Journal of Sustainable Mining 18 (2019) 150–161

Contents lists available at ScienceDirect

Journal of Sustainable Mining

journal homepage: www.elsevier.com/locate/jsm

Research paper

Life cycle assessment of cobalt extraction process

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ARTICLE INFO

Keywords:
Life cycle assessment
Environmental impact
Cobalt extraction
Mining
Sustainability

ABSTRACT

This paper presents the results of an investigation carried out on the impacts of cobalt extraction process using a life cycle assessment by considering a cradle-to-gate system. Life cycle inventory data was collected from the EcoInvent and Australian Life cycle assessment database (AusLCI) and analysis were performed using SimaPro software employing the International Reference Life Cycle Data System (ILCD) method, and Cumulative Energy Demand method (CED) for per kg of cobalt production. Several impact categories are considered in the analysis i.e. global warming, ozone depletion, eutrophication, land use, water use, fossil fuels, minerals, human toxicity, ecotoxicity, and cumulative energy demand. The analysis results indicate that among the impact categories, eutrophication and global warming impacts are noteworthy. Medium voltage electricity used in cobalt production and the blasting operation appears to be causing most of the impact and emission into the environment. The sensitivity analysis was carried out using three different case scenarios by altering the electricity generation sources of UCTE (Synchronous Grid of Continental Europe) to investigate the proportional variation of impact analysis results. Furthermore, the impacts caused by cobalt production are compared with nickel and copper production processes to reveal their relative impacts on the environment and ecosystems.

1. Introduction

Cobalt is a valuable metal found in the earth's crust which is extensively used in a wide range of industrial and military applications (Tkaczyk, Bartl, Amato, Lapkovskis, & Petranikova, 2018). In recent years, due to the diverse range of its industrial application, the demand for cobalt has increased significantly and, as a result, the global production of cobalt has increased. Consequently, the environmental impacts are also increasing with the increased production level. Particles emitted during cobalt mining consists radioactive emissions, cancer-causing particles, and particles which may cause vision problems, vomiting and nausea, heart problems, and Thyroid damage. Cobalt is an important gamma-ray source which is used as a radio therapeutic agent for cancer treatment (Baskar, Lee, Yeo, & Yeoh, 2012). A high concentration of cobalt may cause asthma or pneumonia, through the breathing of a high concentration of cobalt (Ruokonen, Linnainmaa, Seuri, Juhakoski, & Söderström, 1996). Cobalt particles may also affect ecosystems through accumulation in fruit or plant seeds which grow in contaminated soils. In the natural environment, cobalt comes into contact with soil, water, rocks, and plants and once it enters the environment, it cannot be destroyed (Fordyce, 2013). Cobalt reaches the environment through air-blown dust, surface water, and radioactivity or from mining areas. Therefore, identifying the possible impacts on human health and ecosystems, and minimizing them is the prime motivation of this research to ensure the sustainable extraction process of cobalt worldwide. To date, no research has reported the life cycle assessment of the cobalt extraction process and quantified the environmental effects on human health and ecosystems.

Life cycle assessment is a valuable tool that is used to conduct the environmental impact assessment of different metal extraction processes. Life cycle assessment assesses impacts on the environment, human health, land, water, and soil during mining and other similar processes, as visible in some previous studies (Mahmud, Huda, Farjana, & Lang, 2018a, 2018b). There are several pieces of published research based on the life cycle assessment of metal mining processes, which quantified the environmental burdens associated with the metal or process studied. Among others, research on aluminum, copper, coal, gold, nickel, iron, zinc, manganese, steel, ilmenite, rutile, and uranium has been published to date. Most of these studies are primarily focused on assessing the impacts on global warming, energy demand, and acidification potential. Only a few studies consist of a full LCA study which contains impact analysis based on several categories of human health, ecosystems, and resources.

Table 1 highlights some of the significant pieces of research

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https://doi.org/10.1016/j.jsm.2019.03.002
Received 30 November 2018; Received in revised form 1 March 2019; Accepted 1 March 2019

Table 1
Research comparison of significant LCAs on mining processes.

Metals	Summary of the work	Methods in use	Impact on global warming and human health	Impactful material/process and impact category
Aluminum (Shahjadi Hisan Farjana, Huda, & Mahmud, 2019a; Tan & Khoo, 2005)	Life cycle assessment of the aluminum supply chain in Australia was conducted, which consisted of the mine, smelter, and refinery.	EDIP or UMIP 96 method using SimaPro software, ILCD and CED method using SimaPro software	1.83E07 g CO_2 eq./g GWP 6.49E08 g based on EDIP human toxicity	Smelting and refining, electricity consumption
Copper (Haque & Norgate, 2014; Norgate & Haque, 2010; Northey, Haque, Lovel, & Cooksey, 2014)	Life cycle assessment of copper production processes in Australia and globally	ReCiPe and Australian indicator method	1 to 9 t CO_2 eq. GWP	Solvent extraction and electrowinning, electricity consumption
Gold (Chen et al., 2018)	A life cycle assessment was conducted based on China and Australia	ReCiPe method	5.55E4 kg CO_2 eq. GWP 4.37E3 kg 1,4-DB eq. human toxicity	Mining and comminution, electricity consumption
Iron (Ferreira & Leite, 2015)	Life cycle assessment based on an iron mine located in Brazil was conducted	IPCC method using SimaPro software	23.32 kg CO_2 eq. 1.05E-05 DALY	Agglomeration, loading and haulage, electricity consumption
Ilmenite-rutile (Farjana, Huda, Mahmud, & Lang, 2018b)	Life cycle assessment of ilmenite and rutile extraction processes was conducted in Australia	ILCD method using SimaPro software	0.29 kg CO_2 eq. 2.4E-10 CTUh	Mining, electricity consumption
Nickel (Khoo, Haque, Woodbridge, McDonald, & Bhattacharya, 2017; Mistry, Gediga, & Boonzaier, 2016)	Life cycle assessment of nickel production processes in Australia and Indonesia	IMPACT 2002+, ReCiPe method, Australian Indicator method.	29 kg CO_2 eq. GWP	Primary extraction, nickel reduction and smelting, electricity consumption
Steel (Burchart-Korol, 2011; Burchart-Korol, 2013)	Life cycle analysis of steel production in Poland is assessed	IPCC 2007, GWP 100a, and CED method	2459 kg CO_2 eq. for blast furnace steel 913 kg CO_2 eq. for electric arc furnace steel	Integrated steel production and electric arc furnace routes
Uranium (Farjana, Huda, Mahmud, & Lang, 2018a)	Life cycle impact assessment of different uranium extraction processes was conducted on a global scale	ILCD method using SimaPro software	6.27 kg CO_2 eq. 1.68E-08 CTUh	Fuel enrichment, well field related activities, electricity consumption

conducted for different metals in the metal mining industries through life cycle assessment, their impacts on human health and global warming. The key aspects of their methodologies and analysis results are presented in Table 1 for aluminum, copper, gold, iron, ilmenite-rutile, nickel, and uranium. Most of the studies considered impacts on the environment and human health. The geographic region most focused on for aluminum, copper, gold, ilmenite-rutile, and nickel is Australia; for iron it is Brazil, and uranium is considered on a global scale. The most common analysis methods used by LCA experts in mining industries are the ReCiPe method and the ILCD method. Other methods include the CML method, the IPCC method, the IMPACT 2002 + method, and the EDIP method. The material with the greatest impact is electricity which is consumed for mining processes that are responsible for the increasing effects on global warming. Electricity is consumed on a large scale for smelting, refining, electrowinning, and leaching operations. There are some other studies based on the life cycle assessment of coal mining, ferroalloy mining, manganese mining, rare earth element mining, and zinc mining, which mostly validate the reasons provided for the high environmental effects of mining. However, as the environmental impact varies between their geographic location, analysis methodology, and software used, it is hard to make an accurate comparison due to their differences in units and location. It is evident from the literature survey presented here that the life cycle impacts of the cobalt extraction process have never been assessed previously.

