SCIENCE INTEGRITY KNOWLEDGE

# GREENHOUSE GAS EMISSIONS ASSOCIATED WITH VARIOUS METHODS OF POWER GENERATION IN ONTARIO

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GREENHOUSE GAS EMISSIONS ASSOCIATED WITH VARIOUS METHODS OF POWER GENERATION IN ONTARIO

## EXECUTIVE SUMMARY

Intrinsik Corp. (Intrinsik) has been retained by Ontario Power Generation Inc. (OPG) to compare greenhouse gas (GHG) emissions associated with various methods of energy production in Ontario over the next 40 years. Along with technical and economic factors, environmental impacts are an important element to consider when establishing a system of mixed electricity generation. Utilizing both renewable and non-renewable resources with low-carbon impact that can provide a consistent and reliable supply of electricity will address Ontario's energy requirements while minimizing impacts to the environment.

The objective of the study was to provide an impartial, scientifically defensible evaluation of the GHG emissions associated with various types of energy production projected to be utilized in Ontario until 2055. This period represents the projected operating life span of the refurbished Darlington Nuclear Generating Station. The study focused exclusively on the estimated GHG emissions released to the Ontario environment as a result of the operations and maintenance of facilities producing electricity rather than a Lifecycle Assessment (LCA) that addresses all potential upstream and downstream activities. This approach is consistent with the emissions forecast provided by the Independent Electricity System Operator (IESO) as part of Ontario's Long-Term Energy Plan.

Numerous LCAs have characterized GHG emissions for various forms of energy production. For conventional facilities utilizing fossil fuels such as coal or natural gas, the majority of GHG emissions occur during the production of energy as fuel resources are consumed. For other methods of energy production, the mining and processing of resources, the production of equipment, or the construction of facilities may represent the most emission-intensive stages. The overall lifecycle GHG emissions for nuclear, wind and hydro are often found to be similar and slightly below those for solar, with emissions for each of these more than an order of magnitude lower than lifecycle emissions for natural gas (Figure E-1).

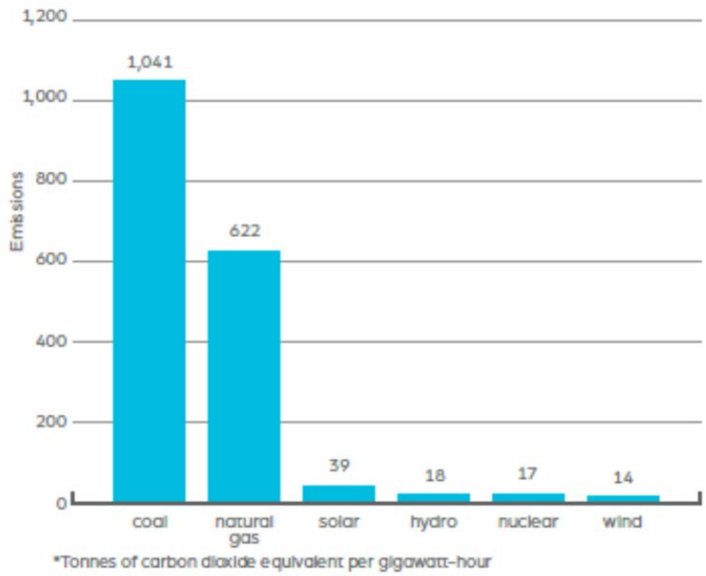


**Figure E-1 Comparison of Lifecycle Emissions for Various Methods of Energy Production (Asthma Society of Canada and Bruce Power, 2014).**

Utilizing literature-based values, provincial databases of self-reported GHG emissions, and energy production estimates, resource-specific GHG emission rates per unit of electricity generated (*i.e.*, gram of $CO_2$ equivalents per kilowatt hour (g $CO_2$e/kWh)) were estimated for nuclear, wind, natural gas, solar PV, and hydroelectric energy production in Ontario (Table E-1).

**Table E-1 Estimated Resource-Specific GHG Emission Rates for the Operation and Maintenance Stage**

| ***Resource*** | ***GHG Emissions per Energy Production (g $CO_2$e/kWh)*** |
|---|---|
| Hydroelectric | 0 |
| Nuclear | 0.15 |
| Wind | 0.74 |
| Solar | 6.15 |
| Natural Gas | 525 |

Resource-specific GHG emission rates were then used to estimate the total amount of GHGs emitted to meet Ontario's energy requirements for three (3) distinct scenarios:

1. Current energy production, with nuclear representing approximately 60% of Ontario's energy requirements, until 2024 during a period of staggered refurbishments to the Darlington and Bruce Generating Stations.
2. Projected future scenario after 2024 with a reduction in nuclear capacity following the scheduled closure of the Pickering Nuclear Generating Station and the completed refurbishment of the Darlington Nuclear Generating Station. Under this scenario it was assumed that the necessary capacity lost with the closure of the Pickering Station would be replaced by a combination of renewable sources (*i.e.*, hydro, wind and solar PV) and natural gas.
3. Alternate projected future scenario after 2024 in the absence of the Darlington refurbishment resulting in a reduction in nuclear capacity associated with the closure of both the Pickering and Darlington Stations. Under this scenario it was assumed that the

necessary capacity lost with the closure of the Pickering and Darlington Stations would be replaced by a combination of renewable sources (*i.e.*, hydro, wind and solar PV) and natural gas.

The loss of nuclear capacity with the closure of the Pickering Station after 2024 (Scenario 2), and the combined losses of capacity with the closure of both the Pickering and Darlington Stations in an alternate future scenario (Scenario 3), result in an increase in total GHG emissions to 16 and 26 MT $CO_2$e in 2025, respectively, relative to the total GHG emissions of 12 MT $CO_2$e in 2024 prior to the closure of these facilities and 7.2 MT $CO_2$e under the current 2016 scenario (Figure E-1). Fluctuations in emissions in Scenarios 2 and 3 are largely attributed to planned refurbishments to the Bruce Station occurring until 2031. The total reduction in GHG emissions from 2024 to 2055 associated with the continued use of the Darlington Station following refurbishment is estimated to be 297 MT $CO_2$e, with an average reduction of 9.6 MT $CO_2$e per year. This is equivalent to removing approximately 2,000,000 cars from Ontario's roads per year. A reduction of 9.6 MT $CO_2$e per year also contributes to Ontario's GHG emissions reduction targets under Ontario's Climate Change Mitigation and Low-Carbon Economy Act, 2016, which calls for reductions from 1990 emissions levels (181.8 MT $CO_2$e) of 15% in 2020, 37% in 2030, and 80% in 2050 (MOECC, 2016), representing reductions of 27, 67 and 145 MT $CO_2$e, respectively.


