Lifecycle Assessment Literature Review of Nuclear, Wind and Natural Gas Power Generation

Prepared for

The Canadian Nuclear Association

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This report is a meta-analysis of independent LCA studies and, accordingly, all estimates and projections contained herein are limited by the accuracy and availability of data available from published LCA studies. Therefore, while the work, results, estimates and projections herein may be considered to be generally indicative of the nature and quality of the Project, they are not definitive.

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Executive Summary

The Canadian Nuclear Association (CNA) commissioned Hatch Ltd. to conduct an independent comparison of Life Cycle Assessment (LCA) data covering the environmental performance of nuclear, wind and natural gas power generation scenarios relevant within a Canadian context.

Using a combined literature review and meta-analysis methodology, the present study compiles data from previous LCA projects and synthesises the data to conform to a common set of model parameters and system boundaries. The study focuses on four power generation scenarios:

- Onshore wind generation;
- Nuclear power, considering all types of commercial reactors;
- Natural gas combined cycle (NGCC); and
- A total generation mix of onshore wind (20%) and NGCC (80%) generation.

The system boundaries of the study cover the full lifecycle of each power generation scenario, encompassing a broad range of processes for each power generation scenario, including:

- Upstream and downstream supply chain processes from extraction and processing of fuels through to waste management;
- Power plant operations;
- The lifespan of the power generating facility itself, from acquisition and application of construction materials through to decommissioning at end of life.

For each generation scenario and process stage, the study presents the distribution of LCA data available on the greenhouse gas emissions (GHG), nitrogen oxides (NO_X), sulfur oxides (SO_X), particulate matter (PM) and ionizing radiation (IR) associated with the generation of electricity delivered to the power grid. The information presented in this report is intended to provide the basis with which to make qualified comparisons of the average contribution of nuclear, wind and natural gas to each emission category, while considering the full range of LCA data presented in the literature.

To ensure a transparent and unbiased assessment of the literature, a systematic approach was applied to review the LCA studies and incorporate them into the final dataset and results. A statistical screening process based on a cluster analysis was performed to flag cases where a detailed review of system boundary conformance was required before inclusion in the final dataset. A statistical representation of the distribution of LCA data in the final dataset was provided, documenting the mean as well as the standard deviation and uncertainty of the mean, to help qualify the variation in LCA results and the reliability of the mean value reported by this study.

Figure I and Table I present the total mean lifecycle emissions for each generation scenario, representing the full range *(top)* comparing NGCC relative to the other scenarios and a close-up range *(bottom)* comparing the differences between wind and nuclear.

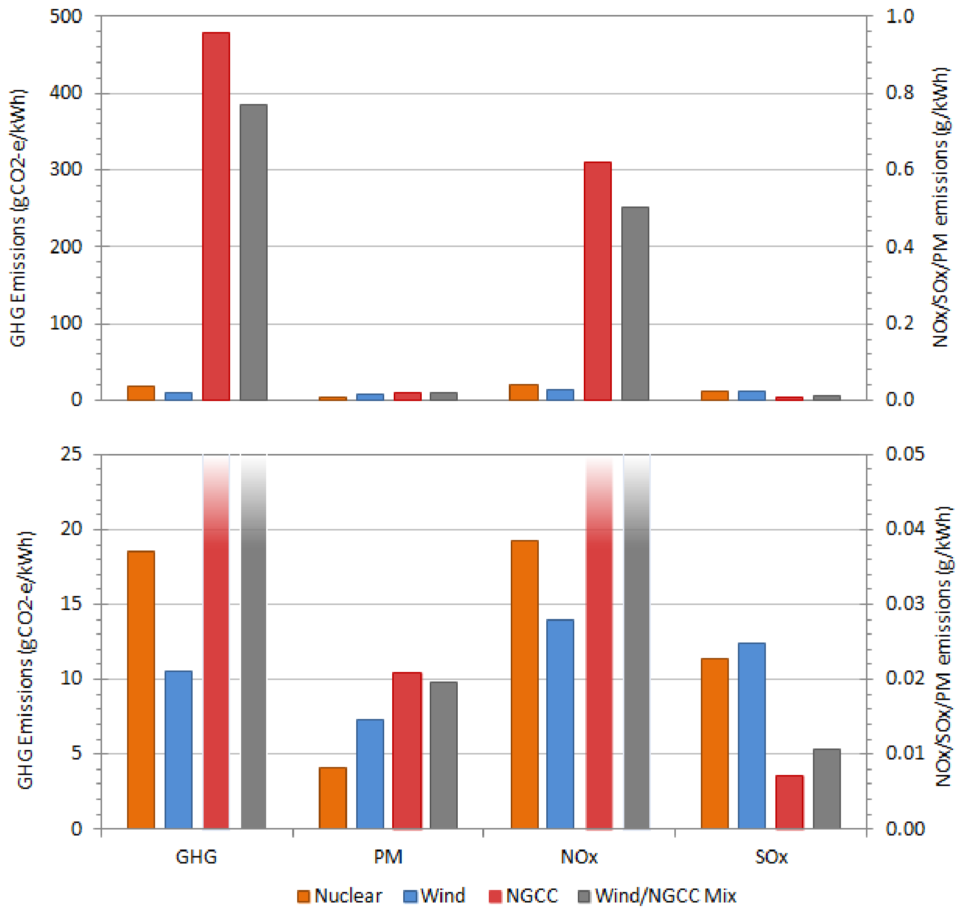

Figure I. Summary of Total Lifecycle Emissions

Table I. Statistical Mean Total Lifecycle Emissions

Scenario	GHG (gCO2-e/kWh)	PM (g/kWh)	NO_X (g/kWh)	SO_X (g/kWh)
Onshore Wind Turbine	10.5 ± 0.9	0.015 ± 0.003	0.028 ± 0.003	0.025 ± 0.003
Nuclear Power Plants	18.5 ± 1.7	0.008 ± 0.003	0.039 ± 0.006	0.023 ± 0.003
NGCC Power Plants	478 ± 10	0.021 ± 0.012	0.62 ± 0.03	0.007 ± 0.001
Mix Wind-NGCC	385 ± 8	0.02 ± 0.01	0.50 ± 0.02	0.011 ± 0.001

The study concludes that GHG and NO_X emissions from nuclear and wind power plants are orders of magnitude less than NGCC power plants, while the difference in emissions of PM and SO_X for each scenario is less pronounced, and difficult to resolve due to limited availability of LCA data.

Wind and nuclear power are similar, where the average emissions from nuclear relative to wind are slightly elevated for GHG and NO_X and reduced for PM and SO_X, respectively. However, when the intermittency of wind is compensated for by a steady power supply – in this case modeled in the wind-NGCC scenario – the emissions profile takes the shape of the backing power source (i.e. NGCC), diluted by wind power.

The study also investigated the differences in emissions between upstream natural gas sources, determining that GHG emissions from shale gas are slightly larger than conventional natural gas, while the difference in NO_X, SO_X, and PM was inconclusive.

By representing the range of data available in the literature for each individual process stage, variations in the results could be linked to the modelling parameters used in the LCA literature as well as the influence of technological and process differences within the system boundaries of each scenario. This additional information, documented in this report, provides a basis of understanding of the strengths and weaknesses of the data, and helps explain some of the root causes for discrepancies across LCA studies applied to the power sector.

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1. Introduction

1.1 Background

The future of the energy and electricity supply sector in Canada will have a profound and long-lasting role in reducing greenhouse gas emissions and facilitating the transition to a low-carbon economy. Rapidly changing technology including the emergence of shale gas requires an up-to-date understanding of the environmental performance of available energy supply options to develop a roadmap towards meeting Canada's environmental and economic objectives.

The Canadian Nuclear Association (CNA) commissioned Hatch Ltd. (Hatch) to conduct an independent comparison of the environmental performance of various power generation scenarios relevant within a Canadian context. Hatch is an employee-owned global multidisciplinary engineering consulting company headquartered in Mississauga, Ontario. Hatch serves the global mining and metals, energy and infrastructure sectors with projects in more than 150 countries. As part of its experience, Hatch has designed and constructed facilities spanning the entire electricity generation supply chain for a range of renewable and non-renewable power generation. Hatch has an in-house LCA group working together with our industry experts to incorporate lifecycle thinking and environmental design into projects.

Using a combined literature review and meta-analysis methodology, the present study compiles previous Life Cycle Assessment (LCA) projects pertaining to the supply chain of nuclear, wind and natural gas combined cycle generation under comparable parameters and system boundaries. The purpose of the study was to compile accurate, objective, and comparable scientific data on the environmental footprint of each generation scenario.

LCA, standardized under ISO 14040, is the most widely accepted comprehensive measure of environmental performance. This study builds off of previous LCA literature reviews with updated data representing technology improvements and incorporating a broader range of upstream and downstream processes associated with construction, decommissioning, and waste management. The meta-analysis approach adopted synthesized LCA literature data to conform to similar system boundaries with which to compare each power generation scenario.

For each generation scenario and process stage, the study presents the distribution of LCA data available on the greenhouse gas emissions (GHG), nitrogen oxides (NO_X), sulfur oxides (SO_X), particulate matter (PM) and ionizing radiation (IR) associated with the generation of electricity delivered to the power grid. The information presented in this report is intended to provide the basis with which to make qualified comparisons of the average contribution of nuclear, wind and natural gas to each emission category, while considering the full range of LCA data presented in the literature.

1.2 Objectives and Scope

The ultimate aim of this study was to provide an objective, scientific-based comparison of the environmental emissions associated with the supply chain and lifespan of nuclear, natural gas and wind power generation facilities. Specific objectives of the study were to:

- Focus on published LCA data that is well documented, relevant, and current;
- Maintain the same conditions and system boundaries for each generation scenario;
- Understand and document the range of LCA data represented in the literature;
- Limit any manipulation of the data to the minimum number of approximations and assumptions necessary to model each generation scenario.

With these objectives in mind, the study compiled and documented LCA data covering a broad scope of processes for each power generation scenario, including:

- Upstream and downstream supply chain processes from extraction and processing of fuels through to waste management;
- Power plant operations;
- The lifespan of the power plant from acquisition and application of construction materials through plant decommissioning at end of life.

For each scenario and process stage, the literature review covered emissions of GHG, NO_X, SO_X, PM and IR.

While wind is presented as a standalone scenario, the study also presents a merged wind and natural gas combined cycle scenario reflecting a hypothetical electricity grid mix where wind power is supported by natural gas to compensate for the intermittency of wind supply. Based on grid infrastructure currently in place in Canada, this scenario considers 20% of total electricity generated as a practical maximum proportion of intermittent power supply possible without compromising the ability of the grid to respond to changing electricity demand.

Within the natural gas combined cycle generation scenario, the supply of natural gas has been divided into conventional, unconventional and shale gas for comparison.

1.3 Approach

Hatch used a two-phased approach, starting with a literature review and gap analysis, followed by a meta-analysis and LCA modeling phase to combine and synthesize the literature data to conform to a common set of system boundaries for each generation scenario.

The literature review focused on documenting a broad range of LCA studies, covering each generation scenario, process stage, and emission type. The goal of the literature review was to gather the greatest number of relevant and current LCA studies possible to cover the scope of the study with the largest dataset possible. Following the review, a gap analysis was performed to evaluate the strength of coverage achieved by the dataset.

The meta-analysis and modeling phase involved compiling LCA data extracted from the literature review, and assembling the data in LCA models representing each power generation scenario. The modeled data was assessed using a number of statistical approaches to refine the data to match the system boundaries of the study. The results of the analysis comprise the main findings of the study, including the mean, uncertainty of the mean, and standard deviation of emissions associated with each generation scenario and process.

1.4 Lifecycle Assessment Overview

Lifecycle Assessment (LCA) measures the environmental impacts of a product by modeling the processes, materials consumed and emissions at each stage of the product lifecycle, extending beyond the conventional operational boundaries of any one company or process stage (1). The process of conducting an LCA is standardized under ISO 14040, consisting of a four-step process including goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1).

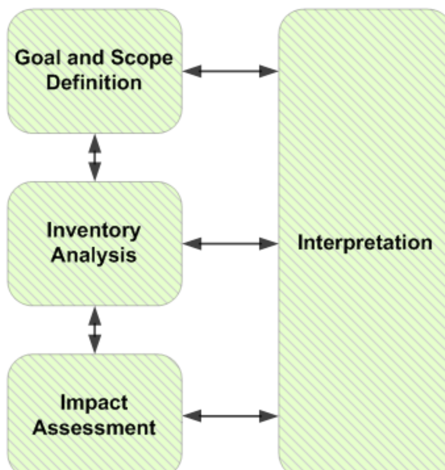

Figure 1. ISO 14040 LCA Project Stages

The goal and scope aligns the stakeholders and project team on the course and outcomes of the LCA study . The goal determines the context of the study, the audience and how the results are intended to be used. The scope of the study defines what is included and excluded in the system, defining the system boundary of the project (process/activities included), the functional unit, and the geographical, temporal and technological coverage.

The inventory analysis stage consists of data collection and modeling to produce a lifecycle inventory (LCI) containing all inputs and outputs for each of the process stage within the system boundary. The LCI serves as the basis for calculating potential environmental impacts during the Lifecycle Impact Assessment (LCIA) stage. The final step is the interpretation of the results to provide conclusions and recommendations.

1.5 Report Structure

This report presents the goals, system boundaries, methodology and results of the meta-analysis LCA. The following list provides an outline of the contents of each chapter:

- **Section 2 – LCA Scope and System Boundaries** defines the scope and system boundaries of the study for each power generation scenario, including the supply chain, lifespan, temporal, geographical and technological coverage included in the study.
- **Section 3 – Literature Review and Meta-analysis Methodology** documents the methodology used to carry out the study and ensure validity of the results, including a description of the literature review and gap analysis, the data compilation and synthesis approach and the LCA modeling procedure.
- **Section 4 – Description of Power Scenarios** documents each power generation scenario in greater detail than Section 2, including a description of the supply chain and lifespan of each generation scenario as well as technological variations found in the literature.
- **Section 5 – Results** presents the mean, uncertainty of the mean and distribution of emissions data for each power generation scenario, supply chain and lifespan process stage relative to a kWh of electricity produced.
- **Section 6 – Discussion** presents a discussion of the results to provide an overall comparison between the power generation scenarios, limitations of the study, and a comparison of the results to similar literature review studies.
- **Section 7 – Conclusions** provides conclusions and key findings in the context of the overall study objectives. Recommendations and future opportunities are also incorporated.

2. LCA Scope and System Boundaries

This study is intended to generate LCA data based on a meta-analysis of literature data found in the public domain. In order to ensure that each power generation scenario was compared on the same basis, a common set of system boundaries was defined for all power generation scenarios.

The system boundaries define what is included and excluded in the range and mean results for each power generation scenario and process stage presented in Section 5. This chapter outlines the general LCA system boundaries considered in the study, while detailed descriptions of each power generation scenario is provided in Section 4. Section 3 documents the methodology used to execute the literature review and meta-analysis while adhering to these system boundaries.

The scope and system boundaries include the various power generation scenarios, environmental emissions, process stages, technologies and time periods covered by the study. In some cases, slight variations in the system boundaries have been permitted in order to incorporate studies with minor differences between them, typically contributing to less than 1% of the total lifecycle emissions in any category. These variations are also documented in this section.

2.1 Power Generation Scenarios

This study provides a complete lifecycle comparison of the environmental performance of various power generation scenarios using a similar set of system boundaries. The lifecycle of the following power generation scenarios have been considered:

- Nuclear power production;
- Onshore wind power production;
- Natural gas combined cycle (NGCC) power production fed by a mix of conventional, unconventional and shale gas sources;
- A mixture of total electricity generated by onshore wind (20%) and NGCC (80%), reflecting a grid mix with a high proportion of intermittent wind power backed by NGCC.

The following sections discuss aspects of the scope including functional unit, environmental indicators, regional, temporal and technological coverage, and the system boundaries applying to each scenario.

2.2 System Boundaries

The LCA meta-analysis is a cradle-to-gate study spanning from resource extraction up to the production of electricity at the point (or gate) of delivery to the electricity grid. The study encompasses all upstream and downstream processes associated with the generation of 1kWh of electricity, excluding transmission and distribution losses.

The environmental impacts and emissions in this study were obtained taking into account two dimensions of their lifecycle:

- **Supply Chain –** processes corresponding to the on-going operation of the power generation facility, including the upstream systems associated with fuels and consumables and downstream systems associated with the management and disposal or wastes.
- **Lifespan –** processes corresponding to the entire lifetime of the power plant from inception to eventual decommissioning, not otherwise captured in the day-to-day operation of the plant.

Figure 2 presents the general system boundaries applied to each generation scenario, showing the supply chain and lifespan definitions used throughout this study.

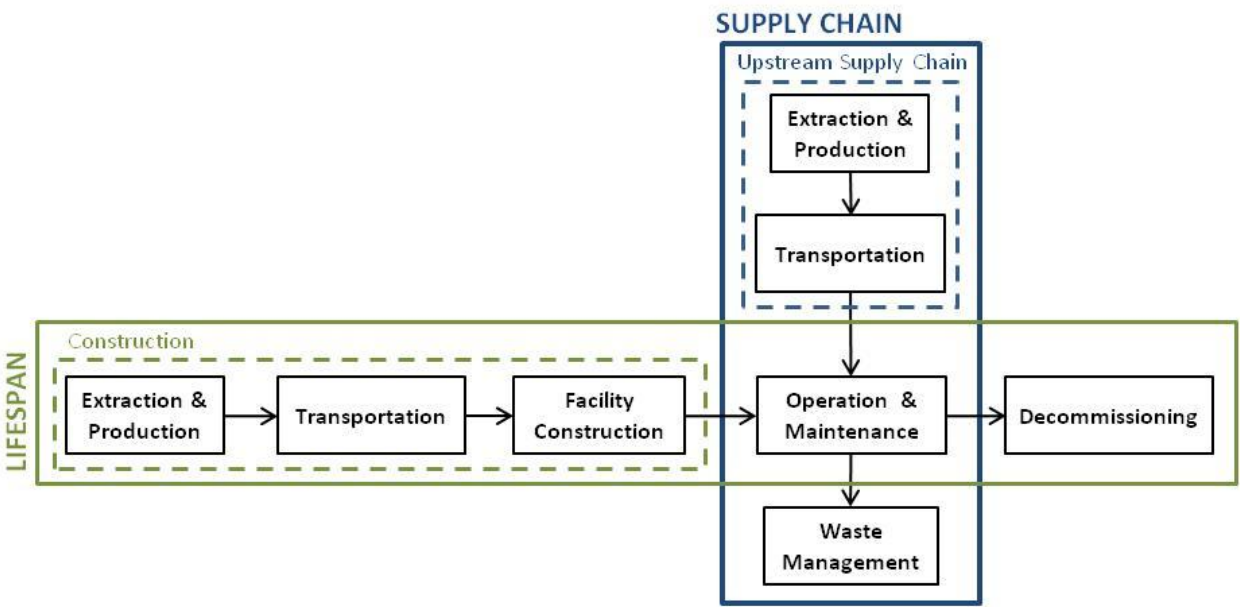

Figure 2. General System Boundary

The supply chain encompasses the extraction, production and transportation of raw materials (fuels and consumables) to the power plant, operations and maintenance, and the management of all waste associated with the activities of the power plant.

The lifespan includes all the process stages required build and disassemble the power plant at the start and end of the plant's lifetime, including the extraction, production, transportation and application of materials and fuels used during construction, as well as the disassembly and disposal or re-use of plant materials during decommissioning.

Combined, the supply chain and lifespan represent the complete range of processes directly and indirectly required to generate electricity from each generation scenario.

The following subsections present a general description of the system boundary of each process stage selected for this study. A detailed description of each stage of the lifecycle, for each of the power generation scenarios, is presented in Section 4.

2.2.1 Supply Chain

The supply chain consists of all upstream, on-site and downstream processes associated with the regular operation of the power plant. Supply chain emissions are primarily associated with the fuel consumed to generate electricity. The supply chain has been divided into three process groups – upstream supply chain, power plant operations, and waste management, each represented relative to 1 kWh of generated electricity.

Upstream Supply Chain

The upstream supply chain includes the environmental impacts associated with the extraction, production and transportation of all fuels and auxiliary substances and chemicals used in the operation of the power plant. Note that the upstream supply chain excludes resource exploration for each generation scenario.

Operations & Maintenance

The operations stage encompasses the environmental impacts associated with the normal operation and maintenance of the power plant. Emissions from power plant operations are primarily a result of fuel consumption.

Waste Management

Waste management includes emissions associated with the waste disposal and treatment of all wastes generated during normal operation and maintenance of the power plant, occurring on site or downstream of the facility.

2.2.2 Lifespan

The lifespan consists of all upstream, on-site and downstream processes at the start and end of the plant's natural lifespan. Lifespan emissions are primarily associated with the fuels and building materials consumed during construction and the disassembly and waste management activities during decommissioning. The lifespan has been divided into two process groups – construction and decommissioning, each represented relative to 1 kWh of generated electricity.

Lifespan emissions were distributed to each unit of power generated by the plant by incorporating the operating lifetime of the facility. The literature reviewed considered a range of plant operating lifetimes for each of the scenarios, which were normalized in order to compare all the scenarios on the same basis. This methodology is described further in Section 3.3.2.2.

Construction

The construction stage includes the environmental impacts associated with the extraction, production and transportation of all necessary materials required for the construction of the power plants. The electricity and fuel required for construction activities are also included in this stage.

Decommissioning

The decommissioning phase covers all environmental impacts associated with the site work for the dismantling of the power plant, the transportation of waste to authorized agents, and the impacts/credits associated with waste management and treatment.

2.2.3 Exclusions

The following processes are not included within the system boundaries of the study:

Resource Exploration

The resource exploration preceding extraction of raw materials has been excluded from this study due to insufficient coverage of this process by previous LCA studies. The exploration phase includes prospecting, surveying and drilling and forms only a minor contribution to the lifecycle of each power generation scenario, below the cut-off criteria of most LCAs. Moreover, the link between the extent of exploration activities that lead to an operating mine is difficult to establish. While minor, exploration is expected to contribute emissions to each power generation lifecycle, principally through energy exploration but also through mineral exploration associated with construction materials and on-going maintenance.

Transmission and Distribution

Transmission and distribution (T&D) infrastructure and electricity losses were not considered in accordance with the end-gate of the study – at the point of delivery to the electricity grid. In cases where a study included T&D losses, emissions were back-calculated to isolate and remove T&D losses. A detailed description of this procedure is described in Section 3.3.2.1.

Carbon Capture & Storage

This study does not consider any technology with carbon capture as no such technology appears to be available for general use at grid scale in the near future.

Energy Storage

Energy storage technologies under development aiming to regulate the power supply from intermittent energy sources including wind and solar power were not considered in this review.

2.2.4 Partial Inclusions

Some processes are permitted to be within or outside the system boundaries to accommodate a greater proportion of the LCA literature. These processes are limited to minor variations in system boundaries that result in a negligible change in the total lifecycle emissions.

Pipeline Construction

Pipeline construction, primarily within the natural gas lifecycle were partially included and excluded from the system boundaries of the studies investigated. Based on a study conducted by the National Energy Technology Laboratory in May 2011, the construction of pipelines contributes 0.1% of the cradle-to-gate emissions from the natural gas lifecycle (2).

