human health, these effects may vary across different health issues. For example, sulfur dioxide itself is not toxic, but its atmospheric conversion into sulfate particulates can result in respiratory health effects. The scrubbers can release carcinogens during their life-cycle, but the concentrated dual-alkali scrubber releases significantly higher amounts of such substances compared to the acid production process (Fig. 7). Figure S4 in the Supplementary Electronic Material suggests that this is a result of soda ash and lime production, as well as of truck transportation which is a feature of both interventions.

The treatment of previously emitted gaseous pollutants clearly requires the mobilisation of other resources, and can cause their potential depletion. In LCIA this is captured in impact categories such as abiotic resource depletion and fossil energy depletion. In this study, both these impact categories increase with increasing SO_2 recovery for the dual-alkali process, but decrease with increasing amounts of acid production (Figures S5–S8, Supplementary Electronic Material).

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[1] The key life cycle inventory results of the modelled foreground processes are included in Tables S1 and S2, in Supplementary Electronic Material. The technical modelling is discussed in greater length in Munyongani (2016).

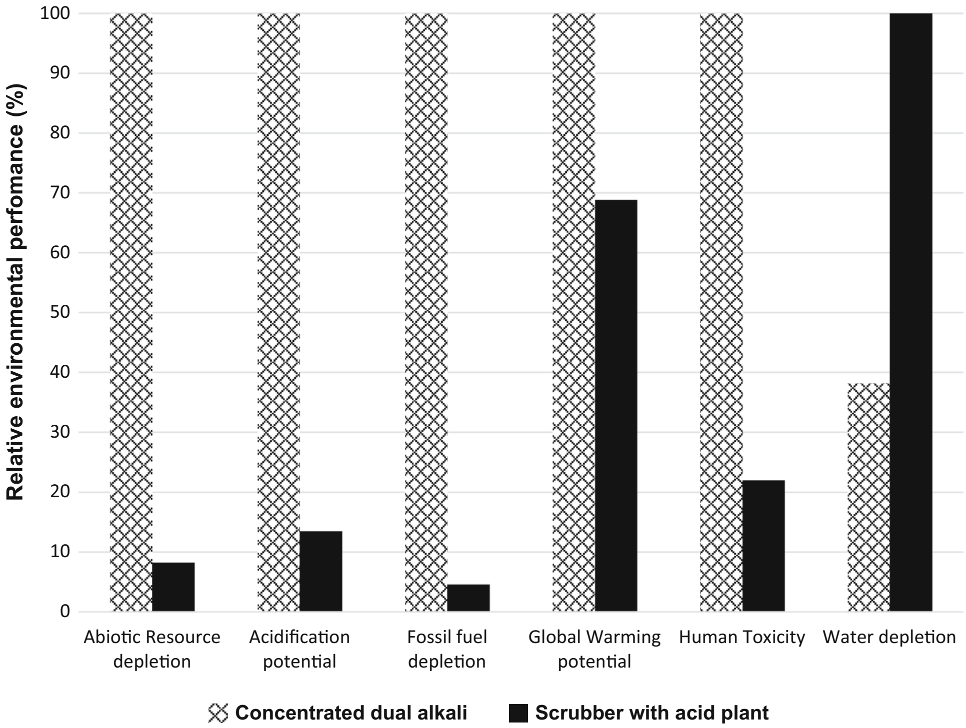


Fig. 4 Relative environmental impact for the two technology options, with systems expansion for the concentrated dual-alkali scrubber set to 92% recovery and the acid plant option set to 99% recovery

