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Comparative assessment of the environmental impacts of nuclear, wind and hydro-electric power plants in Ontario: A life cycle assessment

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ABSTRACT

In this study, we analyze, assess and compare the environmental impacts of nuclear, wind and hydro power generation in the province of Ontario, Canada through a comprehensive life cycle assessment approach. The upstream, downstream and operation phases during the life cycle of these power generation methods are included. The output emissions inventoried in the study are carbon dioxide, methane, sulphur oxides, nitrogen oxides and total particulate matter. The CML 2001 impact assessment methodology is utilized for impact assessment. The environmental impacts included are global warming potential, acidification potential, eutrophication potential, photochemical ozone creation potential and human toxicity potential. Hydro reservoir facilities with bio mass decay are found to have a life cycle GWP100 of 15.2 g CO_2-eq/kWh, which is comparatively higher than wind (12.05 g CO_2-eq/kWh) and nuclear power life cycles (3.402 g CO_2-eq/kWh). However, hydropower is found to have substantially low impacts when other environmental impact categories, such as acidification potential, eutrophication potential, photochemical ozone creation potential and human toxicity potential are considered. This indicates only greenhouse gas emissions are not sufficient to describe the environmental performance of any product system. Wind power life cycle contributed most significantly to acidification, eutrophication, photochemical ozone creation and human toxicity potentials. This is mainly attributed to the construction phase of the life cycle. Hence, development of more environmentally benign wind turbine construction methods is suggested. For the nuclear power scenario, both upstream and decommissioning phases are identified as major contributors to environmental impacts.

1. Introduction

In this modern era, energy production forms an integral part of any economy. Incessantly increasing energy demands have caused detrimental effects on the environment. Increased usage of conventional fossil fuels to meet energy demands was found to have devastating effects on global warming and environmental pollution. To overcome these problems, renewable energy resources are being utilized across the world. In 2014, 14.1% of the global primary energy supply was obtained from renewable resources of energy (International Energy Agency, 2016). In addition, Canada was one of the top five energy producers in the world. However, majority of Canada's energy is generated from environmentally benign resources, such as renewables (hydro and wind) and nuclear power. These power generation technologies are considered environmentally benign, as they do not consume fossil fuels. On the contrary, fossil fuels have adverse effects on the environment through unavoidable greenhouse gas emissions. Fossil fuel based thermal power plants utilize combustion of fossil fuels to produce energy. Burning of such fuels results in various environmentally detrimental emissions. Since, nuclear, wind and hydroelectric power generation methods do not utilize fossil fuels during operation, they have considerably lower environmental impacts during the operation stage. In 2014, hydropower accounted for 62.6% of total energy generated in Canada, making it the third largest producer of hydropower in the world (Canadian Electricty Association, 2015). Furthermore, in the province of Ontario, electricity generation from coal was completely eradicated in 2014. Currently, 36% of Ontario's installed generation capacity includes nuclear power, 23% involves

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hydro power, whereas 11% comprises of wind power (Ontario Independent Electricity System Operator, 2016). These three power generation methods have low environmental emissions while in operation. However, the overall environmental impacts can be better comprehended when studied on a life cycle perspective. Life cycle assessment is a useful technique to quantify the environmental impacts of any product, process or technology during different stages of its life cycle. Nuclear, wind and hydroelectric power plants produce substantially lower environmental emissions as compared to other fossil fuel based energy production methods. However, an environmental impact assessment of these technologies on a life cycle basis, would allow evaluating, analyzing and comparing their impacts on the environment.

Some previous LCA studies have been conducted on these power generation methods. A few studies pertaining to nuclear power include White and Kulcinski (2000), Rashad and Hammad (2000), Dones et al. (2004, 2005), Hondo (2005), Tokimatsu et al. (2006) and Fthenakis and Kim (2007). Nearly all of these studies quantified the greenhouse gas (GHG) emissions, and were performed for different countries. In these studies, the GHG emissions were found to be in the range of 5–200 g CO_2-eq/kWh. A wide range of GHG emissions found in these studies can be attributed to various reasons, such as system boundaries considered, size, type and location of power generation facilities. The system boundaries indicate which life cycle stages are included in the study. Variations in selecting the system boundaries for assessment, cause variations in study results. The system boundary definition is hence, a critical step as it is done in the goal and scope definition, which is the first step of a life cycle assessment study. Furthermore, different power generation technologies have different life cycle environmental impacts. Moreover, the life cycle environmental impacts of a given power generation technology may also vary with location. Facilities situated in countries having an electricity mix comprising primarily of renewable energy resources, will have lower life cycle environmental impacts.

In addition, some previous studies on wind and hydropower have been conducted. Studies related to wind power include Schleisner (2000) and Hondo (2005). The range of GHG emissions in these studies was 9–15 g CO_2-eq/kWh. They included wind turbines of different power ratings with an estimated lifetime of 20 years. In addition to this, Turconi et al. (2013) conducted a review of various LCA studies on different electricity generation methods. GHG emissions for wind power were found to be between 3 and 28 kg CO_2-eq/MWh in a survey of 22 process based LCA studies. The nitrogen oxides (NO_x) and sulphur oxides (SO_x) emissions were found to be in the range 0.02–0.06 kg NO_x/MWh and 0.02–0.04 kg SO_2/MWh respectively. Infrastructure was identified as the main contributor to these emissions. Furthermore, the range of GHG emissions for hydro reservoir facilities was found as 11–20 kg CO_2-eq/MWh, whereas, NO_x and SO_x emissions were found to be reported in only two studies having a range of 0.004–0.06 kg NO_x/MWh and 0.004–0.03 kg SO_2/MWh. A few studies focusing specifically on Ontario have also been undertaken. Mallia and Lewis (2013) assessed the greenhouse gas emissions from different electricity generation facilities in Ontario for the year 2008. Life cycle GHG emissions of 4.8 and 22.5 t CO_2-eq/GWh were reported for nuclear and hydro reservoir facilities respectively. Whereas, a range of 9.03–12.23 t CO_2-eq/GWh for wind power facilities was reported. Andseta et al. (1998) have also reported GHG emissions related to the life cycle stages of CANDU reactors. In addition, CERI (2008) conducted a LCI analysis of electricity generation in Ontario. GHG emissions of 1.836 t CO_2-eq/GWh were reported for the nuclear power life cycle. Whereas, nitrogen oxide and sulphur oxide emissions were reported as 2.45 and 8.54 t/TWh respectively.

Most of the LCA studies on nuclear, wind and hydropower have been focused on quantifying the GHG emissions. Whereas, studies including criteria air contaminant (CAC) emissions are a rare instance. CAC emissions include nitrogen and sulphur oxides, particulate matter and volatile organic compounds. Assessing environmental impacts solely based on GHG emissions may be misleading as is revealed by this study. A power generation technology may emit higher GHG emissions as compared to other methods, however, if other emissions such as CAC are considered, it may have significantly lower emission factors. In addition to this, very few studies converting inventory flows to environmental impacts were found. Particularly, for the perspective of Ontario, in order to evaluate and analyze the environmental impacts of nuclear, wind and hydro power, it is essential to inventory various output emissions and convert them to different impact categories.

This study conducts a cradle to grave life cycle assessment of nuclear, wind and hydro power generation in Ontario in accordance with ISO (International Organization for Standardization) standards (ISO 14040:2006 and ISO 14044:2006), to determine, analyze and compare their environmental impacts. CO_2, CH_4, SO_X, NO_X and TPM emissions have been inventoried and converted to different environmental impact categories. These output emissions have been chosen due to the contribution they have on various important impact categories under CML 2001 impact assessment method. The results of this study aid in quantifying and assessing the life cycle environmental impacts of these power generation methods for the context of Ontario. In addition, they help to identify which life cycle stages may have higher environmental impacts. Furthermore, the study compares the impacts these power generation methods have on the environment during their life cycle. Hence, the findings of this study are expedient for policy makers, academicians, researchers and organizations associated with nuclear, wind and hydro power, specifically, in the province of Ontario.

