A streamlined life cycle assessment of a coal-fired power plant- The South African case study

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Abstract

Non-renewable energy sources have detrimental environmental effects, which directly and indirectly affect the biosphere as environmental deposits from their use for energy generation exceed a threshold. This study performs a streamlined lifecycle assessment (LCA) of a coal-fired plant in South Africa. The cradle-to-grave LCA focuses on the coal cycle to determine hotspots with high environmental impacts in the process. Four impact categories were considered in this study; global warming potential, photochemical ozone creation potential, eutrophication potential, and acidification potential. Coal transportation, coal pulverization, water use, and ash management were identified as hotspots in the coal cycle. The coal process has 95% potential for global warming, 4% potential for eutrophication, 1% potential for acidification and a negligible percentage for photochemical ozone creation. Susceptibility to climate change, eutrophication, acid rain, soil degradation and water contamination among others are major concerns of the coal cycle. Outsourcing coal from nearby mines with train as medium of transportation reduces environmental impact. Similarly, the use mitigation technologies like flue gas desulphurization, carbon capture storage or selective catalytic reduction will reduce concentration of flue gas emitted. Ultimately, substituting the coal process with renewable energy sources will ensure environmental sustainability in South Africa. This study will serve as a good resource for further studies on LCA of coal power plants not only in other African countries but in other developing countries with similar situation.

Keywords: Coal cycle; coal-fired power plant; environmental sustainability; lifecycle assessment; South Africa.

1. Introduction

Coal is one of the primary global sources of electricity that constitutes the major raw material in coal-fired power plants. In 2010, coal-fired plants supply about 42% of the global electricity demand (IEA, 2010), occupies 41% of the energy resource nexus in 2013 (IEA, 2015) and 38% in 2017 (IEA, 2018). A long term forecast by International Energy Agency reveals that by 2040, coal will have 30% share of the global electricity nexus (IEA, 2015). A gradual decrease in the global use of coal for electricity has lately been complemented with increase in the use of renewable sources. Renewable sources constitute 25% of the global energy mix in 2017 (IEA, 2018). Despite the global gradual decline in the use of coal, it forms the dominant source of energy in South Africa. The South African electricity mix comprises 13 coal-fired plants (Eskom, 2016). Asides the merits of coal-fired plants in electricity generation, their operation also has environmental impacts such as global warming, acid rain, and negative health effects resulting from air pollution caused by the release of greenhouse gases, particulate matter and heavy metals(Wang et al., 2018b; Wu et al., 2018).

Several studies have attempted to evaluate environmental effects of coal-fired power plant and its associated processes with emphasis on greenhouse gas (GHG) emission and particulate matter (Mittal, 2010; Singh et al., 2016; Zhao et al., 2018). As a means of remediating these effects, carbon capture and storage (CSS), selective catalytic reduction (SCR) and flue gas desulphurization (FGD) technologies were evaluated with focus on their plausibility in reducing environmental pollution. An example of a study which focuses on CCS is that by (Koornneef et al., 2008). The study explored possible challenge in applying Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) on CCS activities in Netherlands, focusing on the scooping and screening phases of both techniques. A complete life cycle modelling and comparative assessment of current clean power generation technologies in China was also investigated by (Liang et al., 2013). The study assessed energy and environmental analysis with economic implications of electricity generation using coal fired plants before final consumption; the mining, transportation, and power generation phase. It was established from the study that CCS has a high potential of immensely reducing CO_2 emissions from coal power plants, even though higher CO_2 level is produced during operation of these technologies. A similar study carried out in India by (Singh et al., 2016) developed a normalization factors (the egalitarian, hierarchist and individualist perspectives) for LCA in India. The selected normalization factors gave a more accurate assessment of environmental benefits of CO_2, NOx and SO_2 mitigation technologies (i.e. FGD, CCS, SCR). The study established that the use of combined mitigation technologies has significant decrease in the environmental impact of electricity (EIE) across the three perspectives. A consistent environmental benefits were observed to be associated with these technologies which validates the studies by (Karmakar and Kolar, 2013; Singh and Rao, 2015, 2014; Sngh and Rao, 2014).