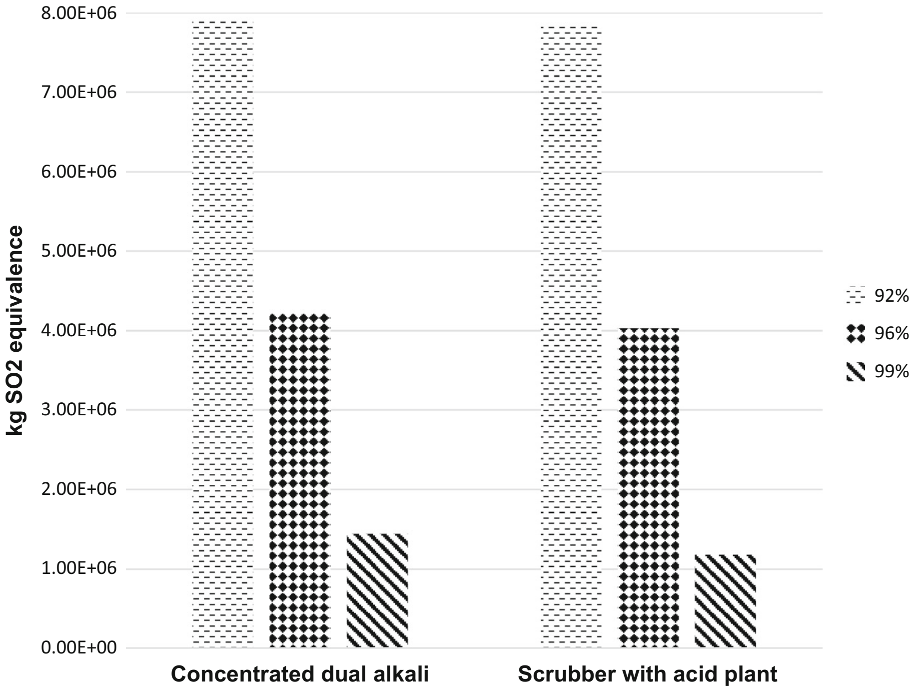
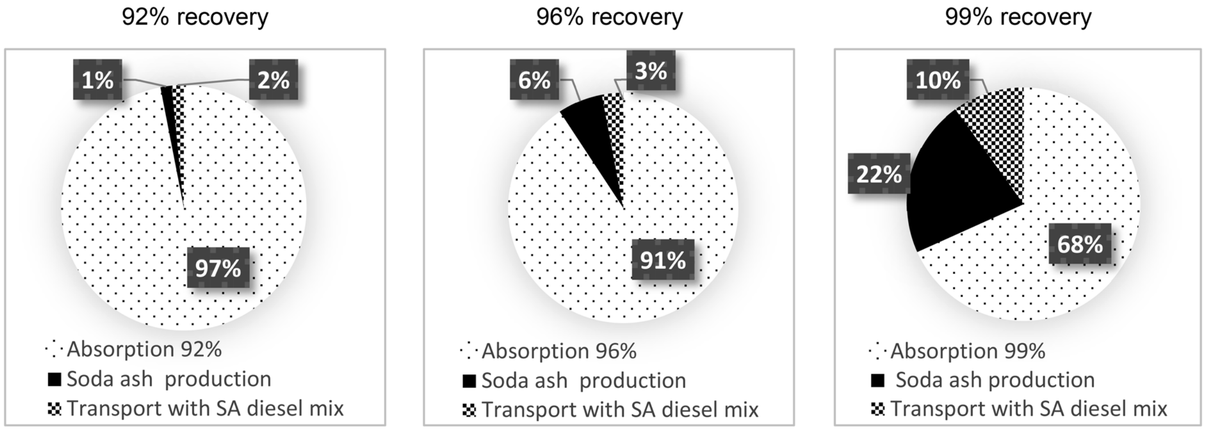
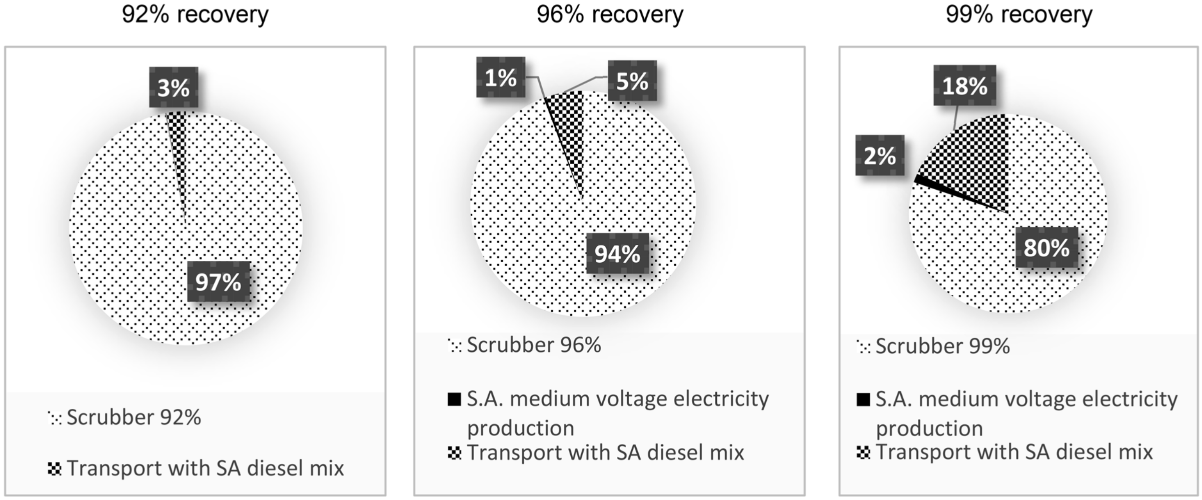