**Figure E-1 Projected Greenhouse Gas Emissions associated with Power Generation in Ontario (2016 to 2055)**

The emissions profile is driven almost exclusively by energy production from natural gas facilities for each of the three (3) scenarios. Although the contribution of natural gas to the total energy production ranges from 9 to 32%, it consistently represents the largest source of GHGs since the combustion of natural gas is the most emission-intensive operational process of each of the energy-producing resources. These significant increases in annual GHG emissions are anticipated even though an optimal scenario was assumed in which renewable resources such as wind, solar PV and hydro were able to increase their contribution to meet energy demands beyond the forecasted increase in production. Despite this assumption, a large portion of the capacity lost with the closure of the Darlington Station under Scenario 3 was assumed to be replaced by energy generated by natural gas facilities. Natural gas facilities were assumed to provide approximately 75% (or 20 TWh) of the total capacity lost under Scenario 3 from the closure of the Darlington Station in 2025 until 2036. It was assumed that if the Darlington Station refurbishments were not approved, a 20-year planning, approvals and construction phase would allow for a 10% increase (4.2 TWh) in energy production from hydroelectric facilities beginning in 2036. A subsequent 1% increase in hydroelectric capacity was assumed for every year after 2036. The technical feasibility of the assumed increased capacity for energy production for each resource was not evaluated as part of the current study.

Given that nuclear represents a large source of energy production in Ontario and the operational stage produces a low rate of GHG emissions, the loss of energy-generating capacity due to the closure of nuclear facilities would result in a significant increase in annual GHG emissions in order for Ontario to meet its future energy requirements.

**GREENHOUSE GAS EMISSIONS ASSOCIATED WITH VARIOUS METHODS OF POWER GENERATION IN ONTARIO**

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# 1.0 INTRODUCTION

Intrinsik Corp. (Intrinsik) has been retained by Ontario Power Generation Inc. (OPG) to compare greenhouse gas (GHG) emissions associated with various methods of energy production in Ontario over the next 40 years. Along with technical and economic factors, environmental impacts are an important element to consider when establishing a system of mixed electricity generation. Utilizing both renewable and non-renewable resources with low-carbon impact that can provide a consistent and reliable supply of electricity will address Ontario's energy requirements while minimizing impacts to the environment.

A literature and database search was conducted to characterize GHG emission rates associated with regular operating activities for various methods of power generation utilized in Ontario, specifically nuclear, wind, solar photovoltaic (PV), hydro, and natural gas. This information was used to estimate total GHG emissions associated with Ontario's energy requirements under current and potential future scenarios. This study focuses exclusively on GHG emissions released in Ontario as a result of the operational stages of energy production.

## 1.1 Background

The province of Ontario's Long-Term Energy Plan (LTEP) was released in 2013 (MOE, 2013). This report detailed the proposed plan to meet Ontario's forecasted energy demands up to the year 2032, as well the predicted GHG emissions associated with the production of this energy. As part of the province's GHG emissions reduction program, Ontario has adopted measures to reduce GHG emissions associated with the electricity sector. This included the phasing-out of coal-fired electricity generation as of April 2014 largely through increasing generation from nuclear units and adding new natural gas-fired generating facilities, and the implementation of the Feed-in-Tariff (FIT) program under the Green Energy Act which guarantees long-term rates for electricity generated using renewable resources such as wind and solar. These efforts have contributed to the steady decline in GHG emissions from the electricity sector since 2008. The Ontario Ministry of Environment and Climate Change (MOECC) reported that these declines were expected to continue for the next few years followed by an increase in emissions associated with a growing Ontario population, a recovering economy, and a reduction in energy production from nuclear units during a period of refurbishment resulting in an increased reliance on natural gas-fired plants (MOECC, 2013).

Currently, Ontario's energy demands are met through a mix of renewable and non-renewable resources, with nuclear representing approximately 60% of production followed by hydro (24%), natural gas/oil (10%), wind (6%), bioenergy (0.3%), solar (0.2%) and other minor contributors, as reported for actual energy production in 2015 (IESO, 2016a). In 2032, while nuclear continues to provide Ontario's base load (44%), a reduced capacity in energy production from nuclear will shift energy demands to a greater dependence on natural gas and renewable resources (Figure 1-1).