2. System description

This section discusses the cradle to grave life cycle stages included in the study. The life cycle flowcharts and system boundaries are shown in Figs. 1–3.

2.1. System boundaries

In a LCA study, system boundaries indicate which life cycle stages and material inflows or outflows have been considered in the analysis. In addition, they indicate the cut-off decisions taken to conduct the study. A product system may comprise of numerous process flows, however, a system boundary indicates which process flows of the product life cycle have been included in the study. Furthermore, the product system may have various input and output flows. A system boundary indicates which flows have been considered in the study. This section describes the life cycle stages and the system boundaries considered for nuclear, wind and hydroelectric power.

2.1.1. Nuclear fuel supply

The life cycle stages, system boundaries, output emissions inventoried and the reference flow for the nuclear scenario are shown in Fig. 1. The life cycle stages included in the nuclear fuel supply are discussed in detail further in this section.

2.1.1.1. Mining. Canada is one of the leading uranium producers in the world. This process stage of the nuclear fuel cycle involves extraction of Uranium ore from the earth's crust. Conventional mines utilize the process of crushing the ore and grounding it in water to produce a slurry of water and suspended ore particles. Acids are used to leach the slurry to dissolve the uranium oxides.

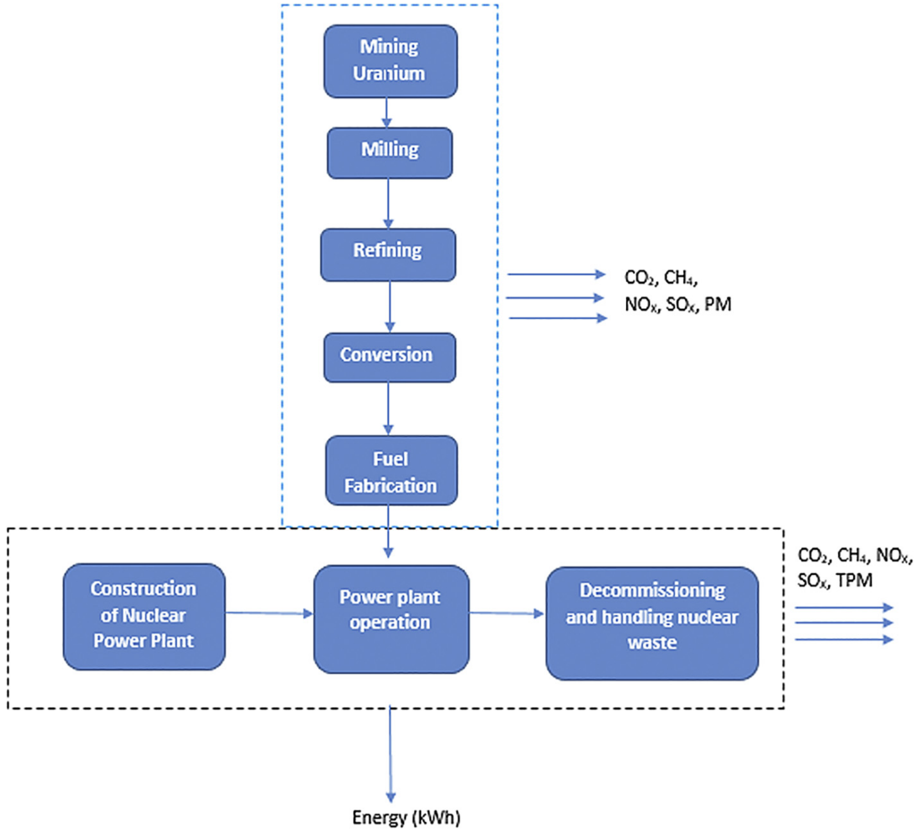

Fig. 1. System boundary and life cycle stages for nuclear power scenario.

The remaining rock and minerals remain undissolved as mine tailings. However, at present, nearly half of the mines globally use in situ leaching. In this method, no major ground disturbances are produced. Groundwater rich in oxygen content is circulated through the ore. A solution with dissolved uranium is obtained at the surface (World Nuclear Association, 2016). Currently, mining of uranium in Canada takes place primarily in the province of Saskatchewan. Operational Uranium mines in the province, their Uranium reserves, ore grades and operators are listed in Table 1. This study considers the process of mining in the nuclear fuel cycle for these listed mines. Several mining methodologies are in use. Cigar Lake, Rabbit Lake, and McArthur River are operated through underground mining. Whereas, McClean Lake is classified as open pit.

2.1.1.2. Milling. After the uranium ore is obtained at surface, uranium is separated from its ore through milling. The ore undergoes several physical and metallurgical treatments. Strong acid and alkaline solutions are also used during the process. The product of milling is Uranium oxide (U_3O_8) which also known as 'Yellow cake' in the uranium industry. Canada has the largest uranium mill facility in the world situated at Key Lake in Saskatchewan (CERI, 2008). Mined uranium is milled at this facility before being transported to Ontario.

2.1.1.3. Refining. Milled uranium or 'Yellow cake' is transported to the Blind River refinery in Ontario for refining. This process stage includes conversion of yellow cake (U_3O_8) to uranium trioxide (UO_3) through a series of chemical as well as physical processes.

2.1.1.4. Conversion. During the conversion process, uranium trioxide is converted to uranium dioxide (UO_2) or uranium hexafluoride (UF_6). For CANDU reactors, uranium dioxide is used for fuel fabrication. This process takes place in the Port Hope facility operated by Cameco in Ontario. Note that in case of light water reactors, the enrichment stage also exists in which the uranium hexafluoride undergoes an enrichment process. Hence, in case of light water reactors, the enrichment stage is also considered in a life cycle assessment study. Once the process of enrichment is conducted, the conversion to uranium dioxide fuel pellets is performed.

2.1.1.5. Fuel fabrication. Fuel fabrication process involves the production of fuel bundles. The fuel bundles comprise of fuel pellets and rods. Fuel pellets are produced from uranium dioxide, whereas, zirconium alloys are usually used to manufacture cylindrical rods. After fabrication, these bundles are transported to nuclear power plants for electricity generation (World Nuclear Association, 2016).

2.1.2. Plant operational system

The life cycle flow charts and system boundaries for nuclear, hydro and wind power scenario are shown in Figs. 1–3 respectively. This section discusses the construction, operation and decommissioning phases of these power generation methods.