Fig. 5 Variation of acidification potential with change in recovery

Fossil energy resources are used to treat the atmospheric emissions and transport the materials, by-products and waste. This energy use contributes to greenhouse gas emissions, which are captured in this LCA through the global warming potential impact category. Figure 8 shows that the major contributor to global warming potential (for both the concentrated dual-alkali scrubber and the scrubber with acid plant) is the transportation of the $CaSO_x$ and the produced acid, followed by the actual SO_2 scrubbing processes. The scrubbing processes contribute 33% of the total global warming potential in the concentrated dual-alkali option and 14% in the scrubber with acid plant option at a



(a) **Concentrated dual alkali scrubber**



(b) **Scrubber with acid plant**

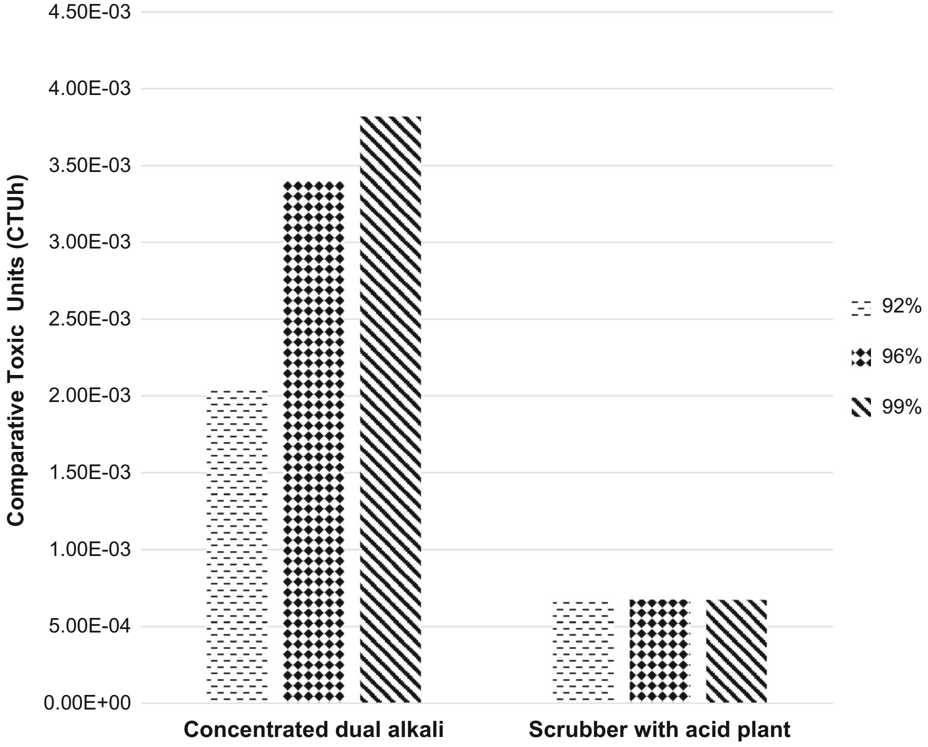
Fig. 6 Unit process contributions to acidification potential for **a** the concentrated dual-alkali scrubber and **b** the scrubber with acid plant

recovery of 92%. However, as SO_2 recovery increases, the environmental impact related to the production of soda ash and the transportation of the waste increase for the concentrated dual-alkali process (Fig. 9). The contribution of background processes increases with increasing recovery for the scrubber with acid plant (see Tables S3, S4 in Supplementary Electronic Material).

The global warming potential increases with increasing recovery for both the concentrated dual-alkali scrubber and the scrubber with acid plant; however, the rates of increase are significantly different. Figure 9 reveals that for the concentrated dual-alkali scrubber, global warming potential increases by 46 and 12% as SO_2 recovery increases from 92 to 96, and from 96 to 99%, respectively. This can be attributed to impacts associated with soda ash and lime production, which increase significantly with increasing recovery compared to the smaller increase of transportation impacts related to $CaSO_x$ production. It should be noted that for the concentrated dual-alkali process, when the SO_2 reacts with the dual-alkali, in addition to $CaSO_x$ also CO_2 is emitted (see Supplementary Electronic Material, Eq. S1). This further increases the total CO_2 emissions of the dual-alkali option. On the other hand, the global warming potential of the scrubber and acid plant increases slightly by 1.8 and 0.3% as recovery increases from 92 to 96, and from 96 to 99%, respectively. This is attributed to the slight increase in fuel requirements for the transportation of the produced acid.