Frequency and Significance of Wind Turbine Maintenance

The literature reviewed included variations in the modelling approximations and assumptions surrounding turbine maintenance, including travel associated with periodic inspections, the degree of replacement of worn parts, lubrication and change of oil, or a combination of the above. The frequency of the maintenance in each study also varied, between four times a year (3) to once every 5 years (4). For the purpose of this study, data covering all approximations and assumptions were included, including those studies that did not specifically reference turbine maintenance.

Wind Farm Size and Capacity

Some studies conducted LCAs on wind farms (group of wind turbines), while others were conducted on a single wind turbine. For the purpose of this study, LCAs based on wind farms and individual wind turbines were considered provided each turbine exceeded 100 kW total capacity.

Maintenance at NGCC Plants

Few studies specifically identify emissions from NGCC plant maintenance separately from normal plant operations. Moreover, most studies do not provide a full breakdown on the type of activities considered or the approximations used. As a result, some variations in the type and frequency of activities are expected. For the purpose of this study, all studies (with and without specific mention of maintenance activities) were included. The overall impacts of maintenance activities are negligible relative to combustion-related emissions.

Well Construction for Natural Gas Extraction

While some of the studies specifically included well construction in the system boundaries, other studies did not document the inclusion or exclusion of this process, but were still considered in this assessment. Based on a study conducted by the National Energy Technology Laboratory in September 2013, the construction of wells contributes 2% of upstream GHG and NO_X emissions and 30% of upstream SO_X and PM. Over the entire natural gas power generation lifecycle, well construction generates negligible GHG and NO_X emissions while having a small to moderate contribution to total SO_X and PM emissions (5).

2.3 Geographical, Temporal and Technological Scope

The literature reviewed in this study covered primary and modeled LCA data representing various plants, regions, technologies, and time periods. The following lists the coverage of the literature review and any limitations applied during the process.

Geographical Coverage

There were no restrictions placed on the regional scope of LCA data reviewed, author origins or other region-specific mechanism, although English was the language of all literature reviewed. As a result, notwithstanding other scope and system boundary limits, this study covers the set of global LCA data corresponding to each generation scenario. The relative regional weighting in this study is proportional to the regional distribution of LCA literature and does not necessarily reflect the true proportion of global electricity production.

It is important to note that the location of the study can play a significant role in the environmental impacts due to the variation of the grid electricity mix, and the availability of resources. These variations are addressed in further detail in Section 6.

Technological Coverage

The literature was evaluated to restrict the scope of the literature data to the following technologies for each power generation scenario:

- Nuclear: including a mix of upstream uranium processing and/or enrichment, reactor technology and spent fuel management techniques;
- Wind: covering large onshore wind turbines and excluding small-scale and off-shore turbines;
- Natural gas: covering natural gas combined cycle (NGCC) generation sourced by conventional, unconventional and shale gas sources, excluding other natural gas fired power plant technology and applications of carbon capture and storage.

While wind is presented as a standalone scenario, the study will also present a merged onshore wind turbines and NGCC scenario, reflecting a conservative maximum proportion of intermittent wind power that can be supplied to a power grid, and reflecting the consequent need for wind generating capacity to be associated with similar capacity of some flexible, non-intermittent generation to support it.

Temporal Coverage

The temporal coverage of the study refers to the time span covered by the LCA model. This study covers the full lifespan of the power plant from construction through to decommissioning, considered to be 20 years for wind turbines, 30 years for NGCC power plants and 40 years for nuclear power. These operating times are consistent with the median operating lifetimes considered in the LCA studies captured during the literature review (Section 3.3.2.2).

2.4 Environmental Indicators

The environmental indicators cover each process stage within the lifespan and supply chain, for each generation scenario. Within the system boundary, this study has been assessed for the following set of five environmental metrics:

- Greenhouse gases (GHG)
- Particulate matter (PM)
- Sulphur oxides (SO_x)
- Nitrogen oxides(NO_x)
- Ionizing radiation (IR).*

* IR is only quantified for nuclear power and omitted for natural gas and wind-based scenarios.

2.4.1 *Greenhouse Gases (GHGs)*

Global Warming Potential (GWP) is a total measure of the atmospheric heat-trapping (greenhouse) effect of air emissions (GHGs) contributing to climate change, typically over a 100-year period. The most significant GHGs associated with power generation are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), associated with the combustion of fuels for electricity production and transportation.

GWP is calculated by a weighted sum of each GHG according to its relative heat-trapping effect, aggregated in units of carbon dioxide equivalents ($kgCO_2e$). The relative effect of each GHG may vary based on the impact model used although the variation is minor. A typical example of GWP factors is presented in Table 1, from the International Panel on Climate Change (IPCC) Fourth Assessment Report (6).

Table 1. Global Warming Potential (GWP) for 100 Year Time Horizon

Greenhouse Gas	Fourth Assessment Report GWP
Carbon dioxide (CO2),	1
Methane (CH4)	25
Nitrous oxide (N2O)	298

2.4.2 *Nitrogen Oxides (NO_X)*

Nitrogen oxides (NO_X) are atmospheric emissions generated during combustion when nitrogen and oxygen are present in the combustion zone. After release, NO_X reacts with other compounds in the atmosphere, producing a variety of reaction products which have adverse environmental and health effects, including respiratory illnesses, ground-level ozone or smog, and acid rain.

NO_X emissions are influenced by several factors, including the nitrogen content of fuels and combustion air, and the temperature profile of the combustion zone. A variety of emissions control technologies may be used to control NO_X. Combustion-related technologies such as low-NO_X burners focus on reducing combustion temperature or the concentration of nitrogen and excess oxygen in the reaction zone. Post-combustion-related technologies focus on chemically stripping NO_X from the off-gas stream. NO_x emissions are produced along the power generation lifecycle generated principally from fuel combustion.

2.4.3 Sulphur Oxides (SO_X)

Sulphur oxides (SO_X) are atmospheric pollutants generated during combustion of sulphur-containing materials such as coal and oil. After release, SO_X reacts in the atmosphere to form a variety of compounds with adverse environmental and health effects including ground-level ozone and acid rain.

The degree of SO_X formation is related to the concentration and type of sulphur compounds present in the combustion zone. SO_X can be reduced by stripping sulphur from input materials and fuels, or during or after combustion by addition of lime, limestone or dolomite. SO_x emissions are produced along the power generation lifecycle generated principally from combustion and processing of high-sulphur content fuels.

2.4.4 Particular Matter (PM)

Particulate matter (PM) is a category of air emissions describing the total mass of suspended solid and liquid particles in air, regardless of the chemical composition of the particulates. PM is sub-divided by particle size: PM_{10} refers to particulate between 2.5 µm and 10 µm; $PM_{2.5}$ refers to particulate smaller than 2.5µm. Coarser PM_{10} particulates have a limited resident time in air, eventually settling back to the ground within hours, while finer $PM_{2.5}$ particulates may stay in the air for several days or weeks. PM can be generated during combustion activities, construction and decommissioning and in the handling and transportation of raw materials.

Particulates of any size and composition have adverse environmental and health effects when inhaled, damaging the respiratory system, with increasing penetration and damage occurring for smaller particulates. PM has been linked to increased incidence of respiratory disease, asthma, and mortality.

2.4.5 Ionizing radiation (IR)

Ionizing radiation potential (IR) is a measure used in selected LCAs to characterize the emissions of ionizing radiation, radiation with enough energy to ionize atoms as it propagates through space (7). IR includes the high energy end of the electromagnetic spectrum such as x-rays and gamma rays as well as some particles produced during radioactive decay such as neutrons and alpha and beta particles.

In LCAs included in this review, IR potential is reported in becquerels (Bq), the number of atoms decaying per second in a given source material. However, becquerels do not specify the energy or character of the ionizing radiation products emitted by the radioactive decay or the potential effect they may have on human health.

IR is generated by a variety of natural and man-made sources, including cosmic rays and naturally occurring radioactive isotopes on Earth as well as isotopes used in medical imaging and cancer treatment. IR potential measured by LCA focuses on man-made IR emissions to the environment. IR exposure from nuclear power generation is generally exceeded by exposure from medical sources, which in turn are generally exceeded by exposure from natural sources such as sunlight.

Natural sources of radiation vary according to factors such as location and altitude (8). Sources of natural background radiation include:

- Cosmic radiation - Radiation emanating from sources outside Earth's atmosphere;
- Terrestrial radiation – Radiation found in the natural environment, mainly from radon-222 and radionuclides from the decay of uranium-238.
- Internal radiation – Radiation found in elements such as potassium-40, carbon-14, lead-210, and other isotopes inside human body. (9)

Table 2 shows radioactivity of some common materials to serve as a comparison for the IR emissions estimated in this study.

Table 2. Radioactivity of Selected Materials (10)

Source	Radiation
1 adult human (65 Bq/kg)	4,500 Bq
1 kg of coffee	1,000 Bq
1 kg of brazil nuts	400 Bq
1 banana	15 Bq
The air in a 100 sq metre Australian home (radon)	3,000 Bq
The air in many 100 sq metre European homes (radon)	Up to 30,000 Bq
1 household smoke detector (with americium)	30,000 Bq
Radioisotope for medical diagnosis	70 million Bq
Radioisotope source for medical therapy	100,000,000 million Bq (100 TBq)
1 kg 50-year old vitrified high-level nuclear waste	10,000,000 million Bq (10 TBq)
1 luminous Exit sign (1970s)	1,000,000 million Bq (1 TBq)
1 kg uranium ore (Canadian, 15%)	25 million Bq
1 kg uranium ore (Australian, 0.3%)	500 000 Bq
1 kg low level radioactive waste	1 million Bq
1 kg of coal ash	2000 Bq
1 kg of granite	1000 Bq
1 kg of superphosphate fertilizer	5000 Bq

Based on the literature reviewed, there is a wide range of types of radionuclides assessed in determining the IR potential in an LCA. Most of the studies reviewed include Rn-222, radioactive noble gases, and tritium. Some selected studies consider a broader range of radionuclides, including: Rn-222, Pb-210, Th-230, Ra-226, U-234, U-235, U-238, Th-228, Th-230, Th- 232, Th-234, U-234, U-235, Xe-133, I-129, I-131, I-133, Mn-54, Co-58, Co-60, Cs-134, Cs-137, H-3, Zn-65, Ag-110m, Sb-124, Sb-125, PU-238, PU-239, H-3, C-14, and aerosols. Quantitatively, Rn-222 emissions is the majority contributor to IR potential over the nuclear power generation lifecycle, as presented in Table 3. Therefore, studies that do not consider Rn-222 were excluded.

Table 3. Total Lifecycle IR Emissions for Nuclear Power (11).

Radionuclide	Value (kBq/kWh)	%
Radon	7.29E+02	65.10%
Other noble gases, H^3, C^{14}	3.74E+02	33.40%
Aerosols	2.22E-04	0.00%
Actinides	4.62E-04	0.00%
Radium	6.32E-02	0.01%
Tritium	1.68E+01	1.50%
Sum of Emission	1.12E+03	100%

2.5 Functional Unit

The functional unit in LCA is the basis or normalizing unit used to represent environmental emissions and impacts on similar terms. Thus, the functional unit determines the equivalence between systems and enables comparison between each power generation scenario.

For the purpose of this study, the functional unit has been defined as 1 kWh of electricity produced at the gate of the power plant, at the point of delivery to the electricity grid. Accordingly, all environmental emissions considered in this study are reported in units of mass or becquerels per kWh produced.

3. Literature Review and Meta-analysis Methodology

This section documents the literature review and meta-analysis methodology defined to carry out the study. The methodology was developed to ensure that the study was performed in a transparent and unbiased manner, and as a mechanism to ensure the results are complete, representative and accurate.

While the previous section defined the scope and system boundaries of the LCA studies reviewed, this section describes the mechanisms used to gather and assess the most relevant and up to date information within the public domain, and then to use that information to build LCA models covering each generation scenario on a common basis.

3.1 Overview

A two-phased methodology was developed to address the study objectives in Section 1.2. An overview of the methodology is presented in Figure 3. The first phase consisted of a literature review and gap analysis, followed by the second phase encompassing a meta-analysis of the LCA data to build LCA models representing the entire lifecycle of each power generation scenario.

The first phase – literature review and gap analysis – captured a broad picture of each power generation scenario, spanning the full lifecycle (supply chain and lifespan) and a range of technologies and environmental indicators. The review focused on gathering as much recent and high quality LCA data as possible in order to provide the most reasonable average and distribution of LCA results as possible. A gap analysis was performed to evaluate the coverage of LCA data in meeting the scope and system boundaries defined in Section 2.

The second phase – meta-analysis and LCA – compiled and synthesized published LCA data to conform with the common scope and system boundaries used in this study. The meta-analysis consisted of a screening process to filter or adjust studies with dissimilar scope and system boundaries and linking process stage LCA data together to represent the complete supply chain and lifespan of each power generation scenario.

The results of this process, presented in Section 5, consists of the average emission values of each generation scenario, process stage and emission type. The results also report the distribution of data and a measure of the uncertainty of the mean in order to understand the differences in the basis, methodology and results existing within the LCA community.

In all cases, the approach was to limit the influence of the authors on the results of the literature compilation.

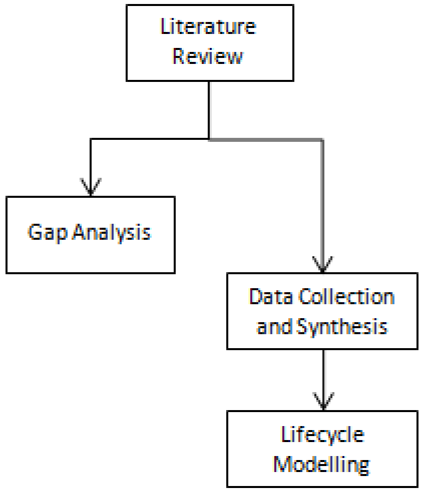

Figure 3. Literature Review and Meta-analysis Methodology Steps

3.2 Literature Review

The first phase of this study was a literature review and gap analysis, intended to gather scientific literature to determine the level of information available in the public domain, in terms of the lifecycle stages (supply chain and lifespan), and the environmental metrics (GHG, NOx, SOx, PM, and IR) corresponding to wind, nuclear and natural gas electricity generation.

A systematic and objective approach was used to find the most relevant and up to date articles and studies within the public domain. The approach included a literature search, scope and system boundary screening process, study documentation, quality assessment and gap analysis. An overview of the process is presented in Figure 4.

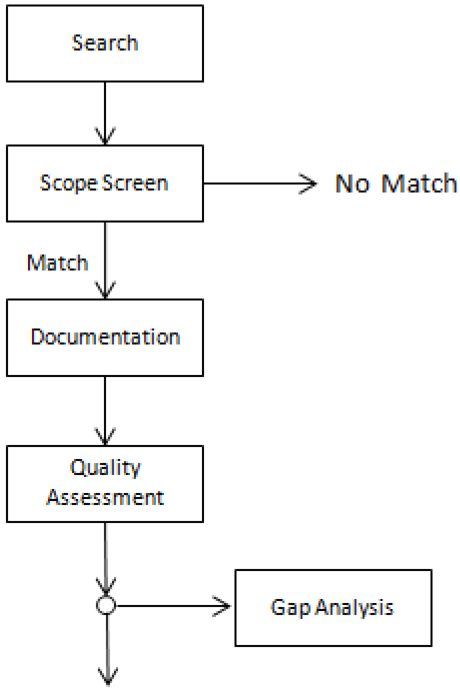

Figure 4. Data Collection Methodology

3.2.1 Search

During the literature review, an exhaustive search of English-language publications was performed to compile a list of published LCA studies covering the lifecycle for each generation scenario.

The initial search involved a keyword search in scientific journal indices and internet search engines. A forward and reverse citation search was subsequently performed on each of the studies found in the initial search. The sources of literature reviewed included, but was not limited to:

- Canadian Energy Research Institute's (CERI) 2008 study;
- Scientific papers/presentations;
- Lifecycle databases, such as GaBi and Eco-Invent;
- Technical journals, such as, International Journal of Life Cycle Assessment, Renewable and Sustainable Energy Reviews, Renewable Energy, Journal of Industrial Ecology, etc.;
- Master/PhD thesis from different universities, such as University of Florida, Carnegie Mellon University, University of Sydney, University of Manchester, etc.;
- Industry data, such as Vestas, Gamesa, Vattenfall, Enel, National Energy Technology Laboratory (NETL), IFC consulting, etc.

The search was focused on studies with LCA-derived data, excluding studies that did not follow LCA methodologies to measure environmental emissions.

3.2.2 Scope Screen

The articles found in the public domain were reviewed to determine their relevance in terms of the defined scope and system boundaries (Section 2) and the age of the study.

Studies that did not match any segment of the scope and system boundaries, or failed to clearly present the scope and assumptions of the study were removed from the list of available literature. Any study preceding the year 2000 were also excluded.

3.2.3 Documentation

All articles passing the screening process were summarized and stored in a literature review database, used throughout the rest of the study. The database consisted of a variety of data tags used to categorize each study. Key information stored in the database included author, title, publication year, and a variety of categories outlining the scope and system boundaries, including:

- Supply chain and lifespan coverage;
- System boundary segmentation;
- Temporal, geographical and technological coverage;
- Environmental indicators/emissions considered;
- Key assumptions/approximations and approaches.

3.2.4 Quality Assessment

A subjective quality assessment was conducted for all studies passing the scope and system boundary screening process. The quality assessment provided a quality score to each study to help inform the quantitative data screening process in the second phase of the project. The quality assessment focused on the methodology and documentation of each LCA study, giving preference to articles that are:

- Conducted based on ISO 14040 principles or are ISO 14040 compliant;
- Peer reviewed by an independent third party;
- Authored by well-established and objective academic and research organizations;
- Well documented, transparent, and reproducible with a clear description of the scope, boundaries, methods, assumptions and approximations;
- Presenting LCA results derived directly from primary and secondary sources.

The results of the quality assessment alone were not used to remove any LCA study. Instead, the quality scores were revisited for statistical outliers identified in the second phase of the study as part of a process to understand the underlying causes for discrepancies between the quantitative data provided by the literature review.

3.2.5 *Gap Analysis*

A gap analysis was performed following the literature review to assess the strength of scope and system boundary coverage achieved by literature in the public domain. A colour matrix was developed to show gaps and strengths in the supply chain and/or the lifespan, and in the environmental impacts for each scenario.

Figure 5 presents the results of the gap analysis, colour-coded such that:

- Green cells indicate several studies were available;
- Orange cells indicate moderate data availability;
- Pink cells indicate moderate data availability but requiring some approximations and assumptions to conform to the system boundaries of the study;
- Red cells (none shown) indicated insufficient data found through the literature review. Red cell are not presented in Figure 5, as a series of iterations to the system boundary were performed to address these critical areas (described below).

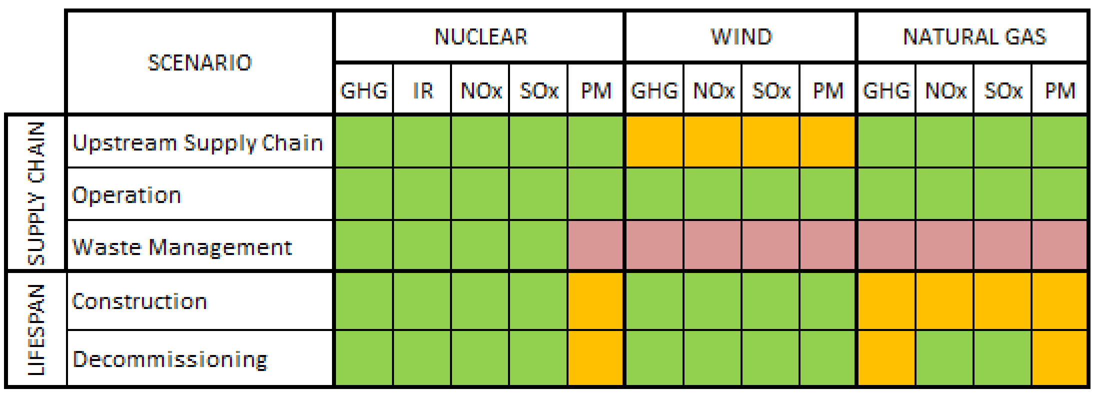

Figure 5. Gap Analysis for Final Scope and System Boundaries

The gap analysis was an iterative process, leading to a refinement of the scope and system boundaries to better match the data available in the LCA literature. The following gaps were identified and addressed in the initial analysis:

- **Resource Exploration –** insufficient data was available to capture the exploration phase of each power generation scenario. Based on the type of activities typically associated with exploration, it is not expected to be a major contributor of any of the emissions included in this study. As a result, the exploration phase was excluded from the system boundaries of the study.
- **IR Potential for Wind and Natural Gas** – review of literature data for the IR potential of wind and natural gas-based generation showed limited data sources available as well as data derived from generic LCA datasets covering indirect, upstream sources, primarily associated with the use nuclear-derived electricity in the production of consumables and construction materials. As a result, a comparison of IR potential between power

generation scenarios was not possible, and only the IR potential of nuclear power generation was reported.

- **Waste Management at Natural Gas Power Plants** – the amount of data available for waste management is limit and often aggregated with power plant operations. This has a negligible impact on the total lifecycle emissions as outlined in Section 4.3.3, but limits the ability to draw accurate findings associated with waste management.
- **Supply Chain Segmentation** – while some studies separate upstream extraction, production and transportation of materials, several studies merge each stage together. As a result, the upstream supply chain is represented in this study as one process group in order to increase the amount of data available to improve the statistics of the study.
- **Lifespan Segmentation** – a key strength found during the gap analysis was the level of information gathered for the lifespan of the power generation scenarios (i.e. construction and decommissioning). However, the information presented for construction was typically not separated into extraction, production, transportation and construction activities. As a result, all on-site and upstream construction activities were grouped in order to increase the statistics of the dataset.

3.3 Data Collection and Synthesis

Data management and assessment is a key element of this study, to ensure that multiple data sources can be compared along similar scope/system boundaries so that the aggregated results are technically accurate.

While the literature and gap analysis phase assessed the qualitative aspects of each literature source (scope, methods, etc.), the meta-analysis phase focused on the quantitative results of each study. By comparing quantitative results across studies, statistical outliers could be identified and evaluated separately to ensure the modeling assumptions, limitations and system boundaries are appropriate for including in the final dataset.

A transparent, systematic and statistics-based methodology was applied consistently throughout the assessment and screening process with the objective to maximize the number of studies included in the results (improved range and statistics) while adhering to the scope and system boundaries of the study.

Figure 6 presents the data collection and synthesis approach used in this study. First, quantitative LCA data was compiled and grouped according to its coverage of the scope and system boundaries. Next, a system boundary adjustment was performed on selected data when necessary in order to conform better with the system boundaries of the study. A cluster analysis was then performed, identifying trends in the LCA data by comparing the similarities and differences in the results across multiple independent LCA studies, and linking these trends to geographical scope, technological representation, modelling assumptions and a number of other factors. A statistical analysis was performed on each process stage and data cluster to identify statistical outliers for further examination.