2.1.2.1. Construction. Emissions resulting from construction of nuclear power plants have been included in the study. In addition, as depicted in Fig. 2, the activities included in this phase of the hydropower life cycle are construction of the facility and production of construction materials. Furthermore, the manufacture of turbine and generator and the production of raw materials required is also included. Ontario power generation has 65 operating hydroelectric

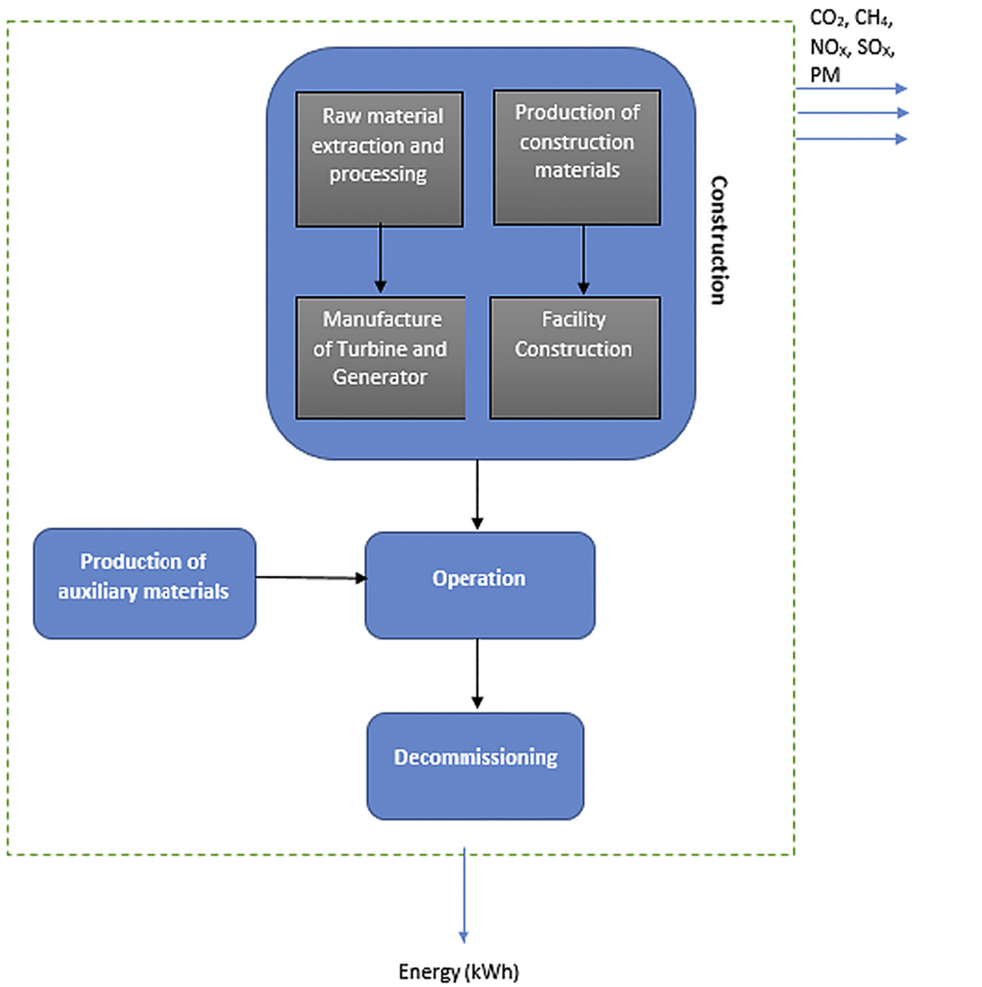

Fig. 2. System boundary and life cycle stages for hydropower scenario.

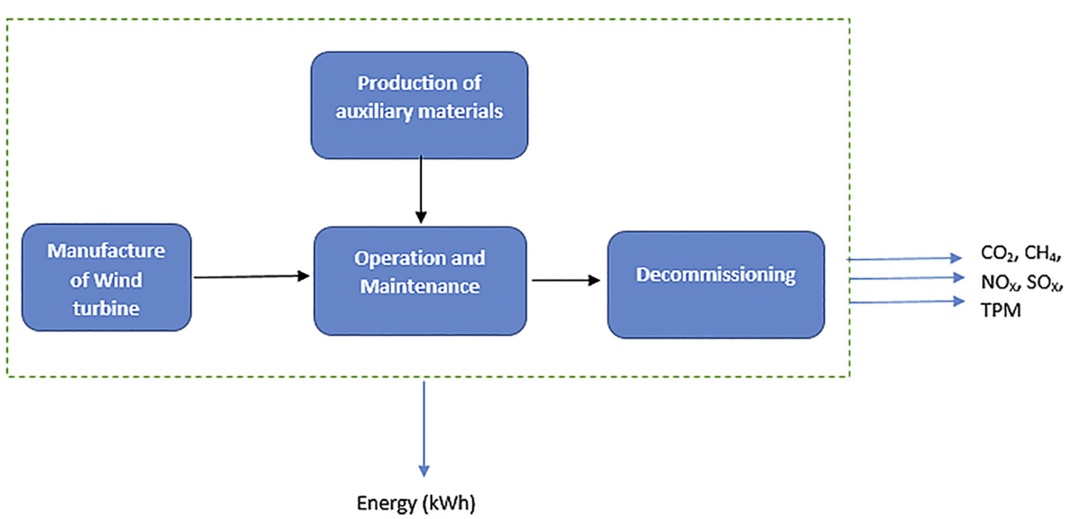

Fig. 3. System boundary and life cycle stages for wind power scenario.

power plants with different generation capacities. Sir Adam Beck II Generating Station situated at Niagara river is a large scale hydropower facility operated by the corporation which has a capacity of 1499 MW (Ontario Power Generation, 2016a). Emissions arising from activities conducted in the construction stage of the wind turbine have been included in the current study. A summary of wind power facilities in Ontario is listed in Tables 3 and 4.

Table 1
Tonnes of produced uranium products from operational mines in Saskatchewan (World Nuclear Association, 2016).

Mine Location	Corporation Operating	Tonnes Uranium	Tonnes U_3O_8	Average ore grade U_3O_8	Category of reserves
McArthur River	Cameco	97,350	115,000	9.62%	Proven
		31,930	37,660	18.84%	Plausible
		2150	2540	3.8%	Measure and indicated
		22,550	26,590	7.7%	Inferred
McClean Lake	Areva	337	397	0.42%	Proven and plausible
		5220	6156	4.81%	Measured and indicated
Rabbit Lake	Cameco	4580	5400	0.59%	Proven and plausible
		10,270	12,100	0.86%	Indicated
Cigar Lake	Cameco	42,050	49,590	18.3%	Proven
		43,200	50,950	13.5%	Plausible
		1270	1500	7.5%	Measure and indicated
		39670	46780	16.4	Inferred

Table 2
Installed power generation capacity and number of reactors for nuclear power plants in Ontario (Ontario Power Generation, 2016a,b; Bruce Power, 2011).

Nuclear Power Generation Station	Operator	Installed capacity (MW)	Number of reactors
Bruce A and B	Bruce Power	6232	8
Pickering	Ontario Power Generation	3100	8
Darlington	Ontario Power Generation	3512	4

Table 3
Summary of total installed capacity of wind turbine facilities in Ontario as of December 2015 (Canadian Wind Energy Association, 2016).

Wind Power in Ontario as of December 2015	
Installed facilities	79
Number of Wind Turbines	2302
Total Installed Capacity (MW)	4361
Average turbine capacity (MW)	1.89

Table 4
Summary of wind farms in Ontario according to power generation capacity (Canadian Wind Energy Association, 2016).

Capacity (MW)	Number of Wind Farms
0.5–1	5
1 to 10	29
10 to 100	30
100 to 200	13
200 to 270	2

2.1.2.2. Operation and decommissioning. Operation of the nuclear power plant involves the fission of uranium U-235 which releases energy. This energy is utilized to produce steam with high pressures. Power plants with CANDU reactor technology operate with subcritical-pressure regenerative Rankine steam-turbine cycle. Operational nuclear power plants and their respective power outputs are listed in Table 2. Operation of hydroelectric power plants include utilizing potential energy of stored water or kinetic energy of running water to generate power. During operation, reservoir facilities have biomass decay, which produces significant amount of greenhouse gas emissions, unlike run-of-river facilities. These emissions are dependent on the geographical location, depth and size of the reservoir, weather conditions and type of ecosystem. However, the operational stage of wind turbine facilities is known to produce comparatively fewer emissions. This stage includes periodic maintenance activities required for smooth functioning of the power plant. These activities include periodic lubrication, inspection and repairing of damaged parts. In addition to this, the wind power life cycle includes the production of auxiliary materials life cycle stage. This phase of the life cycle includes the production of ancillary supplies that are required for smooth operation of the plant. Lubricants, chemicals or oils are examples of such supplies that are utilized during operation. In addition, the decommissioning phase of the life cycle has also been included in the system boundaries. This is the final stage of the life cycle that includes dismantling of the facilities at the end of their lifetime. After dismantling of nuclear facilities, the radioactive waste requires appropriate treatment and storage. However, waste management is excluded from the scope of this study.