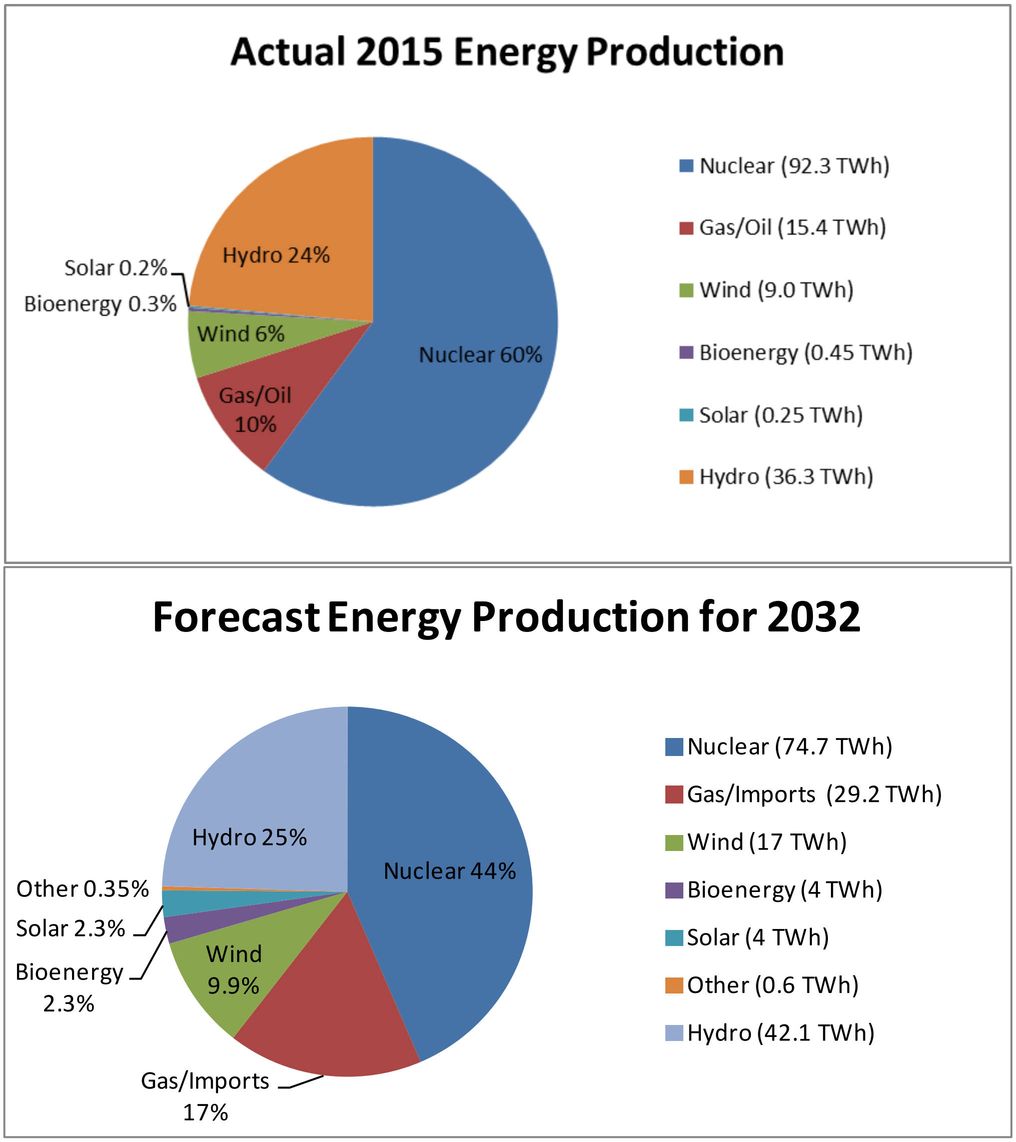



**Figure 1-1 Actual Energy Production in 2015 (IESO, 2016a) Compared to Forecast Energy Production in 2032 (OPA, 2014)**

While energy conservation is anticipated to significantly contribute to Ontario's energy efficiency, representing approximately 16% of the forecast energy demand for 2032 (MOE, 2013), achieving continued reductions in GHG emissions while meeting an overall increase in energy requirements will be dependent on the ability of clean resources to meet the majority of the energy demand.

GHG emissions are an important factor to consider when evaluating advantages and disadvantages of various energy producing options as it represents the contribution of these processes to global warming and climate change. Facilities in Canada report GHG emissions as carbon dioxide equivalents ($CO_2e$), which is calculated by applying a global warming potential (GWP) (UNEP, 2010) to emissions for $CO_2$ (GWP =1), methane ($CH_4$) (GWP= 21) and nitrous oxide ($N_2O$) (GWP=310). For the current study, the unit of measurement for GHG emissions is the emission rate per unit of electricity generated (*i.e.*, gram of $CO_2$ equivalents per kilowatt hour (g $CO_2$e/kWh)).

The estimation of GHG emissions for various methods of energy production often involves the use of life cycle assessments (LCAs) that consider energy requirements and emissions associated with all aspects of an energy generating facility or system, including construction, operation (energy production) and decommissioning (Figure 1-2). For conventional facilities utilizing fossil fuels such as coal or natural gas, the majority of GHG emissions occur during the production of energy as fuel resources are consumed. For other methods of energy production, the mining and processing of resources, the production of equipment, or the construction of facilities may represent the most emission-intensive stages. Although nuclear and renewable resources such as wind, solar and hydro are often regarded as emission-free energy sources because GHGs are not directly emitted during the electricity generating stages, standard operating and maintenance activities require energy inputs, many of which may involve the use of fossil fuels (Lenzen, 2008).

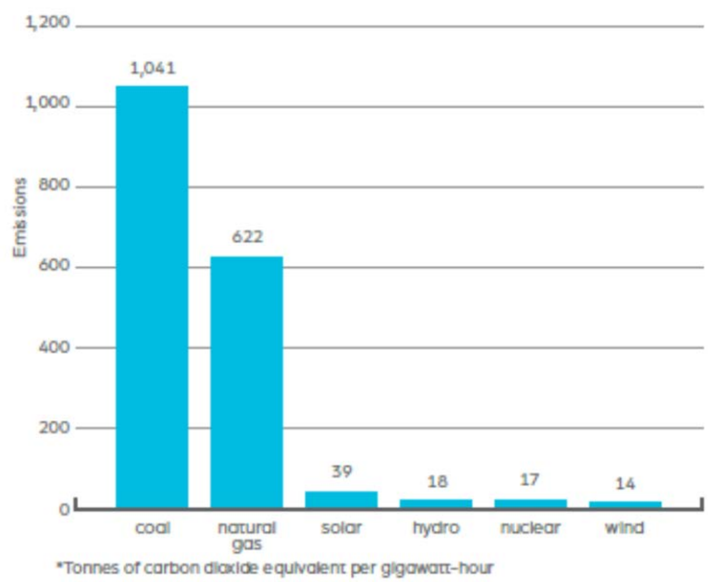



**Figure 1-2 Comparison of Lifecycle Emissions for Various Methods of Energy Production (Asthma Society of Canada and Bruce Power, 2014).**

Numerous studies have been conducted to characterize GHG emissions associated with various forms of energy production. These have included LCAs as well as critical reviews and meta-analyses of pooled data extracted from individual studies. While many have derived information from international resources, others have focused specifically on the generation of electricity within Canada, as well as within Ontario alone. To derive GHG emission rates associated with the operational stage of energy production in Ontario, the current study utilized information from several of these studies including Mallia and Lewis (2013), Hatch (2014), CERI (2008), Andseta *et al*. (1998), Lenzen (2008), Sovacool (2008), Warner and Heath (2012), Fthenakis and Kim (2007), and Nugent and Sovacool (2014). Information provided within these resources was either used directly to represent emission estimates, or indirectly to provide context surrounding the use of facility-specific GHG emission rates reported to Federal or Provincial databases for energy-generating facilities in Ontario.

## 1.2 Study Scope and Objectives

The objective of the study was to provide an impartial, scientifically defensible evaluation of the GHG emissions associated with various types of energy production projected to be utilized in Ontario over the next 40 years. This period represents the projected operating life span of the refurbished Darlington Nuclear Generating Station. The study focused exclusively on the estimated GHG emissions released to the Ontario environment as a result of the operations and maintenance of facilities producing electricity to meet the province's energy requirements rather than an LCA that addresses all potential upstream and downstream activities. This approach is consistent with the emissions forecast provided by the MOECC and the Independent Electricity System Operator (IESO) as part of the LTEP.

A literature and database search was conducted to characterize GHG emissions associated with regular operating activities for various methods of power generation utilized in Ontario, specifically nuclear, wind, solar PV, hydro, and natural gas. This information was used to estimate total GHG emissions associated with Ontario's energy requirements under three distinct scenarios:

1. Current energy production, with nuclear representing approximately 60% of Ontario's energy requirements, until 2024 during a period of staggered refurbishments to the Darlington and Bruce Generating Stations.
2. Projected future scenario after 2024 with a reduction in nuclear capacity following the scheduled closure of the Pickering Nuclear Generating Station and the completed refurbishment of the Darlington Nuclear Generating Station. Under this scenario it was assumed that the necessary capacity lost with the closure of the Pickering Station would be replaced by a combination of renewable sources (*i.e.*, hydro, wind and solar) and natural gas.
3. Alternate projected future scenario after 2024 in the absence of the Darlington refurbishment resulting in a reduction in nuclear capacity associated with the closure of both the Pickering and Darlington Stations. Under this scenario it was assumed that the necessary capacity lost with the closure of the Pickering and Darlington Stations would be replaced by a combination of renewable sources (*i.e.*, hydro, wind and solar) and natural gas.

Although GHG emissions from each resource (*i.e.*, nuclear, wind, solar PV, hydro and natural gas) were considered independently, the overall evaluation considered the total GHG emissions produced by all resources in order to meet Ontario's energy requirements under each of the three scenarios listed above. The technical feasibility of the assumed increased capacity for energy production for each resource was not evaluated as part of the current study.