Coal cycle constitutes one of the cycles in electricity production from a coal-fired power plant (Rathnayake et al., 2018), which possesses significant environmental hazards. Little has however been done in investigating environmental impacts of this cycle, most especially in coal rich countries like South Africa. Coal, which is the principal resource in coal power plants is mined through opencast method or underground mining (Zhang et al., 2018). The extraction process is associated with several environmental effects, most especially the opencast method. The opencast method causes severe damage to the original soil profile and to the terrestrial habitat at large through its associated activities like striping, excavating and dumping (Wang et al., 2018a; Zhang et al., 2018). Compared to the underground mining technique, which could result in subsidence, the opencast mining technique is an earth-moving operation accompanied by blasting of the overburden (Mangena and Brent, 2006). This obviously constitutes a significant air pollution. A study by Zhang et al., (2018), which used Yimin mining area in China as case study established that dust contributes 36.81% to this process asides 29.43% and 22.58% contribution rate of global warming and acidification respectively.

LCA is a branch of sustainability that primarily focuses on the environmental footprint of products, wherein the goal and scope of the work is first set, then the inventory analysis (which is data collection) is carried out. Thereafter environmental impacts are assessed, and results from the environmental impacts interpreted (ISO Number, 1997).

There have been several thermal power plant LCA studies conducted in the past of varying degrees. However, Africa has not done much in this regard. Mbohwa conducted an LCA study of an old 100MW coal fired plant within the Africa context. One of the challenges encountered by Mbohwa in his study was lack of cooperation, and this stemmed from unfamiliarity with LCA from stakeholders (Mbohwa, 2013). Despite the strength of LCA in evaluation of environmental impact of processes, its acceptability by stakeholders needs improvement. LCA should rather be viewed as a tool to sustainable production rather than a threat to production systems.

It was estimated that South Africa's coal deposits can last for the next 250 years (Prevost, 2004). This prediction, however, is highly controversial considering the present rate of coal exploration. Prevost identified the un-economical exploration of better reserves located at the central basin with low quality coal left. South Africa does not have 250 years of coal reserves but still has a good amount of coal to explore both for export and local use. Consequently, 95% of the country's electricity supply comes from non-renewable energy sources, which coal fired power plants top the strata (Thopil and Pouris, 2015). The primary type of coal used in South African power plants, based on carbon content of the samples prepared by Makgato & Chirwa, (2017) has high ash content due to the low combustible element in the compound. However, the National Environmental Management Act [NEMA] of South Africa encourages power plants throughout the country to make use of FGD plants to ensure that SO_2 emission is minimized (Candice et al., 2014). The dominance of coal as the main energy source that may continue as it is for some time to come before the national implementation of FGD technology in all the country's coal-fired plants necessitated this LCA study.

This study focusses on a streamlined LCA of the coal cycle in a coal fired power plant situated in South Africa. It aims at (i) identifying environmentally unfriendly hotspots in the coal cycle. (ii) proposing ways of eliminating or minimizing the environmental toxics from these hotspots from the current coal-cycle system. Moreover, results of this study would be found useful by policy makers in making informed decisions between the various energy generating systems as well as regarding various possible updates on the existing coal power plant(s). It would also be a good resource in the development of new (green) coal power plants.

2. Methodology

2.1 Description of the plant's coal cycle

The South African coal power plant used as the case study can produce more than 712 MW of electricity at its maximum continuous rating (MCR). It should be noted that the stated MCR is for a single power plant unit. There are two main cycles in a coal power plant i.e. the steam cycle and the coal cycle. Fig. 1 shows the flow process diagram of the coal cycle considered.