Water use is a very important impact in the context of semi-arid South Africa as the scrubbing processes for both technology options make use of water as the scrubbing agent. Figure 10 shows the relative contributions to water

Fig. 7 Human toxicity (cancer causing) impacts for the two technology options at different recoveries



depletion for both processes at different recoveries. The dominant contributor to water depletion for the concentrated dual-alkali process is the actual scrubbing process (foreground system) contributing at least 65% to the impact category. Other significant contributions come from the production of soda ash and lime. For the scrubber and acid plant the water used for the scrubbing process dominates this impact category with a 98% contribution for the 92% recovery, and as the recovery increases to 99% the contribution of the foreground system increases to 100%. Sulfuric acid production for systems expansion and transport make a further contribution of 2% at a recovery rate of 92%.

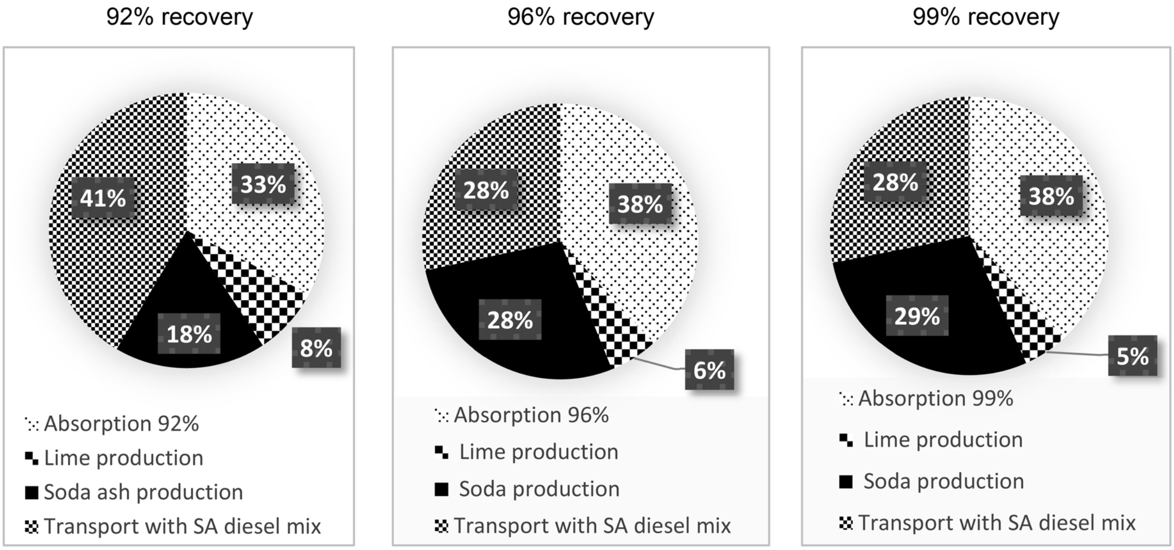
It is evident from the Fig. 11 that the amount of water required for both technology options increases with increasing recovery. This is to be expected as higher recoveries are associated with higher solvent quantities in scrubbing processes. However, the scrubber with acid plant uses higher quantities of water compared to the concentrated dual-alkali plant. This is primarily because the scrubber with acid plant only requires process water as the scrubbing agent, whereas the concentrated dual-alkali scrubber uses water and hydrated sodium carbonate to scrub the SO_2. Water treatment and recycling were not modelled in the process. Therefore the amounts of water for the foreground system are purely indicative of once-through processes.