In this paper, the environmental impacts caused by the cobalt extraction process is thoroughly assessed by comparing the production phases. Life cycle inventory data is collected from the Australian Life cycle assessment database and the EcoInvent database. The analysis is performed using SimaPro software employing the ILCD method and the CED method for several impact categories. The paper starts with a brief introduction followed by a detailed overview of cobalt extraction and processing routes in Section 2. Section 3 discusses world producers, their respective deposits, and the production of cobalt. Section 4 illustrates life cycle assessment assumptions and methodologies for analysis. Section 5 analyzes and compares the environmental impacts. Section 6 discusses the overall results of the impact analysis and makes future recommendations which aim to make the cobalt manufacturing process more sustainable and environmentally friendly. Section 7 provides the concluding remarks.

2. Cobalt extraction and processing

Cobalt extraction routes can be in the form of open-pit mining, underground mining or a combination of open-pit and underground mining depending on ore grade, size and surface type. These two mining methods can be employed separately or combined depending on the body or deposit type, which may contain significant amounts of cobalt. The cobalt extraction method involves three basic processes: pyrometallurgy, hydrometallurgy, and vapor-metallurgy (Pazik, Chmielewski, Glass, & Kowalczuk, 2016). A brief description of the cobalt extraction process in described by a flowchart in Fig. 1.

2.1. Open-pit mining

This method can be used if the ore is close to the surface and it is known to be the most economical mineral extraction method. In this type of mining, overburdens are removed to extract the desired metals using trucks or other conveying machines (Zhao et al., 2013).

2.2. Underground mining

When the ore body is deeper than 100 m below the surface, the underground mining method employing standard mining systems are used.

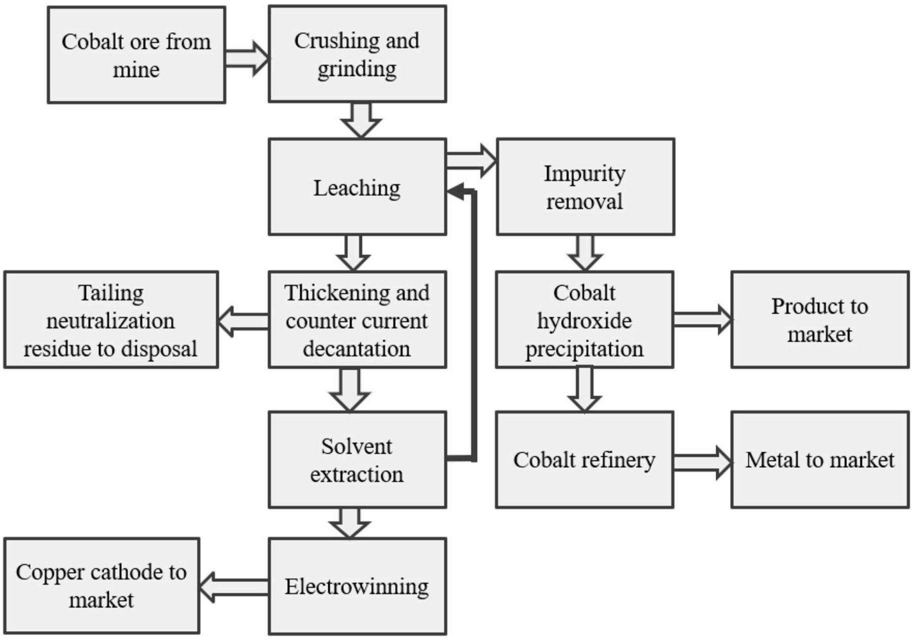

Fig. 1. Cobalt metal extraction process flow sheet.

2.3. Hydrometallurgy

Pressure acid leaching is the most common form of hydrometallurgical processing. In pressure acid leaching, slurred ore is preheated and mixed with a sulfuric acid solution in high temperature and pressure for 90 min. After this time, primary and secondary metals are converted into sulfate salts. These sulfate salts are then washed using a counter-current decantation circuit (CCD) which produces a clear nickel and cobalt solution, and residue. This mixed metal solution is sent for re-leaching with high-pressure oxygen. Then an oxide reagent is used to separate the cobalt from the nickel. The pressure acid leaching method is suitable for ores where acid consumption should be lower (Zhao et al., 2013).

2.4. Electro-winning

These processes are used for filtering the metal-rich solution in copper belt mining. After filtering, heating and electrolyting are carried out. During electrolyting, cobalt precipitates onto stainless steel which forms high purity cathodes and then the acid is recycled (Li, Rao, Li, Peng, & Jiang, 2010).

2.5. Vapometallurgy

These processes are used for extracting cobalt from laterite ores at normal atmospheric pressure. Cobalt can be recovered and refined from ore, matte and concentrate. The extracted metal containing ore is vaporized by passing carbon monoxide and other gases, and vaporized gases then pass through to a separate chamber to deposit cobalt (Fisher, 2011).

2.6. Pyrometallurgy

This is used to heat ore to separate the metals based on their specific properties and characteristics, such as melting point and density. This processing is applied in sulfide ores where smelting-based recovery is possible. Carbonates and oxide-based cobalt products are formed by smelting (Li et al., 2010; Zhao et al., 2013).

3. Producers of cobalt and their environment

As cobalt is produced as a by-product of copper and nickel, countries which produce a high quantity of those two metals also produce a high quantity of cobalt. The top ten producers of cobalt in the world are identified by the US geological survey of 2017 and are listed below in Table 2.

Table 2
Global producers of cobalt (Ober, 2017).

Country name	Production in 2017 (metric tons)	Reserve (metric tons)
Democratic Republic of Congo (DRC)	64000	3500000
Russia	5600	250000
Australia	5000	1200000
Canada	4300	250000
Cuba	4200	500000
Philippines	4000	280000
Madagascar	3800	150000
Papua New Guinea	3200	51000
Zambia	2900	270000
New Caledonia	2800	Not available
South Africa	2500	29000

The **DRC** produced 66,000 metric tons of cobalt in 2016 which was an increase of 3,000 metric tons from 2015. However, in 2017 this figure fell to 64,000. It produces 60% of the world's cobalt. In **China**, cobalt production has not changed from 2015 to 2016. China is the world's largest refined cobalt producer and the largest exporter of cobalt to the US. In **Canada**, cobalt is mostly a by-product of nickel and copper mines. In 2016, **Russia** was the world's fourth-largest cobalt producer. Russia planned to increase its cobalt production and was the second highest produced in 2017. In **Australia**, cobalt production dropped between 2015, 2016, and 2017. Like Russia, most of the produced cobalt in Australia comes as a by-product of copper and nickel mining. Due to environmental circumstances, the Philippines Government decided to cut down on cobalt production, which may continue in the future, to retain environmental sustainability (Ober, 2017; U.S. Geological Survey, 2018).

