Life Cycle Assessment on a 500 MW Oil-Fired Power Plant in Sudan

Omer Ahmed Eltayeb, Md. Mizanur Rahman, Aminuddin Saat and Hasan Mohd Faizal
School of Mechanical Engineering
Universiti Teknologi Malaysia
81310 Johor Bahru, Johor, Malaysia
omer44088@gmail.com, mizanur@mail.fkm.utm.my

Abstract

In this study, the methodology of life cycle assessment was used to assess the environmental impacts of a 500MW oil-fired power plant in Sudan. Ecoinvent database along with primary data obtained from the Sudanese Thermal Power Generating Company Ltd (STPGC) were utilized. Life cycle analysis was conducted with the aid of OpenLCA software and the ReCiPe method was employed. Results revealed that the environmental impact is dominated by climate change with a value of 1.07992 kg CO_2-eq followed by the fossil fuel depletion category, which is equal to 0.39320 kg oil-eq. Furthermore, the third most pronounced category is human toxicity with a value of 0.08983 kg 1,4-DCB-eq followed by ionizing radiation category with a value of 0.07341 kg U235-eq. Additionally, in regard to the endpoint level, it was found that 46% of the overall life cycle impact damages the resources , 36% affects human health and 18% contributes to ecosystem quality damage. Moreover, the operation phase and oil upstream processes were found to be the most burdensome on the environment. Finally, a sensitivity analysis was conducted to determine the primary influential factors on environmental impacts, it was evidently clear that plant efficiency is the most dominant parameter affecting the results.

Keywords
Life cycle, environmental impacts, oil-fired, power plant, electricity generation

1. Introduction

In recent years, growing concerns regarding global warming, air pollution, increasing energy costs and security of energy supply, have generated a heated debate among policymakers, related experts, and the general public (United Nations 2015). The demand for a green and more sustainable power grid has become internationally urgent, causing the implementation of new energy-saving and emissions reduction strategies, at both international and European level (Orfanos et al. 2019). In 2015, at the Paris Climate Change Conference, the Paris agreement was born (United Nations, 2015). It laid the basis for how countries, including the European Union, should work together under the umbrella of a legal framework to tackle the threats of climate change by the year 2020 and beyond.

Between 1973–2013, the gross electricity production around the world grew from 6144 TW h to 23,391 TW h by an average annual growth rate of 3.4% (Hertwich et al. 2015). In 2013 over 67.2% of the world electricity production was generated from fossil fuel-powered plants, consequently, a considerable amount (about 40%) of global greenhouse gas (GHG) emissions are produced by electricity generation, constituting a very essential role for this sector in GHG mitigation strategies as demonstrated by (Treyer and Bauer 2016) and (Jaramillo et al. 2007). Furthermore, it is worth mentioning that the use of fossil fuels in electricity generation not only contributes to climate change by emitting greenhouse gases but also has other environmental impacts such as ozone depletion, acidification, eutrophication and the depletion of natural resources as well, caused by other environmental stressors (Song et al. 2017).

Decisions are no longer being based solely on economic perspectives, instead, potential environmental impacts of electricity produced by existing technologies and alternatives are now taken into consideration. Nevertheless, only direct emissions of power plants have been widely addressed, which only include emissions from the combustion of fossil fuels. Instead of only focusing on direct emissions, attention should likewise be paid to account for indirect emissions, comprising upstream materials and energy mining and processing along with the disposal processes (second and third-degree processes) (Ardente et al. 2008) and (Pacca et al. 2007).

According to (International organization for standardization [ISO] 2006) and (Song et al. 2013), Life Cycle Assessment (LCA) is a broadly adopted approach to conduct environmental analysis of a product, system or even a service from “cradle to grave” including all processes involved. The tool of LCA can help to disclose the significance of hidden processes and materials pertaining to an individual product or component that otherwise unnoticed (Song et al. 2012) and (Turconi et al. 2013). It can facilitate the identification of environmental impacts from each technology in terms of its share in environmental effects such as climate change or other detrimental phenomena (Sastre et al. 2015) and (Dewulf et al. 2015). The comprehensive scope of LCA is useful in the avoidance of problem-shifting from one life cycle phase to another, from one region to another, or from one environmental problem to another by taking all into consideration.

While the world now is advancing towards sustainability, in Sudan, and due to complexity caused by economic, operational, siting, social, and policy constraints, among other factors, fossil fuel-powered plants are expected to continue being the only suppliers for electricity to the national grid for quite some time. Nevertheless, there is still room for potential mitigation of the emissions generated by the dependence on non-renewable sources while furthering the development of green renewable energy sources. The present paper aims to evaluate the life cycle environmental impacts of electricity generation from an oil-fired power plant in Khartoum (the capital city of Sudan) using LCA, further analysis is to be performed to identify the major impactful processes in the power plant’s life cycle along with conducting a sensitivity analysis to determine the primary influential factors on environmental impacts.