Discussion

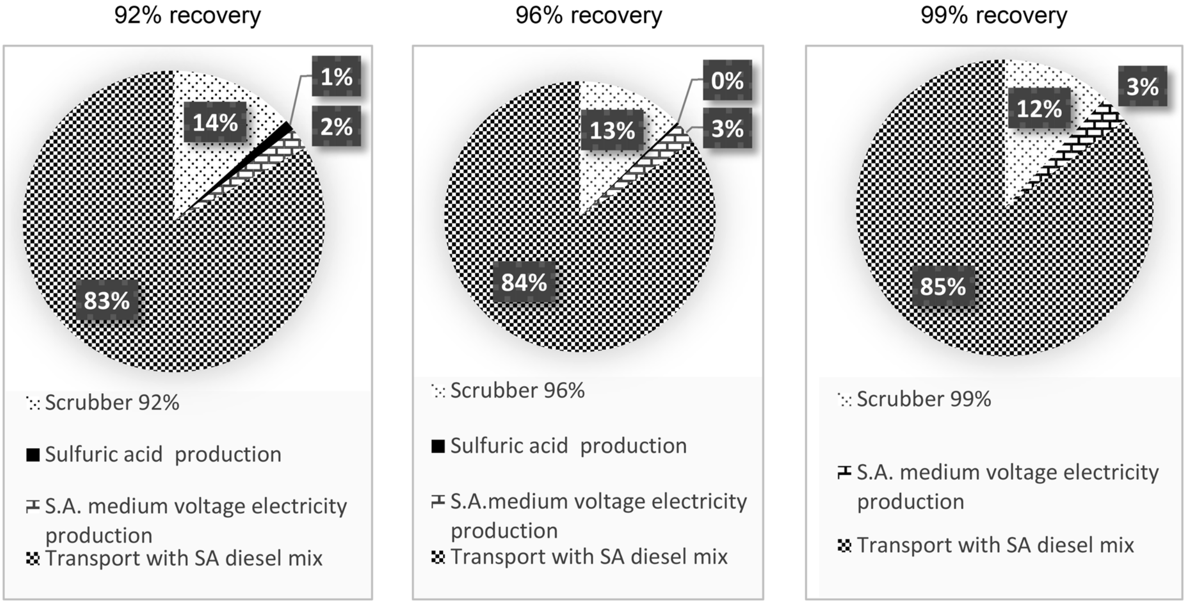
Interpretation of the SO_2 abatement life cycle assessment

For the LCA part of the study two key variables were assessed: technology choice and SO_2 recovery. The magnitude of impacts increases with increasing recovery for the concentrated dual-alkali option, with the only exception being the acidification potential as more SO_2 is recovered. The principal driver of environmental impacts was the higher demand for materials such as soda and lime for the concentrated dual-alkali scrubber, with the foreground system dominating acidification potential and water use. Though the energy requirement increased exponentially with increasing recovery, the impacts of this increase were over-powered by the background processes.

Conversely, for the scrubber with acid plant, the magnitude of impacts decreased with increasing recovery for the acid plant, with the exceptions being water use and global warming potential. The dominant contributor to most environmental impact categories was the production of sulfuric acid used for the systems expansion (background process) and the transportation of the acid produced by the foreground system (background process). The acidification potential and water use were however dominated by the foreground system.



(a) Concentrated dual alkali scrubber



(b) Scrubber with acid plant

Fig. 8 Unit process contributions to global warming potential for **a** the concentrated dual-alkali scrubber and **b** the scrubber with acid plant

Overall, the LCA reveals that the choice of key variables results in quantifiable differences in environmental impacts. The LCA shows that the scrubber with acid plant choice has, for the most part, significantly lower environmental impact compared to the concentrated dual-alkali scrubber. From this, it becomes evident that by carrying out a LCA on different key variables it is possible to identify how burdens can be shifted either within a technology option (as determined by the chosen recovery rate), or across technology options.

Significantly, the LCA result indicates that higher abatement efficiency is environmentally beneficial when useful by-products (sulfuric acid in this case) are produced. Our study does not assess the sensitivity of this insight relative to the modelling choice made to deal with a multi-product system, i.e. co-production allocation vs. substitution (as used in this case). The earlier used practice of co-product allocation had raised significant debate in metals-related LCA (Dubreuil 2005), as it can make the metals look a lot less impactful if done on the basis of mass.