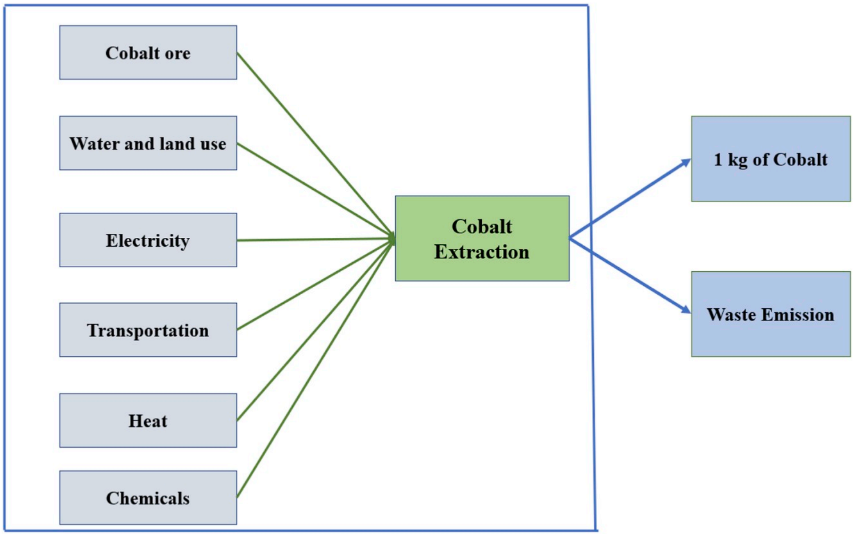

Fig. 2. System boundary of the cobalt mining process considered for the life cycle assessment.

4. Materials and methods

Life cycle assessment is a systematic tool to assess environmental effects using ISO 14040 standards through 4 defined steps. These steps are goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of the results (Curran, 2012; Farjana, Huda, & Mahmud, 2019a, 2019b; PE; International, 2014).

4.1. Goal and scope definition

The goal of this life cycle assessment is to analyze the cradle-to-gate environmental impact of cobalt production. This assessment analyzes environmental impacts under several impact categories (Farjana, Huda, & Mahmud, 2018a). The scope of this study is to calculate all the emissions or impacts generated from the steps of ore mining to final waste emission (M A Parvez Mahmud, Huda, Farjana, & Lang, 2019). Fig. 2 describes the system boundary, where cradle activities also include previous processes like extraction, production, processing of the product, transportation using different means up to the final delivery of the product, generation of electricity and finally waste emission (Farjana, Huda, & Mahmud, 2018b). A similar approach was considered by other published works in the field of the life cycle assessment of the metal mining sector (Farjana, Huda, & Mahmud, 2019a; Hischier et al., 2010; Marguerite et al., 2015).

Fig. 3 shows material flow using a Sankey diagram. This diagram shows the material flow of elements using the ILCD method. The percentage value of the elements shows single scored results. As the copper and nickel ions remain inside the system and, additionally, the amount is very small (Table 4 – life cycle inventory outputs), considered as a unit process with 100% allocation to cobalt (Westfall, Davourie, Ali, & Macgough, 2016). In this study, co-product allocation is avoided by using system expansion. As cobalt is produced in conjunction with copper and nickel, it is assumed that no other product is leaving the system. The functional unit is chosen as 1 kg of cobalt and the system boundary is cradle to gate. Co-product allocation must be avoided whenever possible as an important part of LCA methodologies (ISO 14040). This method is used when there are by-products of the original product which are contributing to the emissions (Awuah-Offei & Adekpedjou, 2011; Schmidt & Thrane, 2009; Weidema & Norris, 2002).

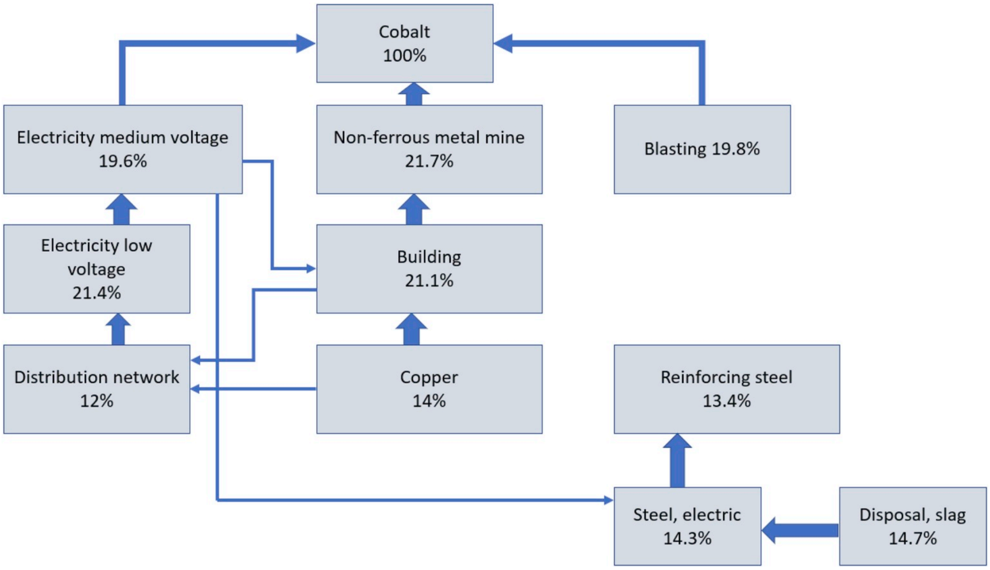

Fig. 3. Sankey diagram for the cobalt extraction process (single scored results using the ILCD method).

4.2. Life cycle inventory analysis

Table 3 and Table 4 illustrates the life cycle inventory datasets which are comprised of material inputs and outputs consisting of fuels, energy, materials, electricity, emissions to air and water, and waste emissions. Inputs include diesel burned in building machines, medium voltage electricity used for production, heat, transportation system, etc. Outputs include emissions to air, emissions to water and non-sulfidic waste emissions. The life cycle inventory dataset is gathered from the EcoInvent database, which consists of global data for the cobalt production mix and electricity mix. As the original dataset is from the EcoInvent database, this dataset is the representation of the unit process cobalt production. The geographical coverage of this dataset is global. All of the production stages are considered from metal extraction, processing, delivery as a final product, waste emissions, recycling and end of life emissions (Hischier et al., 2010; Frischknecht et al., 2005).

Table 3
Life cycle Inventory dataset-inputs (Nuss & Eckelman, 2014).