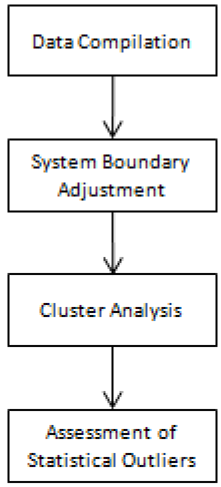

Figure 6. Data Collection and Synthesis Approach

3.3.1 Data Compilation

Quantitative LCA data was extracted from each of the studies matching all or part of the scope and system boundaries defined in Section 2, grouped by generation scenario, process stage, technology and other criteria and compiled into a database.

During data compilation, the database was divided into the process stages defined in Section 2.2, with tags indicating author, publication year, coverage (temporal, geographical and technological), and other key elements of the scope. The database was linked to the qualitative documentation of each study outlined in Section 3.2.3, and formed the basis of the meta-analysis to follow.

3.3.2 System Boundary Adjustment

Selected data points extracted from the literature required minor adjustments so that the data compiled conforms to the system boundary definition in this study, thereby ensuring that the results are technically comparable across all power generation scenarios. Adjustments were limited to cases where only minimal changes to the original study methodologies were required. Cases involving significant changes and assumptions were excluded from the results. The system boundary adjustments included adjusting to:

- Isolate and remove transmission and distribution losses;
- Normalize plant operating lifetime for all data;
- Represent upstream natural gas extraction and production studies relative to units of electricity produced.

The methodology and rationale behind these adjustments are explained in the following sections.

3.3.2.1 *Transmission and Distribution Losses*

The system boundaries of this study was up to and including the production of electricity, prior to delivery to the electricity grid and represented, accordingly, using a functional unit of 1 kWh of electricity produced. LCA studies which include transmission and distribution losses required an adjustment to conform to the system boundaries and functional unit reported in Section 2.

The adjustment consisted of:

- Changing the functional unit from electricity delivered to the consumer to electricity produced at the power generating facility;
- Isolating and removing power losses occurring during transmission and distribution.

A percentage of the electricity produced at the generating facility is lost to transmission and distribution (T&D) infrastructure while in transit to the consumer. This T&D loss is dependent on the characteristics of the regional power grid considered in the study, and acts to increase the relative magnitude of emissions when represented in units of electricity delivered.

To make the adjustment, the percentage of T&D losses was used to re-scale the data, thereby excluding the T&D losses from the LCA results. When available, the T&D loss figure provided by the study was used. In the absence of study-specific figures, a typical industry value of 7% was used.

The range of losses presented in the literature range between 5% and 7%, while non-LCA data reported by various energy organizations typically report T&D losses higher than 7%. In fact, based on data from the World Bank, the electric power transmission and distribution losses worldwide for 2011 averaged 13%. For the purpose of this study, a 7 % loss was assumed based on the upper bound of LCA studies, consistent with a U.S. National Energy Technology Laboratory study on the T&D network in the U.S., and was used in cases where the study did not provide enough information to back-calculate to kWh-produced.

3.3.2.2 *Plant Operating Lifetime Normalization*

The literature review considered different plant operating times within each of the power generation scenarios. To compare all the studies for each scenario using the same basis, the lifespan segment of the lifecycle (construction and decommissioning) was normalized to a standardized lifetime reflecting the median lifetimes considered in the LCA literature for each scenario, respectively.

The distribution of operating lifetime figures used across the LCA studies pertaining to each power generation scenario are reported in Figure 7, indicating a median plant operating lifetime of 20, 40 and 30 years respectively for wind, nuclear and natural gas power generation, respectively. Accordingly, this study considers a 20 year lifetime for wind turbines, 40 years for an average nuclear power plant, and 30 years for an NGCC power station. For example, over a 60 year span, the LCA model considers the construction and decommissioning of 1.5 nuclear plants, 2 NGCC plants and 3 wind farms.

The distribution of operating lifetimes considered during LCA modeling are narrowly defined for wind and natural gas. A wider distribution for nuclear power was observed, reflective of the mix of technologies considered in the nuclear power generation scenario defined in Section 2.3.

It is important to note that while most nuclear LCAs considered a reactor lifespan of 40 years, CANDU reactors normally operate for roughly 30 years, with an option to refurbish the plant for an additional 30 years of operation. Due to the wide range of nuclear reactors considered in this study, and the fact that not every LCA study reviewed was explicit on their consideration of refurbishment in their estimation of lifetime, the contribution of refurbishment to the total life cycle of nuclear power plants was not explicitly quantified.

Standardizing the lifespan process stage data to the median lifetime was not possible for studies that did not document their chosen operating lifetime. In these cases, the data was simply included without any adjustment, in effect assuming that the chosen operating lifetime is equal to the median lifetime observed across the LCA literature. Of all studies included in each scenario, 6%, 17% and 23% of wind, natural gas and nuclear studies, respectively, either do not document or contain a mix of operating lifetimes. Including these data points improved the size of the dataset while introducing uncertainty in the true distribution of the operating lifetime values considered in the LCA data. To address the uncertainty, all LCA data still had to pass the statistical outlier screening process outlined in Section 3.3.4.

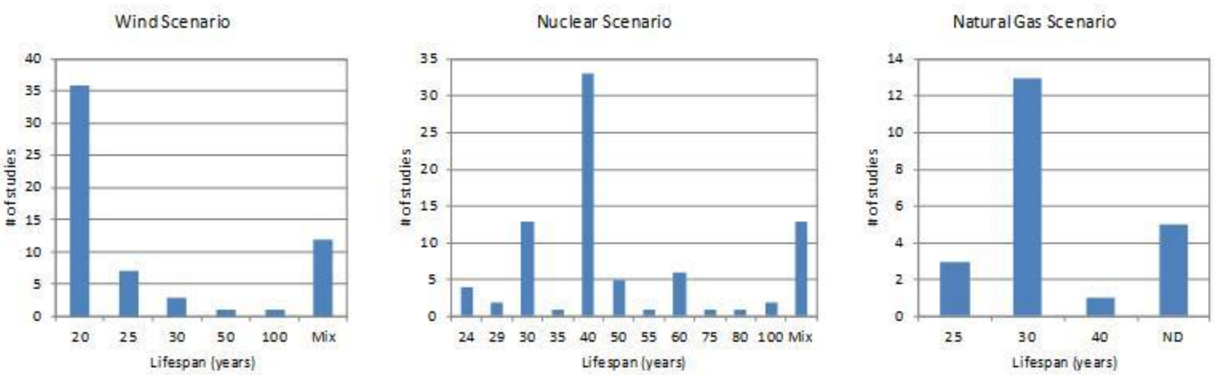

Figure 7. Distribution of Operating Lifetimes Found in LCA Literature by Power Generation Scenario*

The choice of operating lifetime by LCA studies has an important effect in distributing the emissions from construction and decommissioning to each kWh of power generated during a plant's operating life; if the operating time is increased, emissions are diluted over a longer time period, while if the operating time is decreased, the emissions are concentrated per kWh of power generated. The effect of operating lifetime on the overall lifecycle totals can be significant when emissions from construction and decommissioning (lifespan processes) are

* "ND" refers to studies where the operating lifetime was not disclosed.

large relative to plant operations (supply chain processes). The impact of changing the operating lifetime on total lifecycle emissions is examined in Figure 8. When lifespan (construction/decommissioning) emissions greatly exceed supply chain emissions (e.g. 90%-lifespan), doubling or halving the length of time the plant is operating leads to a decrease and increase in total life cycle emissions of 45% and 90%, respectively. When supply chain emissions dominate (e.g. 10%-lifespan), doubling or halving the operating time results in less than a 10% change in total life cycle emissions.

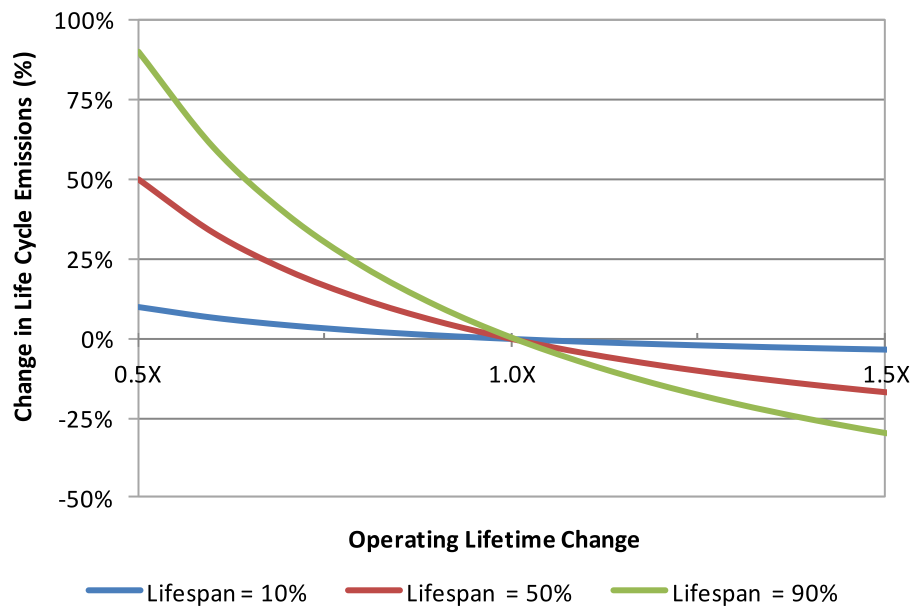

Figure 8. Influence of Operating Lifetime Over Total Lifecycle Emissions

3.3.2.3 Natural Gas Combined Cycle (NGCC) Power Plant Efficiency Factor

In order to closely examine the various sources of natural gas, the literature review included LCA studies spanning only the upstream extraction and production of natural gas. The LCA data contained in these studies were correspondingly represented relative to units of natural gas (typically 1 MJ) rather than power plant electricity generation.

To represent the upstream data relative to 1 kWh of power produced, upstream emissions were scaled according to the amount of natural gas required to produce 1 kWh of electricity via NGCC generation. Based on the literature reviewed, NGCC efficiencies typically varied between 50% to 57.5%, based on a mix of turbine and boiler technology. In cases where the study did not provide the necessary figures, an average efficiency of 50.2% was applied. This value was taken from the study “Life Cycle Analysis: Natural Gas Combined Cycle (NGCC)

Power Plant", National Energy Technology Laboratory (12), an aggregated value of average NGCC efficiency in the United States.

3.3.3 *Cluster Analysis*

A cluster analysis was performed on the literature LCA data following the scope and system boundaries adjustment. The analysis consisted of grouping similar LCA data points within the overall distribution of data points representing a given process stage and power generation scenario and then examining the cluster or subset of data to identify common characteristics in their studies' methodology, technology selection and modelling approximations. The cluster analysis involved the following steps:

- Identify clusters of similar data points by examining the distribution of data points in the literature database;
- Evaluate clusters to identify common study characteristics and trends underlying cluster formation;
- Examine the distribution of all data pertaining to the common study characteristics and trends (e.g. a particular technology) to confirm the cluster and identify statistical outliers.

Trends identified as part of the cluster analysis informed the evaluation of statistical outliers and helped in understanding how the system boundaries and other LCA parameters influenced the range of data observed in the literature. Initial findings of the cluster analysis also led to refinements in the scope and system boundaries through an iterative process. Examples of findings from the cluster analysis include:

- The inverse relationship between wind turbine capacity and turbine emissions, becoming pronounced for wind turbines less than 100 kW. Small-scale wind turbines, below the capacity of turbines used in large wind farms have since been excluded from the scope of the study.
- The type and presence of uranium enrichment in the upstream supply chain has a pronounced influence on the total lifecycle emissions associated with nuclear power generation. For instance, GHG emissions from gas centrifuge enrichment technologies have a mean of 4.1 ± 0.8 gCO2-e/kWh, compared to 14.0 ± 5.0 gCO2-e/kWh for diffusion enrichment. Similarly, GHG emissions are substantially lower for nuclear reactor technologies utilizing using natural-grade fuel (i.e. no enrichment). While all enrichment technologies (including no enrichment) are included within the scope of the study, the cluster analysis helps explain the range of LCA data observed in the literature.

The results of the cluster analysis form the basis for the discussion in Section 6.

3.3.4 *Assessment of Statistical Outliers*

The final stage of data collection and synthesis focused on statistical outliers identified as a result of the cluster analysis. Rather than removing statistical outliers from the final dataset, the purpose of this stage was to identify outlying data for a comprehensive review. The review, in turn, attempted to find a root cause for the differences between the outlying data point and the rest of the results and take appropriate action if necessary.

The methodology to identify and treat statistical outliers is presented in Figure 9. The process was applied to each cluster and process stage. For the purpose of this study, a statistical outlier was defined as any point outside of a two standard deviation band about the mean.

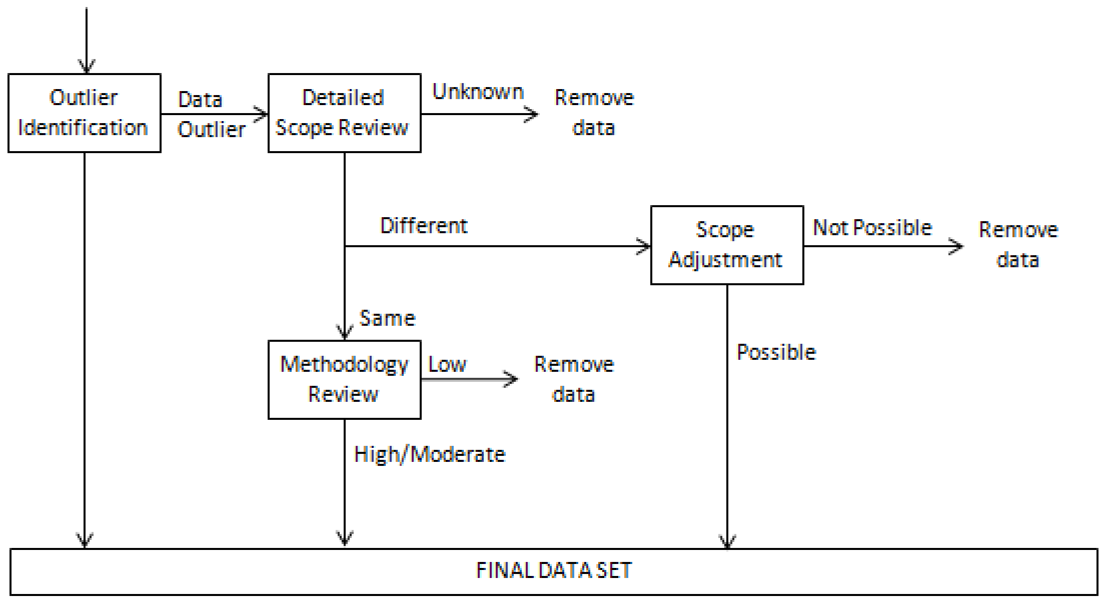

Figure 9. Treatment of Statistical Outliers

If the data is within the lower/upper limit, the data point is included in the analysis as part of the final data set. If the data point is defined as an outlier, a further analysis to determine the equivalence of the scope/assumptions is conducted as follows:

- **Detailed Scope Review –** to confirm that the scope and system boundary definitions are similar or different. If the documentation of the scope and system boundaries is insufficient to perform the review the corresponding data point was removed.
- **Scope Adjustment** – performed when a difference in scope was identified as the cause of the outlier. If the data point can be adjusted to conform with the scope definition by using article information, the data point is adjusted and included as part of the final data set. If the data point cannot be accurately extracted by using the article information, the data point is excluded from the final dataset.
- **Methodology Review –** performed when the outlier cannot be explained by differences in the scope and system boundaries. The methodology review evaluates the quality ranking of the study (Section 3.2.4) to assess whether the study is well documented and conducted in accordance with accepted standards and practices of

LCA. Articles scoring below average, loosely based on LCA practices or lacking in detailed documentation of methods assumptions and approximations were removed from the final dataset. Despite their outlier status, all data from moderately and highly ranked studies were considered in the final dataset.

This approach helped to address statistical outliers in an objective way, improving the conformance of the dataset with the scope and system boundaries of the study while minimizing the decision to exclude data to a last resort.

Following the assessment of outliers, a statistical comparison of the final dataset to the original dataset was performed to confirm that the uncertainty in the determination of the mean was reduced by the process. The analysis reviewed statistical metrics characterizing each dataset, including standard deviation, minimum/maximum, mean and uncertainty of the mean.

The uncertainty of the mean, a measure of the standard error in the determination of the mean was compared with the original value, to compare the impact of narrowing the distribution of the data and reducing the size of the dataset due to the removal of each outlier. Decreases in the uncertainty of the mean implies that the removal of the outlier was effective in improving the accuracy of the determination of the mean for each process stage and power generation scenario.

3.4 LCA Dataset Characteristics

The combination of the literature review, gap analysis and data collection and synthesis produced a final database of LCA data grouped by power generation scenario, process stage and type of environmental emission. This database formed the basis of the meta-analysis based LCA modelling outlined in Section 3.5 and results presented in Section 5. This section outlines key characteristics of the coverage achieved by the dataset to consider when evaluating the findings of the study.

3.4.1 System Boundary Coverage

The process of matching scope and system boundaries narrowed the number of literature sources included in the final dataset in order to provide a comparison between each generation scenario on similar terms. Table 4 presents an overview of the number of studies considered in the final dataset addressing each generation scenario.

The gap analysis outlined in Section 3.2.5 revealed that the best coverage was achieved for the plant operations process stage and for GHG emissions across the lifecycle of each generation scenario.

Minor process stages within each generation scenario were given less attention in the LCA literature, including the upstream supply chain for wind power, management of wastes produced by wind and NGCC generation, and the start and end-of-life activities associated with NGCC generation. In each case, these process stages form only a minor contribution relative to the other process stages such as wind turbine construction and NGCC plant operations.

The LCA literature focused on GHG emissions above all other environmental emissions categories. Coverage of PM emissions generated during construction and decommissioning activities were the most limited of any environmental emission category.

Table 4. Number of Screened Studies Considered

Electricity Generation	Number of scenarios[1] on final data set [2]
Onshore Wind Turbines	46
Nuclear	79
Natural Gas Combined Cycle	27

[1] The number of individual lifecycle scenarios in the literature database. The number of scenarios is not an indication of the number of studies considered, the type of emissions covered or number of process stages included.
[2] Final data set represents the database after all statistical outliers were removed.

3.4.2 *Geographical Coverage*

The scope of the literature review covered studies with a variety of regional focus areas, including Europe, North America, Asia, Australia, South America and Worldwide (as a mix or average), as presented in Figure 10.

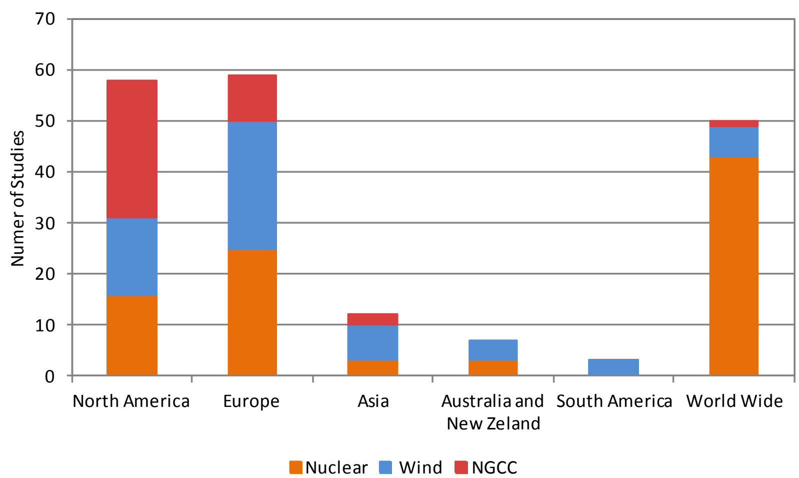

Figure 10. Regional Coverage

Wind and nuclear are predominantly covered by European data, followed by North America and worldwide averages. Natural gas is predominantly covered by North American data, followed by European data.

Although a focus area of the literature review, Canadian data is not widely available in the literature, representing only 16% for nuclear, 10% for wind and 12% for natural gas.

3.4.3 *Temporal Coverage*

A focus of the literature review was to gather up-to-date information, especially covering the period from 2008 to 2013. However, to provide complete coverage of the scope and system boundaries the period was extended to cover 2000 to 2013. The number of studies contributing to the final dataset are presented in Figure 11 divided by the year of publication.

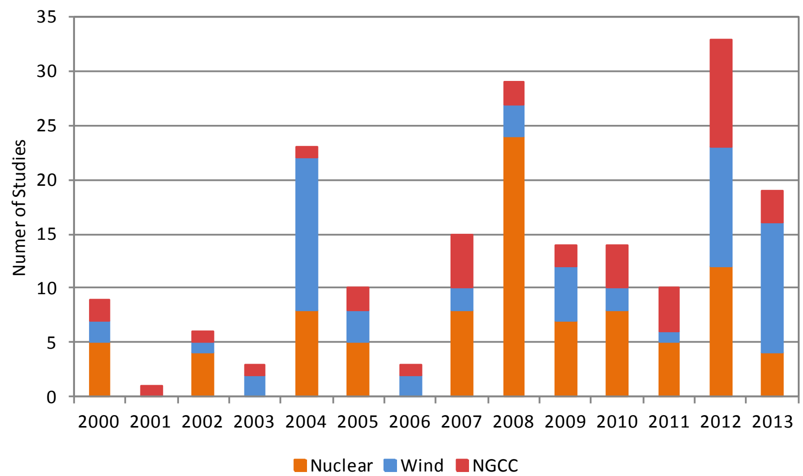

Figure 11. Temporal Coverage

3.4.4 Technological Coverage

The scope of the study is restricted to on-shore wind turbines and NGCC plants for wind and natural gas generation, while the nuclear power generation scenario covers the full range of enrichment and generator technologies.

Of the entire set of literature reviewed covering wind power and natural gas generation, 56% and 40% of studies specifically addressed on-shore wind power and NGCC, respectively.

Nuclear power generation is represented by technologies such as pressurized water reactors (PWR), boiling water reactors (BWR), light water reactors (LWR) and CANDU reactors. CANDU reactors represent 10% of the articles collected. A mixture of fuel supply chain technologies are also captured, including no enrichment and diffusion and centrifuge based enrichment.

3.5 Lifecycle Modelling

The data collection and synthesis stage produced a final database of data points derived from LCA literature representing individual process stages as well as aggregated data representing the supply chain, lifespan and/or entire lifecycle. The focus of the lifecycle modelling phase was to build LCA models to incorporate individual process stage data into the aggregated lifecycle totals.

This approach increased the number of studies considered in the mean and distribution of data for each power generation scenario by including studies which only address a segment of the system boundaries.

The steps involved in the lifecycle modelling process are outlined in Figure 12. Total data, data points representative of the entire lifecycle, are considered separately from data representing individual process stages. A process stage linking process was applied to the individual process stage data to assemble the data into lifecycle models in order to provide additional data to the analysis of the aggregated lifecycle. The process stage linking procedure scaled process stage data based on the average contribution of each stage towards the total lifecycle emissions using a weighted average approach. After linking, both the total lifecycle data and individual process data were analyzed to produce statistical data representing the mean and distribution of emissions, presented in Section 5.

