Application of Life Cycle Assessment (LCA) in measuring the environmental impact of coal-fired power plant - A review

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Abstract. Coal-fired power is among the most significant electric generated in most developed countries. The environmental impact of coal-fired power plants is usually associated with air, water and waste pollution. Life cycle assessment (LCA) is a standard method used to evaluate the potential of environmental impacts of a product or process over its life cycle stages. This paper aims to review the application of LCA in evaluating the environmental impact of coal-fired power plant fields. The results were summarised in term of goal, scope, functional unit, system boundaries, impact assessment method and impact category.

1 Introduction

Coal is a flammable organic rock consisting primarily of carbon, hydrogen, and oxygen with less sulphur and nitrogen that could be used to produce electricity [1]. Most countries, including Australia, China, United States, Russia, India, Indonesia, Singapore, Thailand, Philippines and Malaysia continue to rely significantly on fossil fuels as their primary energy source with over 79% average of energy [2]. It was predicted that from 2020 Malaysian Energy Statistics Handbook that coal contributes the highest electric generation in Malaysia with 42.8% from 175 164 GWh electric produce in 2019 [3]. Coal has become a good choice of fossil fuel since the resources are abundant; affordable and possess matured technology; however, coal usage needs to be reduced since coal-fired power plants emit a significant amount of greenhouse gases [4].

In the electricity sector, coal generation is the most significant contributor to carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions among fossil fuel energy sources. Most of the methane (CH_4) emissions come from systemic leakage during natural gas transportation and coal mining [2]. Besides, the airborne release from coal-fired power plant able to give adverse health impact on residence surrounding coal-fired power plant neighbourhood and power plant workers [5]. It also found that there is elevated amounts of metal concentrations

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in water bodies near coal-fired power plants that will risk the aquatic organisms inhabiting sites [6]. But according to Wong et al. [7] the environment performance of coal-fired power plant is good and can be improved through strict enforcement of plant management in order to meet the environmental requirements.

Life Cycle Assessment (LCA) is a framework to quantify product's environmental impact over its life cycle stage. It is a valuable technique for evaluating the environmental impact of product or service operations since the concept focuses on a precautionary principle where it analyses the potential impact from system boundary [8]. LCA results allow companies to benchmark and optimize the environmental performance of products for sustainable consumption and production [9]. In the power industry, LCA is utilized to evaluate the potential environmental load of individual power plants in producing electricity as a product [10] or assist the power company with effective mitigation measures towards cleaner electric production by comparing different technology [11].

The application of LCA in assessing the environmental impact of electric production of various energy types has been done by several countries such as China [12], Chile [11], Turkey [13], Portugal [14], Mexico [15] and Japan [16]. The results strongly support that coal-fired power plants have significant environmental impact especially on climate change and global warming potential. It has high effect of carbon dioxide emission especially during operation and maintenance stage [12]. Compared to gas and oil, coal has the worst environment performance [11]. The greenhouse gas (GHG) emissions of fossil fuels are significantly greater than those using nuclear or renewable energy [16]. Coal indicates significant impacts on global warming, antibiotic depletion and eutrophication potential based on CML impact method assessment [13]–[15].

This paper intends to review on the application of LCA methodology focus solely on coal-fired power plant. The review summarised 22 studies conducted worldwide that had been published in the year of 2008 till 2021. The generic search was performed using "Life Cycle Assessment" and "Coal-Fired Power Plant" keywords. Through this review, the potential of conducting such study on Malaysian coal-fired power plants would benefit since LCA results help to indicate and determine the sustainability of electric generation.

2 Previous study on LCA of coal-fired power plant

Figure 1 shows the Life Cycle Assessment (LCA) framework according to ISO14040. Based upon the LCA framework, the application of LCA can enhance of product development and improvement, strategic planning, public policymaking, and marketing purposes. The framework consists of four phases: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA)and life cycle interpretation.

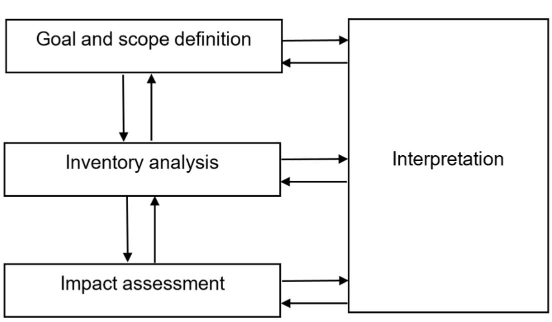

Fig. 1. Life Cycle Assessment (LCA) framework according to ISO14040 [17].