Input	Amount	Unit
Cobalt	1.32	Kg
Water, river	0.038	m^3
Water, well	0.22	m^3
Carbon monoxide	0.292	Kg
Chemicals inorganic	0.085	Kg
Hydrogen	0.02	Kg
Chemicals organic	0.025	Kg
Hydrogen cyanide	3.9E-03	Kg
Sand	45.6	Kg
Portland calcareous cement	3.62	Kg
Limestone	0.05	Kg
Conveyor belt	4.2E-6	M
Diesel, burned in building machine	12.1	MJ
Electricity, medium voltage	4.69	kWh
Aluminum hydroxide	9E-10	P
Non-ferrous metal mine	5.5E-09	P
Heat, natural gas	2	MJ
Transport, lorry >16 t	2.48	tkm
Blasting	0.166	kg

Table 4
Life cycle Inventory dataset-outputs (Nuss & Eckelman, 2014).

Output	Amount	Unit
Cobalt	1	Kg
Carbon disulfide	0.01	Kg
Heat, waste	16.9	MJ
Particulates <2.5 um	1.9E-03	Kg
Particulates >10 um	0.02	Kg
Particulates >2.5 μm and <10 um	0.018	Kg
Aluminum	1.9E-5	Kg
Arsenic, ion	6.49E-7	Kg
Cadmium, ion	6.96E-8	Kg
Calcium, ion	0.151	Kg
Chromium	1.21E-7	Kg
Cobalt	1.7E-07	Kg
COD, chemical oxygen demand	2.3E-03	Kg
Copper, ion	1.75E-6	Kg
Cyanide	4.1E-04	Kg
Iron, ion	6.4E-5	Kg
Lead	6.16E-7	Kg
Manganese	5.44E-6	Kg
Mercury	8.3E-9	Kg
Nickel, ion	5.36E-6	Kg
Nitrogen	5E-03	Kg
Suspended solids	1.1E-03	Kg
Sulfate	0.519	Kg
Zinc, ion	1.68E-5	Kg
Disposal, non-sulfidic overburden	34.9	Kg
Disposal, non-sulfidic tailings	65	Kg

Tables 3 and 4 illustrate the inputs and outputs of the cobalt extraction process.

5. Results

In the third stage, the life cycle impact assessment was carried out using SimaPro software version 8.5. This subsection illustrates the impact analysis results using the International Reference Life Cycle Data System (ILCD) method under fourteen major impact categories. The ILCD method is an outcome of a project conducted by the Joint Research Centre (JRC) of the European Commission which analyzed several life cycle impact assessment methodologies to provide consensus between different LCA methodologies for each environmental theme, for both midpoint and endpoint indicator-based categories. The midpoint indicator-based method analyzed impacts on climate change, ecotoxicity, human toxicity, eutrophication, acidification, and land and water use (Agwa-Ejon & Pradhan, 2018; ILCD Handbook, 2010, 2011; Acero, Rodriguez, & Ciroth, 2015).

5.1. LCIA from ILCD method

This subsection presents the life cycle impact assessment results using different impact assessment methods. According to the results presented here, medium voltage electricity is responsible for global warming, ecotoxicity, and human toxicity. Blasting which is widely used for eutrophication and burning diesel oil in industrial machinery is responsible for ozone depletion. Eutrophication is the largest of the five major impact categories, followed by global warming and ecotoxicity. Cobalt particles which are released into the environment during cobalt mining cannot be destroyed. Cobalt is released into the environment from coal, oil, fuels used in trucks and industrial processes as a metallic compound. Acid drainage happens in many mining sites due to the exposure of sulfide minerals to both air and water. Though mines are most commonly associated with water pollution, they also cause air pollution. The most common air polluting elements from mines are dust and airborne particulate matter. Dust is created by drilling, blasting, loading and unloading, waste rocks, etc. These sources of air pollution cause breathing problems for mine workers as they may contain very small metal particles. This dust also contaminates local soils, plants, and animals (Chang, Simmers, & Knight, 2010). A detailed characterized results of life cycle assessment using the ILCD method are showed in Table 5.

5.1.1. Global warming

According to the results for Global Warming using the ILCD method, it is one of the largest impact categories from the analysis of cobalt mining production routes. In the global geographical context, medium voltage electricity production is the largest contributor to global warming. Analyzing the life cycle inventory dataset, fossil fuel-based carbon dioxide makes up the greatest portion of global warming. In the ILCD method, fossil fuel-based carbon dioxide is responsible for 9.52 kg CO_2 eq. Out of a total 10.8 kg CO_2 eq.

5.1.2. Human toxicity

Human toxicity can be classified as cancer or non-cancer. According to the impact assessment results, medium voltage electricity, blasting and the cobalt ore used in mining cobalt metal lead to detrimental human health effects. Among others, arsenic, cadmium, cobalt, and manganese contribute most to human toxicity effects. Arsenic and manganese are responsible for a non-cancer effect while cadmium and cobalt for a cancer effect.

5.1.3. Ozone depletion

Ozone depletion potential is another major impact category caused primarily by the diesel burned in machines in the cobalt production process. By analyzing the inventory results from the total value of 3.68E-7 kg CFC 11-eq, methane and bromotrifluoro halon 1301 are

Table 5
Life cycle assessment results using the ILCD method (characterized results).

Impact category	Unit	Total	Blasting	Diesel	Electricity
Climate change	kg CO_2 eq.	11.73	0.53	1.14	4.74
Ozone depletion	kg CFC-11 eq.	4.07E-07	1.36E-08	1.34E-07	5.94E-09
Human toxicity, non-cancer	CTUh	1.2E-06	3.25E-08	3.2E-08	1.46E-07
Human toxicity, cancer effects	CTUh	3.15E-07	3.44E-08	3.02E-08	5.59E-08
Particulate matter	kg PM2.5 eq.	5.9E-03	2.2E-03	1.4E-03	5.01E-04
Ionizing radiation HH	kBq U235 eq.	0.012	5.4E-04	3.7E-04	7.1E-04
Ionizing radiation E (interim)	CTUe	3.54E-08	1.65E-09	1.09E-09	2.13E-09
Photochemical ozone formation	kg NMVOC eq.	0.11	0.06	0.015	0.01
Acidification	molc H+ eq.	0.11	0.07	0.012	9.2E-03
Terrestrial eutrophication	molc N eq.	0.54	0.37	0.056	0.05
Freshwater eutrophication	kg P eq.	1.03E-03	2.84E-05	9.45E-06	1.5 E_04
Marine eutrophication	kg N eq.	0.043	0.023	5.1E-03	4.6E-03
Freshwater ecotoxicity	CTUe	7.32	0.56	0.39	1.99
Land use	kg C deficit	40.97	0.38	3.043	0.4
Water resource depletion	m^3 water eq.	0.059	4.8E-04	4.67E-04	1.6E-03
Mineral, fossil & ren resource depletion	kg Sb eq.	4.14E-12	2.54E-14	1.45E-14	4.01E-14

responsible for 3.52E-7 kg CFC 11-eq.