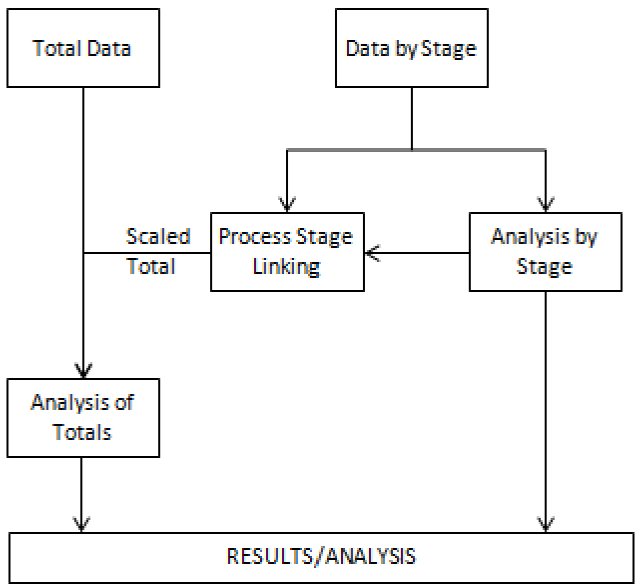

Figure 12. LCA Modelling Methodology

3.5.1 Analysis of Process Stage and Aggregated Lifecycle Data

Statistical metrics were extracted to represent the average and distribution of emissions data available in the LCA literature contained in the final data set. The statistical metrics included the mean ($\bar{x}$), standard deviation (σ) and uncertainty of the mean as a representation of the error (δ), used to represent the data grouped by:

- Power generation scenario;
- Environmental emission type;
- Process stage;
- Total supply chain;
- Total lifespan;
- Total lifecycle (supply chain and lifespan)

While the mean identifies the central location of the data, the uncertainty of the mean provides a measure of the confidence in the accuracy of the calculated mean (i.e. how well the sample mean represents the 'true' mean). The standard deviation represents the spread of the data from the mean, where larger values reflect a broader distribution. The standard deviation alone is not a measure of the accuracy of the sample mean. The mean, uncertainty of the mean and standard deviation are calculated using the following formulas, respectively:

$$\bar{x} = \frac{\sum x}{n}$$

$$\sigma = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$$

$$\delta = \frac{\sigma}{\sqrt{n - 1}}$$

$\bar{x} =$ Mean value

$\sigma =$ Standard deviation

$\delta =$ Uncertainty of the mean

$x =$ Individual data point

$n =$ Numer of data points

3.5.2 Linking Process Stages

Individual process stage data was incorporated into the aggregated totals representing the supply chain, lifespan and total lifecycle. The procedure improved the amount of data available to determine the total lifecycle emissions to compare each power generation scenario.

The linking process considered process stage data in the aggregated totals by:

1. Determining the average contribution of each process stage to the total lifecycle;
2. Completing the lifecycle system boundaries for each data point by applying the average contribution of each process stage not represented by the particular study;
3. Summing the literature source data and averaged data to yield a calculated value for the total lifecycle;
4. Weighting the value of the calculated total according to the percentage contribution of the source data relative to averaged data used to complete the lifecycle.
5. The weighting was applied when determining the mean, standard deviation and uncertainty of the mean for the total supply chain, lifespan and complete lifecycle.

The weighted average approach was built based on the premise than the significance of the data considered in the supply chain, lifespan and total lifecycle should be equal to the proportion of the total scope covered by the data. Using this approach, the weighting of GHG emissions data from upstream natural gas extraction and processing will be less than a data point covering the combustion of natural gas during power generation and lesser still compared to a data point covering the entire natural gas supply chain.

This approach allowed the study to consider all process stage data points into the total, while weighting their influence on the total according to the significance of the particular process stage.

4. Description of Power Generation Scenarios

This chapter details how the general scope and system boundaries in Section 2 applies specifically to each power generation scenario considered in the study. The following sections provide a description of the processes and technologies included in each process stage in order to understand what is represented by the results of the study presented in Section 5.

4.1 Wind Power Generation

The lifecycle of wind power generation covers the extraction, production, transportation and waste management of all consumables for construction, decommissioning and normal operation of on-shore wind farms. A detailed system boundary for the wind scenario, and the process stage divisions included in this study, is presented in Figure 13.

As a form of renewable power, the lifecycle of wind-based power is dominated by the lifespan process stages covering the construction and decommissioning of the wind farm, as opposed to the on-going supply of fuels and other site consumables.

In this study, the wind power scenario is limited to on-shore wind farms comprising turbines greater than 100 kW in capacity. The operating lifetime considered to annualize the lifespan emissions is 20 years, the median lifetime observed in LCA literature.

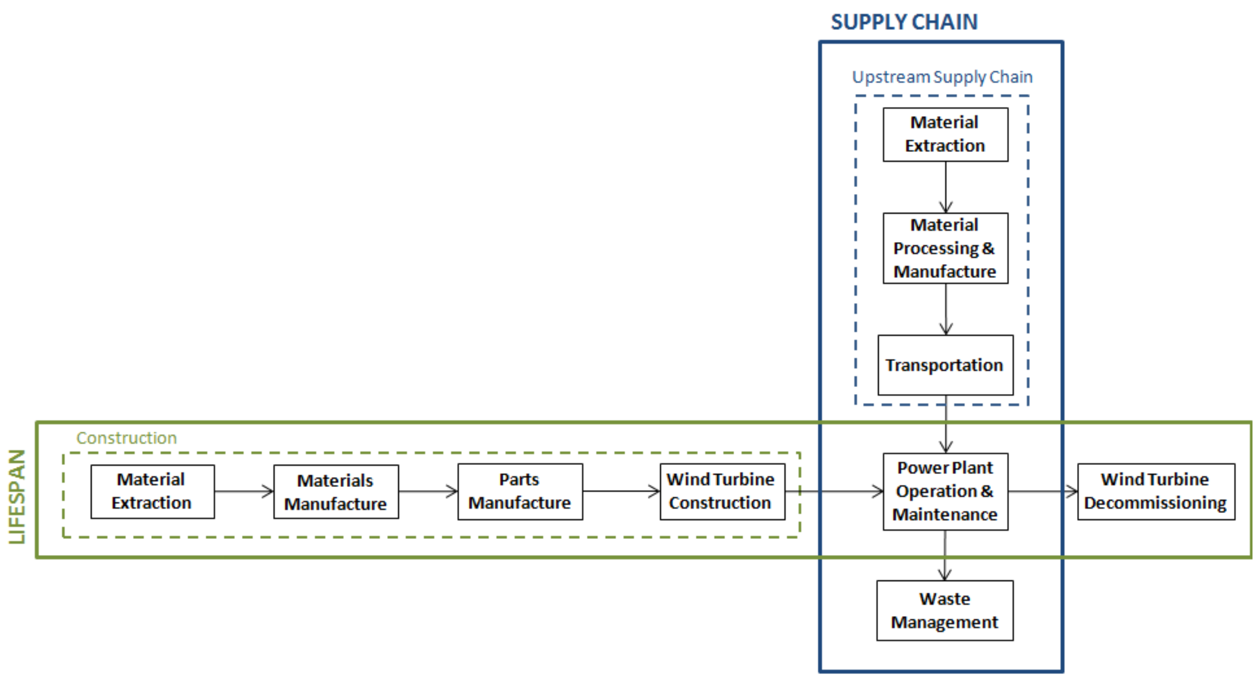

Figure 13. Wind Scenario Detailed System Boundaries

4.1.1 Upstream Supply Chain

The upstream supply chain includes the impacts associated with the extraction, production and transportation of all necessary auxiliary substances and chemicals for the proper operation and maintenance of wind turbines. The main consumables used during operations include hydraulic oil, lubricants and grease. The upstream supply chain for wind is minor compared to other forms of electricity production requiring a steady supply of fuel in order to operate.

Environmental emissions during this stage are influenced, to a certain extent, by the distance and mode of transportation of materials from the extraction and production center to the wind farm.

4.1.2 Operation

The operational stage of the wind power generation scenario encompasses the environmental impacts primarily associated with the periodic maintenance of wind farms. Again, relative to other forms of power generation, the on-going operation of a wind farm requires minimal activities or input to operate relative to non-renewable power generation.

Maintenance includes all activities necessary to maintain the correct operation of the turbines. Some of the maintenances activities include change of oil, lubrication, replacement of worn parts, and travel to and from the turbine for inspections and repairs.

The literature reviewed included variations in the modelling approximations and assumptions surrounding turbine maintenance, including the travel and frequency of inspections, the degree of replacement of worn parts, and lubrication and oil change requirements. Other variations included whether a single turbine was considered in the assessment, rather than a full-scale wind farm. In all cases, the variations between studies were accepted within the scope and system boundaries of this study (Section 2.2.4).

4.1.3 Waste Management

Waste management includes emissions associated with the disposal and treatment of wastes generated during normal operation of wind turbines, consisting primarily of the waste products generated as a result of turbine maintenance.

Variations within the literature consist of the type and location of waste disposal, covering a combination of landfill, incineration and recycling. Waste management data may also be influenced by the regulated waste management requirements in the region of study.

In the case of recycling, a significant number of studies credited the beneficial environmental impact of recycling the materials in the future to the overall environmental impact of the lifecycle (13).

4.1.4 Construction

The construction stage includes the upstream extraction, production and transportation of materials and on-site construction activities required to erect a wind turbine or wind farm. Construction activities include any civil work associated with the wind turbine.

It should be noted that materials for construction vary among the studies reviewed, dependent on the physical size of the turbine (capacity and hub height), turbine technology (turbine with gearbox and without gearbox), and turbine type (horizontal and vertical axes).

Different types of turbine materials influence the upstream extraction, production and manufacturing. For the purpose of this study, all variations in this respect were included within the system boundaries.

Similarly to the upstream supply chain stage, emissions generated by the construction process stage are influenced by transportation from the extraction and production center to the location of the wind turbine

4.1.5 Decommissioning

The decommissioning process stage includes emissions resulting from the decommissioning of a turbine or wind farm at the end of its useful life.

Typical activities involved in this stage include the dismantling and disassembly of the wind turbine, the transportation of all turbine components to their respective waste management facility, and the impacts/credits associated with the final waste management and disposal, either by recycling, incineration, or landfill (14).

The range of literature results for decommissioning was primarily affected by the choice of waste management, where a significant number of studies modeled decommissioning to include the recycling and re-use of components. Studies which included beneficial impacts of recycling and re-use provided an emissions credit for recovering useful materials from the turbines (13).

4.2 Nuclear Scenario

The lifecycle of electricity generation from nuclear power plants, as presented in Figure 14, includes the extraction and production of uranium fuel and auxiliary supplies, operation of the nuclear reactors, the construction and decommissioning of the power plant, and the management of nuclear waste.

Compared with other generation options, the environmental emissions from nuclear power generation are distributed across its lifecycle, including upstream fuel supply, plant construction and decommissioning. Unlike other forms of non-renewable power, nuclear power does not rely on fossil production, limiting the air emissions generated during normal plant operations.

In this study, the nuclear power scenario covers all methods of upstream production and power generation covered in the LCA literature. The operating lifetime considered to annualize the lifespan emissions is 40 years, the median lifetime observed in LCA literature.

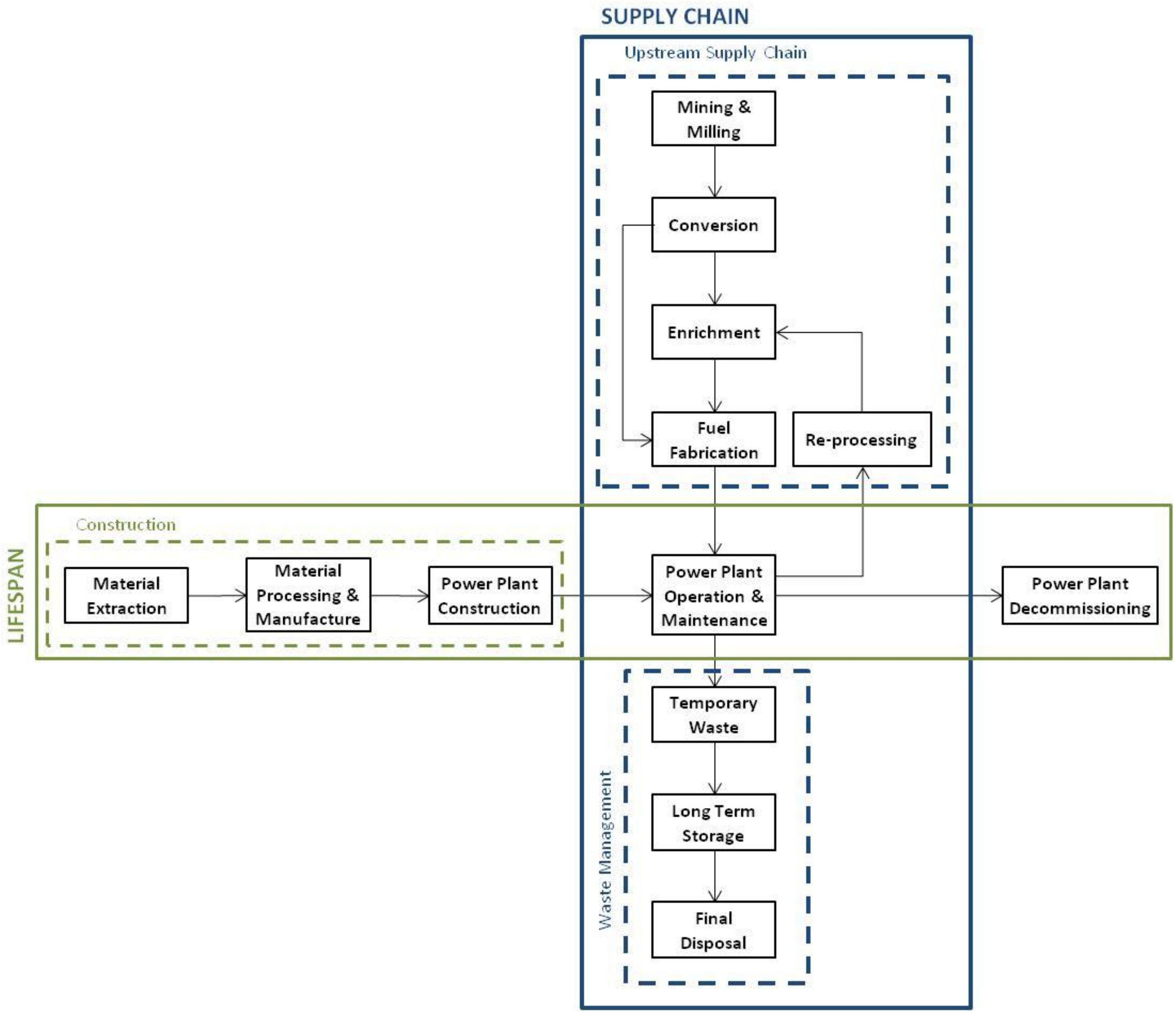

Figure 14. Nuclear Scenario Detailed System Boundaries

4.2.1 Upstream Supply Chain

The upstream supply chain describes all the processes required to extract and produce uranium oxide in the form suitable for the variety of nuclear reactor technologies considered in this study.

Mining & Milling

Uranium is a heavy metal found in rock, soil and water containing natural levels of radioactive isotopes. The two isotopes most commonly found in nature are U-238 (99.28%) and U-235 (0.72%) (15). Enriched uranium required for some reactor technologies contains increased proportions of U-235, the fissile isotope.

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Uranium is mined in open pit mines, underground mines and by in-situ leaching (ISL), where a leaching solution is pumped into the ore body to dissolve the uranium; the dissolved uranium is then pumped to the surface. In line with the global scope of this study, all uranium mining methods were considered, although the in-situ leaching process is not used anywhere in Canada, and given the local geology, is an unlikely candidate to ever be applied in Canada.

The concentration of uranium varies greatly depending on the substance and the location of the ore deposit. Based on the LCA literature review, the ore grade varies from 0.01% to 12.7%, although the International Atomic Energy Agency states provides a broader range varying between 0.03% and 20% (16).

The environmental emissions of the upstream nuclear fuel supply chain increase by orders of magnitude for very low grade ores (less than 0.2%), as more material must be unearthed and processed in order to produce fuel suitable for power generation.

During the data analysis, selected data points were discarded as statistical outliers when the ore grades considered were below (0.2%). This decision was made to focus on the ore and power production most typical of global production. Ore grades in Canada are some of the highest in the world, evidenced from the McArthur River mine, containing an average uranium content of 18% (17). Due to the high grade of uranium deposits in Canada, the extraction of uranium destined for Canadian reactors is expected to be at the lower end of the emissions spectrum.

The extracted ore is sent to a milling process, where the ore is crushed and treated with acid or alkaline solutions to dissolve and separate the uranium from the waste rock. The uranium, in the form of uranium oxide (U_30_8) or yellow cake, is then recovered from the solution and precipitated with a concentration higher than 80% (16).

Conversion

The conversion process converts yellow cake to uranium dioxide (UO_2) and subsequently to uranium hexafluoride (UF_6) gas, which solidifies in large cylinders prior to transport (18). Uranium dioxide (UO_2) can be used directly as the fuel for CANDU reactors, which can operate on un-enriched uranium, while uranium hexafluoride (UF_6) gas is a feedstock for the enrichment process required to produce fuel for other types of reactor technology.

Enrichment

Most nuclear reactor technologies require a U-235 concentration between 3% and 5% (16). To increase the level of U-235 to the required levels, the UF_6 undergoes an enrichment process involving gaseous diffusion or gas centrifuge technology. Some LCA studies provide emissions associated with only one method, while others provide emissions from a mix of enrichment methods. According to several studies, gas diffusion is more energy and emissions intensive than gas centrifuge technology (19); in fact, the gas centrifuge process consumes 2% to 2.5% as much energy as gaseous diffusion (20).

Certain reactors, such as CANDU reactors, do not use any enrichment process, designed instead to consume uranium with natural levels of U-235 (0.7%). For the purpose of this study, all enrichment methods (including a lack of any enrichment) were included.

Fuel Fabrication

As a product of the enrichment phase, two streams of UF_6 are generated: the enriched uranium and the tails or depleted uranium. The enrichment uranium (UF_6) is converted back to uranium oxide (UO_2) in the first step of the fuel fabrication process.

The converted enriched uranium oxide is then pressed and sintered at a high temperature (over 1,400°C) to produce cylindrical fuel pellets (5 – 15 mm in diameter, and 10 – 15 mm in length) (18), (16). The fuel pellets are then loaded into long tubes called rods. Rods are made of a noncorrosive material, usually a zirconium alloy. Once grouped together into a bundle, rods form a fuel assembly (16). A similar process is performed for un-enriched uranium oxide destined for CANDU reactors.

Reprocessing

Some studies consider the reprocessing of the spent fuel, where the fuel bundles are cut, and the fuel is dissolved and separated into its constituents, i.e., 96% uranium, 1% plutonium and 3% high level waste products (16). The recovered uranium can be returned to the conversion plant to follow the same nuclear fuel cycle, to be reused as fuel after conversion and enrichment. The recovered plutonium can be mixed with uranium to produce mixed oxide fuel (MOX) which, in certain reactors, can substitute the U-235 (18).

Based on the literature reviewed, 27% of the studies include reprocessing, while 39% omit this stage. The remaining studies, 34% of the literature reviewed, do not specify whether reprocessing is included or not. Based on the study “Life Cycle Inventories for the Nuclear and Natural Gas Energy Systems, and Examples of Uncertainty Analysis” (21), reprocessing counts less than 5% of the total GHG emission of the total lifecycle of nuclear power. For the purpose of this study, papers with and without reprocessing were included.

4.2.2 Operation

Once the fuel is loaded into the nuclear reactor the controlled fission reaction starts. During the fission process, the splitting of the U-235 atoms release energy, which is used to heat water and produce high pressure steam. The steam is then used to turn a turbine, to generate electricity. The exact operational process is fully controlled, and depends on the type of nuclear reactor, the type of fuel, moderator and coolant used (18).

To maintain reactor performance, fuel is used for 3 to 6 years before being replaced. The replacement cycle occurs every 12 to 18 months, where one third of the spent fuel is replaced with fresh fuel (18). At this point, the concentration of U-235 is less than 1% (22).

The literature reviewed addressed several types of nuclear reactors. For the purpose of this study, all technologies were considered. The technologies addressed in the literature include light water reactors (LWR), pressurized water reactors (PWR), boiling water reactors (BWR), advanced boiling water reactors, advanced gas-cooled reactors (AGR), Canada deuterium uranium reactors (CANDU), European fast reactors (EFR), European pressurized reactors (ERP), fast breeder reactors (FBR), and GEN III reactors, either represented alone or as a mix of technologies.

A major difference between CANDU reactors and the other nuclear reactors assessed in this study is the use of heavy water as a moderator and coolant. Since CANDU reactors are included in this study, emissions associated with heavy water are accounted for in the final results and within the plant operations process stage.

4.2.3 Waste Management

After the rods are unloaded from the nuclear reactor, they generate intense heat and radiation. To control the heat and radiation, the fuel assemblies are submerged into water in concrete ponds (18).

After a few years, when the temperature and the level of radiation from the spent fuel have decreased, the spent fuel can be re-processed, or can be transferred to a long term and final disposal facility, without reprocessing. As stated by the World Nuclear Association, "about 97% of the used fuel can be recycled leaving only 3% as high-level waste" (18); however, the reprocessing is not a common practice and only a small amount of the spent fuel is reprocessed.

This study includes LCA studies covering GHG and other air emissions generated in the process of managing various grades of nuclear waste generated by nuclear power plants, It should be noted that only emissions associated to the waste management process are considered in this stage; emissions associated with reprocessing are accounted for in the upstream supply chain process.

Wastes from the nuclear fuel cycle are categorized as high-, intermediate- or low-level wastes, depending on the amount of radiation emitted (18), (23):

- Low-level wastes (LLW) contain small amounts of short-lived radioactivity, and are produced throughout the nuclear fuel cycle.
- Intermediate-level wastes (ILW) emit higher levels of radioactivity than LLW, requiring shielding, but not cooling. ILW are produced during reactor operation and by reprocessing.
- High-level wastes (HLW) emit higher levels of radioactivity than ILW requiring shielding and cooling. HLW are generated from reprocessing, or, depending on the country, the spent fuel itself.

Currently, LLW and ILW are disposed of in near surface strata such as abandoned mines (22). High level waste can be calcined and encased in solid materials such as glass (vitrified), concrete and metal, to be stored into ponds or casks until the radioactivity levels and the concentration are reduced to less than 1% of its original value (18), (22).

Currently, operating facilities managing HLW focus on storage rather than permanent disposal. Potential final disposal sites include deep geological formations, such as salt domes or granite bodies (18). Manfred Lenzen in “Life cycle energy and Greenhouse Gas Emission of Nuclear Energy: A Review” notes that, to prevent any groundwater contamination, the formations will have to “exhibit a lack of contact with ground water, tectonic stability, sufficient heat conductivity and low permeability for radionuclides” (22).

4.2.4 Construction

The upstream lifespan stage includes the extraction, production and transportation of all necessary materials required for the construction of nuclear power plants. Construction of the waste management facilities for radioactive wastes is also included. It is important to note that construction activities are dependent on the type of nuclear reactor.

Similarly to the upstream supply chain, emissions from plant construction are influenced by the transportation from the extraction and production center (e.g. steel mill, cement plant, etc.) to the site of the nuclear power plant.