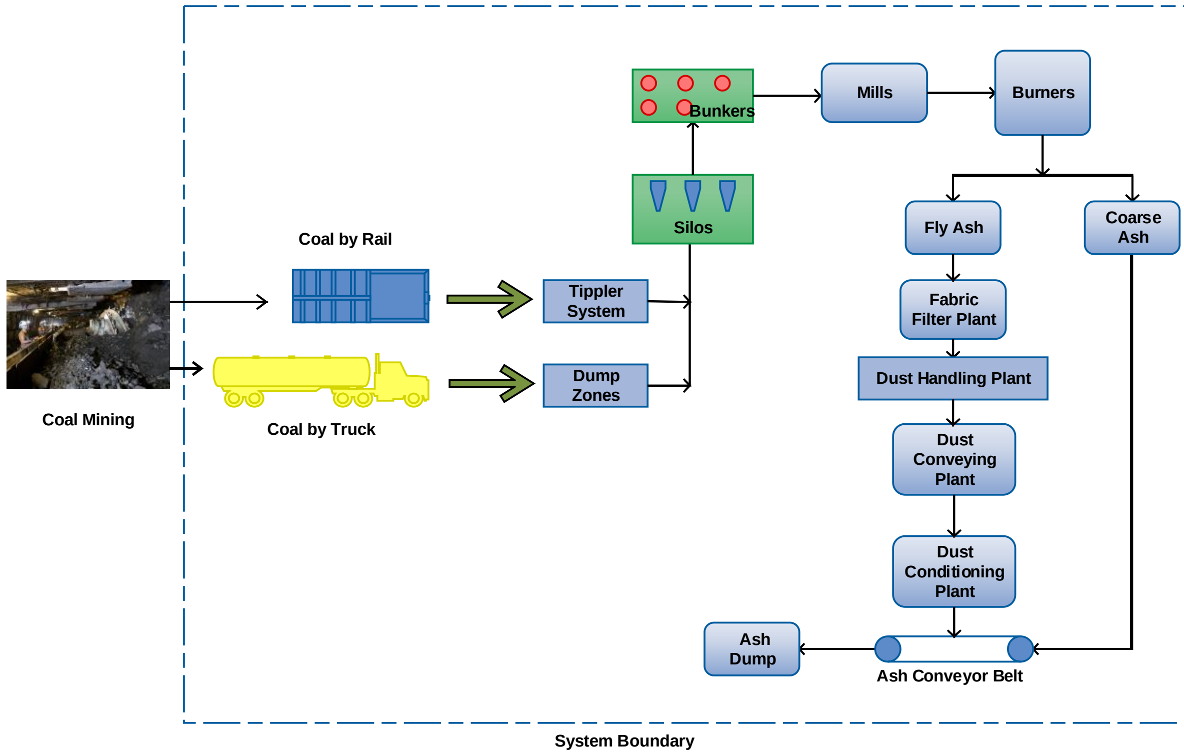

Fig. 1 Coal combustion process lifecycle of a thermal power plant

The power plant receives about 40% of its coal supply by rail and the remainder by truck. In the coal supply chain, the stock pile receives both coals transported by rail and by trucks, even though trucks dispatch directly while coal by rail dispatch by a conveyor system. The plant operates on two stock piles: the live stock pile and the emergency stockpile. While the live stock pile feeds the generation system in real time, the emergency stockpile feeds the generation system during shortage of coal supply to the boilers. Coal in the stockpile area is compacted to minimize the airflow circulation in the stockpile, thus reducing the probability of spontaneous combustion (Sloss, 2015).

Unit bunkers in the coal cycle serve as temporary storage units for coal before further processing into pulverised fuel (PF) using ball mills. For the combustion process of the PF in the boiler, both the primary air (PA) and the forced draught (FD) fans are used to dry and convey the PF into the unit's boiler. It should be noted that this streamlined LCA is based on 100% boiler maximum continuous rating (BMCR). It excludes both the cold and warm starting operation that needs to be complemented by either the auxiliary boiler or the use of oil burners.

The power plant makes use of a Benson type boiler. The boiler operates under negative pressure caused by the induced draught (ID) fan (Bhowmick and Bera, 2008). The ID fan primarily handles flue gas, and carries fly ash into the fabric filter plant (Bhowmick and Bera, 2008). Conditioning of the trapped fly ash (with water) is essential prior to its loading onto the ash conveyor belt. A large percentage of South Africa's coal power plants make use of coal with a relatively high ash content. The ash composition comprises of about 80% fly ash and 20% coarse ash. In the coal process, the coarse ash is quenched in the submerged scrapper conveyor (SSC) prior to it being conveyed onto the ash conveyor belt for final disposal into the ash dump.