5.1.4. Eutrophication

The blasting stage is responsible for causing eutrophication. From the life cycle inventory datasets, it is evident that nitrogen oxides emitted in this stage cause eutrophication. The amount contributed by nitrogen oxides is 0.0115 kg PO_4-eq. From a total of 0.0179 kg PO_4-eq. Nitrogen oxide emissions cause smog and acid rain, which in turn causes eutrophication.

5.1.5. Ecotoxicity

ILCD method classifies ecotoxicity as freshwater. The medium voltage electricity used in cobalt mining process is responsible for freshwater aquatic ecotoxicity. From the life cycle inventory dataset, it can be observed that the fluoride is the main contributor to ecotoxicity, where the ecotoxicity value varies among ecotoxicity categories and impact assessment methods.

5.1.6. Land and water use

Land and water use is the least impactful category from the cobalt extraction process. However, a few environmental effects are evident from the analysis results. The disposal of cobalt extraction which involves non-sulfidic tailings has an impact on land use. The land use category can be subdivided into the ecosystem and biodiversity.

5.1.7. Fossil fuels

This category indicates the adiabatic depletion of fossil fuels based on the energy content of the fuel. This category gives an insight into the depletion of natural resources from the earth. Cobalt extraction has minor impacts on the fossil fuel category, while medium voltage electricity production consumes most of the fossil fuels which emits carbon monoxide and Portland cement.

5.1.8. Minerals

This category illustrates the adiabatic depletion of minerals which is based on the concentration of the current economic reserve and the rate of deaccumulation. According to the analysis results presented here, minerals are mostly consumed in the blasting process, while mineral use in other processes is negligible.

Fig. 4 illustrates the comparative life cycle assessment results of the cobalt extraction process using the ILCD method.

5.2. LCIA from CED method

The impact categories of the cumulative energy demand (CED) method provide the breakdown of fuel use by the materials/processes involved. This is based on fuel input across the system, which considers fossil, renewable, nuclear, biomass and all other energy sources. This method provides the total amount of energy consumed based on high and low heat values. The amount of energy available from the combustion of fuel without recovering energy associated with water condensing vapor produced in the combustion is known as low heating values.

On the other hand, high heating values include the energy recovery associated with the latent heat of vaporization and condensation. This method aims to quantify primary energy usage throughout the life cycle of a process or product. The energy usage is quantified through the direct and indirect use of energy, but not the waste used for energy purposes. This method is comprised of eight different impact categories where no normalization or weighting data is included in this method (Hischier et al., 2010).

From the analysis results presented in Table 6 and Fig. 5 below, it is clearly shown that medium voltage electricity production consumes the most energy, with the greatest amount of energy coming from coal. Blasting is another energy-intensive process which is dependent on oil-based fossil fuels.

6. Discussion

From the results of the impact analysis on different impact categories, such as: ozone depletion, global warming, acidification, eutrophication, ecotoxicity, and human toxicity, the impacts of cobalt production are quite clear. The main reason for the environmental impact of cobalt extraction is fossil fuel consumption. From the analysis results presented in this paper, cobalt mining is greatly affecting human health. It may or may not be cancer causing, but it is mainly caused by the electricity used in the cobalt mining process, blasting and cobalt ores used in production. The harmful particles are arsenic, cadmium, cobalt and manganese. The LCA results found from the present research validates the fact that cobalt mining is harmful not only for people living near the mining area but also for the cobalt miners as they inhale large amounts of particles which are mixed with the air. From the analysis results of this paper, cobalt mining consumes large amounts of electrical power which is responsible for significant environmental effects. Similar insight if found from the emission results of fossil fuels. However, the effect is very few from sulfidic tailings or waste emissions from cobalt mining. However, the form of cobalt released into the environment and its impacts are not known. It may impact human health, soil, air, water, plant life or animals.

6.1. Sensitivity analysis

For the sensitivity analysis carried out in this study, four different case scenarios are chosen including a base case scenario. The details are outlined below:

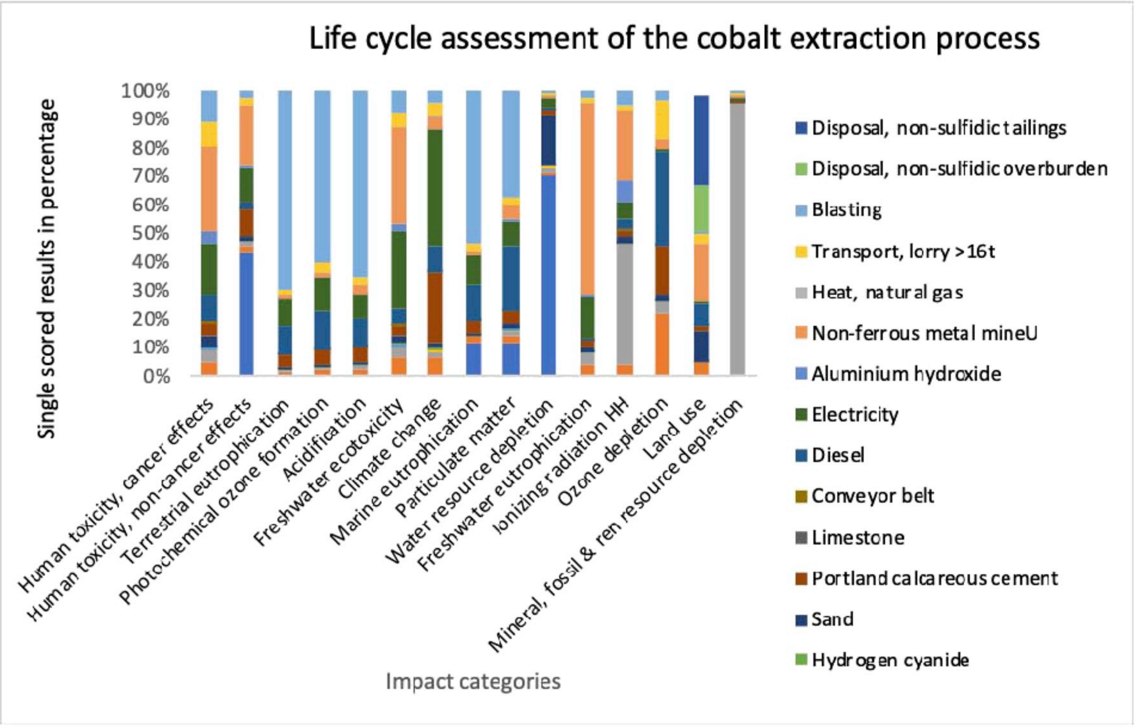

Fig. 4. Impacts of cobalt extraction process using the ILCD method (single scored results).

Scenario 1. The base case with the required amount of medium voltage electricity (4.69 KWh) produced from UCTE (the Synchronous Grid of Continental Europe) network, supplying medium voltage electricity.

Scenario 2. The arbitrary case with the required amount of medium voltage electricity (4.69 KWh) produced from UCTE (Synchronous Grid of Continental Europe) network, produced using natural gas.