## 2.0 METHODOLOGY

To provide an accurate assessment of GHG emissions for electricity generating facilities in Ontario, priority was given to annual emissions data reported under the Greenhouse Gas Emissions Regulation (Regulation 452/09) available at: https://www.ontario.ca/data/greenhouse-gas-emissions-reporting-facility. Introduced in 2009, Regulation 452/09 requires all large GHG emitters to report their annual emissions. For electricity generation, the threshold requirement for reporting is 25,000 tonnes $CO_2$e/year. For those facilities or energy generating methods with emissions that are below the reporting threshold, alternate resources were utilized to estimate GHG emissions. This included GHG emissions data provided by OPG for the Darlington and Pickering nuclear stations. GHG emissions data retrieved from the Regulation 452/09 database or provided by OPG was paired with the corresponding sector-specific electricity generation data proved by IESO (http://www.ieso.ca/Pages/Power-Data/Supply.aspx) to establish the emission rate on a g $CO_2$e/kWh basis.

In addition to the utilization of Ontario-specific GHG emissions data, a review was conducted of the most recent white and grey literature (literature that is not commercially published) as it relates to the GHG emissions during regular operating activities for each source of power generation (*i.e.*, nuclear, wind, solar PV, hydro and natural gas) considered in this study. Although facility-specific emission rates were considered for some resources, a single emission rate for each resource was derived for use in the GHG emission scenarios.

The objective of the literature search and review was to identify the most accurate and relevant resources to characterize GHG emissions in Ontario and to describe any uncertainties associated with this information. The literature review was used to fill data gaps in the Ontario GHG emissions database, as well as to ground-truth the database and provide a description of the operations and maintenance activities that may have resulted in the reported emissions. Resources considered in the current study are those that clearly described the methodology for calculating GHG emissions, were publicly available, and are reflective of current technologies and practices.

Following the estimation of emission rates for each energy resource, rates were applied to the IESO/Ontario Power Authority (OPA) energy generation forecasts (Table 2-1) to describe the GHG emissions for the years 2015 to 2024 for Scenario 1, as described above.

**Table 2-1 Ontario's Energy Production Forecast (IESO/OPA)**

| *Year* | *Energy Production (TWh)* | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***Nuclear*** | ***Hydro*** | ***Natural Gas/Imports*** | ***Wind*** | ***Solar PV*** | ***Bioenergy*** | ***Total*** |
| 2016 | 84.6 | 39.9 | 13.6 | 12 | 3 | 2 | 154.8 |
| 2017 | 79.7 | 40.4 | 14.5 | 13 | 4 | 2 | 153.5 |
| 2018 | 79.7 | 40.6 | 16.4 | 13 | 4 | 3 | 156.4 |
| 2019 | 75.7 | 40.8 | 18.5 | 14 | 4 | 3 | 156.2 |
| 2020 | 74.2 | 40.8 | 18.7 | 15 | 5 | 3 | 156.9 |
| 2021 | 55.3 | 40.9 | 31.2 | 17 | 5 | 4 | 153.4 |
| 2022 | 56.1 | 41.8 | 31.2 | 17 | 5 | 4 | 155.6 |
| 2023 | 56 | 42.1 | 31.7 | 17 | 5 | 4 | 156 |
| 2024 | 58.9 | 42.2 | 30.1 | 17 | 5 | 4 | 157.5 |

| **Table 2-1** | **Ontario's Energy Production Forecast (IESO/OPA)** | | | | | | |
|---|---|---|---|---|---|---|---|
| ***Year*** | ***Energy Production (TWh)*** | | | | | | |
| | ***Nuclear*** | ***Hydro*** | ***Natural Gas/Imports*** | ***Wind*** | ***Solar PV*** | ***Bioenergy*** | ***Total*** |
| 2025 | 60.9 | 42.2 | 29.7 | 17 | 5 | 4 | 158.8 |
| 2026 | 65.3 | 42.2 | 27.2 | 17 | 5 | 4 | 160.6 |
| 2027 | 62.3 | 42.3 | 30.2 | 17 | 5 | 4 | 160.7 |
| 2028 | 65.9 | 42.4 | 28.5 | 17 | 5 | 4 | 163 |
| 2029 | 64.4 | 42.3 | 30.9 | 17 | 5 | 4 | 163.6 |
| 2030 | 69.2 | 42.3 | 29.9 | 17 | 5 | 4 | 167.4 |
| 2031 | 71.3 | 42.2 | 29.8 | 17 | 4 | 4 | 169.3 |
| 2032 | 74.7 | 42.1 | 29.2 | 17 | 4 | 4 | 171.6 |

Resource-specific emission rates were applied to the energy forecasts for 2025 to 2055 following an adjustment to account for an assumed reduction in nuclear capacity following the closure of the Pickering Station, as described for Scenario 2, and a further reduction in nuclear capacity following the closure of both the Pickering and Darlington Stations, as described for Scenario 3. Given that the LTEP only provides an energy production forecast to 2032, a linear regression was established to predict energy production to 2055 (*i.e.*, the end of the 40-year period) (Figure 2-1). The linear regression is an extrapolation of anticipated future requirements based on the IESO forecast from 2016 to 2032.