3. Life cycle assessment

A Life cycle assessment study according to ISO standards (ISO 14040:2006 and ISO 14044:2006) is conducted. This section provides a detailed discussion of the steps undertaken in this LCA study in accordance with the standards.

3.1. Goal and scope definition

The objective of this study is to analyze the environmental impacts of nuclear, wind and hydro power plants in the province of Ontario, Canada. A process based Life Cycle Assessment approach was used. These three types of power generation methods are known to have significantly less impacts on the environment during their operation stage as they do not utilize fossil fuels. Fossil fuels are major contributors to environmental pollution. Conventional fossil fuel based thermal power plants utilize burning of fossil fuels for energy production. Burning of fossil fuels results in various emissions, which are detrimental to the environment. Since, nuclear, wind and hydroelectric power generation methods do not utilize fossil fuels during operation, they have considerably lower environmental impacts during the operation stage. However, this study attempts to quantify their environmental effects on a life cycle perspective. The study uses 1 kWh of electricity produced as the functional unit. The study focuses on inventorying carbon dioxide and methane greenhouse gas emissions. In addition, criteria air contaminants including sulphur oxides (SO_x), nitrogen oxides (NO_x) and total particulate matter (TPM) are also included. Further, Impact assessment is conducted using CML 2001 characterization method. The study includes environmental impact categories of Global warming potential, Acidification potential, Photochemical ozone creation potential, Eutrophication potential and Human toxicity potential.

3.2. Inventory analysis

The inventory analysis phase of a LCA involves colleting the input or output data that is required in order to meet the objectives of the study. CO_2, CH_4, SO_X, NO_X and TPM emissions have been inventoried in this study.

3.2.1. Nuclear scenario

The inventory analysis for different life cycle stages included in the system boundary of the nuclear scenario is discussed in detail in this section.

3.2.1.1. Mining and milling. The emission outputs for mining and milling in Saskatchewan which is operated by Cameco and AREVA Resources Canada corporations are determined from Environment and Climate change Canada's National Pollutant release Inventory (Environment and Climate Change Canada, 2014). The facilities and their respective SOx, NOx and TPM emissions for the year 2014 are listed in Table 5. The nuclear energy output in Ontario for the year 2014 (Independent Electricity System Operator, 2014) was utilized to normalize the total emissions to the functional unit. The GHG emissions associated with mining and milling in the province of Ontario were reported by CERI (2008) as 1.609 gCO_2-eq per kWh of electricity generated.

3.2.1.2. Refining and conversion. Emissions from CAMECO Blind River refinery and Port Hope conversion plant are also collected from Environment and climate change Canada's National pollutant release inventory for the year 2014. The NOx and TPM emissions are listed in Table 6. SO_x emissions were not reported possibly due to being less than the reporting threshold value. The GHG emissions for this phase of the nuclear power life cycle in Ontario were estimated as 0.103 gCO2eq per kWh generated electricity (CERI, 2008).

3.2.1.3. Fuel fabrication. Fuel fabrication for Ontario nuclear power plants takes place at Cameco Port Hope fuel manufacturing facility and GNF-Canada Peterborough facility. Andseta et al. (1998) have reported the carbon dioxide emissions resulting from fuel fabrication for CANDU reactors as 0.01 g/kWh. Amounts of other types of emissions from these facilities are not reported, this might be due to the emissions being lower than the minimum reporting threshold.

3.2.1.4. Construction. Andseta et al. (1998) report the energy and resource consumption associated with the construction of CANDU power generation technology. These were utilized along with GREET life cycle assessment software (GREET, 2016) to estimate the amount of emissions which would result in Ontario from construction phase of the nuclear power life cycle. GREET LCA tool allows evaluating emissions arising from electricity, natural gas, diesel and many other energy flows. In addition, it also contains emission factors for various countries including Canada.

Table 5
Tonnes of sulphur oxides, nitrogen oxides and total particulate matter emissions from mining and milling facilities in the year 2014 (Environment and Climate Change Canada, 2014).

Facility	SO_x (Tonnes)	NO_x (Tonnes)	TPM (Tonnes)
McArthur River	0.48	282.65	37.59
McClean Lake	–	30.76	1.68
Rabbit Lake	58.8	51.45	245.87
Cigar Lake	–	33.03	10.53
Key Lake	208.05	137.13	41.79
Total	267.33	535.02	337.46

Table 6
Tonnes of sulphur oxides, nitrogen oxides and total particulate matter emissions from refining and conversion facilities in the year 2014 (Environment and Climate Change Canada, 2014).

Facility	SOx (Tonnes)	NOx (Tonnes)	TPM (Tonnes)
Blind river refinery	–	32.9	0.53
Port hope conversion	–	51.8	7.7

3.2.1.5. Plant operation. The emissions arising during the operation phase are also obtained from Environment and Climate change Canada's 2014 National Pollutant Release Inventory. These are summarized in Table 7.

3.2.1.6. Decommissioning. Sier and Zimmerman (Seier and Zimmermann, 2014) reported the actual energy flows accompanying the decommissioning process of a nuclear facility in Germany. The system boundary of the study included demolition of the nuclear plant, decontamination, conditioning, interim storage and final repository of interim-level and low-level nuclear waste. This information and GREET LCA software was used to estimate the emissions that would result from a decommissioning process conducted in the province of Ontario in Canada.

3.2.2. Hydropower scenario

This section discusses the inventory analysis conducted for the life cycle stages of hydropower scenario.

3.2.2.1. Construction phase and production of auxiliary materials. An environmental product declaration of Vattenfall hydropower (Vattenfall, 2015) estimates the resource and energy consumption associated with various life cycle stages of hydropower facilities. Information reported about the elements included in our Construction as well as Production of auxiliary materials phases is used to estimate the environmental emissions that would occur in Canada using GREET LCA software.

3.2.2.2. Operation. During operation, reservoir facilities may release a considerable amount of CO_2 or CH_4 due to decaying biomass. Various factors including ecosystem, geographical location, size and depth of the reservoir affect these emissions. In a study conducted by Gagnon and Van de Vate (Gagnon and van de Vate, 1997), GHG emissions of 12.5 gCO_2-eq/kWh were found for boreal ecosystems which resemble the ecology in the province of Ontario.

3.2.2.3. Decommissioning. A study conducted explicitly on the decommissioning of hydroelectric dams implied significant emissions are produced as a result of this process in the life cycle of hydro power plants (Pacca, 2007). The study indicates, decommissioning of hydro power plants may emit three times more GHG emissions than construction (Mallia and Lewis, 2013). This information is used to estimate the GHG emissions during this process. In addition, the SO_x, NO_x and TPM releases are also considered to be three times the emissions in the construction phase.

3.2.3. Wind power scenario

The inventory analysis conducted for the wind power scenario is discussed in the sections further.

3.2.3.1. Manufacture, operation and maintenance. Tjæreborg wind

Table 7
Tonnes of sulphur oxides, nitrogen oxides and total particulate matter emissions from operating nuclear power plants in the year 2014 (Environment and Climate Change Canada, 2014).

Nuclear Power Generation station	Operator	SOx (Tonnes)	NOx (Tonnes)	TPM (Tonnes)
Bruce A and B	Bruce Power	26.18	60.83	25.15
Pickering	Ontario Power Generation	–	23.28	–
Darlington	Ontario Power Generation	–	25.06	–

farm in Demark is an onshore facility installed with Vestas V80 2 MW turbines similar to the Kingsbridge wind farm in Ontario. A life cycle assessment study of this facility (ElsamEngineering, 2004) reports the emissions associated with the construction, operation and maintenance of such type of turbines. Kingsbridge wind farm in Ontario is also an onshore facility with the same type of turbine in use, hence the results of this report are used to estimate of emissions during these life cycle stages for wind power.