Table 1 shows the summary of previous studies on the application of LCA in coal-fired power plants. The publications were analyzed based on goal, scope, functional unit, inventory, impact assessment method and impact category. Most past studies related to LCA on coal-fired power plants are from China. Another country that has conducted similar studies includes India, Japan, Indonesia, Pakistan, Brazil, Czech Republic, UK, Netherland, Germany, Poland and Africa.

Table 1. Summary of previous studies on the application of LCA in coal-fired power plant.

Author	Scope	Location	Functional unit	System boundary	Software ;Method	Mid-point	End-point
[4]	Environment	Sahiwal Pakistan	1 MWh of electricity	Gate to gate : B2	SimaPro 8.1; ReCipe Midpoint (H) 2016	✓	✕
[18]	Volatile organic compound (VOC) emission	China	1 MWh of electricity	Cradle to gate : A1, A2, B1, B2, B3, B4, B5	VOC emission inventory analysis	✓	✕
[19]	Environment	Czech Republic	250 MW of power unit	A1, A2, B1, B2, B3, B4, B5, C1	ReCipe 1.08	✓	✓
[20]	Environment cost	China	1 GJ, one year power plant operation	A2, B2	eBalance Software, impact assessmen t method	✓	✕
[21]	Environment	Indonesia	1 GWh of net power	Gate to gate: B2	SimaPro, CML 2001	✓	✕
[22]	Environment	China	350 MJ of energy output	Cradle to gate : A1, A2, B2	Gabi software; CML 2001	✓	✕
[23]	Environment cost	China	1 ton of coal and 1 MWh of power generation	A1, A2, B2	eBalance Software	✓	✕
[24]	Environment	Not sated	Varies depending on study 4 study case : 502.32 MW, 541.3 MW, 412.03 MW and 649.6 MW	Cradle to grave : A1, A2, B1, B2, B3, B4, B5, C1, C2, C3, C4	Gabi6 software ; CML 2001	✓	✕

Author	Scope	Location	Functional unit	System boundary	Software ;Method	Mid-point	End-point
[25]	Carbon dioxide (CO2) emission	China	1 kWh of electric produce	A1, A2, B1, B2, B3, B4, B5	Life cycle inventory of energy consumption and pollutant emission	✓	✕
[26]	Environment	India	500 Mw subcritical and 600 super-critical power plants	B2	Eco-indicator 99	✓	✓
[27]	Environment	Japan	1 kWh of electricity	B2	MiLCA ver 1.1.1.110; LIME2 (Japanese LCA model)	✓	✓
[28]	Carbon dioxide (CO2) emission	China	Not stated	A1, A2, B2, C1, C2, C3, C4	Inventory analysis based on energy consumption and CO2 emission at different life cycle stage	✓	✕
[29]	Environment	Poland	1 GJ of electric produce	B2	SimaPro, Eco-indicator 99	✓	✓
[30]	Environment	Poland	1 MWh of electric produce	B2	SimaPro, Eco-indicator 99	✓	✓
[31]	Energy, environment	China	1MWh of electricity generated	A1, A2, B2	CML 2001	✓	✕
[32]	Environment	Brazil	per kWh of electricity	A1, A2, B2	CMLCA software	✓	✕
[33]	Environment	Africa	Not stated	A1, A2, B2	SimaPro ; Eco-indicator 99 and IPCC 2001	✓	✕

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Author	Scope	Location	Functional unit	System boundary	Software ;Method	Mid-point	End-point
[34]	Environment	Brazil	1 kg of coal for mining activity and 1 MWh of electric produce	A1, A2, B2	SimaPro7.2, Eco-indicator 99 and IPCC 2007a	✓	✕
[35]	Environment	Not stated	1 kWh of net electricity	B2, C1, C2, C3, C4	ReCipe 2008	✓	✕
[36]	Environment	Germany	1 kWh of electric produce	A1, A2, B1, B2, B3, B4, B5, C1, C2, C3, C4	CED, IPCC and CML 1992	✓	✕
[37]	Environment	Netherland	1 kWh of electric produce	Cradle-to-grave : A1, A2, B1, B2, B3, B4, C1, C2, C3, C4	CML 2000	✓	✕
[38]	GHG emissions	UK	1 kWh of electricity	B1, B2, B3	Material based analysis: Emission factor used to evaluate the GHG emission characteristic of power generation technology	✓	✕