2. Methodology

As defined by (ISO 2016), LCA has generally four steps including goal and scope definition, life cycle inventory analysis, life cycle impacts assessment, and interpretation. Firstly, the goal of the study was to evaluate the potential life cycle environmental impacts of electricity generation from an oil-fired power plant in Khartoum and the functional unit, which provides a reference to which inputs and outputs are related, was adopted to be 1 kWh of electricity generation at the wire leaving the power plant.

Moreover, in regards to the system boundary, first-, second- and third-order processes were included in the analysis to broaden system boundaries in order to further minimize truncation error. The life cycle of the power plant was investigated in three life cycle phases, namely, construction, operation and decommissioning. In the construction phase, extraction/production of materials for plant equipment, manufacturing the plant equipment and on-site construction of material was included. In the operational phase, the material inflow during the entire lifetime of the plant, which is inclusive of upstream processes of fuel oil production was addressed. In addition to that, the operational phase also included direct emissions from the combustion of fuel. For fuel oil, fuel extraction, processing at the refinery and fuel transportation were considered. The decommissioning phase encompassed the demolition of the power plant and material recycling.

Secondly, the life cycle inventory, which consists of all recognized inputs and outputs to/from the functional unit. Several methods are used to carry out the LCI step, the most dominant method among LCA practitioners and the one adopted for the present study is a process-based approach. Process flow diagrams illustrate how processes of a product system are interconnected through commodity flows. In process flow diagrams, boxes generally represent processes and arrows the commodity flows as shown in Figure 1. Process-based LCI provides more accurate and detailed process information with relatively more recent data, unlike Input-output based method.

Two sources of data were used in the life cycle inventory phase, LCI data for the product system was mainly taken from the commercially available Ecoinvent database v3.5 (relaxing the geographical constraints) along with primary data gathered from the Sudanese Thermal Power Generating Company Ltd (STPGC). The quality of the data that is available from the Ecoinvent database can be considered high (secondary data). Where primary data (foreground data) obtained from the Sudanese Thermal Power Generating Company Ltd (STPGC) was available, it was given preference as a more up-to-date, reliable source of data that better characterizes the Sudanese energy generation sector.