3.2.3.2. Production of auxiliary materials. Emissions arising from the production of auxiliary materials for wind turbines have been determined from Vattenfall's environmental product declaration of wind farms (Vattenfall, 2010). The environmental product declaration included emissions from the production of auxiliary materials for Horns Rev and Zagórze wind farms. These wind farms in Denmark also use the same wind turbine (Vestas 2 MW) used in Kingsbridge wind farm in Ontario.

3.2.3.3. Decommissioning. The process of decommissioning is an essential part of a LCA study. However, accurate information related to this process for wind farms in Ontario is not currently available. In order to estimate the emissions from this life cycle stage, the energy requirements for decommissioning are considered similar to the manufacturing stage (ElsamEngineering, 2004). The required energy during manufacturing of the wind turbine is reported by Vattenfall (2010). GREET LCA software is utilized to evaluate the emissions that would result from this life cycle stage occurring in Ontario.

A summary of the output emissions after normalizing to the functional unit of 1-kW hour is tabulated in Tables 8–10.

3.3. Life cycle impact assessment

In a LCA study, Life cycle impact assessment (LCIA) is the next stage after the inventory analysis. LCIA involves converting the input or output flows to environmental impacts. Several LCIA methodologies such as CML 2001 (Guinée et al., 2002), TRACI 2.1 (Bare et al., 2003), Eco-indicator 99 (Hofstetter, 2000), and IMPACT 2002+ (Jolliet et al., 2003) have been developed. This study utilizes CML 2001 impact assessment methodology. This impact assessment method includes various impact categories and characterization methods for a variety of input and output flows. It was developed by the Institute of Environmental Sciences, Leiden University (Guinée et al., 2002). The GaBi LCA software tool (GaBi, 2016) was used to perform the impact assessment. The quantity of a given emitted substance (j) is converted to the relevant impact category by multiplying with a classification factor:

The classification factors for different types of emissions can be found in SETAC publications (Society of Environmental Toxicology and Chemistry, 1997). Classification factors are used to convert a given type of emission to an appropriate environmental impact.

The impact categories chosen for this study, their category indicators and contributing flows are discussed further.

3.3.1. Global warming potential

Global warming potential (GWP) refers to the relative trapping of heat in the earth's atmosphere by greenhouse gases. This phenomenon is known as radiative forcing (Ozbilen et al., 2012). Increased greenhouse gas emissions lead to increased radiative forcing, resulting in a rise in the overall temperature of the earth's atmosphere. The category indicator used as a unit for GWP is g CO_2-eq. Emissions included in the inventory analysis of this study that contribute to this impact category are CO_2 and CH_4.

3.3.2. Acidification potential

Acidification potential refers to the rise in hydrogen [H^+] ions of the medium to which emissions are released. This disrupts the pH level of the medium, and thus, results in damage to ecosystems, soil, water and materials (Suleman et al., 2016). Emissions contributing to acidification include nitrogen and sulphur oxides. The category indicator used for this impact category is g SO_2-eq.

3.3.3. Human toxicity potential

Human toxicity potential (HTP) relates to the effects of toxic releases to the human environment. Toxic substances may lead to adverse human health impacts. The category indicator used for this category is 1,4-dichlorobenzene equivalent. Particulate matter, SO_x and NO_x emissions which are inventoried in this study contribute to this impact category (Bicer et al., 2016).

3.3.4. Photochemical ozone creation potential

Presence of ozone in the stratosphere is vital to absorb the incoming radiation from the sun. However, at lower levels, ozone (O_3) can be a harmful gas. Photochemical ozone creation at the troposphere level results in a damage to crops. In addition, O_3 in high concentrations is toxic to human beings. Nitrogen oxides and methane gases inventoried in this study are contributors to this category. The category indicator used as a unit for photochemical ozone creation potential (POCP) is g-ethene eq.

Table 8
Summary of normalized emissions for nuclear power scenario.

Nuclear Scenario	GHG (g CO_2eq/kWh)	NO_x (g/kWh)	SO_x (g/kWh)	TPM (g/kWh)
Mining and Milling	1.61	0.0071	0.0036	0.0045
Refining and conversion	0.10	0.0011	0.0000	0.00011
Fuel fabrication	0.01	–	–	–
Construction	1.03	0.0042	0.0041	0.0025
Plant Operation	0.20	0.0028	0.00048	0.00046
Decommissioning	0.46	0.0007	0.014	0.026

Table 9
Summary of normalized emissions for hydropower scenario.

Hydro power scenario	GHG (g CO_2eq/kWh)	NO_x (g/kWh)	SO_x (g/kWh)	TPM (g/kWh)
Construction	0.67	0.00054	0.0034	0.00024
Production of auxiliary materials	1.16E-04	1.11E-07	1.92E-06	5.37E-08
Operation	12.50	–	–	–
Decommissioning	2.02	0.0016	0.010	0.00073

Table 10
Summary of normalized emissions for wind power scenario.

Wind	GHG (g CO_2eq/kWh)	NO_x (g/kWh)	SO_x (g/kWh)	TPM (g/kWh)
Manufacture of wind turbine	6.19	0.050	0.020	–
Operation and Maintenance	0.70	0.0080	0.0020	–
Production of auxiliary materials	0.058	0.00017	0.00037	0.000068
Decommissioning	5.10	0.0046	0.0086	0.0019

3.3.5. Eutrophication potential

Eutrophication potential (EP) refers to the nutrient enrichment of the medium to which emissions are released. Pollutant emissions to air as well as water may contribute to eutrophication. Enrichment of nutrients results in destruction of ecosystems in water bodies due to algae growth. Furthermore, it may also result in damages to vegetation as well as groundwater when eutrophication occurs in soils. Nitrogen oxides that are inventoried in this study contribute to this impact category. The category indicator used for EP is g-Phosphate eq.

4. Results and discussions

This section includes the Interpretation phase of the LCA. It analyses and discusses the results of the study.

4.1. Interpretation

According to the ISO LCA framework, interpretation is the final phase of a LCA study. Interpretation involves analyzing, comparing and assessing the LCI and LCIA results to draw conclusions and provide recommendations. The following sections present and discuss the results of this study that are valuable in providing comparisons, inferences and recommendations on the environmental impacts of nuclear, wind and hydro power in Ontario.

Fig. 4 depicts the percentage contributions to different environmental impacts of the considered life cycle stages for the nuclear scenario. Mining and Milling contribute nearly 50% of the global warming and eutrophication potentials. In addition, decommissioning phase may also have substantial contribution to life cycle environmental impacts, specifically Acidification (49%), Human Toxicity (48%) and Photochemical Ozone Creation Potentials (46%). However, the operation, refining and conversion life cycle stages have comparatively less impacts on the environment during the life cycle. Hence, in order to reduce the life cycle global warming potential of the nuclear power life cycle in Ontario, it is essential to focus on the mining and milling life cycle stage. The high global warming potential in this life cycle stage can be attributed to the usage of fossil fuels by equipment and machinery. Efforts need to be made to develop and utilize machinery that produce less environmental emissions.