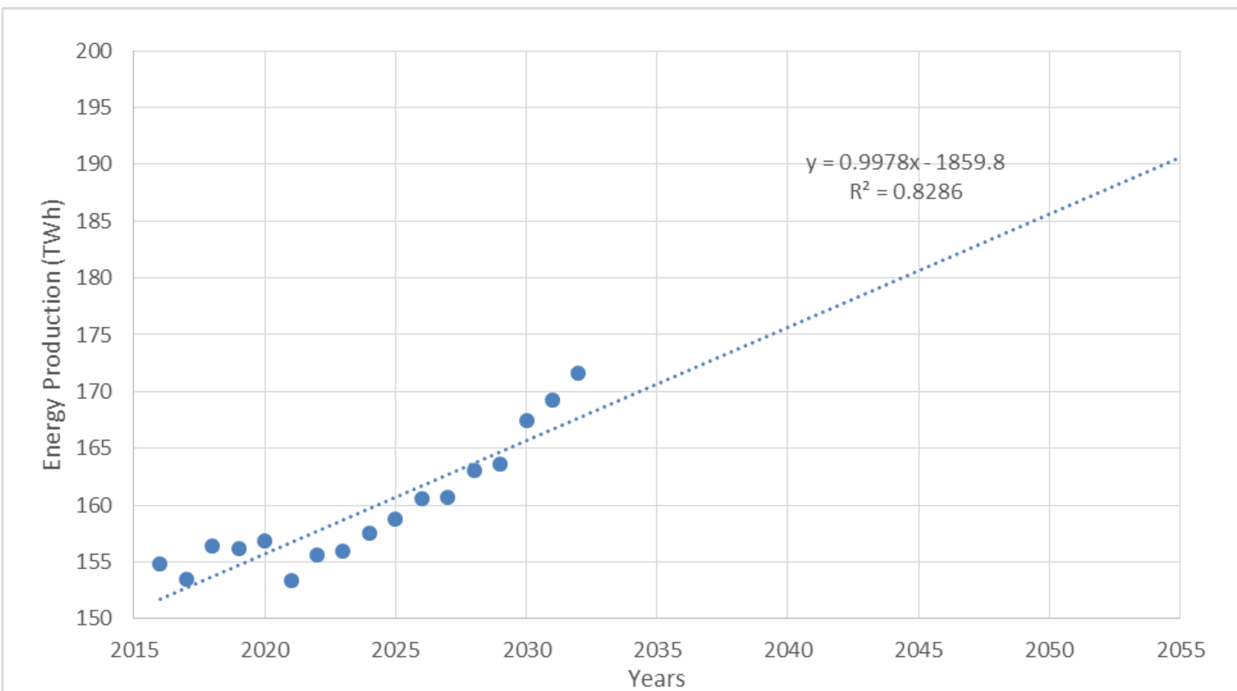



**Figure 2-1 Projected Power Generation in Ontario (2016 to 2055).**

## 2.1 Systematic Search of the Literature

A systematic and comprehensive search of the published literature was conducted to identify, as best possible, all white (peer-reviewed published literature) and grey literature (literature available elsewhere) related to GHG emissions associated with power generation operations in the Ontario context. The literature search was performed in a step-wise manner using three search strategies:

- On-line electronic databases
- Citation sourcing
- Professional experience

A description of the search strategy is provided in Appendix A.

## 3.0 SCENARIO-SPECIFIC OUTPUT AND EMISSIONS

### 3.1 Nuclear

In Ontario, nuclear power is produced using Canada Deuterium Uranium (CANDU) Reactors which use unenriched uranium as fuel and deuterium oxide (or heavy water) as a coolant and moderator. There are currently 18 CANDU reactors operating in 3 facilities in Ontario including: 8 at the Bruce Power Generating Station, 6 in the OPG Pickering Generating Station, and 4 in the OPG Darlington Generating Station. The combined installed capacity for these reactors for 2016 is 11,295 MW, with a projected decrease in capacity to 9,852 MW by 2032. The reduced capacity is associated with the scheduled closure of the Pickering Station in 2024; however, staggered refurbishments to both the Darlington and Bruce Stations will maintain capacity from each of these facilities.

#### *3.1.1 Estimated GHG Emission Rates*

While the generation of electricity from nuclear resources does not directly emit GHGs, emissions occur during various stages of the overall lifecycle. An LCA for Ontario nuclear power plants found that GHG emissions from the Ontario facilities were on the low end of the range reported in the literature for nuclear energy production facilities, likely because the energy-intensive uranium enrichment process is not required for CANDU reactors (Mallia and Lewis, 2013).

The nuclear power lifecycle generally consists of five (5) stages: 1) the front-end consisting of the mining, milling, conversion and enrichment of uranium; 2) the construction of the facility including generators, turbines, and cooling towers; 3) the operation phase in which electricity is produced and energy is required for facility maintenance and fuels for backup generators; 4) the back-end consisting of fuel processing, interim storage and final disposal and management of nuclear waste; and 5) the decommissioning and dismantling of the facility and the reclamation of the mine sites (Sovacool, 2008). The current study focused exclusively on the GHG emissions associated with the operations phase. This restricted the number of applicable studies from which to derive GHG emissions since many LCAs simplified the phases into three aggregate categories (upstream, operation, and downstream), combining uranium mining, milling conversion, enrichment, fuel rod fabrication, transportation, mine rehabilitation with standard operations for the operations phase. Operational processes often were not subdivided into facility operations and processes related to uranium mining and processing since GHG emissions related to facility operations were typically negligible or aggregated with other processes (Warner and Heath, 2012).

As reported by OPG, GHG emissions associated with energy production at the Pickering and Darlington Stations are associated with the burning of diesel fuel for standby generator (SG) and emergency power generator (EPG) testing. Emissions are calculated based on annual fuel deliveries which vary annually. GHG emissions from 2015 were notably higher for the Pickering Station due to extended testing of the SGs and EPGs (Table 3-1). Based on data from 2011 to 2015, the five-year average GHG emissions for the Pickering and Darlington Stations were 7,501 and 3,050 tonnes $CO_2e$, respectively. Emissions generated by the Pickering and

Darlington Stations did not exceed the Reg. 452/09 reporting threshold; therefore, emissions data was only available from OPG directly.

GHG emissions from the Bruce Station historically exceeded the Reg. 452/09 reporting threshold, and as a result, annual emissions are available on the Ontario database. GHG emissions from the Bruce Station have steadily declined since it first started reporting emissions in 2010 under Reg. 452/09 due to the Bruce Steam Plant shut-down strategy, resulting in the reduction in emissions from 68,464 tonnes $CO_2$e in 2010 to 3,681 tonnes $CO_2$e in 2014. GHG emissions from 2014 (3,681 tonnes $CO_2$e) fall within the 5-year averages for Pickering and Darlington (7,501 and 3,050 tonnes $CO_2$e).

Annual energy production for the Pickering and Darlington Stations were provided by OPG and were used to calculate 5-year average emission rates. Given that energy production from the Bruce Station was not reported, it was calculated as the difference of the total energy produced by nuclear facilities as reported by IESO (http://www.ieso.ca/Pages/Power-Data/Supply.aspx) and the energy produced by the Pickering and Darlington Stations as reported by OPG. Due to the significant reductions in emissions reported for the Bruce Station following plant improvements, emission rates were based on data for 2014 as they are considered to be representative of current and future conditions. For 2014, IESO reported that nuclear facilities provided 94,900 GWh to the Ontario grid. Using the production data for the Pickering (20,045 GWh) and Darlington (27,960 GWh) Stations, the estimated production for the Bruce Station was 46,895 GWh.

**Table 3-1 Energy Generation and GHG Emission Rates associated with Operation and Maintenance of Nuclear Facilities in Ontario**

| *Facility* | *GHG Emissions (tonnes $CO_2$e)* | *Electricity Generation (GWh)* | *Emissions per Energy Production (g $CO_2$e/kWh)* |
|---|---|---|---|
| **Pickering**[a] | | | |
| 2011 | 5,657 | 19,675 | 0.29 |
| 2012 | 9,300 | 20,735 | 0.45 |
| 2013 | 4,279 | 19,642 | 0.22 |
| 2014 | 4,351 | 20,045 | 0.22 |
| 2015 | 13,919 | 21,231 | 0.66 |
| Average | 7,501 | 20,266 | **0.37** |
| **Darlington**[a] | | | |
| 2011 | 4,007 | 28,951 | 0.14 |
| 2012 | 1,525 | 28,318 | 0.054 |
| 2013 | 1,224 | 25,051 | 0.049 |
| 2014 | 4,806 | 27,960 | 0.17 |
| 2015 | 3,688 | 23,293 | 0.16 |
| Average | 3,050 | 26,715 | **0.11** |
| **Bruce**[b] | | | |
| 2010 | 68,464 | - | - |
| 2011 | 46,489 | - | - |
| 2012 | 32,311 | - | - |
| 2013 | 16,215 | - | - |
| 2014 | 3,681 | 46,895[c] | **0.078** |

- Emissions per unit of energy were not considered for these years since they are not considered to be representative of current or future conditions.