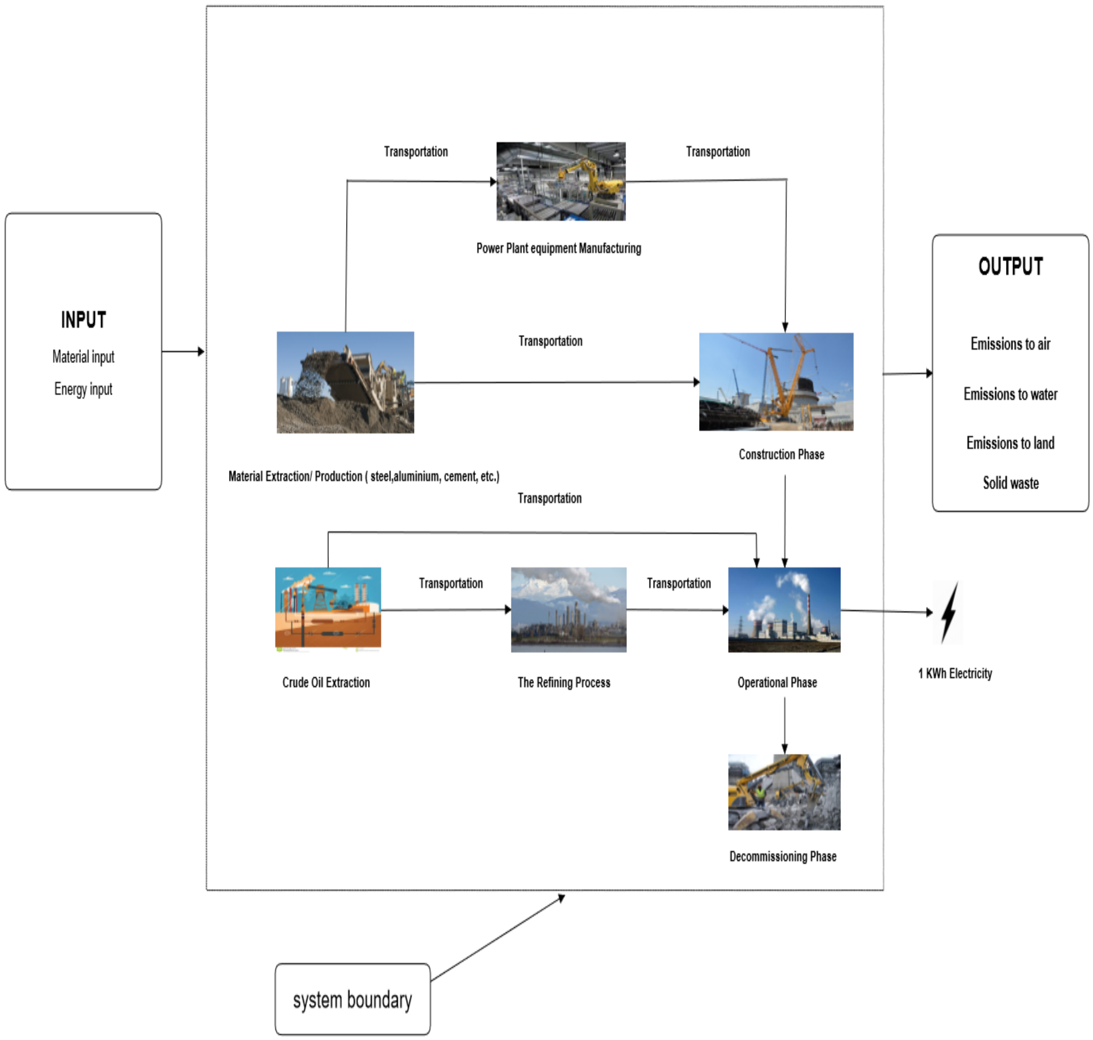

Figure 1. Process flow diagram of the product system with a system boundary

Furthermore, the results from the LCI phase are then converted by the Life Cycle Impact Assessment (LCIA) phase to environmental impact categories.Too wide range of environmental impacts can become inefficient and lead to unclear conclusions due to the difficulty in interpreting the findings and spot correlations between a large number of variables. On the other hand, using too few impact categories or a method that does not include particular impact categories that are most relevant to the life cycle inventory data under study lead to inaccurate results that could portray the product as environmentally friendly contrary to reality (Esnouf et al. 2019). Some authors, (Mouron et al. 2007) and (Pozo et al. 2012), used Principal Component Analysis (PCA), combined with uncertainty analysis or multi-objective optimization to reduce the number of impact categories, by selecting the most relevant impact categories to the conducted study.

The Representativeness Index (RI), was developed by (Esnouf et al. 2018) to explore the relationship between LCI results and LCIA methods. A high RI indicates close proximity between an LCI and an LCIA method and highlights a better representation by the LCIA method. The study was based on the Ecoinvent database, electricity production mixes were chosen as LCIs to determine the most relevant impact categories and therefore the most adequate impact assessment method. It can be drawn from the findings of the study that ReCiPe method is one of the most representative methods of LCIAs for this specific type of life cycle inventory data, therefore, it was selected as life cycle impact assessment method for this present study due to the similarity in the nature of life cycle inventory data. A number of methods used for LCIA convert the emissions into impact category indicators at the midpoint level, while others employ impact category indicators at the endpoint level. The ReCiPe method addresses both levels comprising numerous impact categories at a midpoint level providing a precise description to the product system, these impact categories are then linked to a set of areas of protection at the endpoint level as shown in Figure 2 (Zelm et al. 2008).