Fig. 5 shows the percentage contributions for the wind power scenario. The manufacture of wind turbine may result in comparatively highest environmental impacts with a contribution between 50 and 80% for each impact category as can be depicted from Fig. 5. Hence, in order to obtain lower life cycle environmental impacts for wind power life cycle, it is important to consider the

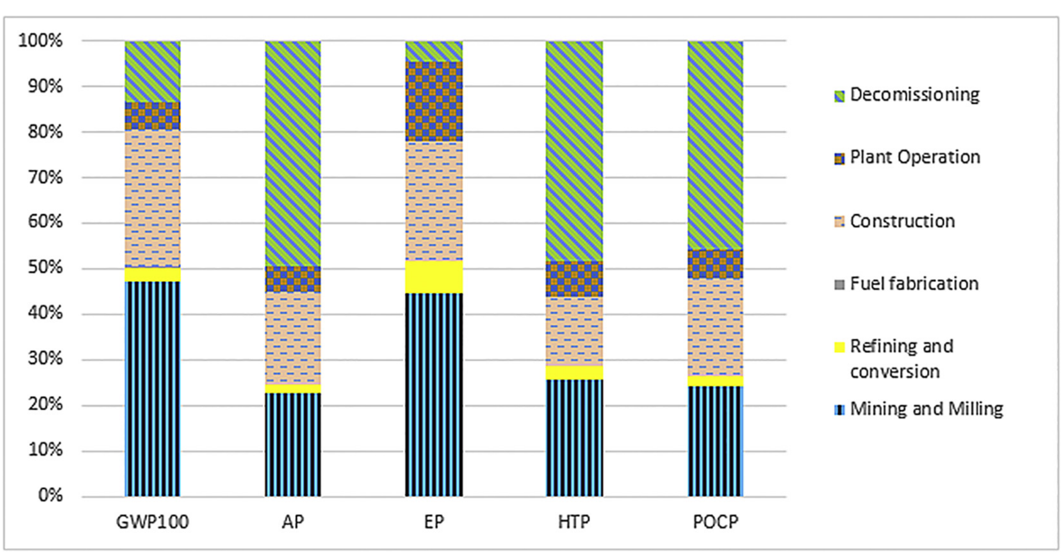

Fig. 4. Percentage contributions of life cycle stages to environmental impacts for nuclear power scenario.

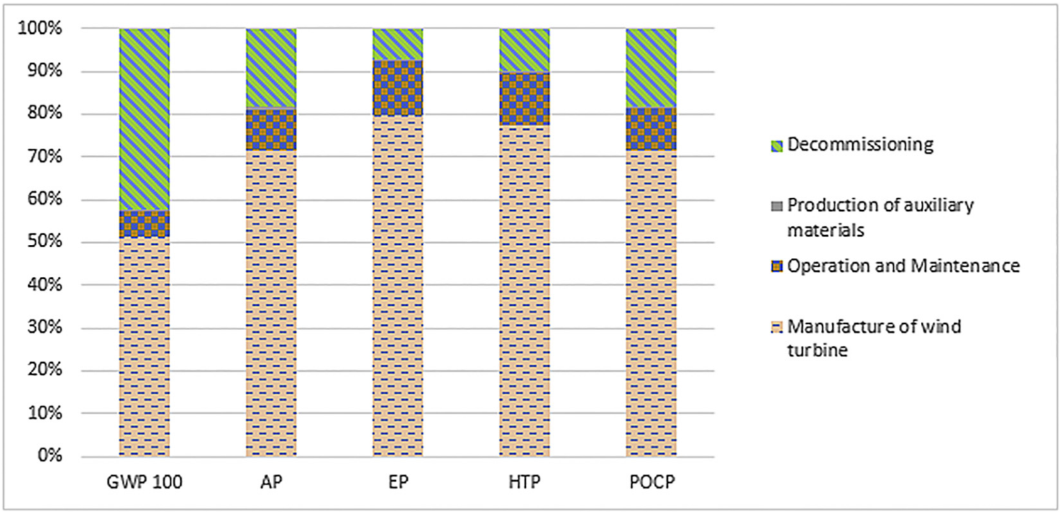

Fig. 5. Percentage contributions of life cycle stages to environmental impacts for wind Power scenario.

manufacturing stage. The high environmental impacts during this life cycle stage can be attributed to the usage of steel that is required to manufacture various parts of the wind turbine, and the electricity consumption during manufacturing. Hence, it is important to consider utilizing electricity from renewable energy resources during manufacturing. This will help to reduce the overall life cycle environmental impacts of wind power.

The life cycle breakdown by percentage contributions for the hydropower scenario is shown in Fig. 6. If biomass decay is considered in the LCA study, it may be a significant contributor to global warming potentials. However, the amount of biomass decay and subsequent CO_2 or CH_4 emissions may vary considerably from one site to another, based on the type of ecology, depth of the reservoir and climatic conditions. Further research is required in this area in order to determine the accurate amount of emissions that arise due to bio mass decomposition. For other impact categories, construction and decommissioning phases are the major contributors to environmental impacts from hydropower life cycle.

4.1.1. Global warming potential

A comparison of global warming potentials for nuclear, wind and hydropower in Ontario is presented in Fig. 7. As can be depicted from Fig. 7, hydro reservoirs with bio mass decay may have comparatively highest global warming potentials of 15.2 g CO_2-eq/kWh. However, reservoirs with no biomass decomposition have substantially low GWP of 2.7 g CO_2-eq/kWh. In this case, wind power scenario has the most significant GWP of 12.05 g CO_2-eq/kWh. Nuclear power scenario has lower impacts due to the higher energy output as compared to wind or hydropower. In a LCA study, the LCIA results are normalized to a common reference unit known as the functional unit. Similar to other studies, 1-kW hour of energy generated was chosen as the functional unit for this study. Hence, as nuclear power plants have higher energy outputs, the LCIA results are normalized to these greater outputs.

4.1.2. Acidification potential

As can be observed from Fig. 8, wind power life cycle is estimated to have the highest acidification potential (AP) of 0.0685 g

Fig. 6. Percentage contributions of life cycle stages to environmental impacts for hydro Power scenario.

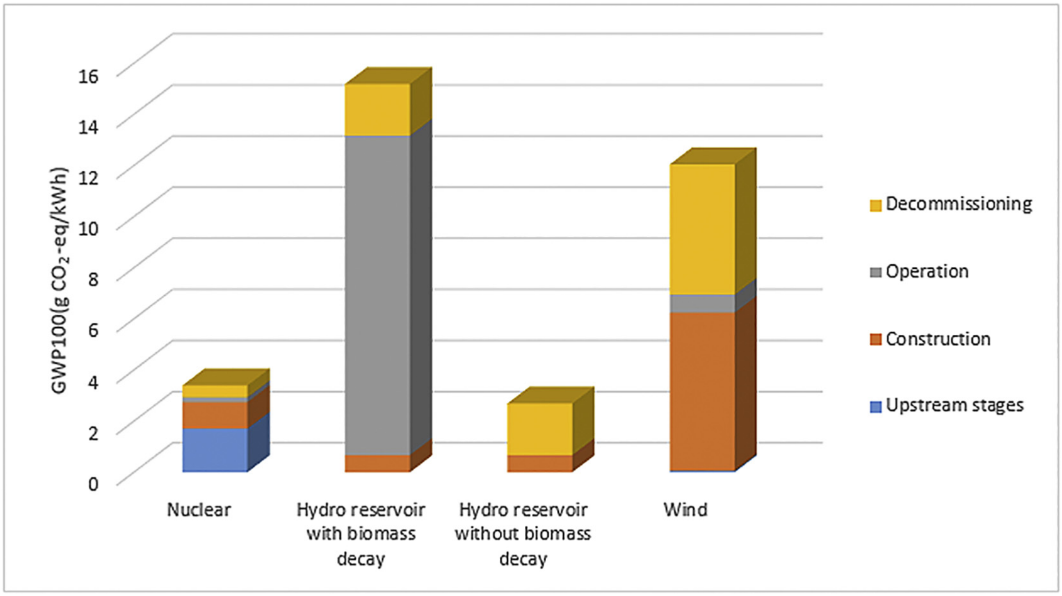

Fig. 7. Comparison of Global warming potentials with life cycle stages (g CO_2-eq/kWh).