2.2 LCA Process

A typical LCA process consists of four steps which include goals and the scope definition, lifecycle inventory, lifecycle impacts assessment, and lifecycle interpretation (Dunmade, 2013, 2012; Guinée, 2002; Jensen and European Environment Agency., 1998). These processes and their relationships are illustrated in Figure 2. These processes and their relationship to this study are further explained.

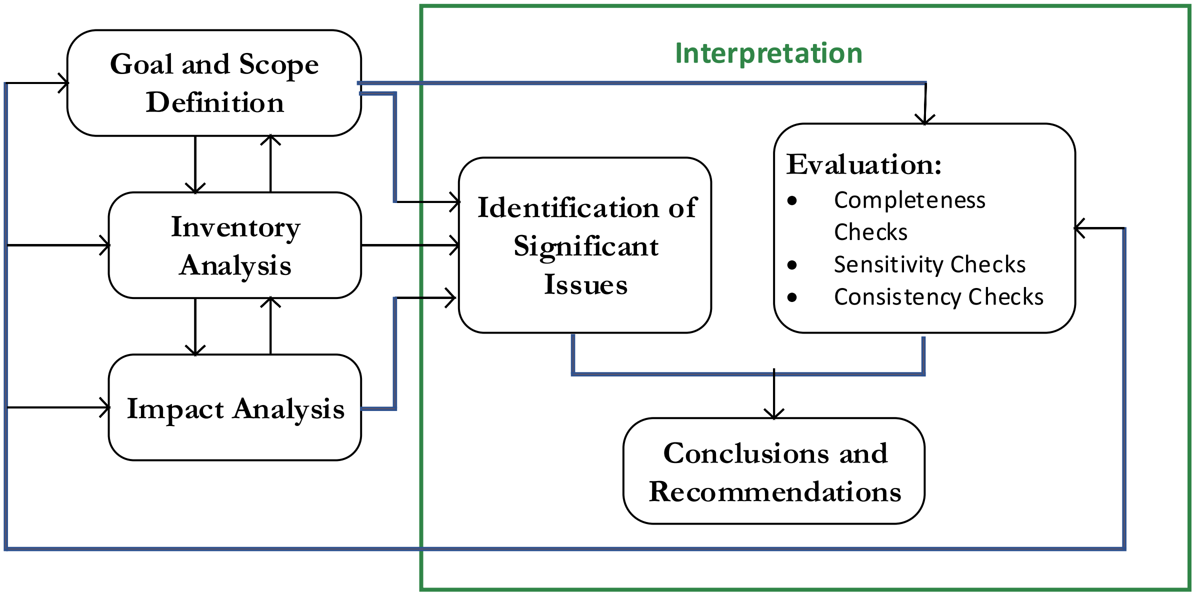

Fig. 2 An illustration of conventional lifecycle assessment process steps (Dunmade, 2014)

Scope definition: The scope of this LCA study is cradle to grave. It involved all the processes from sourcing coal materials to the disposal of the residual ash along the coal cycle. The functional unit for the LCA analysis is 712MW power generating unit of a South African coal power plant.

System boundaries: The system boundary is illustrated in Figure 1. Investigations revealed that larger volume of the coal used for the power plant (Makgato and Chirwa, 2017) is sourced about 68km distance from the power plant. Even though there are other small volume suppliers, they all fall within this radius in distance from the plant. About 40% of the coal is transported by rail while the remaining 60% is transported by trucks. These two sources supply the pulverizer, where it is burned for steam generation. The residue of the combustion process consists of coarse ash that settles at the base of the burner and the fly ash at the top of the burner. Both the coarse ash and the fly ash are collected and dumped at the ash collection site within the power plant facility.

Limitations, Assumptions and Exceptions: The coal mining activities are excluded from this analysis. Energy consumption by the coal loaders from train cargo and energy consumption by front loaders that load coal unto the conveyors were also excluded in the analysis because the data were not available.

Lifecycle Inventory: Operational data provided by the facility and observations made during the power plant tour were used as primary data for the analysis. Secondary data obtained from databases such as ecoinvent databases were used where primary data was not available. The data collected was entered into LCA software Simapro 8.4 version. Table 1 is an extract of major lifecycle inventory outcome from the software. The energy consumption data is given by 43,434.59MJ.