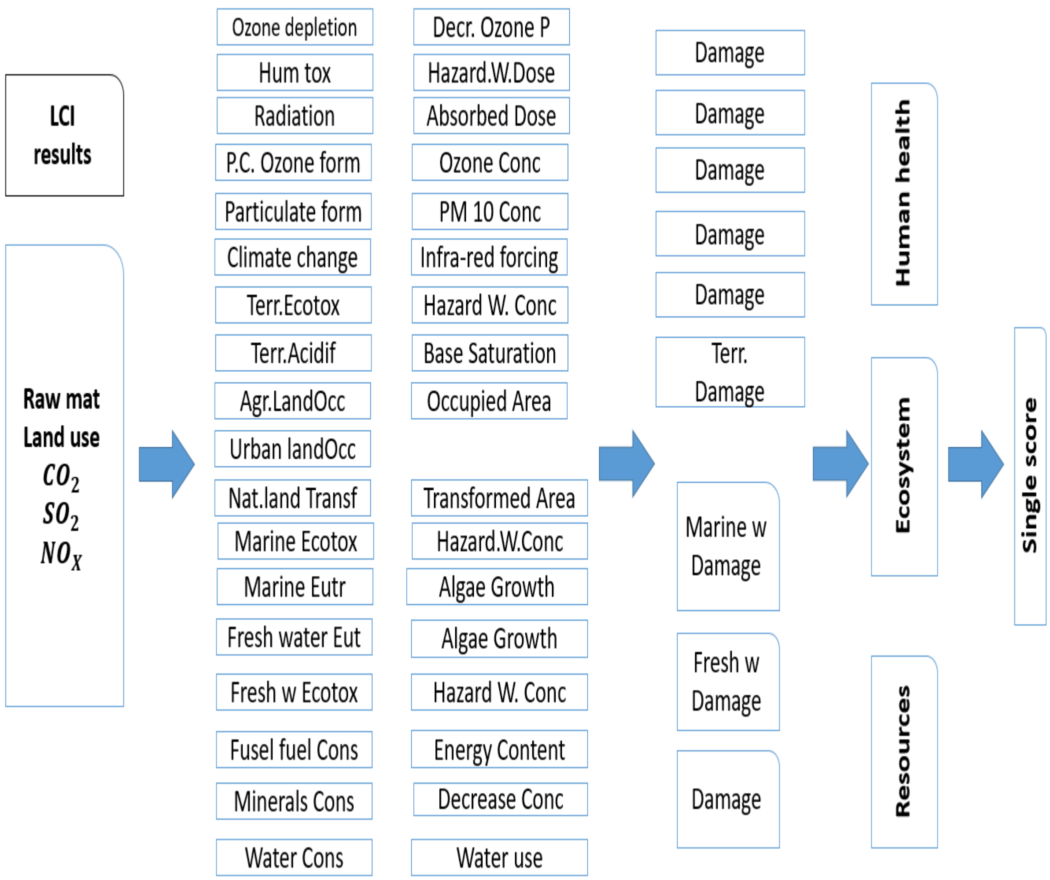

Figure 2. Relationship between LCI parameters, midpoint indicator and endpoint indicator in the ReCiPe method

Equation 1 below (Zelm et al. 2008) is used to calculate impact categories indicators by the aid of characterization factors at a midpoint level from environmental interventions (LCI results):

$$I_m = \sum_i Q_{mi} \, m_i \quad (1)$$

Where m_i is the magnitude of intervention i (e.g., the mass of CO_2 released to air), Q_{mi} the characterization factor that connects intervention i with midpoint impact category m, and I_m the indicator's result for midpoint impact category m.

Starting from the midpoint level using equation 2 below (Zelm et al. 2008), category indicators at the endpoint level are then calculated:

$$I_e = \sum_m Q_{em} \; I_m \quad (2)$$

Where I_m the indicator's result for midpoint impact category m, Q_{em} is the characterization factor that connects midpoint impact category m with endpoint impact category e and I_e is the indicator's result for endpoint impact category e.
A sensitivity analysis was performed to find the key factors (variables) influencing the life cycle assessment findings. To compare the magnitude of the variations, the base case was subjected to both an increment and a decrement in the values of the chosen parameters.

3. Results and Discussion

OpenLCA software was used to analyze the inventory data. Midpoint, endpoint impact category indicators associated with the life cycle of the oil-fired power plant were calculated using the Recipe midpoint method incorporated in the software. Moreover, a sensitivity analysis was conducted for the purpose of identifying the most impactful parameters on the life cycle assessment's results.

3.1 Midpoint Impact Category Results

Figure 3 below reveals an overview of the midpoint life cycle impact assessment results. It is apparent from the chart that by far the most significant contribution to the life cycle impact of the plant is climate change indicator with a value of 1.07992 kg CO_2-Eq followed by the fossil fuel depletion category indicator, which is equal to 0.39320 kg oil-Eq. Further inspection of Figure 3 shows that the third most dominant category is human toxicity with an impact category indicator equivalent to 0.08983 kg 1,4-DCB-Eq followed by ionizing radiation category with a value of 0.07341 kg U235-Eq. Together these impact categories provide important insights into the life cycle assessment of the power plant. It is worth mentioning that the rest of the midpoint impact categories have less significant values due to the absence of substances contributing to these categories as it is clearly noticed in figure 3.