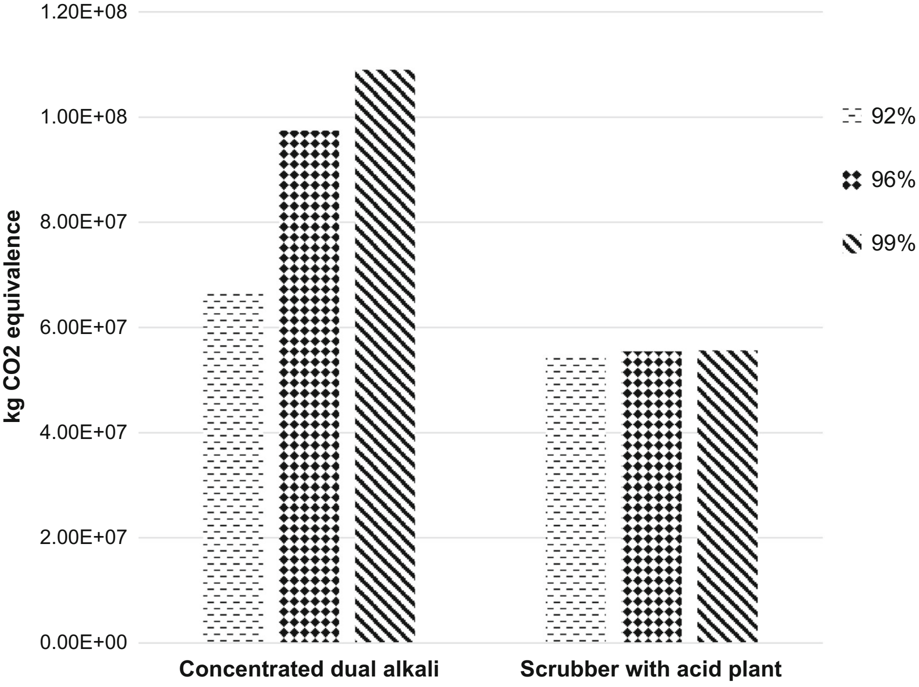


Fig. 9 Variation of global warming potential with change in recovery

ISO14044 does prefer substitution to allocation, which is how we have done the work. If allocation can make the metal look even "greener" by a mass allocation, then it would follow that modelling the processes in this way would make the scrubbing with acid recovery look even more favourable than it already does, in comparison to the dual-alkali process. The environmental preference for the acid production technology does, however, have to be tempered with technical knowledge of technical restrictions imposed by flue gas composition, as described in the Introduction.

Relevance of LCA for design decision-makers

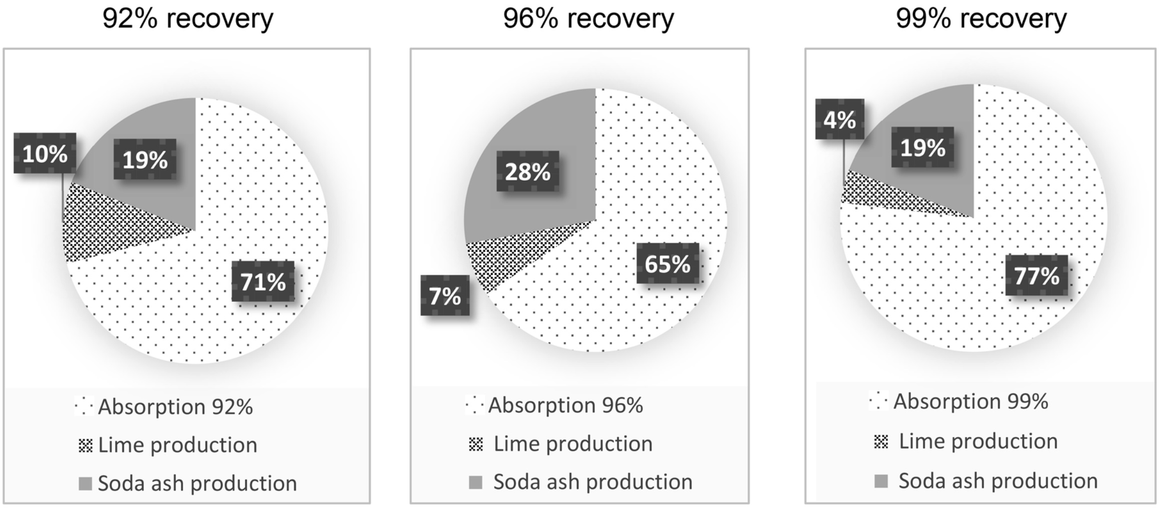
Approaches to design decision making

The expert interviews established that process design decision-making is based on input from different project teams. Before any final decision is made, all members of the design team would need to agree unanimously on a specific technology option, which they would all deem beneficial after conducting a cost–benefit analysis. Key reasons that usually prompted companies in the PMG sector to consider retrofitting technologies within their operations included (a) instances that design specifications were not met, (b) ratification of new regulations or (c) development and availability of improved technologies.