Table 1. Sample Lifecycle Inventory (LCI) of the coal combustion process

Substance	**Amount (kg)**
Nitrate	0.002
NO_x	0.039
Particulates	0.034
Phosphate	0.007
Sulphate	0.166
Chloride	0.062
Sulphurdioxide	0.027
Carbondioxide	7.573
Carbonmonoxide	0.019
Methane	0.015
Nitrogen	0.015
Gravel	3.946
Metamorphic rock	99.060
Water	13.643

3. Results

3.1 Lifecycle Impact Assessment

The lifecycle inventory data for this study was classified into various impact categories such as climate change, ozone depletion, land use, ecotoxicity, acidification, and others. Shown in Fig. 3-7 are the results of characterization of relevant data in each impact category.

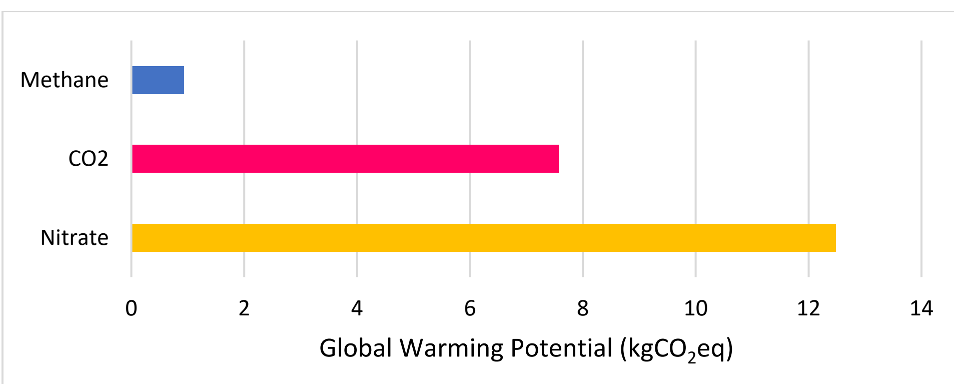

Fig. 3 Global warming Potential (GWP) of the coal cycle

From Fig. 3, all emissions contributing to GWP are expressed in $kgCO_2$ equivalents. Nitrate constituent of coal is responsible for increased global warming potential. It accounts for $12.48kgCO_2eq$. of the total contributing constituents to global warming. From previous studies, it has been shown that the use of CCS technology decreases GWP (Tang et al., 2014). GWP has the highest contribution to the environment (95%) as shown in Fig. 7. GWP category has noticeably occupied the highest influence in the LCA of power plants from the literature (Wu et al., 2017), which consequentially forms a leading factor in climate change (Fig. 8), which South Africa is presently experiencing (FAO, 2017; Mbohwa, 2013; Raubenheimer, 2011; Winkler, 2009).

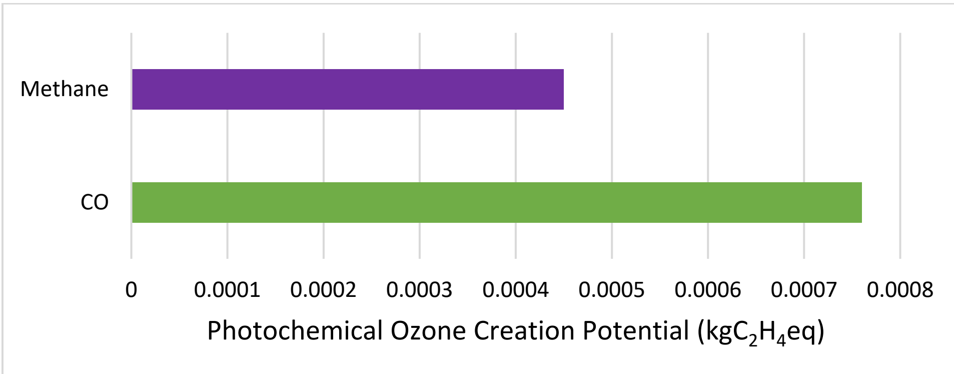

Fig. 4 Photochemical Ozone creation Potential (POCP) Impact from coal cycle

Photochemical Ozone Creation (POCP) are often caused from the release of Nitrogen compounds and their oxides (Curran, 2012) as seen in Fig. 4. Carbon monoxide contributes more to POCP ($0.00076kgC_2H_4eq$) compared to methane ($0.00045kgC_2H_4eq$). The combine effect of these contributors amounts to a negligible percentage of the environmental indicators as shown in Fig 7.