[a] Emission and energy generation data for the Pickering and Darlington Stations was provided by OPG.

[b] Emission data for the Bruce Station was taken from the Regulation 452/09 database https://www.ontario.ca/data/greenhouse-gas-emissions-reporting-facility

**Table 3-1 Energy Generation and GHG Emission Rates associated with Operation and Maintenance of Nuclear Facilities in Ontario**

| Facility | GHG Emissions (tonnes $CO_2e$) | Electricity Generation (GWh) | Emissions per Energy Production (g $CO_2e$/kWh) |
|---|---|---|---|

[c] Represents the difference in total energy production from all nuclear facilities for 2014 (94,900 GWh) as reported by IESO and the energy production reported by OPG for the Pickering and Darlington Stations.

A single emission rate for nuclear energy production was derived by weighting emission rates for the individual Stations by their contribution to total nuclear energy production in 2014 (49.4% Bruce; 29.5% Darlington; and 21.1% Pickering) (*i.e.*, (0.494 x 0.078 g $CO_2e$/kWh)+(0.295 x 0.11 g $CO_2e$/kWh)+(0.211 x 0.37 g $CO_2e$/kWh) = 0.15 g $CO_2e$/kWh). This estimate is consistent with the calculated operational emission rate of 0.2 g $CO_2e$/kWh reported in an LCA by Mallia and Lewis (2013) for the same nuclear facilities based on data from 2008, as well as a rate of 0.11 g $CO_2e$/kWh reported by CERI (2008) based on data from 2005 to 2006 for Ontario facilities.

Although most LCAs have either grouped operation and maintenance with additional life cycle processes, or have not detailed the factors considered in the estimation of emissions associated with standard operation, others have utilized a similar approach as presented above by utilizing fuel usage. Emissions associated with plant operations were estimated based on fuel used for start-up of auxiliary steam generators and in-plant heating from studies conducted in 1970s, 80s and 90s. Fuel usages ranged from 0.1 to 3 million gal/year producing a range in GHG emission rates of 0.1 to 6 g $CO_2e$/kWh (Fthenakis and Kim, 2007). Emission estimates based on fuel usage for the Pickering and Darlington Stations fall within the low end of this range.

Therefore, the estimated GHG emission rate of 0.15 g $CO_2e$/kWh for the operational component of nuclear facilities in Ontario was selected for use in the current study.

### *3.1.2 Assumptions, Limitations and Uncertainties*

Although the mining,milling and refining of uranium is included within the operation stage of some LCAs, the current study did not include GHGs associated with the extraction and processing of fuels or materials for any of the power generating methods to allow for a consistent comparison across each resource.

Some LCAs have reported that the energy-intensive production of heavy water as a coolant and moderator would result in significant emissions for CANDU reactors. The current study does not include emissions associated with the production of heavy water, but rather assumes that production is carbon neutral as it was generated utilizing nuclear-generated steam rather than relying on fossil fuels as a heat source and upgrading occurs at each station.

A critical survey of LCAs for various types of nuclear generators worldwide reported that 17% of the total lifecycle GHG emissions were attributed to operations. This represents an emission rate of 11.58 g $CO_2e$/kWh and is associated with the energy required for maintenance, cooling and fuel cycles, backup generators, and during outages and shutdowns. Of the nineteen (19) studies included in the Sovacool (2008) survey, one (Andseta *et al*., 1998) was specific to CANDU reactors in Canada. Although Sovacool (2008) reported an emission rate of 11.9 g

$CO_2$e/kWh associated with operations from Andseta *et al*. (1998), this was based on the historical production of heavy water utilizing fossil fuel energy sources for this process rather than the most recent production and upgrading of heavy water utilizing steam which has negligible emissions. This is consistent with Mallia and Lewis (2013) which found that operational emissions (0.2 g $CO_2$e/kWh) for nuclear plants in Ontario only represented approximately 4% of the total LCA emissions.

## 3.2 Wind

Wind power development in Ontario has increased significantly over the past decade. Under Ontario's LTEP, this trend is expected to continue, with the contribution of wind power to the province's energy production anticipated to increase from 3% in 2013 to 9% in 2032 (MOE, 2013). Currently, there are 16 commercial wind farms and individual wind operators that provide approximately 2,853 MW in nameplate capacity (*i.e*., the maximum output rating). By the end of 2018, a number of wind power projects currently under development are scheduled to be in service, which will provide an additional 2,862 MW in nameplate capacity (IESO, 2016b). It is important to recognize that nameplate capacity is not representative of actual power generation. According to the Ontario Wind Integration Study (GE Energy, 2006), the capacity factor of wind power, which is the average power output during all hours over a year divided by the nameplate capacity, is approximately 20% in Ontario.

### *3.2.1 Estimated GHG Emission Rates*

While the generation of electricity from wind turbines does not directly emit GHGs, emissions occur during various stages of the overall lifecycle. The wind power life cycle generally consists of four (4) stages: 1) fabrication of the wind turbine consisting of mining, processing materials, and manufacturing; 2) construction of the wind turbine consisting of transporting turbine components, constructing foundation and substations, and assembling support structure and wind turbine; 3) operation and maintenance of the wind turbine; and 4) decommissioning activities consisting of deconstruction of the wind turbine, disposal, recycling of turbine components, and land reclamation, as required (Nugent and Sovacool, 2014). An LCA for Ontario wind farms found that GHG emissions were on the low end of the range reported in the literature, partly due to the exclusive use of onshore turbines rather than the energy- and material-intensive construction of offshore wind farms (Mallia and Lewis, 2013). The current assessment focused exclusively on the GHG emissions associated with the operation and maintenance phase of onshore wind turbines.

The operation and maintenance phase of on-shore wind turbines generally has the lowest GHG contribution to the overall lifecycle (Noori *et al.*, 2015; Nugent and Sovacool, 2014 Raadal *et al.,* 2011; Thomson and Harrison, 2015). While there are no direct GHG emissions associated with wind power generation, there are periodic maintenance activities that are required to ensure continued operation which may indirectly contribute GHG emissions (Nugent and Sovacool, 2014; Crawford, 2009; Hatch, 2014), including:

- regular maintenance and cleaning;
- component replacement over the service life of the wind turbine; and,

- change of oils and lubricants.