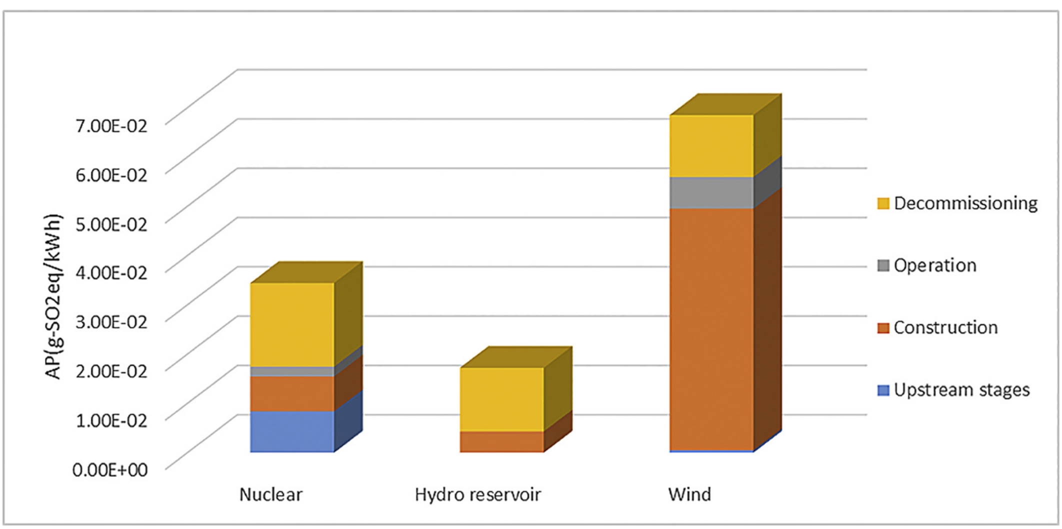

Fig. 8. Comparison of Acidification Potentials with life cycle stages (g SO_2-eq/kWh).

SO_2-eq/kWh. This can be attributed to high SO_x and NO_x emissions arising during the manufacturing stage of the wind turbine. Furthermore, the acidification potential for nuclear power life cycle is estimated to be 0.035 g SO_2-eq/kWh. However, hydro reservoir facilities are expected to have comparatively lower life cycle acidification impacts on the environment.

4.1.3. *Human toxicity potential*

Human toxicity potential comparisons are presented in Fig. 9. Similar to AP, wind power scenario is expected to have the highest HTP of 0.079 g DCB-eq/kWh, owing to the high CAC (NO_x, SO_x and TPM) emissions during manufacturing stage of a wind turbine. As can be depicted from Fig. 9, 0.062 g DCB-eq/kWh HTP results from the construction stage in the wind power life cycle. The nuclear power scenario is expected to have 0.049 g DCB-eq/kWh of life cycle human toxicity potential. In addition, hydropower life cycle is estimated to have a comparatively lower HTP value of 0.0047 g DCB-eq/kWh during its lifecycle.

4.1.4. *Photochemical ozone creation potential*

Fig. 10 shows the POCP comparison. Wind power life cycle is expected to be the most significant contributor to this impact category with a POCP of 0.0033 g Ethene-eq/kWh. This is also mainly attributed to the NOx emissions during manufacturing of wind turbine. As can be observed from Fig. 10, POCP of 0.00238 g Ethene-eq/kWh results from the construction phase. The nuclear power life cycle is found to a have a life cycle POCP of 0.0015 g Ethene-eq/kWh. Furthermore, hydropower scenario is found to have the least POCP of 0.000768 g Ethene-eq/kWh.

4.1.5. *Eutrophication potential*

A comparison of Eutrophication potentials is shown in Fig. 11. Wind power life cycle is found to have the highest life cycle contribution to EP of 0.0082 g Phosphate-eq/kWh. This can be attributed to the high NO_x emissions arising from construction phase of the wind turbine. Life cycle eutrophication potential for nuclear power scenario is found to be 0.0021 g Phosphate-eq/kWh.

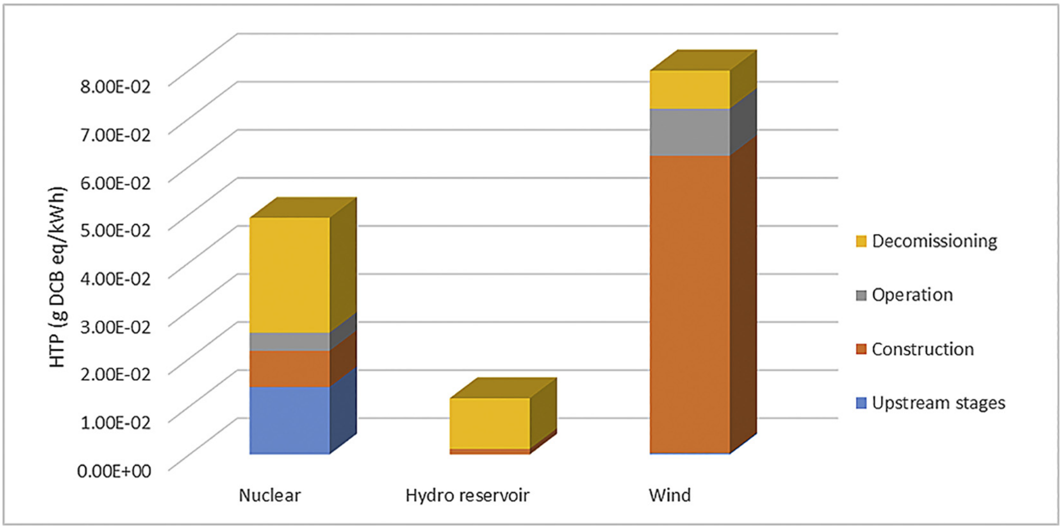

Fig. 9. Comparison of Human Toxicity Potentials with life cycle stages (g DCB-eq/kWh).