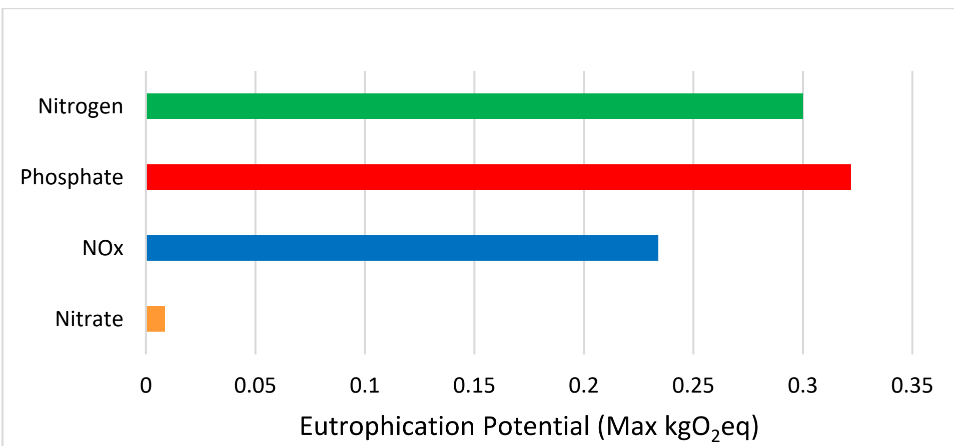

Fig. 5 Eutrophication Potential (EP) impact of the coal cycle

Shown in Fig. 5 are contributors to EP of the coal cycle. Eutrophication is largely attributed to nitrate compounds which also forms a constituent of coal (Petrescu et al., 2017). Asides the propensity of the coal process to cause global warming, it has high propensity of causing eutrophication. The EP environmental indicator contributes to 4% of the entire coal process as shown in Fig. 7.

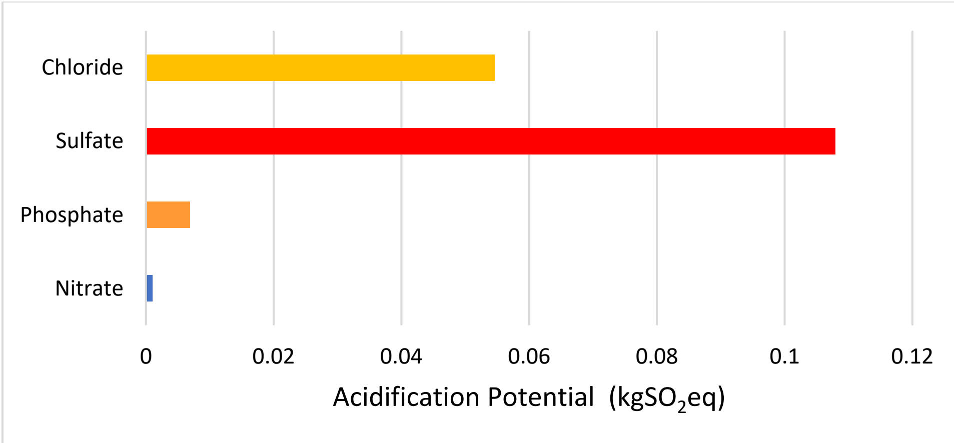

Fig. 6 Acidification Potential (AP) of the coal cycle

Shown in Fig. 6 is the acidification potential of the coal cycle. Sulfate compound is responsible for the increased AP of the coal cycle. It contributes 0.1079kgSO_2eq while nitrate contributes lesser (0.00102kgSO_2eq). AP occupies 1% in the overall percentage contribution of these indicators as shown in Fig. 7.