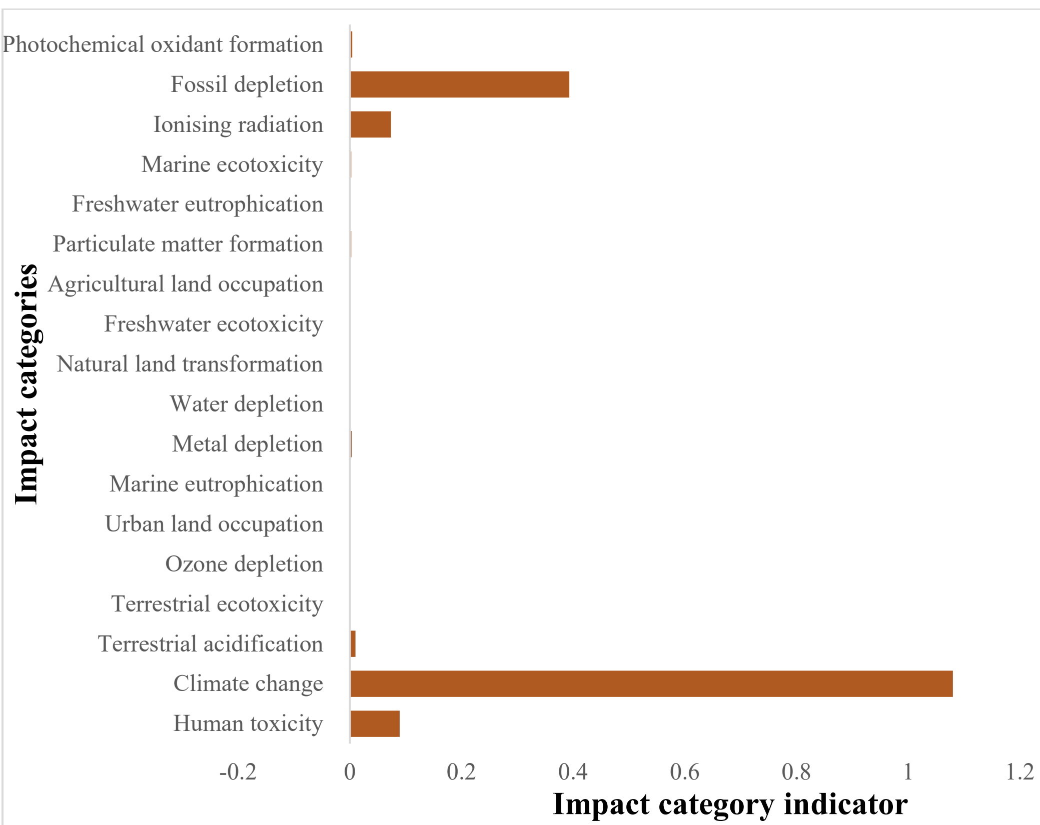

Figure 3. Total midpoint results

Construction, operation, oil upstream processes, transportation and power plant decommissioning are the most dominant processes included in the system boundary. Figure 4 provides a breakdown of their contributions to all midpoint impact categories.

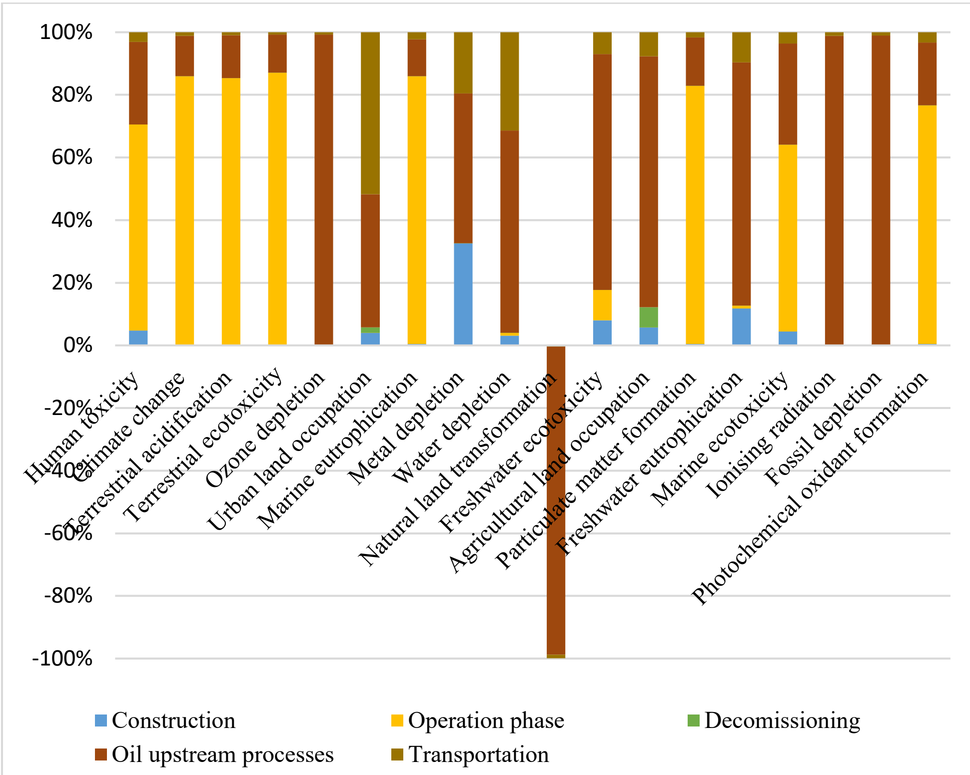

Figure 4. Midpoint impact categories relative results for major processes

As was pointed out by Figure 3, the most crucial midpoint impact categories are climate change, fossil fuel depletion, human toxicity, ionizing radiation. A breakdown of these dominant categories is presented below.

It is apparent from the chart above that the most impactful process in terms of climate change potential is the operation phase, which accounts for 85.66% of the category indicator. Moreover, it can be drawn that the most burdensome processes to fossil fuel depletion are oil upstream processes which include the extraction of crude oil and refinery processes, these processes account for more than 98.74% of the total impact.

Furthermore, in regards to human toxicity indicator, the most impactful process is the operation phase which accounts for 65.81 % of the overall category indicator. It is followed by oil upstream processes that form 26.37 % of the overall score. Finally, what also stands out from Figure 4, is the fact that the overwhelming share of ionizing radiation impact category indicator is formed by oil upstream processes almost 98.8% of the impact category indicator.

Figure 5-8 illustrate the contributions of several substances to those prominent impact categories. These substances were characterized utilizing designated characterization factors and their contributions to the overall score were estimated.