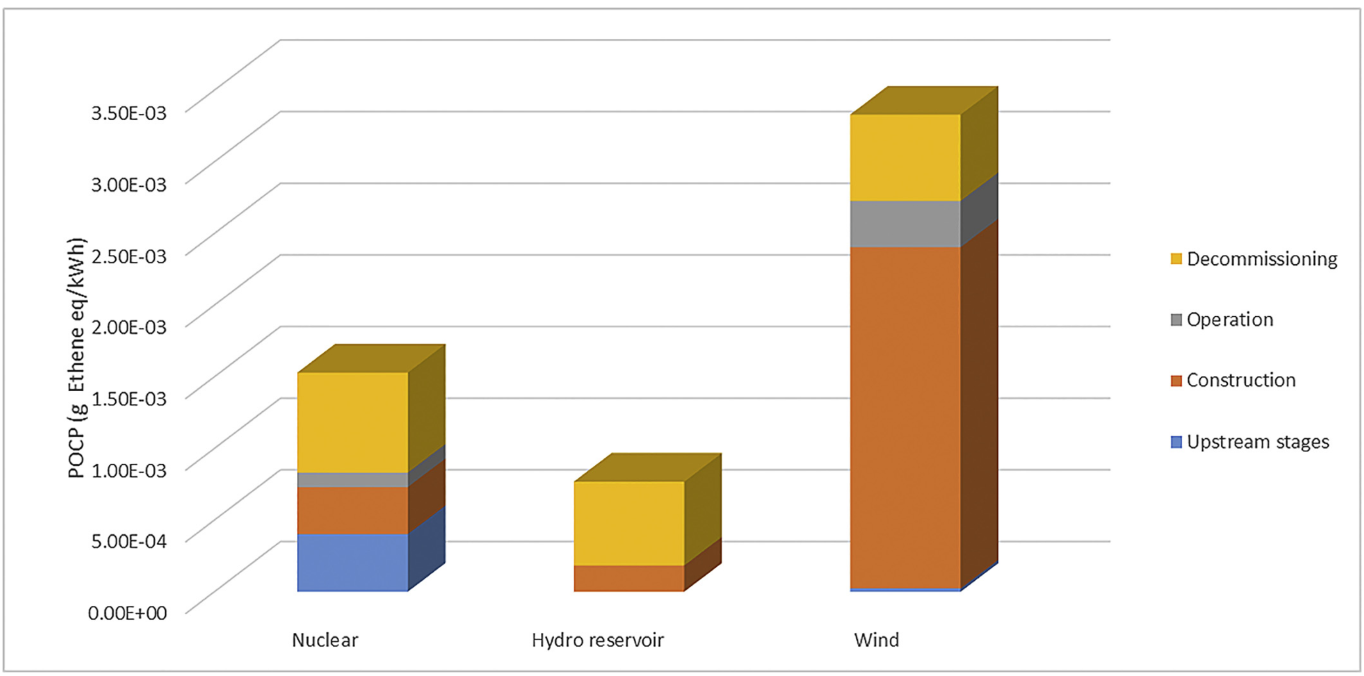

Fig. 10. Comparison of Photo Chemical Ozone Creation Potentials with life cycle stages (g Ethene-eq/kWh).

This is mainly due to the upstream stages, as can be depicted from Fig. 11.

4.2. Sensitivity analysis

In the above analysis, the results were obtained without considering recycling. However, in the wind power life cycle, after decommissioning the waste steel is recycled. The effect of recycling rate on the life cycle environmental impacts of wind power life cycle is summarized in Table 11. At a recycling rate of 80%, the GWP100 is evaluated as 7.97 g-CO_2eq/kWh. This corresponds to a 33.9% decrease in global warming potentials as compared to a base case of 0% recycling. In addition, the acidification potential and photochemical ozone creation potential decrease by approximately 15% at a recycling rate of 80%.

4.3. Limitations

Wind power is intermittent in nature, and is often backed up by an ancillary source. The study does not consider the usage of these back up sources at wind power plants. The LCA results will vary if these sources are included in the system boundary. The study also excludes recycling from the system boundaries of nuclear and hydropower scenario. In the nuclear fuel cycle, some of the waste fuel may be recycled; this might help in reducing emissions that occur from production of new fuel. Similarly, after decommissioning of hydropower plants, waste steel and other materials may also be recycled. However, a sensitivity analysis has been conducted for the wind power scenario to analyze the effect of recycling rate on the life cycle environmental impacts. In addition, the scope and system boundaries of the study capture nearly all processes required for a

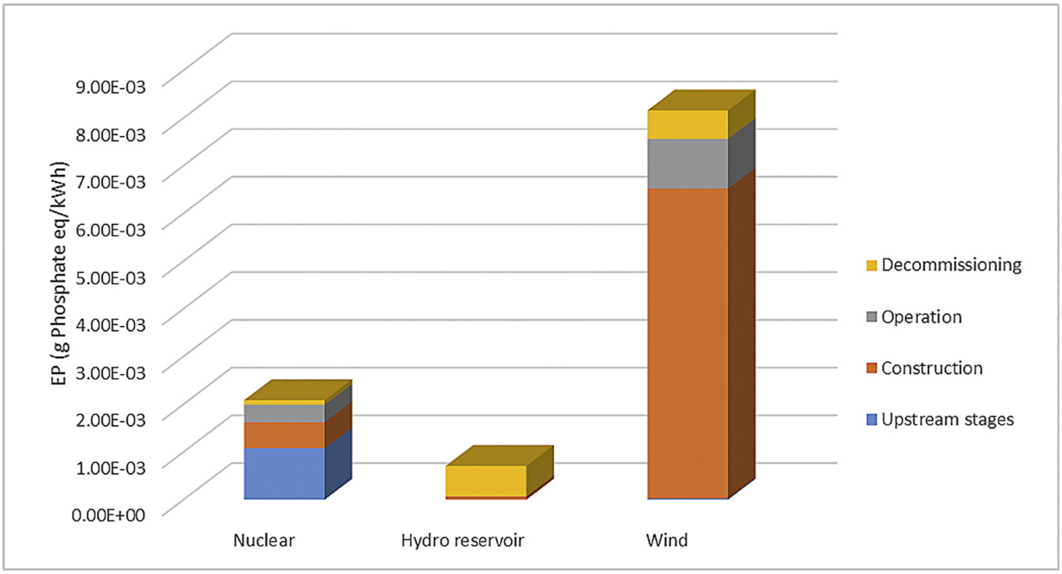

Fig. 11. Comparison of Eutrophication Potentials with life cycle stages (g Phosphate-eq/kWh).

Table 11
Effect of recycling rate on the life cycle environmental impacts of wind power.

Recycling rate	GWP100 (g-CO2eq/kWh)	AP (g-SO2eq/kWh)	HTP (g-DCB eq/kWh)	POCP (g-Ethene eq/kWh)	EP (g-Phosphate eq/kWh)
0%	12.05	0.069	0.079	0.0033	0.0082
20%	11.03	0.066	0.078	0.0032	0.0080
40%	10.01	0.063	0.076	0.0031	0.0079
60%	8.99	0.061	0.075	0.0029	0.0078
80%	7.97	0.058	0.074	0.0028	0.0077

cradle to grave life cycle assessment of these power generation methods and provide a comprehensive comparison of the chosen environmental impact categories for nuclear, wind and hydroelectric power plants during the different stages of their life cycles.

5. Conclusions

This study focuses on determining, analyzing and comparing the environmental impacts of nuclear, wind and hydroelectric power plants in the province of Ontario, Canada. A cradle to grave life cycle assessment methodology is used. Output emission flows inventoried include CO_2, CH_4, SO_x, NO_x and TPM. Five environmental impact categories in accordance with CML 2001 impact assessment methodology are utilized. Wind power life cycle is estimated to have comparatively higher environmental impacts, with a life cycle AP of 0.069 g SO_2-eq/kWh, HTP of 0.079 g DCB-eq/kWh, POCP of 0.0033 g Ethene-eq/kWh and EP of 0.0082 g Phosphate-eq/kWh. This is mainly attributed to the manufacturing phase of the wind turbine. Thus, development of more environmentally benign manufacturing methods is recommended. Furthermore, hydroelectric reservoir facilities with biomass decay yielded comparatively higher global warming potentials of 15.2 g CO_2-eq/kWh. However, as biomass decay is dependent on various factors and may vary from one location to another, further research in this area is recommended to obtain more accurate values of CO_2 or CH_4 emissions which arise from biomass decomposition. Hydropower life cycle, however, is found to have comparatively lower environmental impacts in other impact categories. Henceforth, it is recommended for future LCA studies to include a set of different impact categories, as quantifying only GHG emissions may not provide a complete depiction of the overall environmental impacts. In the nuclear power life cycle, mining, milling and decommissioning life cycle stages are found to be significant contributors to life cycle environmental impacts.

Nomenclature

AP	Acidification Potential
CAC	Criteria Air Contaminant
CANDU	Canada Deuterium Uranium
CH_4	Methane
CML	Centre of Environmental Science of Leiden University
CO_2	Carbon di oxide
EP	Eutrophication Potential
GHG	Greenhouse Gas
GWP	Global Warming Potential
HTP	Human Toxicity Potential
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NOx	Nitrogen Oxides
POCP	Photochemical Ozone Creation Potential
SOx	Sulphur Oxides
TPM	Total Particulate Matter

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