Note : A1-Raw materials mining, A2- Raw materials transportation, B1-Construction of power plant, B2-Power plant operation, B3-Decomissioning of power plant, B4-Flue gas treatment, B5- Waste treatment, C1-Carbon capture, C2-Carbon compression, C3-Carbon transport, C4-Carbon storage

2.1 Goal and scope

Previous studies show that the environmental performance of coal-fired power plants is vital to ensure that sustainable electricity is generated from fossil fuel power plants. During the goal and scope phase, the objective of assessment of product system must first be established as well as setting the functional unit and system boundaries [39]. The scope of previous studies can be grouped into three interest areas: environment performance, environment cost performance, energy environment performance and/or focus on emissions such as GHG emissions, CO_2 emissions or VOC emissions as shown in Table 1.

The most common practise is that LCA is good for evaluating the environmental performance of individual power plants. The environment performance of different electric generation technologies with and without carbon capture and storage (CCS) were analyzed and compared using LCA. Rasheed et al. [4] analyze the life cycle impact of individual super-critical coal-power plant which are the first environment impact quantification of modern coal power plant at Sahiwal Pakistan. The results indicate the super-critical power plant effectively reduce the eco-footprint. LCA also was employed in comparing different type of CCS, the result shows the implementation of CCS it found to reduce greenhouse gas significantly [19, 27, 32, 37].

Li et al. [20] and Wang et al. [23] assess the external environmental costs of the coal-fired power plants. The external environment cost is the total cost of repairing environmental damage since coal-fired power plant emits harmful pollutants that cause environmental deficiencies and human health issues. The cost includes environment maintenance cost, prevention cost, resources consumption cost and environment pollution cost. LCA helps to analyze the environmental impact and suggest measures to optimize resources, control energy consumption and discharge less pollutant to promote clean electric generation from coal-fired power plant

Liang et al. [31] adopts energy and environment analysis by comparing clean coal power generation technology between integrated gasification combine cycle (ICGG), sub-critical coal power generation (Sub-C), super-critical coal power generation (Super-C) and ultra-super critical coal generation (USC) as well as discussing the discuss on capital cost of different generation technology in China. The results indicate USC has the highest life cycle energy efficiency since the net generating efficiency is high and has low auxiliary power consumption. Moreover, the ultra-supercritical and super-critical technology has the lowest capital cost while integrated gasification combine cycle (IGCC) has much expensive capital cost.

2.1.1 Functional unit

The functional unit describes the function of a product that form the foundation for all impact assessment calculations [40]. The functional unit is the reference unit for quantifying the production system's performance [17]. The functional unit used in previous studies is either GJ, GWh, MWh or kWh.

2.1.2 System boundary

System boundary determine the unit process that shall be included within the assessment [17]. Previous studies have utilized different system boundary called as cradle-to-grave, cradle-to-gate and gate-to-gate. Cradle-to-gate is known as full life cycle assessment. It starts from resources extraction, manufacturing and fabrication of the product, distribution of the product to the consumer, and product use by the consumer until product disposal or product recovery after its useful life. Meanwhile, cradle-to-gate assess the product's life cycle starting from the resources extraction to the point of manufacture or product distribution to consumer. There are also studies conducted on a gate-to-gate basis where it only assesses the environment impact on the product manufacturing process.

Petrescu et al. [24] and Koornneef et al. [37] are example of previous studies conduct LCA study using cradle-to-grave system as shown in Figure 2. The cradle-to-grave system boundary in coal-fired power plant were divided into three parts; i) coal extraction, processing, and transportation to power plant, ii) power plant operation including flue gas treatment and waste treatment, there are a few some studies include construction and decommissioning of power plant in study boundary, iii) carbon capture and storage which include the carbon capture, compression transportation and storage.

Peng et al. [18] and Yu et al. [22] conducted studies using cradle-to-gate boundary where the boundary covers coal mining, coal transportation until power plant operation, including construction and decommissioning of power plant flue gas and waste treatment. Rasheed et al. [4] and Arsyad and Setiadi [21] conducted the study employing gate-to-gate system boundary however it only covers the power plant operational only.