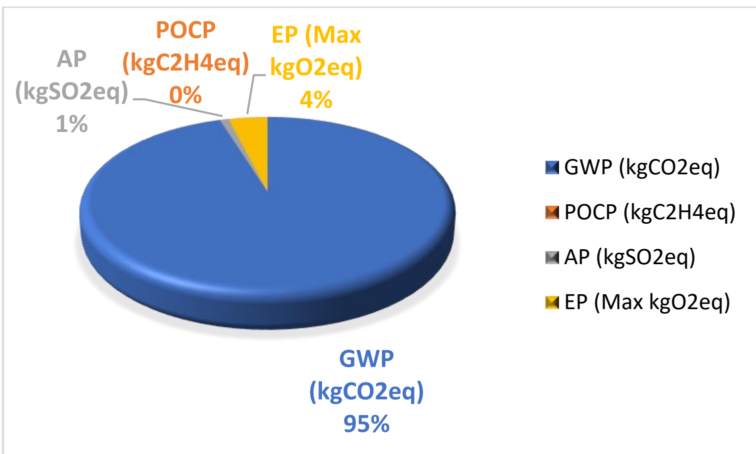

Fig. 7 Environmental impact categories by percentage

Shown in Fig. 8 are the potential impacts of coal combustion process of the coal power plant on human health, ecosystems and resources. All identified eco-indicators have 100% impacts. Rather than the country investing on building more coal-fired power plants, investment on renewable energy sources is highly essential, which is associated with reduced environmental impacts (Cherubini et al., 2009; Evans et al., 2009; Lerche et al., 2011).

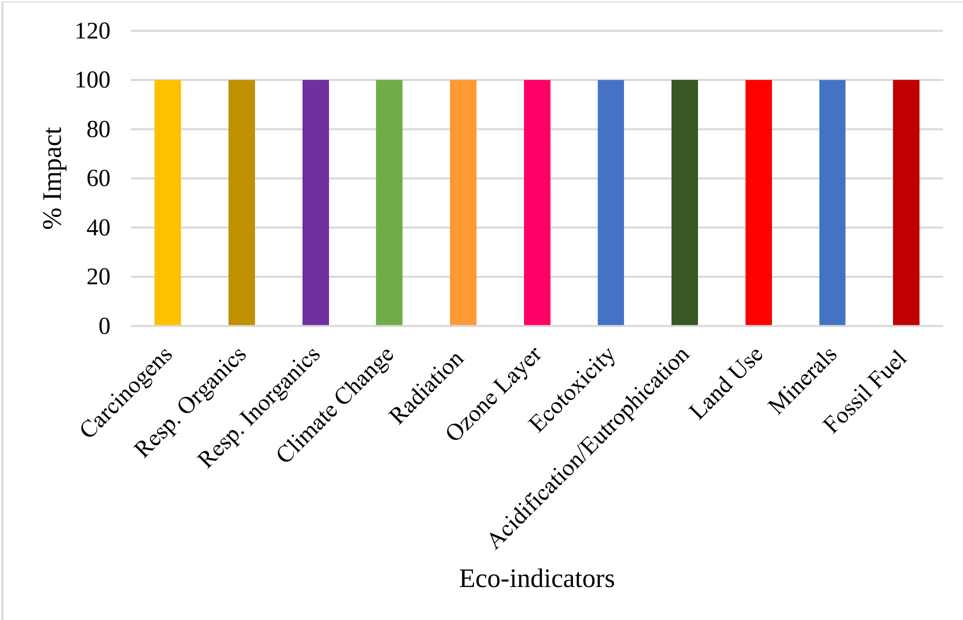

Fig. 8 Eco-indicators with percentage impacts of the coal burning process

The coal burning process is one of the phases of coal power generating plants that negatively affects the environment. Shown in Fig. 8 are eco-indicators with 100% effect on the ecosystem. The coal burning system deposits carcinogenic substances into the environment, which is detrimental to the living organism. The process also contributes 100% to climate change. Coal power plants' release of greenhouse gas emissions (GHG) are responsible for about 60% of South Africa's contribution of 510.2377 Metric tonnes CO_2 equivalents (1.13%) of the global total GHG in 2014 [19]. A regroup of the various environmental impacts of the coal power plant showed (in Figure 9) that it does not only affect ecosystem quality alone but it also has significant negative impacts on human health and resource availability. Similar studies have shown that the coal process has negative impacts on human health. Impacts from few studies shows a contribution rate from eco-indicators less than 100% (Zhang et al., 2018). The coal process is highly detrimental to human health and as such, coal-fired power plants should be situated in a very far distance to residential locations. However, locating this facility in less residentially prone areas does not reduce the effect of its operation on the ecosystem quality. If the coal process has 100% impact on the ecosystem quality (Fig. 9), the whole electricity generation process from coal-fired plants will negatively affect the ecosystem with continuous accumulations of both particulate and gaseous deposits over time. The South African case study where the dominant means of electricity generation is the coal-fired power plant becomes a concern if the ecosystem quality is to be preserved.