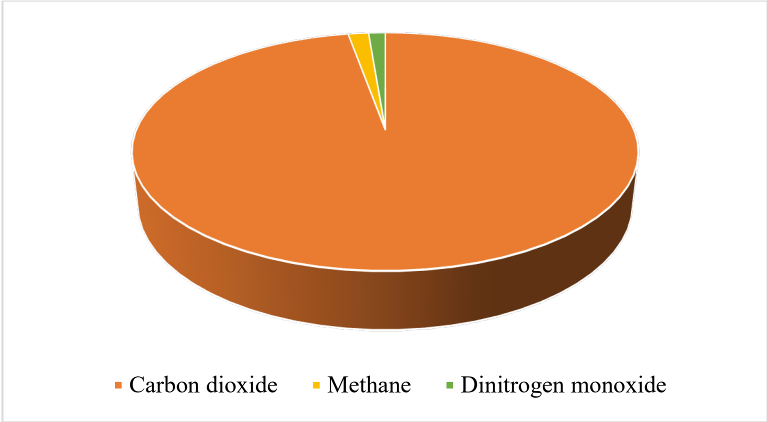

Figure 5. Substances contributions to climate change

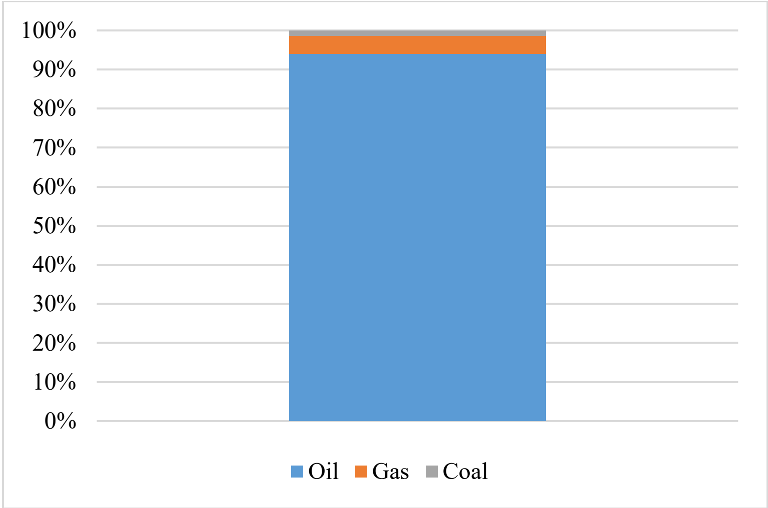

Figure 6. Substances contributions to fossil fuel depletion

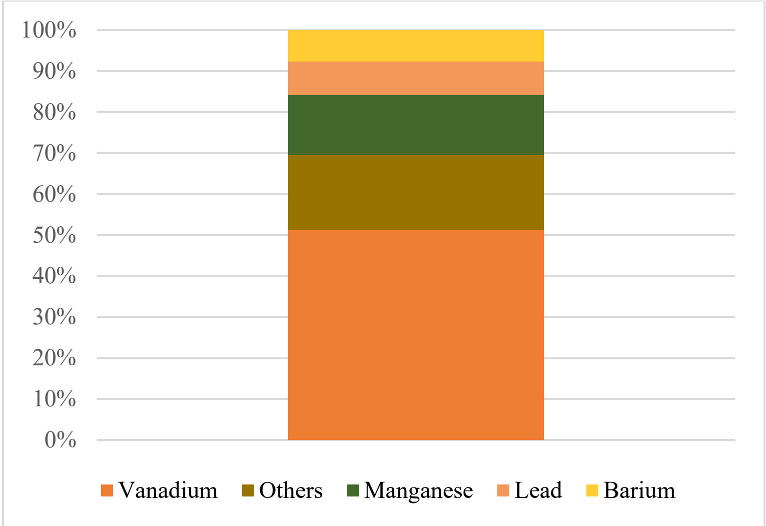

Figure 7. Substances contributions to human toxicity

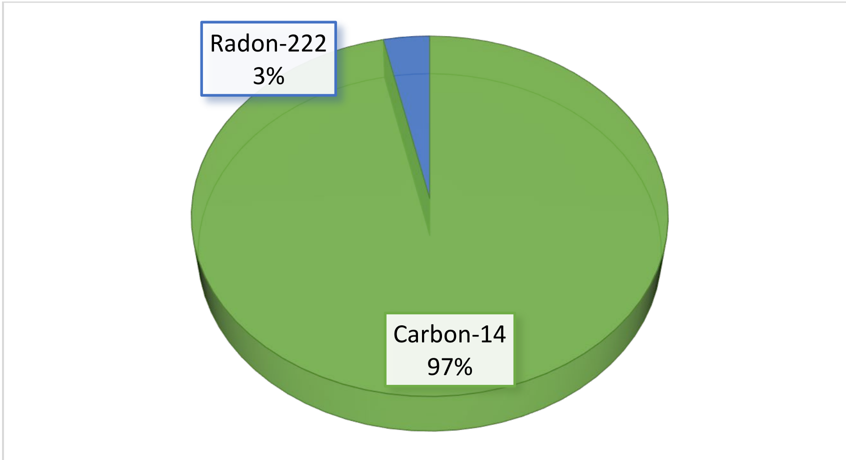

Figure 8. Substances contributions to ionizing radiation

3.2 Endpoint Impact Category Results

Moreover, the results were advanced to the endpoint level, by employing designated characterization factors that further convert midpoint impact categories to endpoint impact categories (damage-oriented approach). Figure 9 demonstrates the endpoint level results.