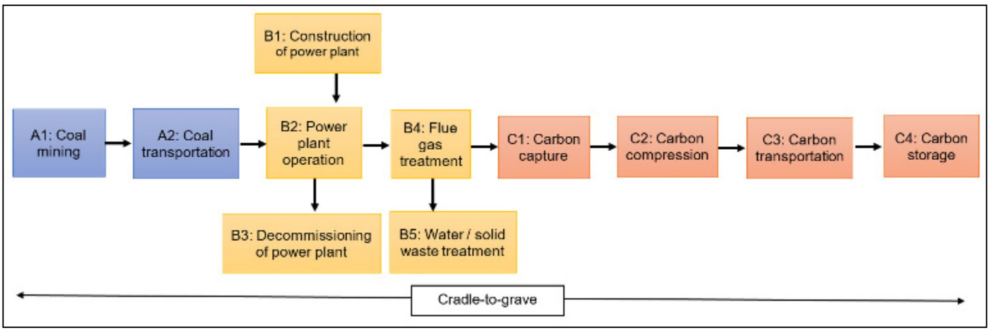

Fig. 2. Cradle-to-Grave system boundary.

2.2 Inventory analysis

Inventory analysis phase compiles and quantifies the product's input and output through its life cycle [17]. Figure 3 shows the input and output data in the inventory analysis. The input data were collected based on the physical flows of resources, materials, and semi-products into the product system, while the output data are based on emissions, waste, and valuable products generated in system boundary [41]. Based on previous studies, the inventory may be taken data from secondary data including literature review, statistic report, laboratory report or using data from Ecoinvent databased.

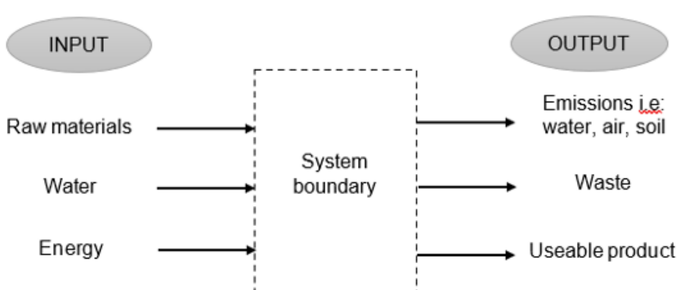

Fig. 3. Input and output data in inventory analysis.

2.3 Impact assessment

Impact assessment is a phase of life cycle assessment designed to determining the amount and relevance of possible environmental consequences for a product system through its life cycle [17]. Different impact assessment methods are applied in the previous studies. The impact assessment consists of five components: selection, classification, characterization, normalization, and weighting [41]. These components often varying according to impact assessment method which may contribute to different LCA results. Characterization factor caused significant changes in LCA results [42].

Based on summary of previous studies on the application of LCA in coal-fired power plant in Table 1, most studies conduct the assessment until the mid-point level and a few studies extend the impact assessment category until the end-point level where it assesses the human health, resources, and ecosystem damage category. Only Eco-indicator and ReCiPe methods offer the end-point damage category. The mid-point impact category was summarized in Table 2.

Table 2. Summary of mid-point impact category of CML, Eco-indicator and ReCiPe method.

Mid-point impact category	CML (baseline)	Eco-indicator 99	ReCiPe
Acidification	✓	✓	✓
Climate change	✓	✓	✓
Resources depletion	✓	✓	✓
Ecotoxicity	✓	✓	✓
Eutrophication	✓	✓	✓
Human toxicity	✓	✓	✓
Ionizing radiation	✕	✓	✓
Land Use	✕	✓	✓
Ozone layer depletion	✓	✓	✓
Particulate matter	✕	✓	✓
Photochemical oxidation	✓	✕	✓

Figure 4 indicate the impact assessment method used in previous LCA studies. Most studies utilised *Centrum voor Milieukunde Leiden* or CML assessment method. CML method is problem-oriented approach while Eco-Indicator 99 is damage-oriented approach [43]. Eco-indicator 99 assessment method suitable to be adopted for product evaluation by computing the eco-indicator score for the material and manufacturing process [44]. ReCiPe assessment method is known as the most updated and globally used in LCA due to its simplicity accuracy and diverse impact modelling options [4]. ReCiPe method combines the CML method’s problem-oriented approach with Eco-indicator 99's damage-oriented approach [19].