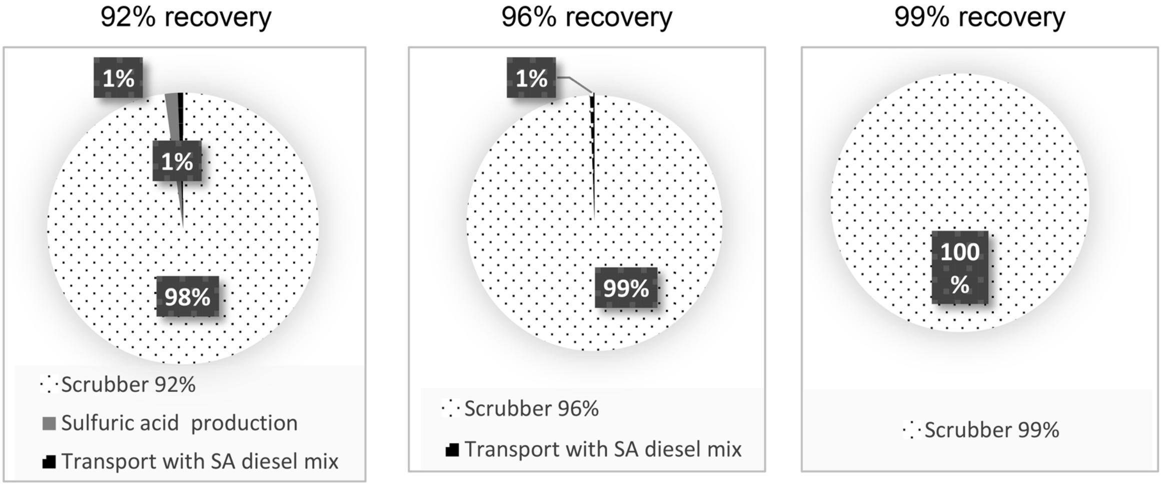
In the case of the SO_2 abatement technologies the quality of gas to be treated was identified as the main determinant to the technology options that a company would consider in the first place considering the different available technologies available. This would be the first step in narrowing down the technological options available. Once this is established the mining company would then approach a consulting firm to help reduce the options to two or three. In most cases this would be achieved by scoring the different options in a decision matrix. From these options the company would then decide on whether they opt for a high OPEX or high CAPEX process depending on their financial stability. This process would result in a single technology option that the company would adopt.

Life cycle assessment as a tool for informing design decision making

Expert interviews identified that companies in the PMG sector tend to incorporate environmental concerns during the design phase almost entirely through the prescribed EIA. Once confronted with the results presented above, they indicated that such LCAs could be very useful tools, especially during the early design stages. By adopting LCA in the early design stages, companies in the PMG sector would be able to justify better to the interested and affected parties during public participation processes why they excluded certain technology options. A key point raised was that it would be good to quantify the impacts that are associated with the different processes. ECC-GC pointed out that by quantifying the impacts it would add great value to the company's decision-making matrix. According to



(a) **Concentrated dual alkali scrubber**



(b) **Scrubber with acid plant**

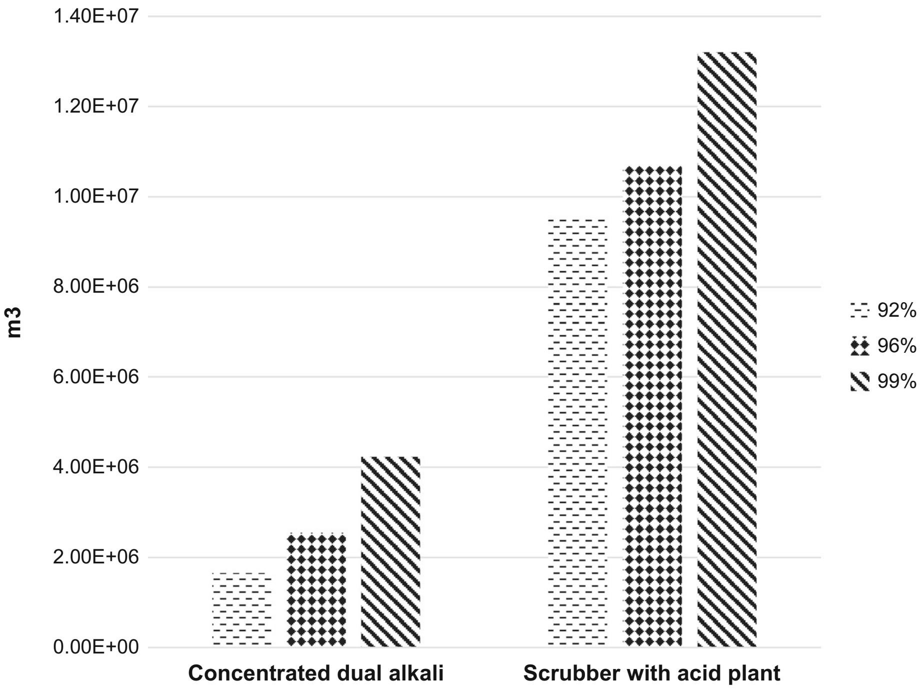
Fig. 10 Unit process contributions to water depletion for **a** the concentrated dual-alkali scrubber and **b** the scrubber with acid plant

CF-C this would be the most crucial in improving the scoring of the environmental aspect of the project, which is currently not being given much attention. ME-SC and PC2-PL2 seemed to steer towards the fact that quantifying environmental impacts would be more useful when a PMG sector company would have to justify why a specific technology option was not adopted. In such situations, the company could present the interested and affected parties with data, showing the impacts associated with the options that were not adopted.