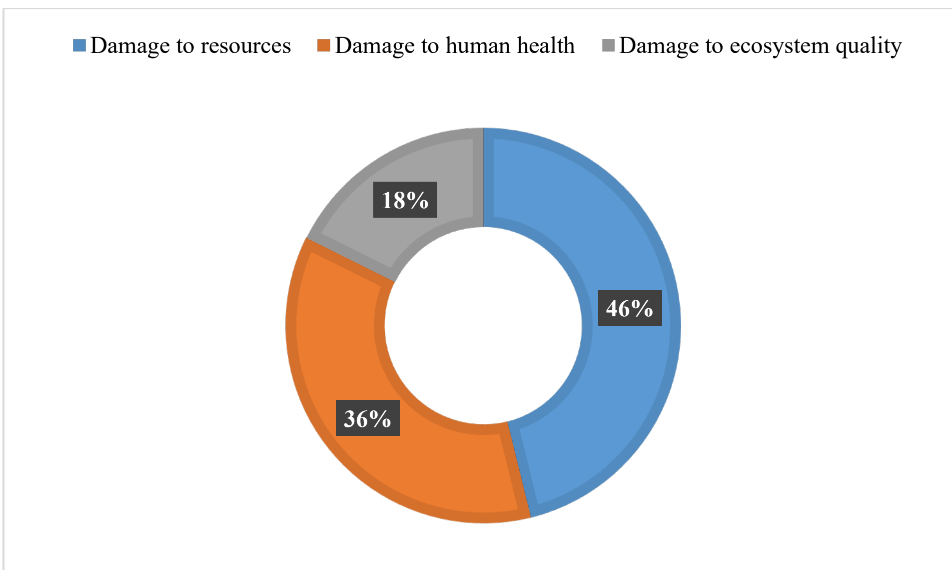

Figure 9. Endpoint impact category results

It can be drawn from Figure 9 that 46% of the overall life cycle impact, which is converted to points with each midpoint impact category contributing a specific amount of points based on its characterization factor, damages the resources and 36% of the overall impact affects human health and the remaining 18% contributes to ecosystem quality damage.

A proper explanation for the relatively large parentage of damage to resources is the high rate of fossil fuel consumption throughout various processes encompassed by the system boundary of the study, along with a minute contribution by metal depletion in the oil power plant construction phase. Additionally, human health damage is dominated by direct emissions from the power plant, due to the lack of flue gas cleaning technology, the damage of these hazardous emissions is highly concentrated. Lastly, for ecosystem quality, Carbon dioxide emission in both the power plant and the refinery is evidently attributable to a significantly large portion of the damage.

3.3 Sensitivity Analysis

Several parameters were selected for the study including plant efficiency, plant lifetime and recycling rate for the decommissioning phase. It was found that plant efficiency is the most dominant parameter that yields a significant influence on the life cycle assessment findings compared to the remaining parameters, therefore, the result of variation in the plant thermal efficiency is solely presented here.

The base case represents the current status of the power plant, which has a thermal efficiency of 32%. Both an increase and a decrease in thermal efficiency were examined, for the upper case, the thermal efficiency was given a value of 37% and for the lower case, the thermal efficiency of 27% was selected. The life cycle inventory findings vary with respect to the changing efficiency resulting in a change in the life cycle impact assessment phase. Figure 10 reveals the effect of variation in thermal efficiency on overall life cycle assessment findings.