A literature search was completed to identify the GHG emissions associated with operation and maintenance of wind facilities within North America. Wind turbines of all nameplate capacities are located both on- and off-shore around the world. Since Ontario only has onshore 1.5 – 2.3 MW wind turbines in commercial operation, studies discussing wind turbines with similar specifications were targeted; however, due to the limited multiple resources reporting GHG emission estimates for the operation and maintenance phase, additional studies were considered. As part of an LCA literature review for power generation in Canada, Hatch (2014) derived an operational emission rate of 0.49 g $CO_2$e/kWh. This value was based on activities associated with the periodic maintenance of onshore wind farms in Canada including wind turbines with a capacity of greater than 100 kW. A similar value of 0.74 g $CO_2$e/kWh was reported by Mallia and Lewis (2013) based on the LCA conducted for Ontario energy production. The relevant GHG emission rates identified for wind is presented in Table 3-2.

Nugent and Sovacool (2014) conducted a meta-survey of lifecycle studies on GHG emissions associated with wind power. Twelve (12) studies were identified that presented GHG emissions for the operational phase of wind power. These studies provided a range from 0.02 to 83.6 g $CO_2$e/kWh, with mean and standard deviation values of 14.36 ± 26.3 g $CO_2$e/kWh. Many of the identified studies were not considered to be relevant to the Ontario context either due to: (1) the very low or very high nameplate capacity of the wind turbines; or, (2) study based on off-shore wind turbines. Three (3) of the studies identified were considered relevant and were also included in Table 3-2.

**Table 3-2 GHG Emissions Rates associated with Operation and Maintenance of Wind Facilities in Ontario**

| *Reference* | *GHG Emissions per Energy Production (g $CO_2$e/kWh)* | *Percentage of Total LCA Emissions* |
|---|---|---|
| Chen et al. (2011)[a] | 0.02 | 3.5% |
| Hatch (2014) | 0.49 | 4% |
| Mallia and Lewis (2013) | 0.74 | 7% |
| Martinez et al. (2009)[a] | 0.35 | 5.3% |
| Oebels and Pacca (2013)[a] | 0.04 | 0.6% |
| Thomson and Harrison (2015) | 0.90 | 6% |

[a] As cited in Nugent and Savacool (2014)

Based on the information presented in Table 3-2, the operation and maintenance phase is estimated to contribute a small percentage of the overall LCA emissions, ranging from 0.6 to 7%. The GHG emissions per energy production value of 0.74 g $CO_2$e/kWh calculated by Mallia and Lewis (2013) was selected for use in the current assessment. This value was derived based on a LCA conducted for Ontario energy production and is most representative of GHG emissions in Ontario. This value is generally consistent with values provided in other studies.

### *3.2.2 Assumptions, Limitations and Uncertainties*

While the operation and maintenance phase of the wind power life cycle generally has the lowest GHG emissions, there is some variability in GHG emission estimates, ranging from 6% (Thomson and Harrison, 2015) to 24% (Nugent and Sovacool, 2014). Some sources of variability in estimating GHG emissions per energy production associated with operation and maintenance of wind facilities include wind speed and maintenance assumptions. The average wind speed plays an important role in determining the GHG emissions per energy production. As a result, the same wind turbine placed in two different locations may produce differing amounts of electricity (Davidsson et al., 2012; Crawford, 2009).

The assumptions regarding the maintenance requirements over the course of a wind turbine's lifetime can significantly alter the GHG emissions per energy production. Currently, there does not appear to be a consistent set of assumptions used in LCAs of wind power facilities. As noted by Arvesen and Hertwich (2012), some LCAs do not consider the replacement of parts in their assessment, while others assume a certain proportion of components will need to be replaced.

### 3.3 Natural Gas

Natural gas power generation provides flexibility to address fluctuations in electricity supply and demand. It is often regarded as a practical source of energy to support the intermittency of energy generated by renewable resources such as wind and solar. Under the LTEP, the contribution of natural gas to the province's energy production was 10% in 2013 and is projected to remain at 10% in 2032 (MOE, 2013). Currently, there are 39 natural gas-fueled generating stations in Ontario that provide approximately 8,900 MW of total capacity (Table 3-3). Four (4) projects are currently under development and are anticipated to provide an additional 1,200 MW of capacity to the Ontario power grid (IESO, 2016c).

Unlike resources such as nuclear, wind, solar and hydro where the majority of GHG emissions are related to the upstream and downstream stages of the life cycle, the combustion of natural gas during the operational stage of energy production represents the greatest source of GHGs. The majority of the natural gas facilities in Ontario utilize combined cycle gas turbines, which incorporates steam generation technologies with the natural gas combustion turbines to improve overall efficiency. The York Energy Centre is the only facility in Ontario that utilizes simple cycle gas turbines, which generates power by creating superheated gas to drive the gas turbines. Twenty-three (23) of Ontario's natural gas stations are cogeneration/combined heat and power (CHP) plants that provide both electricity to the power grid and steam/heat for industrial use.

**Table 3-3 Natural Gas Generating Stations in Ontario[a]**

| *Facility* | *Location* | *Type* | *Nameplate Capacity (MW)* | *GHG Emissions (tonnes $CO_2e$)[b]* |
|---|---|---|---|---|
| **Current Facilities** | | | | |
| Algoma Energy Co-Gen | Sault Ste. Marie | CHP | 63 | 1,331,298 |
| Atlantic Power Kapuskasing | Kapuskasing | Combined Cycle | 40 | 128,971 |
| Atlantic Power Nipigon Project | Nipigon | Combined Cycle | 40 | 102,099 |
| Atlantic Power North Bay | North Bay | Combined Cycle | 40 | 130,117 |
| Atlantic Power Tunis Project | Iroquois Falls | Combined Cycle | 43 | 121,032 |
| Birchmount Energy Centre | Markham | CHP | 2.6 | - |
| Brighton Beach Power Station | Windsor | Combined Cycle | 541.3 | 128,442 |
| Bur Oak Energy Centre | Markham | CHP | 3.25 | - |
| Cardinal Power Gas Cogeneration | Cardinal | Combined Cycle, Cogeneration | 156 | 462,634 |