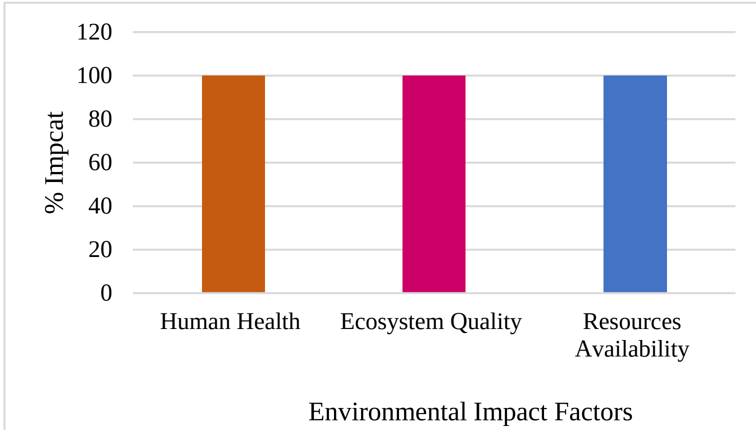

Fig. 9 Lifecycle impacts of the coal combustion process on human health, ecosystem quality and resources

3.2 Interpretation

LCA interpretation stage consists of the identification of environmentally significant issues, evaluation of the LCA data and process, and conclusions from the results.

3.2.1 Identification of significant environmental issues

This is the point at which results obtained at the lifecycle inventory and lifecycle impact assessment stages are examined to identify the most important results of the study in relation to the goal and scope definition. In this study we used contribution analysis method to determine the significance of lifecycle inventory and lifecycle impact assessment results. Examination of the lifecycle inventory data revealed that energy consumption, water consumption and Carbon dioxide emission are the significant environmental issues. The lifecycle inventory also showed that there were significant amounts of rocks and gravel. Furthermore, an examination of the lifecycle impact analysis results revealed that global warming is the greatest potential environmental impact of the coal combustion process. Other two potential environmental impacts of note are eutrophication potential and acidification potential.

3.2.2 Evaluation

At this stage of the LCA process we checked the consistency of the data and processes selection with regard to the methodology of the study. The purpose was to ensure that the process used was consistent with the ISO 14040s standards. Our evaluation confirmed the consistency and reliability of our choices throughout our LCA study.

The study a good number of potential impacts of the coal process. However, a clamour for mitigating against climate change has only been the mantra. It was also discovered that the combustion process can cause eutrophication which may affect surface water and the aquatic life. Other potential impacts of the coal combustion process are acid rain that could result in soil degradation and water contamination. It could also cause some damage to the aquatic lives. A holistic view which addresses associated environmental effect of operating a coal-fired plant is highly essential if environmental sustainability is to be ensured.

4. Conclusions

This study provides an insight on the potential environmental impacts of the coal combustion process of a power plant in South Africa. The coal transportation, coal pulverization, water use, and ash management are the identified hotspots in the coal combustion process for electricity generation. Consequently, a process optimization, which minimizes ecological footprints in the identified hotspots is highly essential in the power plant. Among possible improvements to reduce the potential impacts on the environment include sourcing the coal nearby, 100% transportation of coal by train, producing value-added products from the ash, and efficient water recycling. The use of mitigation technology to reduce the effect of gaseous and particulate effluents is recommended for the plant to reduce the amount of flue gas discharge to the environment.

In addition, a lifecycle costing and social lifecycle assessment study on the coal combustion process is essential for further studies, to provide a holistic view of the economic and socio-cultural aspects of the system. This study thus provides insight into areas requiring attention in for the improvement of the sustainability profile of a coal power plant especially in a setting similar to that of South Africa as well as a valuable resource for the development of improved (green) coal power plants.

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