4.2.5 Decommissioning

The decommissioning stage encompasses all environmental impacts associated with the dismantling of the nuclear power plant, as well as the management of radioactive and non-radioactive waste generated. Similarly to construction, decommissioning is dependent on the type of nuclear reactor.

4.3 Natural Gas Scenario

As presented in Figure 15, the lifecycle of natural gas starts with the extraction and production of natural gas and ends with the final disposal of wastes, including construction and decommissioning activities.

The lifecycle of natural gas power generation considered in this study encompasses natural gas sourced from conventional and unconventional sources such as shale gas, and is limited to combined cycle generation facilities, the most efficient and least emissions intensive commercial natural gas power plant technology. Compared with other generation options, the environmental emissions from natural gas power generation are dominated by the power plant itself, resulting from the combustion of natural gas.

The operating lifetime considered to annualize the lifespan emissions is 30 years, the median lifetime observed in LCA literature.

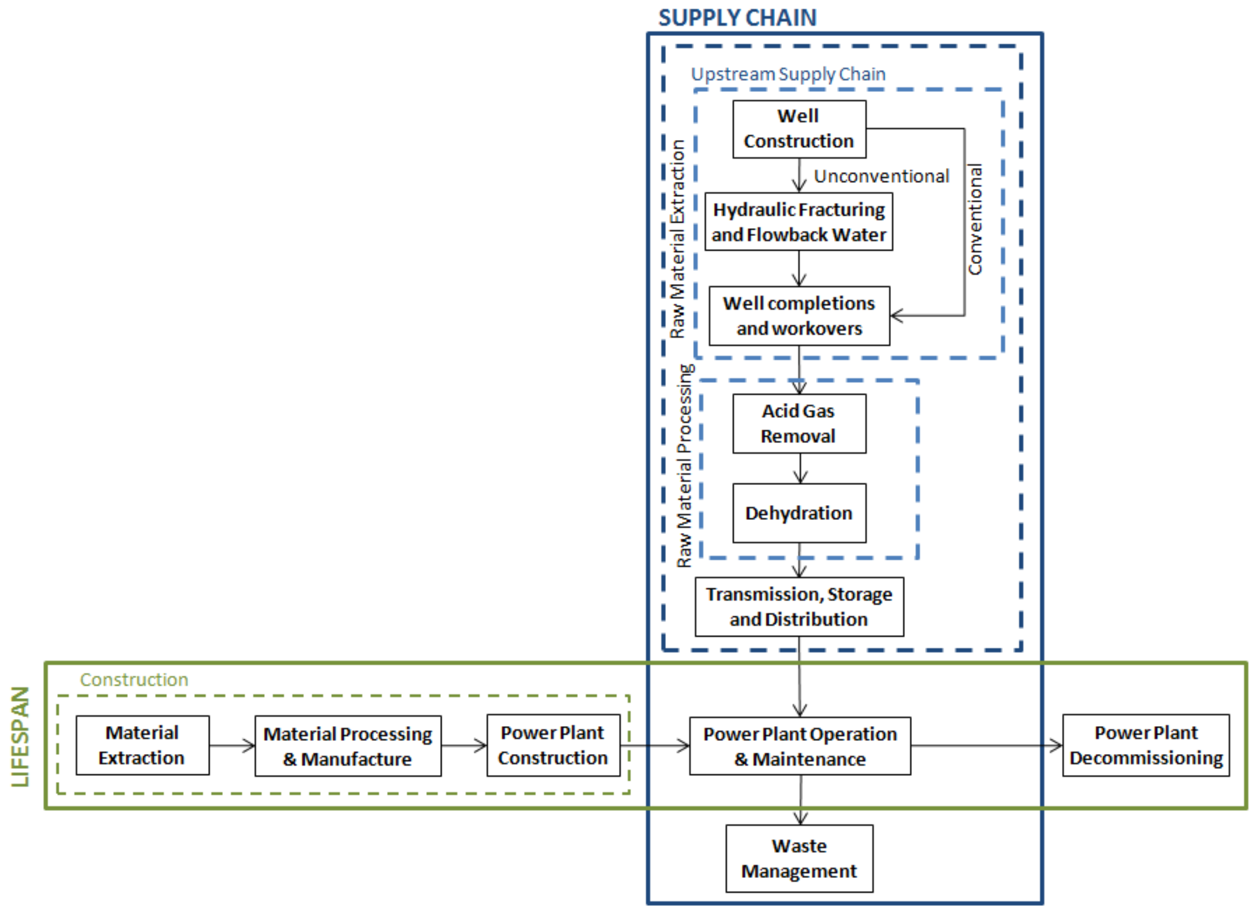

Figure 15. Natural Gas Scenario Detailed System Boundaries

4.3.1 Upstream Supply Chain

Natural gas comes from both 'conventional' and 'unconventional' sources. Conventional gas refers to gas "trapped in structures in the rock that are caused by folding and/or faulting of sedimentary layers" (24). This gas is often difficult to find but, is typically the easiest and most cost-effective to extract. Unconventional gas is "trapped in impermeable rock which cannot migrate to a trap" (24).

Shale gas, a type of unconventional gas, are formations of organic-rich shale, a sedimentary rock formed from deposits of mud, silt, clay, and organic matter. Normally, shale reservoirs are continuous deposits over large areas, with low permeability and low natural production capacities (25).

The upstream supply chain starts with the preparation of the well pad (clearing the well pad area and construction of temporary structures) so the construction and installation of wells can begin. Conventional gas reservoirs do not require significant site preparation to recover the gas using by vertical drilling techniques (5). Shale gas recovery requires the creation of a wellbore that runs the length of a shale formation (horizontal drilling), and hydraulic fracturing (hydrofracking) to allow the movement of the gas to the surface (5). During hydrofracking, a high pressure fluid (a mixture of water, surfactants, and proppants) is inserted to break apart the reservoir of natural gas (26).

After the pre-production phase is completed, the well becomes operational and natural gas is extracted as a mixture of raw natural gas, condensed higher hydrocarbons, free water and particles. Once the well has been producing for some time, some maintenance activities and/or alterations (also know as well workovers (27)) to the well might be required.

The raw gas needs to be purified to meet pipeline specifications (5). Thus, the raw natural gas is sent to a processing plant where it undergoes different processes such as dehydration, acid gas removal (sweetening), flaring and compression (5), to remove the water, carbon dioxide, sulphur and other hydrocarbons mixed with the raw natural gas. Flaring is required in certain occasions when natural gas (or other hydrocarbon) stream cannot be safely or economically recovered (5).

Among the literature reviewed, different assumptions regarding the pre-production and production stage of natural gas are considered:

- Number of wells per pad;
- Equipment required for drilling. Some studies considered only drilling rigs, while other considered a comprehensive list of equipment;
- Length of the well;
- Well completion emissions flared and vented;
- Productivity of the well;
- Number of hydraulic fractures per cycle.

For the purpose of this study, all the different assumptions mentioned above were included.

Once processed, natural gas is ready to be compressed and sent to the power plants by a pipeline transmission system. The transmission system might include some storage to meet seasonal and/or sudden short-term demand (28), (29), (26).

Various parameters such as the length of the pipeline transmission, maintenance (type of activities and frequency) and emissions from the pipeline itself will affect the overall emissions from this stage. For the purpose of this study, all the different parameters mentioned above were considered in the results.

4.3.2 Operation

The operation stage encompasses the environmental impacts associated with the operation and maintenance of the natural gas combined cycle power plant.

In a basic combined cycle power plant, Figure 16, the natural gas is burned in a gas combustion turbine in the presence of compressed air, generating electricity. The heat in the exhaust gas from the gas turbine is recovered and utilized to drive a steam turbine to generate additional electricity, thereby increasing overall efficiency relative to single cycle generation facilities (27).

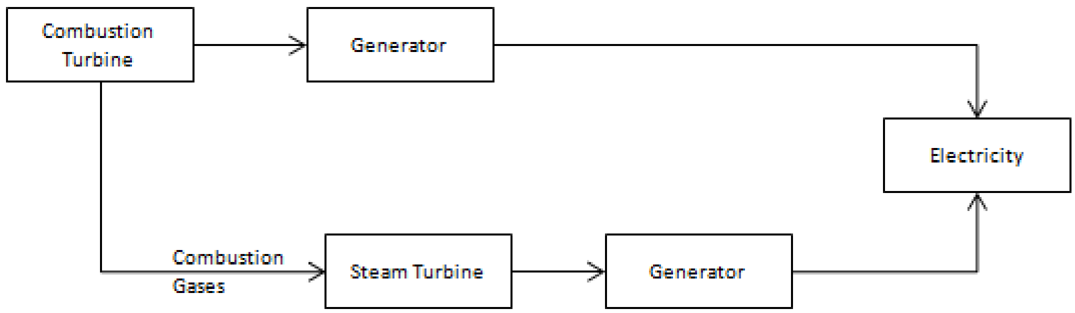

Figure 16. Natural Gas Combined Cycle Generation

4.3.3 Waste Management

This stage includes emissions associated with the management of wastes generated during normal operation and maintenance of the NGCC power plant, including transportation of wastes to waste treatment facilities. Waste management refers to the handling of solid and liquid wastes and does not refer to off-gas pollution control equipment.

Waste management for NGCC power plants is not well defined by the LCA literature included in this study, lacking documentation of the operating parameters and waste management practices considered during modelling. In all cases, waste management was included within normal plant operations or otherwise not explicitly defined.

The overall contribution of waste management is negligible in comparison to the total lifecycle emissions. This assumption was validated with the study “Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System” by Spath and Mann (30). According to this study, 94 wt% percent of the total solid waste comes from the production and distribution of natural gas. The only waste stream from the plant is spent catalyst generated every one to five years from the selective catalytic reduction (SCR) unit. SCR is frequently used to reduce NO_x emissions from power plants, by injecting ammonia (NH_3) into the gas stream before the gas enters the catalyst bed. (30).

4.3.4 Construction

The upstream lifespan stage includes the extraction, production and transportation of all necessary materials for the construction of a NGCC power plant, including steel, cement and other building materials. The electricity and fuel required for construction activities is also considered.

Construction of auxiliary infrastructure (such as pipelines and transmissions lines) is omitted from the study system boundary, as it is determined that they would exist without the construction of the studied facility or fuel extraction operation.

4.3.5 Decommissioning

The decommissioning phase covers all environmental impacts associated with the site work for the dismantling of the natural gas power plant, the transportation of waste to waste management facilities, and the impacts/credits associated with the final waste management, either by recycling, incineration, or by depositing at a landfill site.

4.4 Wind/Natural Gas Scenario

In addition to the stand-alone wind, nuclear and natural gas power generation scenarios, a mix of natural gas and wind power was also considered. In this scenario, the LCA models of wind and natural gas were summed based on a 20% to 80% split of total electricity generation, respectively. Accordingly, the system boundaries of the scenario is equal to a combination of the systems detailed in Section 4.1 and 4.3.

The wind/natural gas scenario was considered to reflect the intermittency of wind power supply. As an intermittent power source, wind generation must be paired with energy storage or an alternate power source capable of responding to changing electricity demand.

The severity of intermittency depends on a number of regional factors including climate patterns and seasonal load variations. Integrating high proportions of wind power also faces practical limits imposed by existing electricity grid infrastructure, which could be alleviated in part by implementing modern smart grid technology.

Technical options to overcome the intermittency of wind turbines include (31):

- Interconnect several wind farms along a wide geographical zone. A disperse geographical area will ensure that power is always produced.
- Implement a smart grid that allows interconnection of renewable and non-renewable resources, by managing the response depending on the availability of renewable energy.
- Integrate wind turbines with a non-variable energy source that can rapidly adjust to the demand, such as NGCC power plants.

For the purpose of this study, an option where wind power is supplemented with NGCC power plant is considered.

Due in part to the range of variables above, a wide range of ratios have been published for the total electricity supplied by wind, ranging in extremes between 10% and 85%. A study published in October 2006 for the Ontario Power Authority (OPA), Ontario Independent Electric System Operator (IESO), and the Canadian Wind Energy Association (CanWEA) examined a number of wind scenarios in Ontario. The study used an "overall yearly capacity value {of} approximately 20% for all wind penetration scenarios". In the study, a high penetration scenario for wind of 13% total yearly energy was considered for Ontario(32).

For the purposes of the present analysis, a basis of 20% total wind penetration (electricity supplied) was considered, with the remaining 80% of annual electricity supply being supported by NGCC.

5. Results

5.1 Guide to Interpreting Results

This section reports the emissions from each lifecycle stage and lifespan of each energy generation scenario. For each generation technology, GHG (as CO_2e), NO_x, SO_x and PM emissions are evaluated per kWh of electricity generated, according to the contributions to the following five lifecycle stages: construction (from extraction of raw materials to construction activities), decommissioning (dismantling activities and waste management), upstream supply chain (from extraction of the fuel to the gate of the plant), operation (operation and maintenance) and waste management (waste disposal from normal operation).

The results are consistent with the scope and system boundaries defined in Section 2 and 4 and the LCA literature review and meta-analysis methodology presented in Section 3. The results document the mean, standard deviation and uncertainty of the mean corresponding to the distribution of data points observed in the LCA literature. First, a comparison of the total lifecycle of each generation scenario is presented in Section 5.2, with a focus on the contributions of individual process stages to follow in Section 5.3. Sections 5.4 and 5.5 cover an analysis of emissions from natural gas sources and the ionizing radiation (IR) potential of nuclear power generation.

Beyond the total average results, a statistical analysis was performed to support the study's overall findings. The statistical approach helps convey the strengths, weaknesses, and characteristics of the literature LCA data and results. Figure 17 shows a sample bar plot used to represent the results of the statistical analysis. The mean *(centre-line)* is the best single-point value representing the LCA literature, the standard deviation *(clear bars)* represents the spread of data points in the distribution of LCA literature, while the uncertainty of the mean *(red bars)* is representative of the confidence (or uncertainty) of the calculation of the mean.

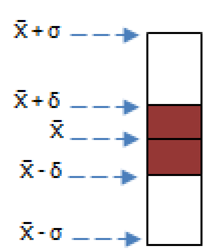

Figure 17. Schematic Plot Used to Represent the Mean and Distribution of Literature Data

The standard deviation helps to characterize the range of LCA literature resulting from the degree of variation in the:

- Measurement and modelling techniques used (e.g. varying modelling assumptions affecting the range of results);

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- Scope and system boundaries considered (e.g. technology variations, regional differences, etc.);
- Environmental performance achieved by the specific plants considered (e.g. best practice facilities, use of emission control technologies, etc.).

The uncertainty of the mean represents the range within which the true mean of the dataset is expected to reside. The uncertainty of the mean becomes smaller when the size of the LCA dataset increases. Comparing the size of this confidence range across each power generation scenario helps determine:

- The strengths and weaknesses in the assertion of the calculated mean;
- Whether the difference in mean emissions between two power generation scenarios is a true result or the result of statistical uncertainty.

In some cases, the lower bound of the standard deviation or uncertainty of the mean may be less than zero. In these cases, the negative value may be a result of the statistical approach used rather than the real distribution of the data itself. Generally, this condition will occur when there is a wide distribution of a small set of data, asymmetrically distributed about the mean.

5.2 Total Lifecycle Emissions

This section illustrates the total lifecycle emissions for each power generation scenario considered by the study:

- Onshore wind generation;
- Nuclear power;
- Natural gas combined cycle (NGCC); and
- A total electricity supply mix of onshore wind (20%) and NGCC (80%) generation.

Figure 18 and Table 5 present the total mean lifecycle emissions for each generation scenario, representing the full range *(top)* comparing NGCC relative to the other scenarios and a close-up range *(bottom)* comparing the differences between wind and nuclear.

Figure 18 shows that nuclear and wind power are similar in magnitude for each emission category and an order of magnitude less than natural gas with respect to GHG and NO_X emissions. The graph also shows that the GHG and NO_X contribution from nuclear power is slightly higher than wind while slightly lower for PM and SO_X.

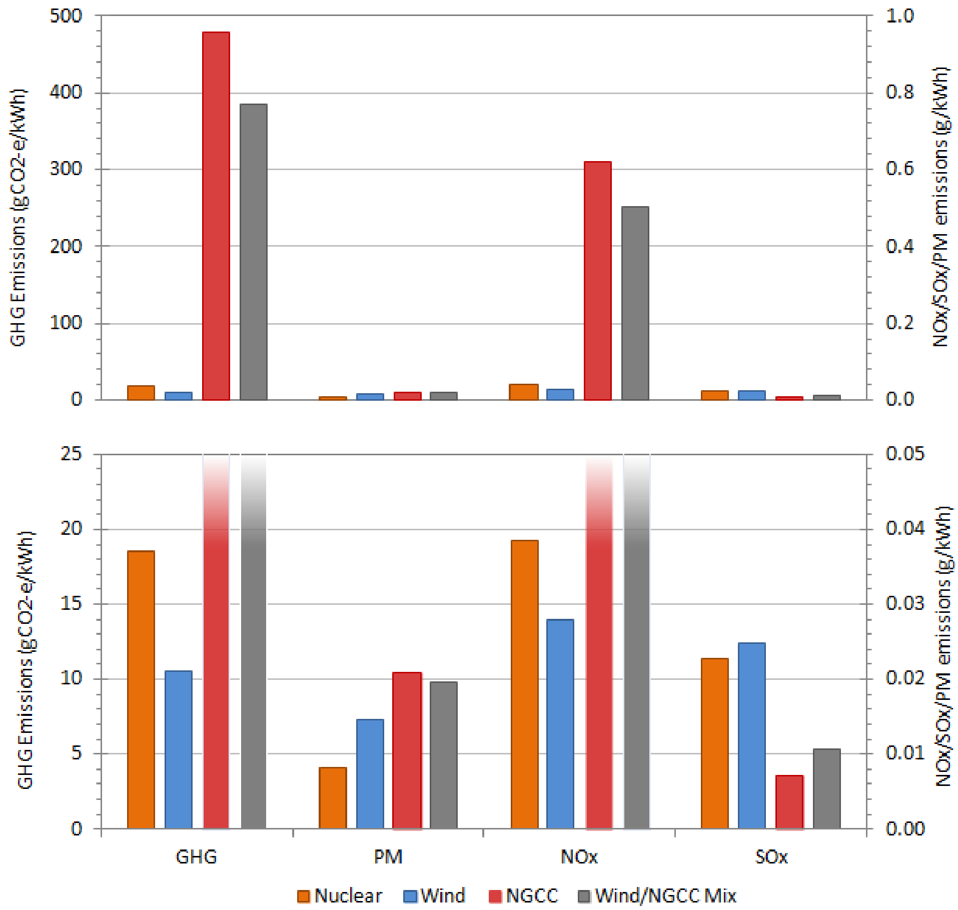

Figure 18. Summary of Total Lifecycle Emissions

Table 5. Statistical Mean Total Lifecycle Emissions

Scenario	GHG (gCO2-e/kWh)	PM (g/kWh)	NO_X (g/kWh)	SO_X (g/kWh)
Onshore Wind Turbine	10.5 ± 0.9	0.015 ± 0.003	0.028 ± 0.003	0.025 ± 0.003
Nuclear Power Plants	18.5 ± 1.7	0.008 ± 0.003	0.039 ± 0.006	0.023 ± 0.003
NGCC Power Plants	478 ± 10	0.021 ± 0.012	0.62 ± 0.03	0.007 ± 0.001
Mix Wind-NGCC	385 ± 8	0.02 ± 0.01	0.50 ± 0.02	0.011 ± 0.001

Total lifecycle emissions from the 20-80 electricity supply mix of wind-NGCC is more comparable to NGCC, where emissions of GHG and NOx exceed nuclear or the stand-alone wind power scenario. The wind-NGCC scenario reflects a potential grid mix based on current grid infrastructure in Canada that (in the absence of energy storage) uses NGCC supply to compensate for the intermittent nature of electricity generation from wind power.

Figure 19 presents the mean and range of total lifecycle emissions for each power generation scenario resulting from the statistical analysis of the LCA literature data. The standard deviation *(clear bars)* represents the spread of data points in the distribution of LCA literature, while the uncertainty of the mean *(red bars)* is representative of the confidence in the calculation of the mean *(centre-line)*. For guidance in interpreting the results, please refer to Section 5.1.

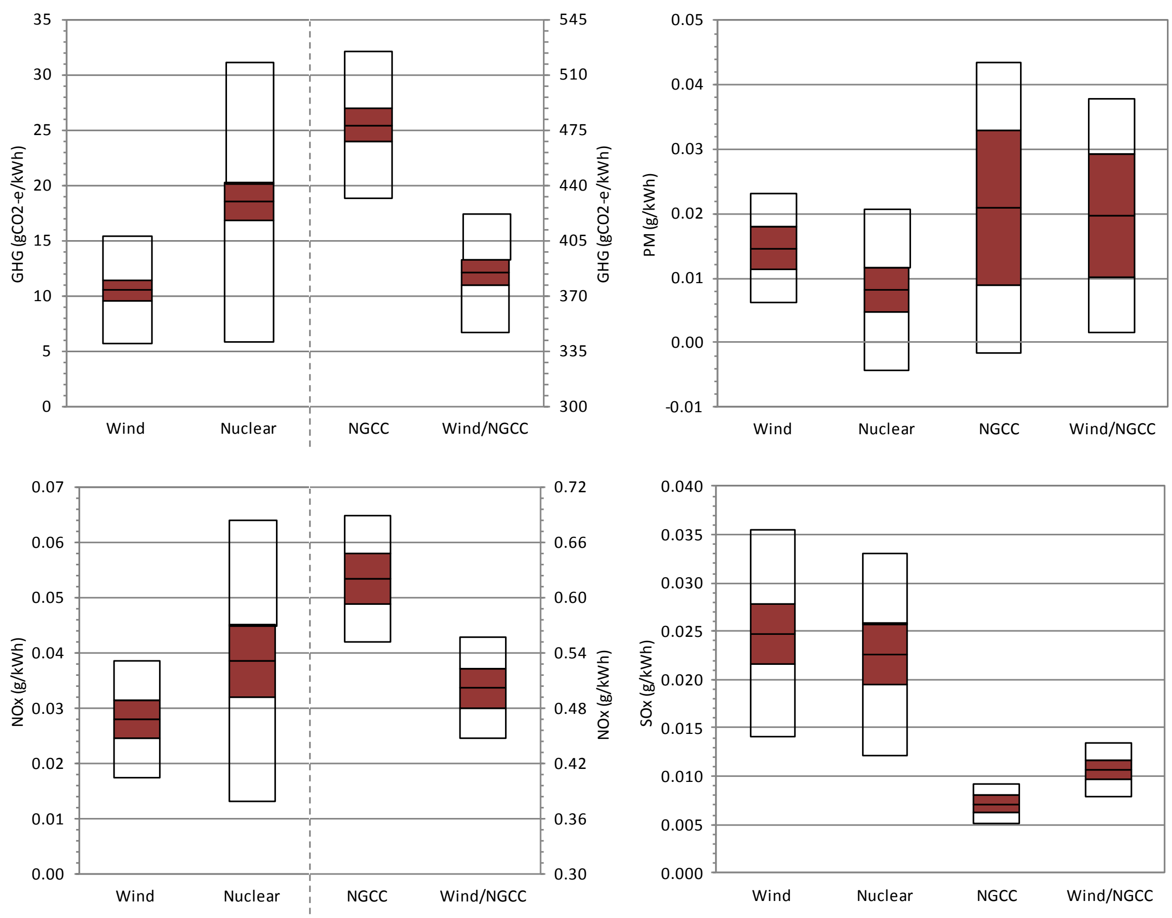

Figure 19. Total Lifecycle Emissions (Statistical Approach)*†

* Standard deviation ranges less than zero are due to the statistical approach used to represent the data. Actual emissions data in all cases exceeds zero.