Scenario 3. The arbitrary case with the required amount of medium voltage electricity (4.69 KWh) produced from UCTE (Synchronous Grid of Continental Europe) network, produced using lignite.

Scenario 4. The arbitrary case with the required amount of medium voltage electricity (4.69 KWh) produced from UCTE (Synchronous Grid of Continental Europe) network, produced using oil.

These arbitrary case scenarios and the base case scenario compare the electricity generation sources of the UCTE network, and whether the alteration of the electricity generation source could reduce the environmental impact or not. The analysis results presented in Table 7 show that the environmental impact could be significantly reduced after integrating a natural gas-based power plant with a cobalt extraction plant. In the base case scenario, the climate change impact is 11.73 kg CO_2 eq., whereas using a natural gas-based power plant it would be 9.73 kg CO_2 eq. The climate change impact would also be reduced using an oil-based power plant, as the impact would be 11.23 kg CO_2 eq. However, from a lignite-based electricity generation source it would be 12.67 kg CO_2 eq.

Similarly, for all of the impact categories, the environmental effect

Table 6
Comparative life cycle assessment results from the Cumulative Energy Demand method as a percentage (characterized results).

Label	Renewables (total 100%)	Fossil fuels – oil (total 100%)	Fossil fuels – gas (total 100%)	Fossil fuels – coal (total 100%)	Biomass (total 100%)	Nuclear (total 100%)	Embodied energy LHV (total 100%)	Embodied energy HHV (total 100%)
Carbon monoxide	10.49	24.99	8.88	10.71	1.34	0.114	14.87	14.75
Chemicals inorganic	1.49	1.05	3.9	1.38	2.34	33.724	1.69	1.75
Hydrogen	0.06	1.8	3.38	0.06	1.18	20.45	1.16	1.19
Chemicals organic	0.24	2.03	3.13	0.2	0.82	29.73	1.27	1.29
Hydrogen cyanide	0.071	0.15	1.75	0.03	0.6	12.22	0.35	0.37
Sand	1.96	2.61	1.54	1.99	0.37	0.29	2.11	2.1
Portland calcareous cement	10.03	12.98	5.67	8.77	0.98	1.186	9.62	9.57
Limestone, milled, packed	0.13	0.024	0.017	0.018	5.89	0.042	0.033	0.03
Diesel, burned in building machines	0.44	38.55	2.92	0.45	0.08	0.24	12.78	12.56
Electricity	71.67	0.89	49.4985	73.22	8.99	0.007	46.59	46.71
Heat, natural gas	0.04	0.004	10.96	0.042	0.005	2.51E-05	1.76	1.9
Transport, lorry > 16 t	0.12	11.53	0.84	0.13	0.025	0.072	3.81	3.75
Blasting	3.23	3.37	7.45	2.97	77.35	1.92	3.94	4

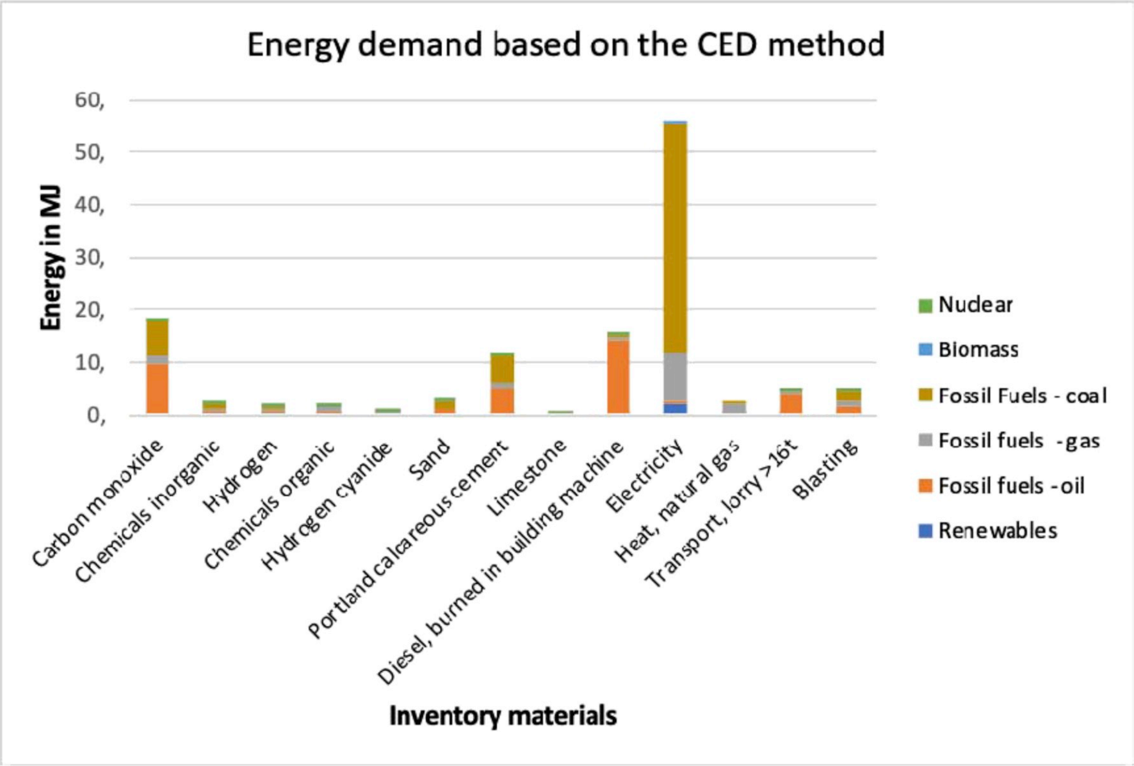

Fig. 5. Comparative life cycle assessment results from the Cumulative Energy Demand method (single scored results).

Table 7
Sensitivity analysis results from 3 different case scenarios.

Impact category	Unit	Scenario 1. Base case, electricity medium voltage, UCTE network	Scenario 2. Electricity based on natural gas, UCTE network	Scenario 3. Electricity based on lignite, UCTE network	Scenario 4. Electricity based on oil, UCTE network
Climate change	kg CO_2 eq.	11.73	**9.73**	12.67	11.23
Ozone depletion	kg CFC-11 eq.	4.07E-07	**4.01E-07**	4.05E-07	8.9E-07
Human toxicity, non-cancer effects	CTUh	1.2E-06	**1.05E-06**	1.28E-06	1.15E-06
Human toxicity, cancer effects	CTUh	3.15E-07	**2.59E-07**	3.4E-07	2.87E-07
Particulate matter	kg PM2.5 eq.	5.9E-03	**5.5E-03**	8.2E-03	9.1E-03
Ionizing radiation HH	kBq U235 eq.	0.012	**0.011**	0.011	0.011
Ionizing radiation E (interim)	CTUe	3.54E-08	**3.33E-08**	3.41E-08	3.41E-08
Photochemical ozone formation	kg NMVOC eq.	0.11	**0.099**	0.11	0.11
Acidification	molc H+ eq.	0.11	**0.1**	0.15	0.15
Terrestrial eutrophication	molc N eq.	0.54	**0.49**	0.52	0.54
Freshwater eutrophication	kg P eq.	1.03E-03	**8.8E-04**	9.5E-04	8.9E-04
Marine eutrophication	kg N eq.	0.043	**0.04**	0.041	0.044
Freshwater ecotoxicity	CTUe	7.32	**5.33**	7.84	8.41
Land use	kg C deficit	40.97	**40.61**	40.68	51.62
Water resource depletion	m^3 water eq.	0.059	**0.059**	0.088	0.13
Mineral, fossil & ren resource depletion	kg Sb eq.	4.14E-12	**4.1E-12**	4.25E-12	4.16E-12