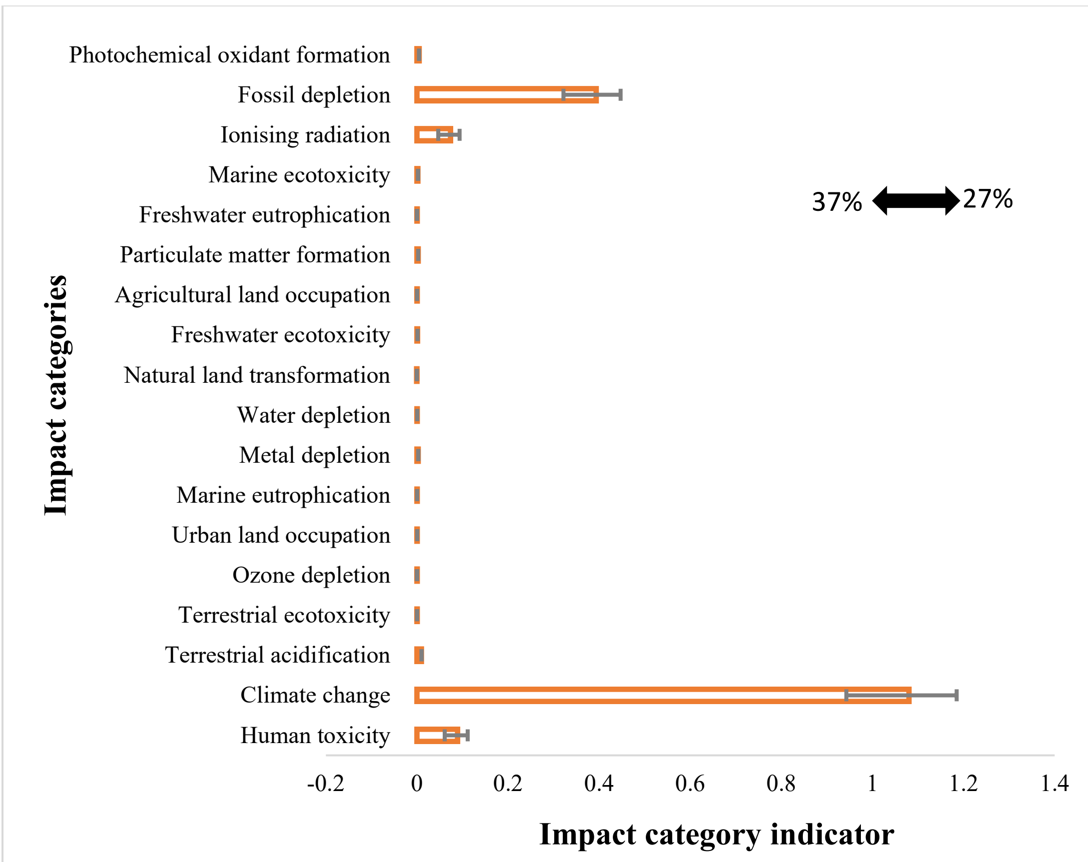

Figure 10. The effect of thermal efficiency on life cycle assessment

Closer inspection of Figure 10 shows a general decrease in all impact category indicators for the upper case with higher thermal efficiency (37%) compared to the other sceneries. In contrast, a general increase is clearly noticed for all impact category indicators for the lower case with less thermal efficiency (27%). Moreover, It can be seen that the most pronounced variation is in the climate change impact category indicator ranging from a value of nearly 0.87 kg CO_2-Eq for the upper case to a value of around 1.18 kg CO_2-Eq for the lower case, a possible explanation for this significant variation is the reduction in fuel consumption for the upper case due to the enhanced thermal efficiency.

In contrast, an increase in fuel consumption is associated with lower thermal efficiency which leads to a higher level of emissions throughout various life cycle processes for the lower case.

4. Conclusions

In conclusion, the environmental impact was evaluated, for the midpoint level, by four major impact categories namely, climate change, fossil fuel depilation category, human toxicity, ionizing radiation. In regard to the endpoint level, it can be concluded that 46% of the overall life cycle impact damages the resources and 36% of the overall impact affects human health and the remaining 18% contributes to ecosystem quality damage.

Furthermore, major impactful processes on the environment encompassed by the system boundary were identified. The operation phase and oil upstream processes account together for more than 80% of the impact in each midpoint impact category. Therefore, these processes are considered to be the most burdensome on the environment and further attention should be directed towards them for the purpose of enhancing the environmental profile of the power plant.

Finally, a sensitivity analysis was conducted to determine the primary influential factors on environmental impacts that could be addressed to mitigate adverse environmental effects, it was found that plant efficiency is the most dominant parameter that yields a significant influence on the life cycle assessment findings compared to the remaining parameters. Consequently, corrective measures should be taken to boost the efficiency of the plant to considerably diminish the environmental impacts caused by the power plant life cycle.

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Biographies

Omer Ahmed Eltayeb is a postgraduate student at School of Mechanical Engineering, Universiti Teknologi Malaysia-UTM, Johor Bahru, Malaysia.

Md. Mizanur Rahman is a senior lecturer in the Department of Thermo-Fluids, School of Mechanical Engineering, Universiti Teknologi Malaysia-UTM. Before joining at UTM, he has served as a postdoctoral researcher at Aalto University School of Engineering, Finland. He received his PhD degree in Mechanical Engineering from Aalto University, Finland and M.Sc. degree in sustainable energy engineering from Royal Institute of Technology KTH, Sweden. His research interests include energy economics, energy system analysis, rural electrification, sustainable and renewable energy, energy efficiency, and distributed power generation.

Aminuddin Saat is a senior lecturer at the Department of Thermo-Fluids, School of Mechanical Engineering, Universiti Teknologi Malaysia. Dr. Aminuddin has earned his PhD in Mechanical Engineering (Combustion and flame studies) from University of Leeds, United Kingdom.

Hasan Mohd Faizal is a senior lecturer at the Department of Thermo-Fluids, School of Mechanical Engineering, Universiti Teknologi Malaysia. Dr. Faizal has earned his PhD from Keio University, Yokohama, Japan.