† Note that a secondary y-axis is presented for GHG and NO_X emissions corresponding to the NGCC and wind/NGCC scenarios *(indicated by a dashed vertical line)*.

Figure 19 confirms that the range of GHG and NO_X emissions for natural gas and a mix of natural gas and wind power are in every case, significantly higher than for the nuclear and wind power scenario. GHG emissions from wind power reside in the lower half of the nuclear power generation studies investigated, although the average GHG and NO_X emissions from nuclear LCA data are distinctly higher than for wind power. Lifecycle emissions from both wind and nuclear power are between 2% - 4%, and 4% - 6% those of natural gas generation for GHG and NO_X, respectively.

The comparison of PM emissions across generation scenarios is less conclusive, due to the low availability and high variability of the LCA literature data. While the range of PM emissions from wind and nuclear power appear on the lower range of natural gas, their means fall within the range of uncertainty for natural gas and the wind/NGCC mix. In this case, the high uncertainty involved in calculating the mean for natural gas generation makes it difficult to make a definitive comparison between the scenarios.

The difference in the mean SO_X emissions for wind and nuclear power is similarly inconclusive due to limited data availability and a range of modelling parameters affecting the results. SO_X emissions are particularly sensitive to the presence of coal in the upstream power generation and supply mix considered in each LCA study. The natural gas scenario has reduced SO_X emissions relative to wind and nuclear.

5.3 Lifecycle Distribution

5.3.1 Overview

Figure 20 presents a breakdown of the average contribution of each supply chain and lifespan process stage to the total lifecycle emissions of each scenario A more detailed breakdown of each scenario is provided separately in Figure 21 to Figure 24, including the range of data represented by the LCA literature investigated.

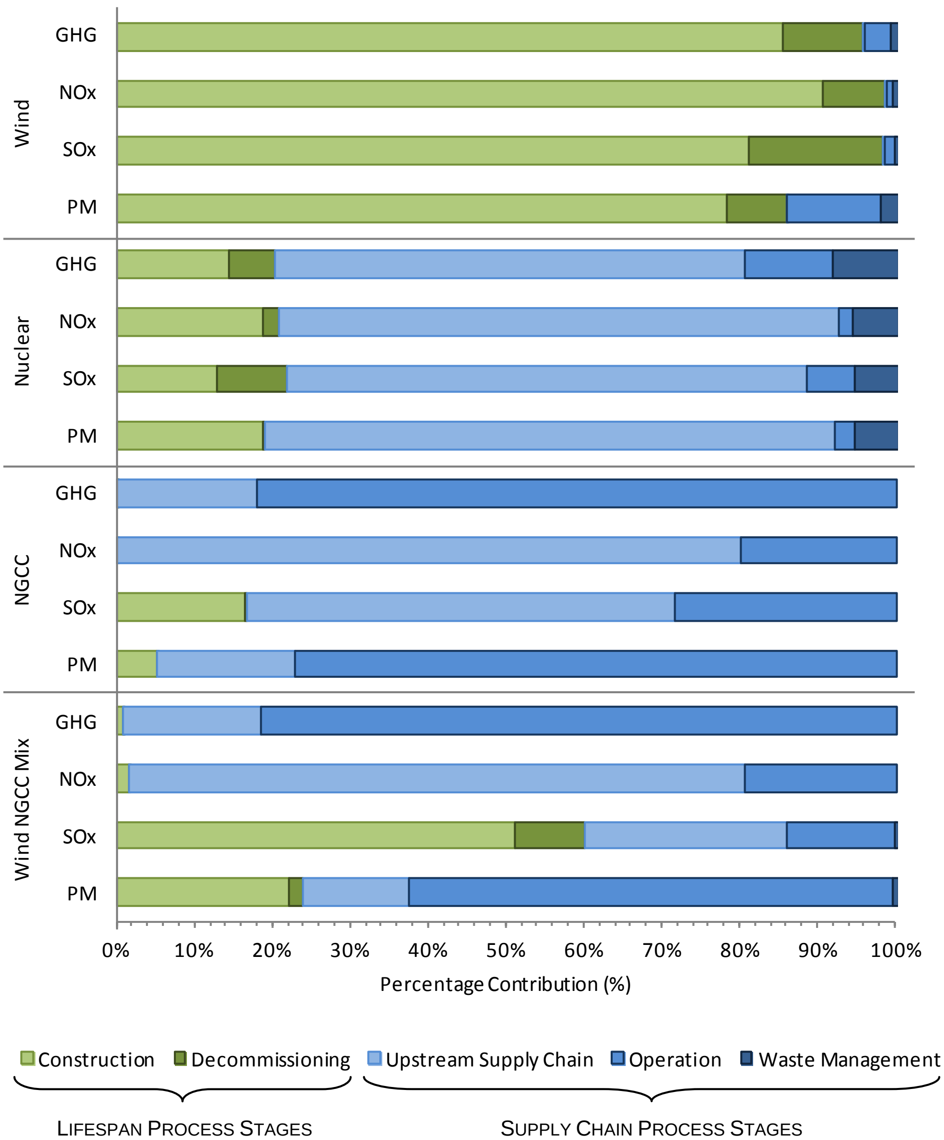

Figure 20. Percentage Contribution of Lifespan and Supply Chain Process Stages to Total Lifecycle Emissions

From Figure 20, the predominate process stages for each generation scenario can be observed:

- Emissions generated during the lifecycle of a wind farm are generated primarily from the production and application of construction materials and the assembly of the turbine itself, as opposed to the requirements of continuously operating the turbine over it's operational phase. Lifespan (construction and decommissioning) activities are the predominant segments of the wind power lifecycle despite being distributed across the operating lifetime of the wind farm (considered to be 20 years), emphasizing the minimal impacts observed during the operating phase. Accordingly, emissions from wind power are especially sensitive to choice of operating lifetime during LCA modelling, where longer operating times act to reduce lifespan emissions when presented relative to power produced.
- Emissions from the nuclear power lifecycle are primarily associated with the supply chain and plant operations, as opposed to construction and decommissioning activities. The upstream supply chain in particular is the most significant emissions source for all emissions types. The upstream supply chain consists primarily of the various extraction, enrichment and fabrication processes involved in delivering fuel bundles to the various nuclear reactor technologies considered in the study.
- Emissions generated across the natural gas (NGCC) scenario are dominated by the supply chain and plant operations rather than plant construction and decommissioning. Emissions across all categories are driven by natural gas combustion during the operational phase and through flaring, fugitive emissions and other sources during extraction and fuel processing.
- The scenario considering a total electricity supply mix of wind (20%) and NGCC (80%) is a linear combination of the wind and NGCC models. Accordingly, the distribution of emissions from this scenario is a combination of wind and NGCC. The NGCC scenario contributes the majority of GHG and NO_X emissions relative to wind power, resulting in a distribution closely matching NGCC. However, the SO_X and PM emissions from wind farm construction are not immaterial, resulting in both the wind and NGCC scenarios contributing to the lifespan and supply chain stages of the aggregated result.

5.3.2 Wind Power

Figure 21 shows the mean and distribution of LCA literature data for environmental emissions pertaining to each stage in the wind power lifecycle. As reported in Section 5.3.1, the average contribution of the lifespan stages – construction and decommissioning – are the most significant contributors to the total lifecycle emissions, representing between 85% and 99% of total lifecycle emissions. By comparison, the other stages – the upstream supply chain, turbine operations, and waste management – are minor, consisting primarily of the activities surrounding periodic turbine maintenance.

The lifespan stages of wind power generation are also the most studied by LCA practitioners, especially for GHG emissions. Consideration of the supply chain and turbine operations was more limited, consistent with the often negligible contribution made to overall lifecycle emissions. These phases may have been excluded from the system boundaries of other LCA studies or implicitly incorporated into the LCA models without specific documentation.

Of the environmental emissions included in the study, GHGs were well documented, while data at the process stage level was limited and varied for NO_X, SO_X and PM. In these cases, the range of confidence in the mean is broad, but sufficient to identify the dominance of the construction phase relative to the other stages.

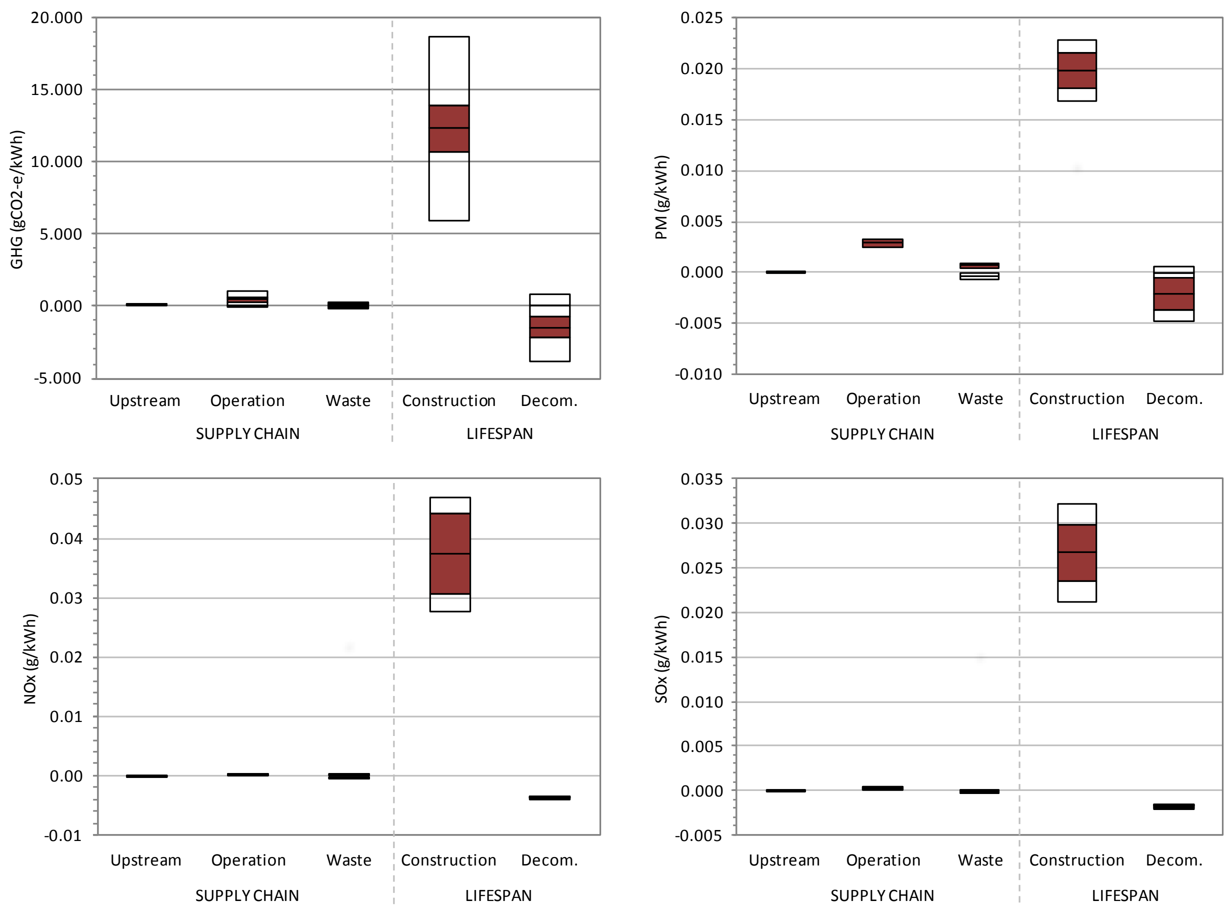

Figure 21. Lifecycle Distribution for Onshore Wind Turbines*

* LCA data for decommissioning may be positive (emissions generated) or negative (emissions avoided) depending on the modelling basis and assumptions considered in each individual LCA study.

A number of observations on the wind power lifecycle and LCA literature can be inferred from Figure 21:

- Despite limiting the scope of the scenario to on-shore wind farms, there is a relatively broad distribution of GHG emission data for construction-related activities. This range of data is also apparent in the range of total lifecycle GHG emissions (Section 5.2). Rather than representing technological differences, this range is indicative of the range of electricity grid emissions factors contributing to the production and fabrication of wind turbine components. GHG grid emission factors can vary by up to two orders of magnitude depending on the power supply mix representing each region, an important contributor to most production and fabrication processes.
- The LCA literature considered a range of approaches to model the decommissioning of a wind turbine, ranging from net positive (impact) to net negative (credit) emissions. On average, LCA practitioners have considered decommissioning as a net negative process, or a credit reducing the total emissions generated by the wind power lifecycle. Net negative emissions can occur when the recycling and re-use of materials is considered to offset emissions generated by another system. In this case, many components of the wind turbines were modeled as recyclable or reusable for other purposes, offsetting the production of virgin materials (33).

5.3.3 Nuclear Power

Figure 22 shows the mean and distribution of LCA literature data for environmental emissions pertaining to each stage in the nuclear power lifecycle. As reported in Section 5.3.1, the upstream supply chain, and primarily the provision of nuclear fuel, is the main contributor to each environmental indicator considered in the nuclear power plant lifecycle. The other process stages each make a small contribution to the total lifecycle, and exhibit a smaller range of data when compared to the upstream supply chain. On average, nuclear power plant decommissioning has a small but net positive effect on total lifecycle emissions.

Of the environmental emissions considered, GHG emissions have been the largest focus area for nuclear LCA studies, exhibited by the relatively well defined mean GHG emissions for each process stage. PM, SO_X and NO_X emissions, while less studied than GHGs, have received more attention for nuclear power than the wind and natural gas scenarios, where data was more limited.

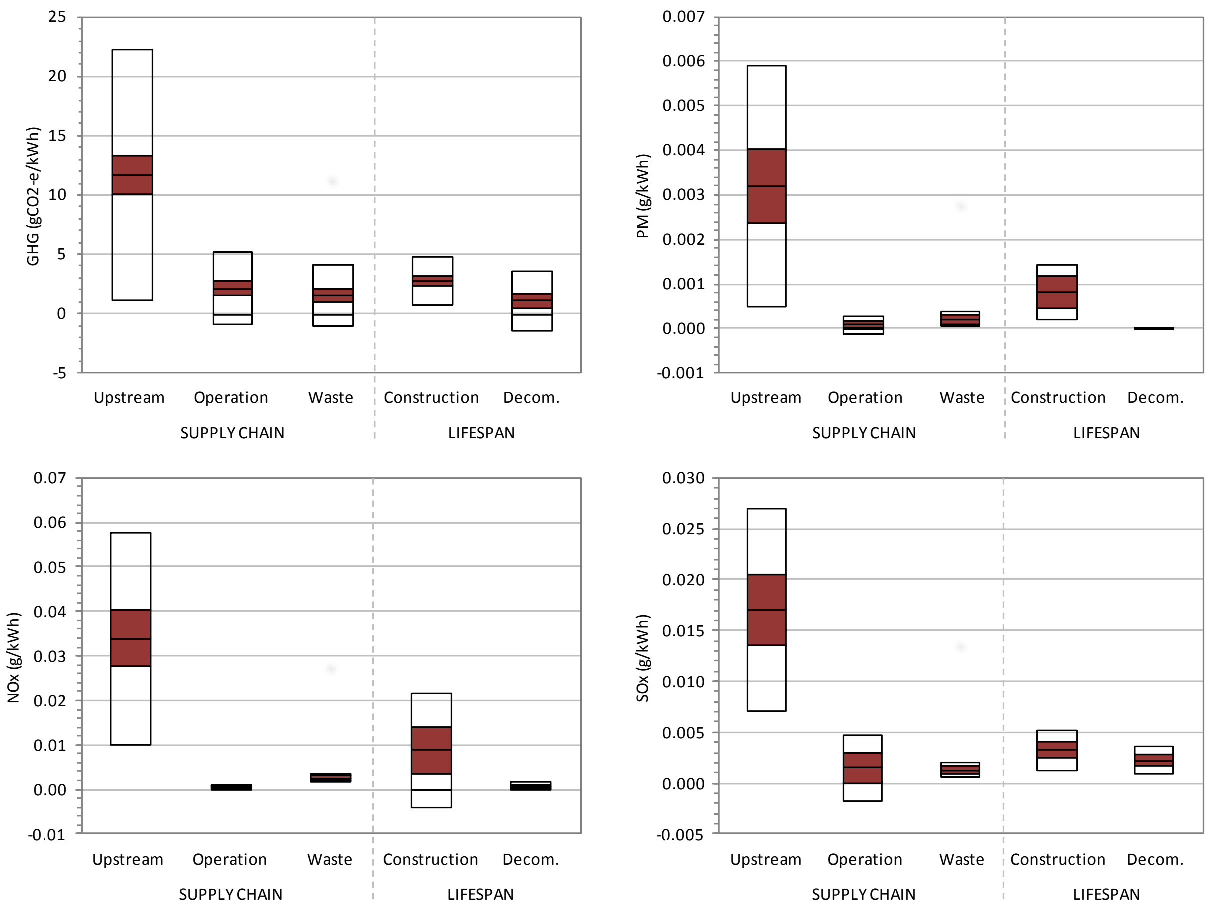

Figure 22. Lifecycle Distribution for Nuclear Power Plants*

A number of observations on the nuclear power lifecycle and LCA literature can be inferred from Figure 22:

- The broad range of upstream supply chain results derived from LCA literature is indicative of the range of nuclear generation technologies considered within the scope and system boundaries of this study. The range of results was affected by uranium ore grade, type of enrichment technology (if any), and other factors discussed in Section 4.2.1.
- Under certain upstream technology configurations, the emissions from the nuclear power lifecycle may equal those of onshore wind generation on a per kWh generated basis. In particular, nuclear fuel supply chains with high grade ore and either no enrichment or centrifuge-based enrichment form the lower band of LCA data observed in the literature.

* Standard deviation ranges less than zero are due to the statistical approach used to represent the data. Actual emissions data in all cases exceeds zero.

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- From an emissions perspective, the influence of reactor technology was more impactful upstream rather than directly at the power plant itself, specifically CANDU reactors able to process un-enriched fuel bundles avoid emissions generated during enrichment. The second largest contribution for all environmental impacts is construction, where the range of data may be explained in part by technological differences, but also other factors including the variation in grid electricity mix by region.
- While data for waste management of spent fuel and plant decommissioning have not been studied to the extent of other stages of the nuclear lifecycle, their overall impact is relatively small and in line with emissions from other phases of the lifecycle.

5.3.4 Natural Gas Power Generation

Figure 23 shows the mean and distribution of LCA literature data for environmental emissions pertaining to each stage in the natural gas (NGCC) power lifecycle.

GHG emissions from NGCC power plants are mainly generated during the operational stage due to the combustion of natural gas, contributing 82% of total lifecycle emissions. Most of the balance of GHG emissions stem from the upstream extraction and processing of natural gas, emitted as fugitives and during flaring. Conversely NO_X and SO_X emissions are generated primarily from the upstream supply chain (80% and 55% of the total lifecycle, respectively) and to a lesser extent from NGCC plant operation.

A wealth of LCA data is available documenting GHG emissions for each stage of the natural gas lifecycle. However, for NO_X, SO_X and especially PM emissions, a lack of available and consistent data reduces the ability to accurately determine mean emissions figures from the LCA literature. PM emission for the operational stage of NGCC power plants were highly variable amongst the literature examined, ranging from effectively zero to 62 mg/kWh. This range may be due to real observations such as a range in the presence and effectiveness of PM control technologies, or undetermined variations in study scope, system boundaries and assumptions.

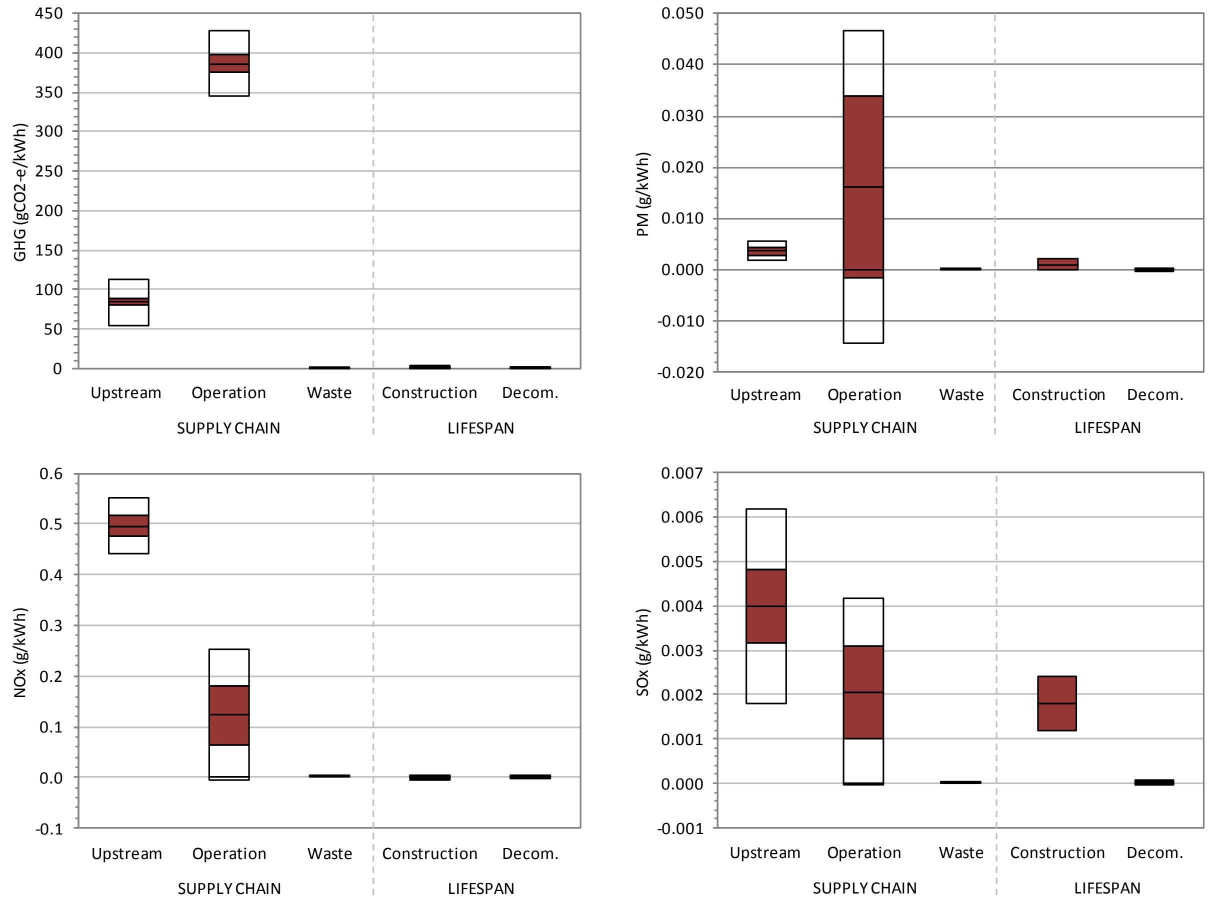

Figure 23. Lifecycle Distribution for Natural Gas Combined Cycle Power Plants*

A number of observations on the NGCC power lifecycle and LCA literature can be inferred from Figure 23:

- GHG emissions produced from NGCC plants (operations process stage) are well-defined across the LCA literature, likely range bound due to its direct correlation with NGCC plant efficiency and the combustion products generated during natural gas consumption.
- Despite the variation of technologies considered for the supply of natural gas, including conventional and unconventional sources, LCA data documenting upstream GHG, NO_X and PM emissions are narrowly defined. The variation (or lack there of) for the upstream natural gas sources considered in this study is presented in Section 5.4.