would be reduced if natural gas based electricity was used during the cobalt extraction process. The ozone depletion impact would be 4.01E-07 kg CFC-11 eq., the human toxicity non-cancer effect would be 1.05E-06 CTUh and the human toxicity cancer impact would be 2.59E-07 CTUh. However, the reduction is not that significant. In summary, from the four cases based on different power generation source, a natural gas-based power plant is better than all of the other UCTE based energy generation systems. The base case shows moderate environmental impacts, while the worst case is when using a lignite-based power generation source. Some studies show that electricity generation source can contribute to decreasing environmental burdens (Mahmud, Huda, Farjana, & Lang, 2018c, 2018d). Future studies could be carried out to reduce the environmental impacts of mining from process heat generation sources. Renewable energy integration in heat generation systems in industrial processes is a state-of-the-art alternative for reducing environmental burdens (Farjana, Huda, Mahmud, & Saidur, 2018a, 2018b).

6.2. Uncertainty analysis

The uncertainty analysis of the cobalt extraction process, with a 95% confidence interval, reveals the variability of the LCA data for determining the significance of the results. The uncertainty analysis in life cycle assessment is defined by ISO 14044 as a systematic procedure for quantifying the uncertainty introduced in the results of the life cycle

Table 8
Uncertainty analysis of the cobalt extraction process.

Impact category	Unit	Mean	Median	Standard Deviation
Acidification	molc H+ eq.	0.11	0.11	0.025
Climate change	kg CO_2 eq.	11.44	11.3	1.66
Freshwater ecotoxicity	CTUe	7.06	5.89	4.81
Freshwater eutrophication	kg P eq.	1E-03	7.2E-04	1.6E-03
Human toxicity, cancer effects	CTUh	3.19E-07	2.74E-07	2.22E-07
Human toxicity, non-cancer effects	CTUh	1.2E-06	1.13E-06	3.25E-07
Ionizing radiation E (interim)	CTUe	3.54E-08	3.26E-08	1.3E-08
Ionizing radiation HH	kBq U235 eq.	0.012	9.8E-03	0.012
Land use	kg C deficit	41.19	39.58	12.7
Marine eutrophication	kg N eq.	0.042	0.04	9.2E-03
Mineral, fossil & ren resource depletion	kg Sb eq.	4.2E-12	3.91E-12	1.55E-12
Ozone depletion	kg CFC-11 eq.	4.05E-07	3.65E-07	1.73E-07
Particulate matter	kg PM2.5 eq.	5.9E-03	5.6E-03	1.6E-03
Photochemical ozone formation	kg NMVOC eq.	0.11	0.1	0.026
Terrestrial eutrophication	molc N eq.	0.53	0.51	0.13
Water resource depletion	m^3 water eq.	0.059	0.058	9.1E-03

inventory analysis, as cumulative effects of model imprecision, data variability, and input uncertainty. The most important impact categories for the cobalt extraction process are global warming, eutrophication, land use, and minerals. These impact categories do not show much variability in their results or their datasets. However, uncertainty in the dataset is more evident in the case of ozone depletion and water use, which are of negligible effect when considering the cobalt extraction process. He uncertainty results of the cobalt extraction process based on the ILCD method (characterized results) are described in Table 8 below.

6.3. Comparison with copper and nickel

The cobalt extraction process is compared with the copper and nickel production process to identify its relative importance. Allocation is avoided in this study by assuming that no byproduct is leaving the system. According to ISO standard 14040 for life cycle impact assessment, the allocation must be avoided wherever possible to enhance the accuracy of the impact analysis results (Hischier et al., 2010; Weidema & Norris, 2002). From the analysis results presented in Table 9 and Fig. 6, nickel extraction is much more impactful than cobalt and copper extraction routes. The major impact categories for nickel extraction are eutrophication, global warming, and ecotoxicity. The reason behind such results is that nickel production is the most energy-intensive process which requires high voltage and low voltage electricity based on coal, hydropower and heavy fuel oils, which is detrimental for ecosystems and global warming. Copper extraction is the safest of the three.

Table 9
Comparative life cycle assessment results from cobalt, copper, and nickel extraction processes.

Impact category	Unit	Cobalt	Copper	Nickel
Climate change	kg CO_2 eq.	10.81	5.44	11.19
Ozone depletion	kg CFC-11 eq.	3.68E-07	2.68E-07	5.12E-07
Human toxicity, non-cancer effects	CTUh	6.95E-07	7.79E-07	2.52E-06
Human toxicity, cancer effects	CTUh	1.45E-08	2.54E-08	4.51E-08
Particulate matter	kg PM2.5 eq.	5.3E-03	0.024	0.095
Ionizing radiation HH	kBq U235 eq.	1.9E-03	0.103	0.52
Ionizing radiation E (interim)	CTUe	1.57E-08	9.37E-07	4.72E-06
Photochemical ozone formation	kg NMVOC eq.	0.11	0.076	0.18
Acidification	molc H+ eq.	0.1	0.42	1.87
Terrestrial eutrophication	molc N eq.	0.52	0.26	0.38
Freshwater eutrophication	kg P eq.	3.18E-05	0.01	0.014
Marine eutrophication	kg N eq.	0.041	0.018	0.026
Freshwater ecotoxicity	CTUe	0.52	9.25	17.52
Land use	kg C deficit	24.69	4.58	6.76
Water resource depletion	m^3 water eq.	0.057	0.032	0.053
Mineral, fossil & ren resource depletion	kg Sb eq.	3.98E-12	2.12E-12	2.93E-12

6.4. Comparison with previous LCA studies and major findings

Comparison with previous significant studies conducted for various metal mining processes indicates the impact category which has the greatest impact and the most impactful material or process in use. The result shows that for the mining processes of aluminum, copper, cobalt, gold, nickel, iron, ilmenite-rutile, and uranium; the largest impact category is global warming potential. Other significant categories consist of metal depletion, eutrophication, and effect on human health. The greatest contributor to the impacts felt from mining industries is electricity consumed for mining operations, smelting and refining processes, mining and comminution, well field related activities, fossil fuel consumption for electricity generation and process heat generation. Table 10 shows a comparison between the main features of this study with some of the previously published research on other metal extraction processes. Notable contributions of this study are: its analysis of the environmental burdens associated with cobalt extraction processes, the identification of major reasons behind the environmental impact, and the suggestion of possible solutions to reduce environmental effects. This study is first ever in open literature based on cobalt.