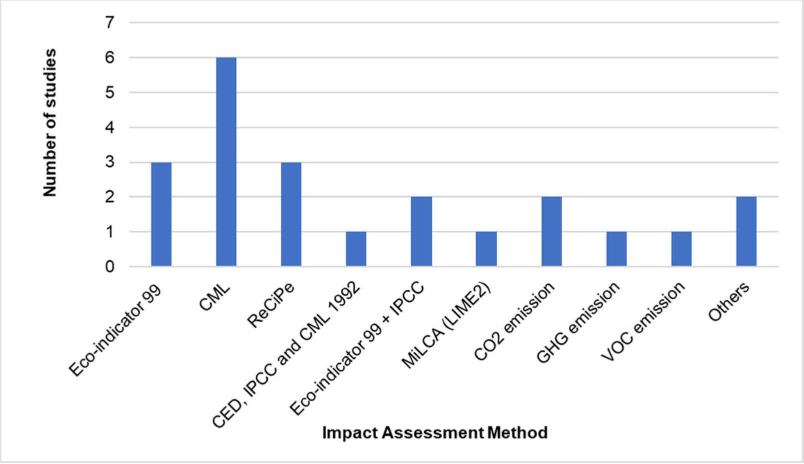

Fig. 4. Impact assessment method.

There is also a method used specifically in certain countries such as LIME 2 where it referred to Lifecycle Impact assessment Method based on modelling version 2 and known as LCA method developed for Japanese environment conditions [27]. Some studies use two assessment method example Restrepo et al. [34] used Eco-indicator 99 method to measure the acidification impact and IPCC 2007 to measure global warming potential. Mbohwa [33] used Eco-indicator 99 to measure carcinogenic compounds, organic compounds, inorganic compounds, climate change, radiation, ozone hole, ecotoxicity, acidification/eutrophication, land use, fossil fuels and used IPCC 2001 to measure global warming potential.

3 Malaysia coal-fired power plant

The high dependency on natural gas and coal as primary resources is a key concern in Malaysia's fossil-fuel power generation sector [45]. Increasing energy demand to support the country's growth in the coming years, CO_2 emissions will inevitably increases as long as fossil fuels are the primary energy source [46]. In Malaysia, ome of the coal-fired power plant that still in operation includes Kapar in Selangor (1600 MW), Janamanjung in Perak (2100 MW), Tanjung Bin in Johor (2100 MW), Jimah in Negeri Sembilan (1400 MW), Sejingkat in Sarawak (210 MW) which owned by independent power producers [47]. Currently, Jimah East Power (2000 MW), Tanjung Bin Energy (2100 MW) and Janamanjung Unit 4&5 (2000 MW) power plant are among coal-fired power plant utilized ultra-supercritical technology. As compare to sub-critical and super-critical technology, ultra-supercritical technology was developed to allow power plant to operate at high pressure and temperature, hence, the net efficiency is much better [48].

LCA is a systematic method in evaluating the potential of environment impact and it has potential to be implemented in Malaysia coal-fired power plant. Besides, the LCA framework is gradually accepted by other countries in implementing an action plan towards sustainable development [8]. The mid-point impact category such as climate change, acidification, eutrophication, and particulate matter are the potential impact variables to coal-fired power plant since the main environment problem is much related to air and water pollution. Furthermore, the assessment could be extended to damage impact category to include measurement on the impact to human health and ecosystem affected by electric generation in coal-fired power plant. Based on Table 1, the LCA study has been conducted at ultra-supercritical coal-fired power plant by Koornneef et al. [37] study in the period of 2011-2013 and Liang et al. [31] study focus on power plant case study in China. Even though both studies use the CML impact assessment method, the study boundary is different. The impact categories from which the data are obtained are varied. Additional research is required, particularly at Malaysian coal-fired power plants, by utilizing our inventory. As mentioned in *Rancangan Malaysia ke-12* [49], Malaysia is committed to have 45% carbon reduction in 2030, therefore this study is relevant since LCA able to measure the amount of carbon release by the coal-fired power.

4 Conclusion

Currently, Malaysia energy mix depends much on coal-fired power plant. However, the production of electricity using coal causes a high impact on climate change and global warming potential. This paper reviews the application of LCA in evaluating the environmental impact of coal-fired power plants worldwide. Previous studies has shown that the electricity generate from the coal-fired power plant may enhance the positive view of future coal-fired power plant. Transition from sub-critical, super-critical, ultra-supercritical to IGCC coal-fired technology and implementation of CCS at coal-fired power plant create diverse opportunities to build much cleaner electricity in future. Based on previous study, life cycle assessment method is able to evaluate the potential environmental impact of electric generation from coal-fired power plant. Thus, Malaysia should take this initiative by conducting similar study at Malaysian coal fired-power plant. Results from LCA also can utilized widely from the regulation at government level, sustainability of production at industry level and green energy choice at consumer level.

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