* Standard deviation ranges less than zero are due to the statistical approach used to represent the data. Actual emissions data in all cases exceeds zero.

- Conversely the range LCA data for NO_X and SO_X emissions from NGCC plants is broad. Combined with the increased level of NO_X and SO_X emissions from natural gas extraction and production, the broad range of data from operations is indicative of a range of NO_X and SO_X control technologies applied to NGCC sites. Without emissions control technologies in place at the plant, the emissions of NOx and SOx might otherwise might otherwise mirror GHG emissions, more closely related to the combustion of natural gas, which is more significant during plant operations than upstream extraction and processing.

5.3.5 Wind and Natural Gas Mix

Figure 24 shows the mean and distribution of LCA literature data for environmental emissions pertaining to each stage in a 20%/80% hybrid wind-NGCC generation mix (i.e. 20% wind power penetration). As a linear combination of the wind and natural gas scenarios presented in Section 5.3.2 and 5.3.4, the characteristics of the LCA data are also a blend of the two scenarios.

In the wind-NGCC scenario, GHG emissions are generated almost exclusively from natural gas supply and NGCC plant operations, each with sufficient data available to determine the mean for each process stage with reasonable confidence.

PM emissions occur primarily from NGCC plant operation and wind farm construction, although a lack of availability and consistency of PM data for NGCC plants limits the ability of this study to draw any definitive conclusions. A small dataset representing PM emissions from NGCC reduced the degree of confidence in the determination of the mean.

NO_X emissions are driven by the upstream supply chain, followed by the operation of the power plant. NO_X emissions represent the emissions from the natural gas supply chain, diluted by the addition of wind power.

The SO_X emissions across the lifecycle of the mixed wind-NGCC scenario are representative of a combination of emissions from the natural gas supply chain and wind farm lifespan. The wind lifespan is the largest contributor of SO_X, potentially resulting from coal-derived electricity and materials used during wind farm construction and turbine assembly. The natural gas supply chain contributes SO_X emissions from fuel extraction and processing as well as NGCC plant operations.

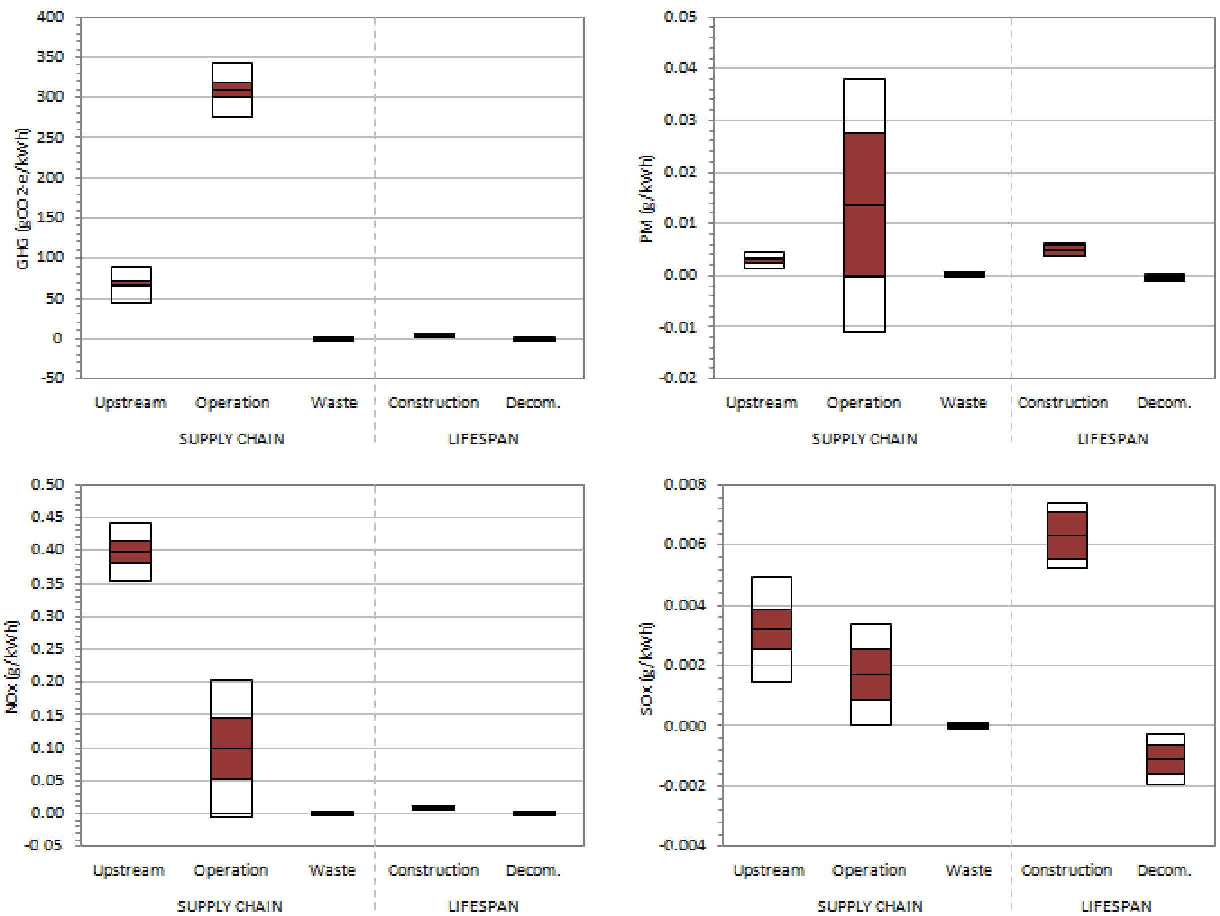

Figure 24. Lifecycle Distribution for Mix of Onshore Wind Turbines and Natural Gas Combined Cycle*

5.4 Natural Gas Sources

The natural gas scenario considers a mix of natural gas sources in the upstream supply chain (Section 4.3.1), broken down into conventional, unconventional, and shale gas sources. Conventional sources include onshore and offshore reservoirs, associated gas and non-associated gas, while unconventional gas includes coal bed methane, tight gas, shale gas and frontier gas. Note that shale gas, is a sub-set of unconventional gas, but presented separately due to its increasing relevance in the natural gas supply mix in Canada.

Supplementing the overall analysis of the natural gas lifecycle (Section 5.3.4) a comparison of each natural gas source was conducted to assess the differences in emissions for conventional, unconventional and shale gas sources. The result of the comparison is

* Standard deviation ranges less than zero are due to the statistical approach used to represent the data. Actual emissions data typically exceeds zero, with the exception of data pertaining to decommissioning of wind turbines, where some studies have considered decommissioning as an emissions credit.

presented in Figure 25, including an aggregated column (mixed) representing natural gas supply in the analysis of the overall lifecycle.

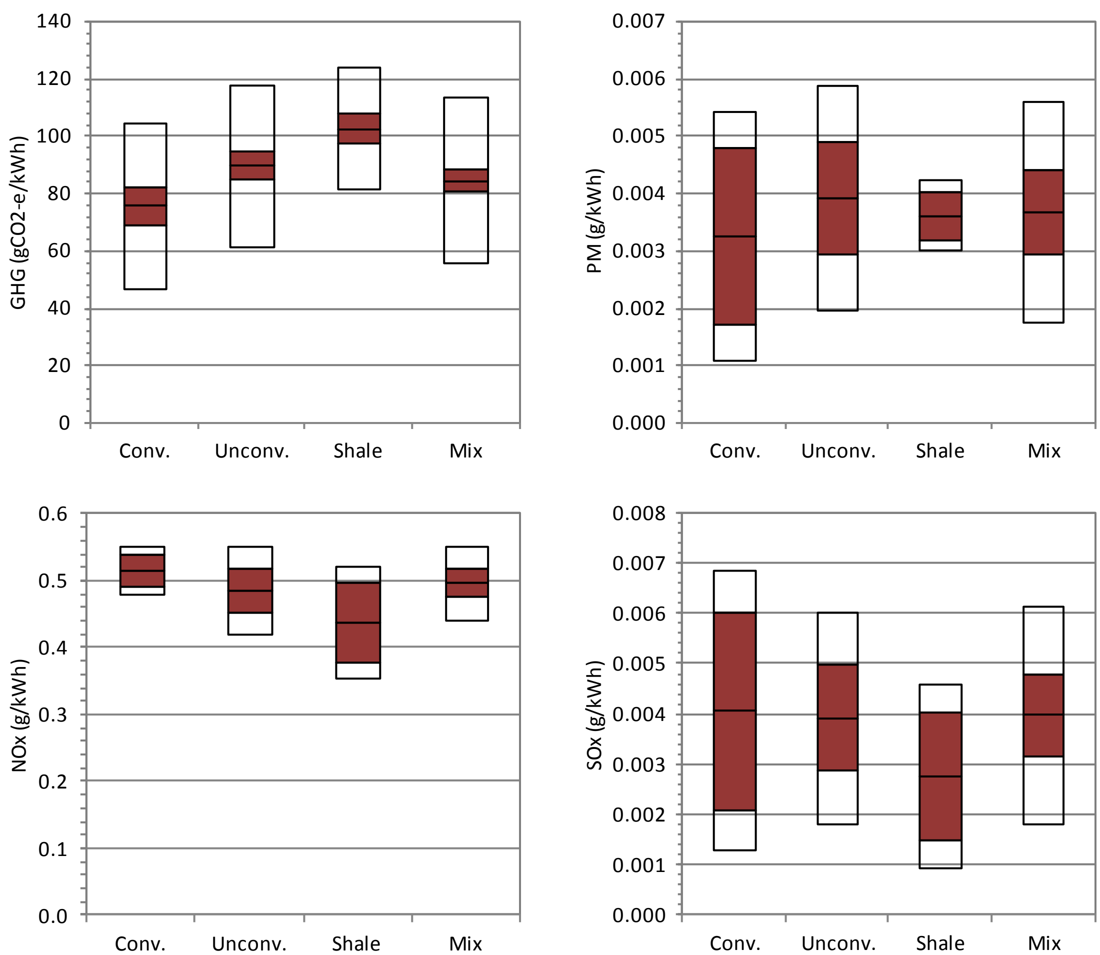

Figure 25. Emissions from Different Natural Gas Sources

Based on Figure 25, only GHG emissions showed a statistically relevant difference when comparing the three sources, with emissions highest for shale gas, followed by unconventional and then conventional sources. This difference between conventional and unconventional gas is consistent with the increased complexity of the horizontal drilling and hydrofracking procedure to access shale gas relative to conventional gas, which requires only vertical drilling techniques. However, the differences in the mean GHG emissions is small, and the range of LCA data shows that an efficient shale gas source may achieve similar results to conventional sources.

The difference between average GHG emissions from each gas source is small when compared with the entire natural gas power generation lifecycle. Emissions from conventional and shale gas sources are separated by 27+/-13 gCO2e/kWh. The difference is even smaller when compared across the entire NGCC lifecycle, roughly 3% of total lifecycle GHG emissions.

Aside from GHG emissions, the volume of LCA data available on other emissions was limited, resulting in a wider confidence band when calculating the sample mean. Combined with the similarity of data for each source, it was not possible to discern a difference in the mean PM, NO_X or SO_X emissions generated by conventional, unconventional and shale gas sources. Instead, within the accuracy of LCA literature data currently available, each source of natural gas appears to produce similar amounts of PM, NO_X or SO_X emissions.

5.5 Ionizing Radiation Potential

An analysis of ionizing radiation (IR) potential was performed separately for the nuclear power generation lifecycle. While each power generation scenario contributes to IR potential, it was not studied in sufficient detail to be considered for the natural gas and wind power lifecycles. The results of the analysis are presented in Figure 26 and Figure 27, respectively.

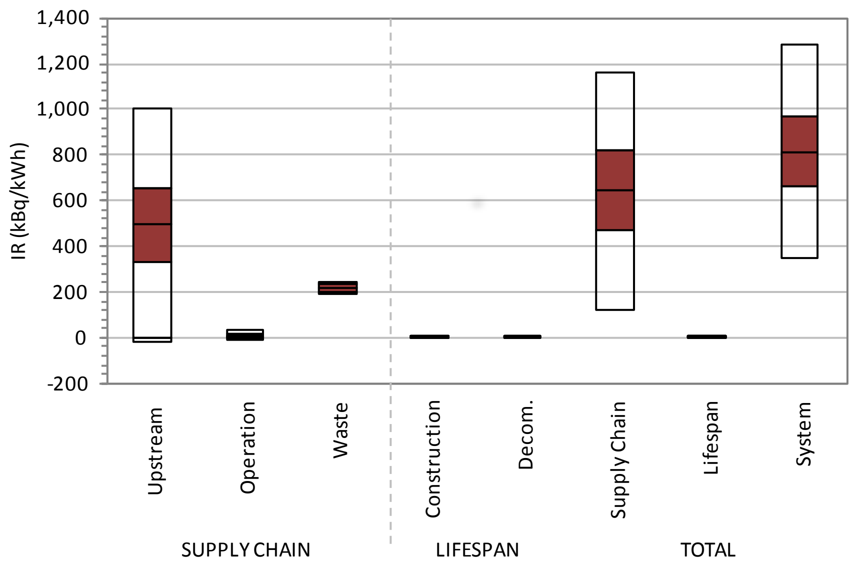

Figure 26. Lifecycle Distribution of IR for Nuclear Power Plants

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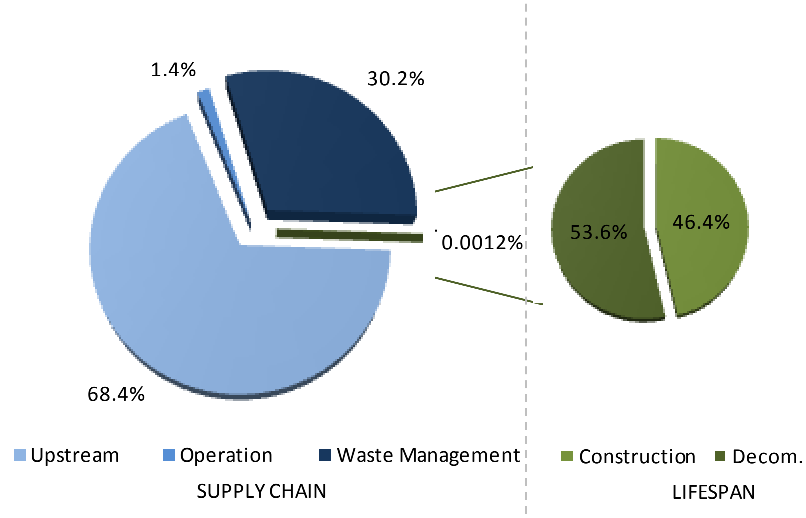

Figure 27. Percentage Contribution of IR to Lifecycle for Nuclear Power Plants

IR emissions for the entire system ranged from 220 – 1,720 kBq/kWh, with a mean of 810 ± 150 kBq/kWh. IR emissions are dominated by the supply chain, while emissions from the lifespan – plant construction and decommissioning are negligible. Within the supply chain, the upstream fuel supply chain and waste management are responsible for 68.4% and 30.2% of lifecycle emissions, respectively. Emissions from power plant operations represent 1.4% of the total lifecycle.

The high variability of the upstream supply chain IR emissions can be explained due to the variation in technologies and processes involved in preparing reactor fuels. Differences affecting the results including mining techniques and ore grade, the enrichment process, and whether any fuel reprocessing occurs.

6. Discussion

6.1 Comparison of Power Generation Lifecycles

The primary objective of this study was to provide a systematic comparison of wind, nuclear, and a mix of wind and natural gas lifecycles based on a review of existing LCA literature. Based on a meta-analysis approach, the literature data was organised by process stage and screened to meet a common definition of scope and system boundaries.

The results of this process showed that GHG and NO_X emissions from natural gas combined cycle (NGCC) generation greatly exceeded the wind and nuclear lifecycles. Based on the statistical mean, lifecycle GHG and NO_X emissions are a factor of 26 and 16 times less intensive than the NGCC lifecycle, respectively. GHG and NO_X emissions are associated primarily with the combustion of natural gas.

The variation in PM and SO_X emissions by comparison were less pronounced, with the average difference between scenarios varying by a maximum factor of approximately 3 times. The LCA literature examined shows overlapping distributions of PM emissions across all generation options. The lowest range of emissions corresponds to nuclear generation followed by wind and natural gas. However, no substantive difference can be discerned when comparing the calculated mean values of each scenario.

SO_X emissions from the wind and nuclear lifecycle exceed the emissions from NGCC and wind-NGCC generation. The construction and upstream fuel supply chain are the dominant sources of SO_X emissions from wind and nuclear, respectively, and may be related to emissions from coal-derived electricity consumption or manufacture of intermediate products such as steel.

The total emissions from the nuclear and wind power lifecycles were similar. Onshore wind power, on average, is a slightly more GHG efficient option than nuclear power over its lifecycle. The distribution of wind LCA data resides in the lower band of the range of nuclear power technologies considered. Of the nuclear power lifecycle, technologies that do not use diffusion-based enrichment produce similar emissions to onshore wind power. Average emissions of PM, SO_X and NO_X are comparable over the lifecycle of wind and nuclear power. No discernable difference in the statistical mean total lifecycle emissions of wind and nuclear power were observed.

Ionising radiation (IR) potential was assessed for nuclear power only, due to a lack of LCA data available for wind and natural gas. IR emissions are associated most with the upstream extraction and production and downstream waste management of nuclear fuels. The level of IR emissions from nuclear power generation can be compared to a number of common materials listed in Table 2.

6.2 Contribution of Lifecycle Process Stages

By grouping literature LCA data by process stage, the results showed variations in where emissions are generated across the lifecycle of each power generation scenario. The lifecycle was broken down into supply chain and lifespan process stages, covering the on-going operations and start-up and closure activities respectively.

NGCC was the only option which generated significant emissions from plant operations, although upstream natural gas production also factored into the total lifecycle emissions. Conversely, almost all of the environmental impacts of wind power are attributed to the construction of the wind farm itself, and only negligible emissions are produced on an on-going basis. The lifecycle of nuclear power, despite the infrastructure requirements, are primarily linked to the upstream supply chain, representing on average between 78% and 81% of total GHG, NO_X, SO_X and PM emissions.

The source of emissions across the lifecycle has an impact on where to target strategies to optimize and reduce emissions. Indirect emissions are less controllable from the perspective of individual power producers, compared to emissions generated directly at the power plant, or exclusively associated with the fuel supply chain of a particular power generation option. The source of the emissions also indicates whether the emissions are occurring as part of on-going electricity production, or a once-only emissions source at the start or end of the plant's lifetime. Emissions associated with construction and decommissioning can be reduced or increased by extending or shortening a plant's life while on-going emissions sources can be targeted to achieve continuous improvement throughout the plant's lifetime.

6.3 Influence of System Boundary and Modeling Variations

The results of the literature review and meta-analysis showed a considerable variability in the range of emissions data representing each scenario and process stage. This section discusses how some of the differences in the scope, system boundaries and modelling parameters of each of the studies considered contribute to the range of data observed in the results.

Electricity Grid Mix

The lifecycle of each power generation scenario requires a source of electricity for the upstream supply chain, plant construction, and production and transport of materials. The electricity required by the lifecycle is typically supplied indirectly by third party operators through regional electricity grids, which can have a significant impact on the environmental performance of individual process stages and the lifecycle as a whole.

The regional electricity grid mix – the proportion of electricity production sources – can vary between low-air emissions sources such as run-of-river hydro, to air emissions-intensive coal power. Air emissions generated from the range of power sources can vary by two orders of magnitude.

In certain cases, the variation of electricity grid mixes led to variations in the LCA literature based on the region of each respective study. By including studies from all regions, the distribution of data presented in the results spans the range of low to high air emissions grids, while the statistical mean is expected to more closely reflect the results for an average grid mix.

Differences in the electricity mix would affect not only the emissions per stage, but also the total emissions accounted for a particular power generation scenario. Variations in grid electricity mix are expected to have the greatest impact on the manufacturing and fabrication of materials and consumables for the supply chain and power plant construction, including the activities associated with the construction phase of the wind power scenario. The close link between SO_X emissions and coal-fired generation may lead to a greater sensitivity of SO_X emissions results for grid electricity mixes that feature high proportions of coal power.

Nuclear Technology & Process Route

While the scope of the wind and natural gas scenarios were limited to specific conditions, onshore wind farms and NGCC plants, respectively, LCA studies on all nuclear power generation technologies have been considered. By broadening the scope of the scenario, the distribution of data has also widened to reflect the variation in environmental performance across the industry. The upstream nuclear fuel supply chain appears to be most affected by technology selection and process route, where some reactor technologies necessitate a potentially emissions-intensive enrichment process. In particular, diffusion-based enrichment is an energy and emissions intensive process relative to centrifuge-based enrichment. Other factors include the extraction technique and ore grade, amongst others.

Emission Control Technologies & Management

For a given technology and process route, the management of emissions and application of environmental control technologies can influence overall environmental performance. Some LCA studies specifically considered control technologies within their system boundaries, or implicitly included control technologies by the selection of particular facilities or regions as focus areas for their respective studies.

Emissions control technologies can attenuate emissions of NO_X, SO_X and PM by orders of magnitude. Control technologies include a variety of pre and post combustion techniques including fuel selection, low-NO_X burners, selected catalytic reduction, fuel desulfurization, flue gas desulfurization, bag houses, wet scrubbers and electrostatic precipitators. Control technologies applied at NGCC plants have contributed to lower NO_X and SO_X emissions during plant operations relative to upstream natural gas supply, despite the amount of natural gas combustion occurring during operations.

Note that carbon capture and storage (CCS) was not considered within the boundaries of this study, limiting the influence that management and control of emissions can have on reducing CO_2 releases, the largest contributor of GHG emissions. Emissions control of other GHGs, including fugitive CH_4 releases during natural gas extraction, in particular, may have a limited effect on lifecycle GHG emissions. Efficiency improvements at NGCC plants have the largest influence on total GHG emissions per kWh of electricity generated from the natural gas lifecycle.

Geography & Efficiency of Wind Generation

The location considered for each LCA study plays a significant role for wind power studies, directly affecting the availability, speed, duration and daily and seasonal variability of wind supply. These parameters greatly influence the efficiency of electricity production from wind power, and therefore the emissions intensity, contributing to the range of data observed in the literature reviewed.

Other Regional Factors

Regional-specific factors are underlying the difference in results observed in the LCA literature. Wind power efficiency and the electricity grid are examples of regional-specific factors. Other regional factors affecting the range of results include but are not limited to local emissions limits, waste management regulations, ore/fuel quality, material availability and proximity, local transportation networks.