A summary of the results from the impact categories is presented in Table 11. From the detailed life cycle assessment results presented, it is evident that the electricity used in the cobalt production process is mainly accountable for the process's environmental impacts. The second largest contributor is the blasting process which emits free particles into the environment. The third largest contributor is diesel fuel burned in industrial machinery. From the life cycle inventory results, it can be observed that the harmful particles which enter the environment from cobalt mining are fossil fuel-based carbon dioxide, nitrogen oxides, fluoride, cadmium, cobalt, arsenic, manganese, and methane.

7. Conclusion

The impacts on human health, resources, and ecosystems during the cobalt extraction process is calculated in this study using a life cycle assessment method by employing the ILCD and CED methods. The results indicate that the electricity consumed is the greatest contributor to environmental emissions during the cobalt mining process and this can

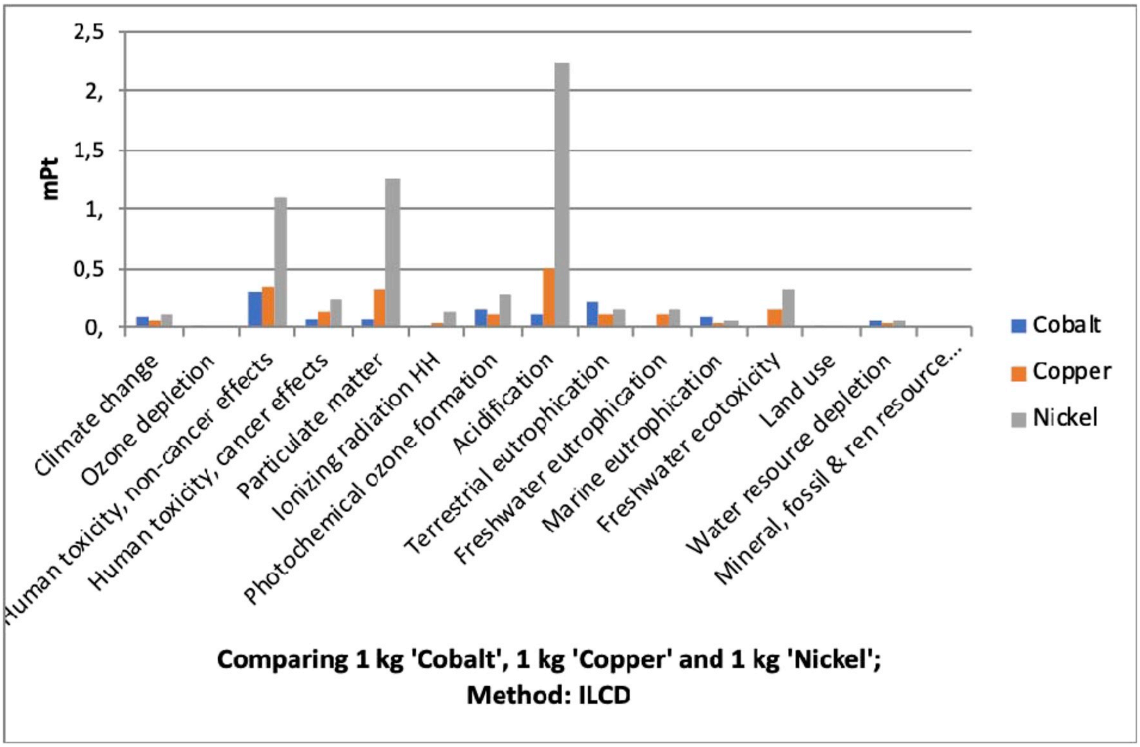

Fig. 6. Comparative life cycle assessment results from cobalt, copper, and nickel extraction processes.

Table 10
Comparison of major LCA based studies.

Metal	Highest impactful category	Impactful process/materials
Aluminium (Nunez & Jones, 2016; Tan & Khoo, 2005)	Global warming potential	Smelting and refining; electricity usage
Cobalt (this study)	**Global warming potential, eutrophication**	**Electricity consumption and usage of blasting**
Copper (Haque & Norgate, 2014; Norgate & Haque, 2010; Northey et al., 2014; Northey, Haque, & Mudd, 2013)	Global warming potential	Solvent extraction and electrowinning, leaching; electricity and sulfuric acid usage
Gold (Chen et al., 2018)	Global warming potential, metal depletion	Mining and comminution, well field related activities; electricity usage, diesel oil usage
Iron (Ferreira & Leite, 2015)	Global warming potential, human health	Agglomeration, loading and haulage, ore processing, vegetation and soil removal; electricity usage, grinding media
Nickel (Khoo et al., 2017; Mistry, Zediga, & Boonjaier, 2016)	Global warming potential	Primary extraction, nickel reduction and smelting; electricity usage, coal usage
Titanium oxides (Farjana, Huda, Mahmud, & Lang, 2018b)	Global warming potential	Mining; electricity usage
Uranium (Farjana, Huda, Mahmud, & Lang, 2018a)	Global warming potential	Fuel enrichment, well field related activities, leaching; electricity usage, use of chemicals, and direct emissions

Table 11
A summary of the results from the impact categories and their insights.

Impact categories	Contributing element from cobalt mining	Harmful emission from respective material
Global warming	Electricity, medium voltage	Carbon-di-oxide, fossil fuel
Eutrophication	Blasting	Nitrogen oxides
Ozone depletion	Diesel burned in electrical machines	Methane, bromotrifluoro halon 1301
Ecotoxicity-freshwater	Electricity, medium voltage	Fluoride
Ecotoxicity-marine aquatic	Blasting	Fluoride
Ecotoxicity-terrestrial	Portland cement	Fluoride
Human toxicity-cancer	Electricity, medium voltage, blasting, cobalt particles	Cadmium, cobalt
Human toxicity- non-cancer	Electricity, medium voltage, cobalt particles	Arsenic, manganese

be reduced by integrating renewable energy generation resources. The second largest contributor is the blasting process which emits metal particles. A suitable mechanism to control particle emission could be employed to reduce environmental effects.

Furthermore, implementing a control mechanism for particle emissions during the blasting process could reduce harmful, non-reversible emissions into the environment. Finally, the results of the environmental impact assessment would be more useful if the process-stage specific dataset would be available in the future.

Conflicts of interest

None.

Ethical statement

Authors state that the research was conducted according to ethical standards.

Funding body

None.

Nomenclature

kg CO_2 eq	Carbon Dioxide Equivalent
kg CFC-11 eq	Ozone Depletion Potential OZDP kg CFC-11 eq
CTUh	Comparative Toxic Unit for Humans
kBq U235 eq	Unit for Ionizing Radiation Described in Kilo Becquerel U-235 Equivalent
Kg NMVOC eq	Non-methane Volatile Organic Compounds Equivalent
Molc N eq	Mole of Nitrogen Equivalent
Kg P eq	Kilograms of Phosphorus Equivalent
Kg N eq	Kilogram of Nitrogen Equivalent
CTUe	Comparative Toxic Unit for Ecosystems
Kg C deficit	Kilograms of Carbon Deficit
m^3 water eq	Volume of Water Equivalent
Kg Sb eq	Kilogram of Antimony Equivalent
MJ	Mega Joule

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