In contrast, PC4-TS and PC2-PL2 did not perceive any value for their companies from performing LCAs similar to the one outlined in the previous sections. They said that mining companies already have practices in place which are addressing all the quantified impacts by this LCA study. They pointed out that the risk assessments implemented by their companies during the preliminary design stages already considered impacts such as acidification and human toxicity. Therefore, extra information that goes beyond mere quantification would be needed to help motivate the widespread adoption of such tools.

A concern that was brought up by CF-C was that as SO_2 abatement is a complex process, LCA tools would need to be able to handle complexity. For example, for the different cases in the acid production route, it would not be possible to use the same process technology. So one would have a single contact acid plant for the 92 and the 96% recovery options and then a double contact for the 99% recovery. This, therefore, means that there would need to be a way of comparing across the variations that would be available within the technology options. If this level of flexibility

Fig. 11 Water depletion for the two technology options at different recoveries



could be incorporated, then indeed, the assessment would provide meaningful results.

Adding to the complexity is the issue of impact significance. According to ECC-GC, though it would be good to quantify environmental impacts, the significance of particular impacts is a more significant issue. In order for such information to influence decision-making they would need to point out something very critical such as that a process is water-intensive in a water-scarce region such as South Africa (see previous section). Simply knowing that a process will result in an increase in human toxicity, for example, would not be enough to drive change unless the impacts are severe. The ability to make a decision on the basis of such information thus depends on what issues the company values most, and which impacts are the most severe. Essentially this points to the need for normalising impacts in a given setting, which is an optional step in LCIA. However, it is still necessary to quantify all relevant impacts to determine those that are the most severe to company operations, not just those that a company might think are significant.

Incorporating LCA thinking as part of the EIA process

There were mixed views among the expert interviewees as to whether incorporating LCA thinking into the EIA process would be beneficial. Two respondents (PC4-TS, PC2-PL2) felt that companies already spend between 18 and 24 months working on the EIA and often by the end of the EIA process the commodity cycle could have turned and the company might actually be out of funds. They felt that introducing another aspect to this process, such as a LCA, would only prolong it. According to PC4-TS there are more "company-critical, industry-critical" issues to be addressed so it is important to reflect the possible effect of adding tools such as LCA to the EIA process. However, it is important to note that in our view the LCA could inform and improve the EIA process and thereby curtail the overall process, rather than prolong it.

PC3-TS on the other end suggested that rather than viewing the LCA as an additional part of the EIA, the EIA should rather follow LCA thinking. This is because the EIA is basically a set of guidelines, and hence incorporating LCA thinking will prompt the EIA to ask the right questions during all the stages of the design phase. Therefore, in such cases the EIA could still be carried out in the same amount of time, with the only difference being the focus and the kind of questions that are asked. This view resonates well with recurring themes in the literature on integrating life-cycle thinking with EIA (Tukker 2000; Manuilova et al. 2009; Morero et al. 2015).

Conclusions

By comparing the two technology options aiming to reduce the amount of SO_2 gas emitted by smelting processes at platinum mines it is possible to identify areas of potential burden shifting that can occur when choosing key variables and technology options during the design phase. The energy requirements were identified to increase exponentially with increasing SO_2 recovery for both technology options. It was also shown that the concentrated dual-alkali process, overall, has higher environmental impacts compared to the scrubber with acid plant.

The expert interviews revealed that incorporating LCA in the decision-making process would likely be more beneficial for guiding the key questions asked in conventional EIA processes, rather than adding it as an extra task. However, this would be more of a long-term goal as EIA processes are already very structured and regulated. A more robust approach for the effective application of LCA in the short-term would be to use LCA results during public participation processes to justify to interested and affected parties why specific technology options were chosen. In addition, it would be beneficial to normalise the LCA results obtained against a specific reference point to highlight the significance of the increases or decreases in the impacts.

It can thus be concluded that, had the life cycle perspective been adopted during the decision-making process, it would have generated further useful insights to the design team about the technology and design variable choices. Consequently, as revealed by expert interviews, there would be some interest from design decision-makers to include such LCA insights into design processes if it did not introduce significant extra work or delays to the EIA that has to be carried out under current regulations.

This case study review of a series of environmental abatement technology retrofits in an area of great importance to the African minerals industry therefore shows that the usage of an advanced assessment tool could not only improve the environmental outcomes of corporate and regulatory decision-making, but potentially also the information basis for the public engagement process.

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