Modeling Plant Operating Lifetime

Plant operating lifetime is an important modelling parameter used to relate the emissions from construction and decommissioning, one time activities, to on-going power production. Extending plant lifetime, either as a modelling consideration or in actuality, acts to reduce the contribution of construction and decommissioning on an emissions per kWh electricity generated basis.

When possible, this study normalized the operating lifetime of the literature LCA data to fixed lifetimes specific to each power generation scenario and based on the median lifetime considered by the LCA literature. This process helps to standardize the treatment of operating lifetime, although some variability is still expected in the results, specifically for studies that did not document the operating lifetime considered.

LCA Data Sources – Primary and Generic Data

Some studies estimate the emissions from the lifecycle of a specific power plant, while other studies assess the industry at a regional, national, or global level for one or more technologies. Depending on the study's goal and scope, a varying combination of primary and generic industry data may be used to reflect an individual site or average of multiple sites, with varying degrees of accuracy and reliability.

6.4 Influence of LCA Literature & Data Availability

The availability of data from previous LCA studies has an important impact on the ability of the literature review to draw meaningful conclusions about the range and average environmental emissions from each of the power generation lifecycles considered. In general, the benefits of increasing the pool of available LCA data include:

- More accurate calculation of the statistical mean emissions;
- Improved resolution of process stages making up the total supply chain, lifespan and lifecycle;

- More complete representation of technologies, processes and study regions;
- Ability to focus on particular technologies, process routes and/or geographic regions of interest.

The coverage of GHG emissions for each power generation source allowed for sufficient data to understand and compare the contribution of each process stage and power generation lifecycle. However, limitations in the quantity of data treating PM, NO_X, SO_X and IR potential emissions placed restrictions on the study. While the assessment of the PM, NO_X and SO_X emissions datasets usually allowed for general conclusions to be drawn, in some cases the accuracy of the statistical mean was too broad to determine any definitive difference between power generation scenarios.

6.5 Comparison to Other LCA Literature Reviews

To validate the information presented in this report, the calculated statistical mean of each power generation lifecycle was compared with recent literature reviews covering wind, natural gas and nuclear power. A number of recent literature reviews were relevant to this study, including:

- A study published in 2012 by Dolan and Heath, which performed a systematic review and harmonization to screen 240 LCAs of GHG emissions from onshore and offshore wind power (14);
- A 2012 study by Turconi, Boldrin, and Astrup, which reviewed 167 studies to compare, among other technologies, natural gas, nuclear and wind power for GHG, NO_X and SO_X emissions (34);
- A 2012 study by Warner and Heath, which performed a systematic review and harmonization to screen 274 LCAs of GHG emissions from nuclear power production (35);
- A study published in 2008 by B.K. Sovacool, screening 103 lifecycle studies of greenhouse gas-equivalent emissions for nuclear power (36);
- A study presented at the LCA XII conference in 2012 covering a systematic review and harmonization for the lifecycle GHG emissions from conventional natural gas power generation (37).

A comparison of the study's results with each literature review is presented in Table 6.

Table 6. Comparison of Lifecycle Emissions from Recent Literature Reviews

Ref. Study [1]	Scenario (Tech.) [2]	Average Current Study [4] (g/kWh)			Range of Reference Study [5] (g/kWh)		
		GHG	NO_X	SO_X	GHG	NO_X	SO_X
(14)	Wind (onshore)	10.5±0.9	0.03±0.003	0.006±0.002	3-45	-	-
(34)	Wind (Mix)				3-41	0.02-0.11	0.02-0.09
(35)	Nuclear (LWR)	18.5±1.7	0.04±0.006	0.02±0.003	3.7-110	-	-
(35)	Nuclear (PWR)				3.7-110		
(35)	Nuclear (BWR)				4.6-17		
(36)	Nuclear (Mix)				1.36-288.25	-	-
(34)	Nuclear (Mix)				3-35	0.01-0.04	0.003-0.038
(37)	NG (NGCC)	478±10	0.6±0.03	0.007±0.001	360-720	-	-
(34)	NG (Mix)				380-1000	0.2-3.8	0.01-0.32

(1) Reference studies is the reference to the studies found in the literature that are compared to the results of this study.
(2) Scenario represents the generation scenario evaluated in the ref. studies. If more than one generation scenario is addressed, more than one row is presented in the table.
(4) Average Meta-Analysis represents the results from this study, including the uncertainty of the mean.
(5) Total Emissions for study represents the range (min/max) values from the reference studies.

The following observations were made by comparing the statistical mean data from the present study with the ranges provided by the literature reviews from Table 6:

- Average emissions results for wind power are within the lower end of the range provided by Turconi, Boldrin, and Astrup (34), which represents a mix of onshore and offshore wind farms, while the current study considers only onshore installations.
- Average GHG emissions results are also within the lower end of the range reported by Dolan and Heath (14). The average reported by the Dolan and Heath study is also higher than the current results, 15 g/kWh compared to 10.5 +/- 0.9 g/kWh, respectively. The slightly lower average may reflect a combination of factors including the consideration of plant operating lifetime, which has a particularly important influence for the wind power lifecycle, which is dominated by emissions relating to wind farm construction. The Dolan and Heath study considers studies between 1994-2010 as opposed to between 2000 and 2013, potentially incorporating less efficient technology.
- The average GHG emissions result for nuclear power generation is within the range for LWR and PWR, but slightly higher for BWR, according to Warner and Heath (35), where the mean values reported are 18, 22 and 11 g/kWh for LWR, PWR and BWR, respectively. Their study used a harmonization process incorporating different

parameters such as capacity factor, lifetime, and thermal efficiency and including a broader temporal coverage, including data from 1992 to 2009.

- The average emissions results for nuclear power generation in the present study are within range when compared to the Sovacool (36) and Turconi, Boldrin, and Astrup (34) studies, which both consider a mix of nuclear power plant technologies.
- The average lifecycle emissions from the NGCC power plant lifecycle are within the ranges presented at LCA XII (37) and by Turconi, Boldrin, and Astrup (34). The results are on the lower end of the Turconi, Boldrin, and Astrup study, and slightly below the range expected for SO_X emissions. This outcome is expected to some extent as the present study focused exclusively on NGCC plants, a high efficiency (low-emissions intensity) technology relative to single cycle gas plants also considered in the reference studies.

6.6 Study Limitations

The specific approach and methodology employed during the literature review and meta-analysis introduced some limitations to consider while interpreting the study's results. This section describes aspects of the study that may affect how well the study's overall results reflect the actual environmental performance of each generation scenario.

Selection of Environmental Emissions

This study is limited to assessing the GHG, NO_X, SO_X, PM and IR (only for nuclear) emissions for different power generation scenarios. These emissions provide an important but incomplete picture of overall environmental performance across the power generation lifecycle, excluding water consumption and quality, solid waste generation, and other types of emissions.

Furthermore, the study does not consider the impacts of each of these emissions sources on location-specific end points including sensitive ecosystems or local communities.

Application of Plant Lifetime Normalisation

Plant lifetime is an important parameter used to represent construction and decommissioning related activities on a per-kWh electricity basis, generated throughout the operating time of a power plant. In order to compare literature on a common basis, the lifetime was normalized for each power generation scenario whenever possible. Applying this approach helped to standardize the scope and system boundaries of the aggregated results but also imposed a new parameter as part of the meta-analysis rather than reporting literature data verbatim.

The potential for introducing bias into the study was minimized by using the median lifetime of the literature representing each generation scenario, such that the choice of lifetime was systematic and representative of the LCA literature. For wind and NGCC, the distribution of lifetimes considered is narrowly defined around 20 and 30 years, respectively. However, the range of nuclear technologies represented by the LCA literature, some which may consider refurbishment, led to a broader distribution of operating lifetimes. As a result, the 40 year median lifetime is not representative of a single reactor technology but, instead is reflective of the broad range of nuclear technologies studied by LCA.

Regardless of normalization procedures, the effect of plant lifetime on total lifecycle results can be significant when emissions from the start and end-of-life activities greatly exceed emissions associated with daily plant and fuel supply operations. This effect is most significant for wind power, where its lifecycle is dominated by emissions associated with wind farm/turbine construction and least significant for natural gas due to combustion related activities during operations.

Sample Bias in Regional & Technology Representation

This study does not place regional restrictions on LCA data considered as part of the literature review. Accordingly, the results of the study do not represent any geographical location in particular. Moreover, no attempt was made to weight the results to be representative of any global or regional technology mix. Instead, the results are, in effect, weighted according to the availability of data in the literature, and may be biased towards regions, technologies or process routes of particular interest to LCA practitioners. Availability of Canadian data, of specific interest to this study, was often limited.

Double Counting Primary Source Data

The literature review considered the distribution of LCA data based on individual LCA publications, rather than according to original primary source data. As a result, well referenced primary data from particularly well-studied facilities has a higher tendency to appear in multiple studies, and consequently to be more heavily weighted in this assessment. Similarly, the approach of a single author or research organization applied in multiple separate studies may lead to data clusters (similar results) reflecting the application of common LCA methods rather than physical phenomena.

The extent of the potential bias on the results due to overlapping studies was not examined nor quantified in this study, but minimized by removing duplicate data points when it could be shown that they were derived from the same source data and methods.

7. Conclusions

The purpose of this study was to conduct a systematic comparison of the environmental emissions generated across the entire lifecycle of nuclear, wind and natural gas power generation by compiling and evaluating lifecycle assessment (LCA) data available in the public domain. The scope of the assessment included GHG, NO_X, SO_X and PM emissions, as well as ionising radiation (IR) potential specifically for the nuclear lifecycle. The system boundaries of each scenario encompassed all processes involved in the supply chain required for on-going plant operations including upstream fuel supply, electricity generation, and waste management, as well as the plant lifespan, consisting of the activities associated with plant construction and decommissioning. The study presented the lifecycle emissions for each power source relative to 1 kWh of electricity generated just prior to delivery to the electricity grid.

A literature review and meta-analysis approach was developed to utilize pre-existing LCA data published between 2000 and 2013, but focusing primarily on data published after 2008. The evaluation considered 246 studies covering various power generation scenarios, system boundaries and emissions types. The literature varied greatly in terms of the process stages covered, with some studies covering only a portion of the complete lifecycle and others providing coverage for the entire lifecycle in enough detail to resolve individual process stages contributing to the lifecycle total. The documentation of previous LCA studies also varied, sometimes lacking clarity of scope and system boundaries, inhibiting the ability to interpret the results. Data gathered during the literature review was compiled, assessed, and grouped into categories representing segments of the system boundaries defined for the study.

The coverage of each process stage was limited in some cases, although the level of coverage improved in line with the importance of a given process stage (in terms of the contribution of emissions to the total). In terms of environmental indicators, the majority of LCA studies addressed GHG emissions, but the number of studies addressing NO_X, SO_X, and PM, were comparatively limited. Future LCA research involving modelling of electricity generation systems would help to better understand the emissions of NO_X, SO_X, and PM along the power generation lifecycle.

The results of the assessment show that the lifecycle of nuclear and wind power generation produces a small fraction of the GHG and NO_X emissions of the natural gas combined cycle (NGCC) lifecycle. The GHG emissions of the NGCC lifecycle are increased when sourcing natural gas from shale gas reservoirs, although the increase is minor relative to plant operations. Emissions of PM were more comparable across generation sources, with the range of emissions from nuclear and wind on the lower end of the range of emissions from NGCC. Emissions of SO_X were similarly comparable with nuclear and wind generating more emissions on average than NGCC.

On average, emissions from wind and nuclear are similar within the accuracy of the study for all emissions except GHG emissions, where wind produces distinctly less GHG emissions on average than the combination of nuclear technologies considered.

When considering wind backed by natural gas power (20%/80% on a total electricity supply basis) to compensate for intermittency, emissions from the modified grid mix closely resembles that of natural gas production, diluted by a low-emissions power source.

Based on the similarity of each generation scenario as well as limitations in the availability of LCA data, the study was unable to resolve any statistical difference in the average PM emissions between wind, nuclear and natural gas generation, or the average PM, NO_X and SO_X emissions between wind and nuclear power.

The range and variability of data published in the LCA literature highlights the importance of literature review in incorporating multiple LCA studies in comparing power generation scenarios, as well as meta-analysis approaches in harmonizing the scope and system boundaries necessary in setting a common basis for comparison. Several regional, process route and technological factors contributed to the range of published data which should be considered in any comparison. As a result, a separate approach utilising primary source data that is region, technology and even site specific is recommended in order to compare specific scenarios. Aside from region and technology-specific objectives, the more general global literature review process employed in this study may be preferred in order to provide an overall comparison of the range and average lifecycle emissions that can result from nuclear, wind and natural gas under a variety of potential applications.

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Appendix A - Summary of Statistical Results

Table 7. Summary Of Statistics of Qualified Studies for Onshore Wind Turbines

Onshore Wind Turbines Statistics	GHG									PM								
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	2.9E-02	4.9E-01	9.7E-02	1.2E+01	-1.5E+00	7.1E-01	1.0E+01	1.1E+01	2.4E-05	3.0E-03	5.5E-04	2.0E-02	-1.9E-03	2.4E-03	1.9E-02	1.5E-02
Uncertainty	1.4E-02	1.7E-01	4.9E-02	1.6E+00	7.0E-01	2.1E-01	1.3E+00	9.0E-01	1.2E-05	3.9E-04	2.7E-04	1.8E-03	1.5E-03	1.5E-03	2.6E-03	3.3E-03
Standard Deviation	-	5.8E-01	-	6.4E+00	2.3E+00	7.7E-01	5.7E+00	4.9E+00	-	3.9E-04	-	3.1E-03	2.7E-03	2.1E-03	5.9E-03	8.5E-03
Contribution to Total	0%	3%	1%	86%	10%	4%	96%	100%	0%	12%	2%	78%	8%	14%	86%	100%

Onshore Wind Turbines Statistics	NOx								SOx							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	9.5E-05	2.6E-04	2.4E-04	3.7E-02	-3.3E-03	3.2E-03	3.4E-02	2.8E-02	1.6E-04	3.9E-04	7.2E-05	2.7E-02	-5.6E-03	8.6E-04	2.2E-02	2.5E-02
Uncertainty	4.7E-05	5.9E-05	1.2E-04	6.8E-03	1.6E-04	1.9E-03	5.1E-03	3.3E-03	8.2E-05	7.5E-05	3.6E-05	3.1E-03	2.4E-03	4.3E-04	1.5E-03	3.1E-03
Standard Deviation	-	8.4E-05	-	9.6E-03	2.3E-04	3.8E-03	1.1E-02	1.1E-02	-	1.1E-04	0.0E+00	5.5E-03	4.2E-03	7.5E-04	3.7E-03	1.1E-02
Contribution to Total	0%	1%	1%	90%	8%	1%	99%	100%	0%	1%	0%	81%	17%	2%	98%	100%

Table 8. Summary of Statistics of Qualified Studies for Nuclear Power Plants

Nuclear Power Plant Statistics	GHG								PM							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	1.2E+01	2.2E+00	1.6E+00	2.9E+00	1.2E+00	1.4E+01	3.4E+00	1.9E+01	3.2E-03	1.1E-04	2.4E-04	8.3E-04	7.2E-06	3.6E-03	7.5E-04	8.2E-03
Uncertainty	1.6E+00	6.0E-01	5.0E-01	3.9E-01	5.5E-01	2.0E+00	6.2E-01	1.7E+00	8.2E-04	7.4E-05	1.1E-04	3.5E-04	2.2E-06	8.5E-04	1.9E-04	3.5E-03
Standard Deviation	1.1E+01	3.0E+00	2.6E+00	2.0E+00	2.5E+00	1.3E+01	3.7E+00	1.3E+01	2.7E-03	2.0E-04	1.6E-04	6.1E-04	3.8E-06	2.7E-03	4.7E-04	1.3E-02
Contribution to Total	60%	11%	8%	15%	6%	80%	20%	100%	73%	3%	5%	19%	0%	81%	19%	100%

Nuclear Power Plant Statistics	NOx								SOx							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	3.4E-02	7.7E-04	2.7E-03	8.9E-03	9.0E-04	3.7E-02	7.4E-03	3.9E-02	1.7E-02	1.5E-03	1.4E-03	3.3E-03	2.3E-03	2.0E-02	4.4E-03	2.3E-02
Uncertainty	6.3E-03	2.2E-04	4.7E-04	5.2E-03	3.4E-04	6.4E-03	3.6E-03	6.5E-03	3.5E-03	1.4E-03	4.3E-04	7.9E-04	5.3E-04	3.0E-03	1.1E-03	3.1E-03
Standard Deviation	2.4E-02	5.8E-04	8.2E-04	1.3E-02	8.4E-04	2.3E-02	1.1E-02	2.6E-02	9.9E-03	3.2E-03	7.5E-04	1.9E-03	1.3E-03	8.4E-03	3.2E-03	1.0E-02
Contribution to Total	72%	2%	6%	19%	2%	79%	21%	100%	67%	6%	5%	13%	9%	78%	22%	100%

Table 9. Summary of Statistics of Qualified Studies for Natural Gas Combined Cycle Power Plants

NGCC Power Plant Statistics	GHG								PM							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	8.4E+01	3.9E+02	-	7.6E-01	1.7E-02	4.8E+02	1.2E+00	4.8E+02	3.7E-03	1.6E-02	-	1.1E-03	1.5E-05	2.0E-02	1.3E-03	2.1E-02
Uncertainty	4.0E+00	1.1E+01	-	3.6E-01	1.8E-03	1.0E+01	3.4E-01	1.0E+01	7.2E-04	1.8E-02	-	1.1E-03	1.8E-05	1.2E-02	6.6E-04	1.2E-02
Standard Deviation	2.9E+01	4.2E+01	-	7.1E-01	3.2E-03	4.7E+01	9.0E-01	4.7E+01	1.9E-03	3.1E-02	-	1.1E-03	1.8E-05	2.3E-02	1.1E-03	2.3E-02
Contribution to Total	18%	82%	0%	0%	0%	100%	0%	100%	18%	77%	0%	5%	0%	95%	5%	100%

NGCC Power Plant Statistics	NOx								SOx							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	5.0E-01	1.2E-01	-	6.7E-04	2.1E-04	6.2E-01	2.1E-03	6.2E-01	4.0E-03	2.1E-03	-	1.2E-03	1.5E-05	6.0E-03	1.4E-03	7.1E-03
Uncertainty	2.1E-02	5.8E-02	-	3.4E-04	1.1E-04	2.7E-02	1.2E-03	2.7E-02	8.3E-04	1.1E-03	-	6.0E-04	7.5E-06	8.5E-04	2.2E-04	9.2E-04
Standard Deviation	5.5E-02	1.3E-01	-	-	-	6.9E-02	2.1E-03	6.9E-02	2.2E-03	2.1E-03	-	-	-	2.1E-03	3.8E-04	2.1E-03
Contribution to Total	80%	20%	0%	0%	0%	100%	0%	100%	55%	28%	0%	17%	0%	83%	17%	100%

Table 10. Summary of Statistics of Qualified Studies for Mix of Onshore Wind Turbines and Natural Gas Combined Cycle Power Plants

Mix Wind-NGCC Statistics	GHG								PM							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	6.7E+01	3.1E+02	1.9E-02	3.1E+00	-2.8E-01	3.8E+02	3.0E+00	3.8E+02	2.9E-03	1.4E-02	1.1E-04	4.9E-03	-3.8E-04	1.6E-02	4.8E-03	2.0E-02
Uncertainty	3.2E+00	8.9E+00	9.7E-03	4.3E-01	1.4E-01	8.2E+00	3.8E-01	8.2E+00	5.8E-04	1.4E-02	5.5E-05	9.5E-04	3.1E-04	9.5E-03	7.5E-04	9.5E-03
Standard Deviation	2.3E+01	3.3E+01	-	1.4E+00	4.6E-01	3.7E+01	1.3E+00	3.7E+01	1.5E-03	2.4E-02	-	1.1E-03	5.3E-04	1.8E-02	1.5E-03	1.8E-02
Contribution to Total	18%	81%	0%	1%	0%	99%	1%	100%	13%	62%	1%	22%	2%	76%	24%	100%

Mix Wind-NGCC Statistics	NOx								SOx							
	SUPPLY CHAIN			LIFESPAN		TOTAL			SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	4.0E-01	9.9E-02	4.8E-05	8.0E-03	-5.0E-04	5.0E-01	8.5E-03	5.0E-01	3.2E-03	1.7E-03	1.4E-05	6.3E-03	-1.1E-03	5.0E-03	5.5E-03	1.1E-02
Uncertainty	1.7E-02	4.6E-02	2.4E-05	1.4E-03	9.1E-05	2.1E-02	1.4E-03	2.1E-02	6.6E-04	8.4E-04	7.2E-06	7.9E-04	4.8E-04	6.9E-04	3.5E-04	9.6E-04
Standard Deviation	4.4E-02	1.0E-01	-	1.9E-03	4.6E-05	5.5E-02	2.8E-03	5.5E-02	1.7E-03	1.7E-03	-	1.1E-03	8.4E-04	1.7E-03	8.0E-04	2.7E-03
Contribution to Total	79%	20%	0%	2%	0%	98%	2%	100%	26%	14%	0%	51%	9%	40%	60%	100%

Table 11. Summary of IR Statistics of Qualified Studies for Nuclear Power Plants

Nuclear Power Plants Statistics	IR							
	SUPPLY CHAIN			LIFESPAN		TOTAL		
	Ups.	Ops.	Waste	Const.	Decom.	SC	LS	System
Mean	4.9E+02	9.8E+00	2.2E+02	8.5E-03	9.8E-03	6.4E+02	1.4E-02	8.1E+02
Uncertainty	1.6E+02	7.9E+00	2.0E+01	8.4E-04	1.7E-03	1.8E+02	2.7E-03	1.5E+02
Standard Deviation	5.1E+02	1.9E+01	2.9E+01	1.2E-03	2.4E-03	5.2E+02	5.5E-03	4.7E+02
Contribution to Total	68%	1%	30%	0%	0%	100%	0%	100%

Table 12. Summary of Statistics of Qualified Studies for Natural Gas Sources

	GHG				PM				NOx				SOx			
	Conv.	Unconv.	Shale	Mix	Conv.	Unconv.	Shale	Mix	Conv.	Unconv.	Shale	Mix	Conv.	Unconv.	Shale	Mix
Mean	7.6E+01	8.9E+01	1.0E+02	8.4E+01	3.3E-03	3.9E-03	3.6E-03	3.7E-03	5.1E-01	4.8E-01	4.4E-01	5.0E-01	4.1E-03	3.9E-03	2.8E-03	4.0E-03
Uncertainty	6.6E+00	4.9E+00	5.3E+00	4.0E+00	1.5E-03	9.8E-04	4.3E-04	7.2E-04	2.5E-02	3.2E-02	5.9E-02	2.1E-02	2.0E-03	1.1E-03	1.3E-03	8.3E-04
Standard Deviation	2.9E+01	2.8E+01	2.1E+01	2.9E+01	2.2E-03	2.0E-03	6.1E-04	1.9E-03	3.5E-02	6.5E-02	8.4E-02	5.5E-02	2.8E-03	2.1E-03	1.8E-03	2.2E-03
Contribution to Total	7.6E+01	8.9E+01	1.0E+02	8.4E+01	3.3E-03	3.9E-03	3.6E-03	3.7E-03	5.1E-01	4.8E-01	4.4E-01	5.0E-01	4.1E-03	3.9E-03	2.8E-03	4.0E-03

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