| Table 3-3 Natural Gas Generating Stations in Ontario[a] | | | | |
|---|---|---|---|---|
| ***Facility*** | ***Location*** | ***Type*** | ***Nameplate Capacity (MW)*** | ***GHG Emissions (tonnes $CO_2e$)[b]*** |
| Durham College District Energy | Oshawa | CHP | 2.3 | - |
| East Windsor Cogeneration Centre | Windsor | CHP | 84 | 85,932 |
| Goreway Power Station | Brampton | Combined Cycle | 839.1 | 862,040 |
| Great Northern Tri-Gen Facility | Kingsville | CHP | 11.3 | - |
| Greenfield Energy Centre | Sarnia | Combined Cycle | 1005 | 988,648 |
| GTAA Cogeneration Plant | Mississauga | Combined Cycle, Cogeneration | 90 | 312,491 |
| Halton Hills Generating Station | Halton Hills | Combined Cycle | 641.5 | 592,862 |
| Lake Superior Cogeneration Plant | Lake Superior | Cogeneration | 110 | 205,735 |
| Lennox Generating Station | Napanee | Natural Gas/Oil | 2000 | 125,226 |
| London Cogeneration Facility | London | CHP | 12 | 39,788 |
| Maitland Site Generation Station | Maitland | Cogeneration | 50 | 163,463 |
| Northland Cochrane Generating Station | Cochrane | Cogeneration | 42 | 247,055 |
| Northland Iroquois Falls | Iroquois Falls | Combined Cycle | 120 | 330,573 |
| Northland Kingston Generating Station | Kingston | Combined Cycle | 110 | 328,112 |
| Northland Kirkland Lake | Kirkland Lake | Combined cycle | 85 | 496,902 |
| Northland Thorold Cogeneration Project | Thorold | CHP | 287 | 311,117 |
| Portlands Energy Centre | Toronto | Combined Cycle | 550 | 415,212 |
| St. Clair Energy Centre | Sarnia | Combined Cycle | 577 | 360,494 |
| Sudbury District Energy Cogeneration Plant | Sudbury | Cogeneration | 5 | - |
| Sudbury District Energy Hospital Cogeneration Plant | Sudbury | Cogeneration | 6.7 | - |
| Transalta Douglas (Mississauga) Facility | Mississauga | Cogeneration | 108 | 1,041,160 |
| Transalta Ottawa Health Science Center CGS | Ottawa | Combined Cycle, Cogeneration | 73.7 | 146,310 |
| Transalta Sarnia Regional Cogeneration Plant | Sarnia | Cogeneration | 506 | 173,390 |
| Transalta Windsor Facility | Windsor | Cogeneration | 72 | - |
| Trent Valley Cogeneration Plant | Trenton | Cogeneration | 6.7 | - |
| Villa Colombo Vaughan | Kleinburg | CHP | 0.2 | - |
| Warden Energy Centre | Markham | CHP | 5.0 | 375,004 |
| West Windsor Generating Facility | Windsor | Combined Cycle | 136 | 179,775 |
| Whitby Cogeneration Project | Whitby | Cogeneration | 50 | 51,175 |
| York Energy Centre | Township of King | Simple Cycle | 393 | 1,331,298 |
| **Facilities Under Development** | | | | |
| Green Electron Power Project | St. Clair Township | Combined Cycle | 289 | - |
| Hanlon Creek District Energy Project | Guelph | CHP | 10.2 | - |
| Napanee Generating Station | Napanee | Combined Cycle | 900 | - |
| Rosa Flora Growers | Niagara | CHP | 4.0 | - |

CHP – combined heat and power

[a] Source: IESO (2016c).

[b] Average GHG emissions between 2010 and 2014 with 87% electricity allocation factor, as appropriate.

\- GHG emission data was not provided by IESO (2016c).

### 3.3.1 *Estimated GHG Emission Rates*

The natural gas power lifecycle generally consists of four (4) stages: 1) the front-end consisting of the extraction and production of natural gas, including both conventional and unconventional sources (*e.g.*, shale gas); 2) the construction of the facility including turbines and generators; 3) the operation phase in which electricity is produced through the combustion of natural gas; and 4) the decommissioning, dismantling and disposal of all facility components.

Despite the existence of numerous literature-based GHG emission estimates for natural gas facilities, it is anticipated that the most accurate method for estimating emission rates specific to the Ontario scenario is through the utilization of facility-specific emission rates reported under Reg. 452/09 combined with the total annual power generation reported by IESO (2016a) for natural gas facilities (Table 3-4). GHG emissions data was not reported for the 9 natural gas facilities with GHG emissions less that the Reg. 452/09 reporting limit; however, due to the low nameplate capacity of these facilities (*i.e.,* less than 11.3 MW capacity), exclusion of this data was not considered to significantly influence the estimated GHG emission rate for the natural gas resource.

For cogeneration and CHP facilities, the GHG emissions are associated with the generation of both electricity and thermal energy (*i.e.,* steam). Mallia and Lewis (2013) derived an electricity allocation ratio of 87% based on energy output capacity data for two cogeneration facilities in Ontario which would result in a 13% reduction in the overall GHG emission rate per unit energy production. In an effort to only consider GHG emissions associated with electricity generation, an allocation factor of 87%, as derived by Mallia and Lewis (2013), was applied to the total GHG emissions for cogeneration and CHP facilities in Ontario.

**Table 3-4 Energy Generation and GHG Emission Rates associated with Operation and Maintenance of Natural Gas Facilities in Ontario**

| ***Year*** | ***GHG (tonnes $CO_2e$)[a]*** | ***Generation (GWh)[b]*** | ***Emissions per Energy Production (g $CO_2e$/kWh)*** |
|---|---|---|---|
| 2010 | 10,440,055 | 20,500 | 509 |
| 2011 | 11,135,590 | 22,000 | 506 |
| 2012 | 11,564,718 | 22,200 | 521 |
| 2013 | 9,798,724 | 18,200 | 538 |
| 2014 | 8,143,841 | 14,800 | 550 |
| Average | 10,216,585 | 19,500 | **525** |

[a] Emission data was taken from the Regulation 452/09 database https://www.ontario.ca/data/greenhouse-gas-emissions-reporting-facility and represents the total reported GHG emissions for all natural gas facilities in Ontario.

[b] Total energy production for natural gas facilities were taken from IESO (2016a).

Based on data from 2010 to 2014, the average annual GHG emissions per energy production for natural gas was 525 g $CO_2e$/kWh. This estimate is generally consistent with the average emission rate of 435 g $CO_2e$/kWh reported in an LCA by Mallia and Lewis (2013) for natural gas facilities in Ontario based on data from 2008, and averages of 390 g $CO_2e$/kWh and 445 g $CO_2e$/kWh reported by Hatch (2014) and CERI (2008), respectively, for facilities across Canada.

Therefore, the estimated GHG emission rate of 525 g $CO_2e$/kWh for the operational component of natural gas facilities in Ontario was selected for use in the current study.

#### 3.3.2 *Assumptions, Limitations and Uncertainties*

Given that a number of the natural gas facilities in Ontario are cogeneration or CHP, GHG emission rates per unit energy production would most accurately be estimated by allocating a portion of the GHG emissions reported for these facilities to the beneficial co-production of thermal energy utilized for other applications. As noted above, Mallia and Lewis (2013) derived an electricity allocation ratio of 87% based on energy output capacity data for two cogeneration facilities in Ontario which would result in a 13% reduction in the overall GHG emission rate per unit energy production. For the current study, insufficient facility-specific information was available to derive a similar allocation ratio. As such, there is the potential for some uncertainty in the derivation of the overall GHG emission rate; however, based on a comparison of the selected GHG emission rate to values presented by Mallia and Lewis (2013), Hatch (2014), and CERI (2008), the selected GHG emission rate is generally consistent with other investigations.

To be consistent with the estimation of GHG emission rates for nuclear and other power generation methods, GHGs associated with the mining, extraction and transportation of fuels and materials was not included in the current study.

### 3.4 Solar Photovoltaic

Solar PV currently plays a minor role in Ontario's power generation. Under the LTEP, the contribution of solar PV to the province's energy production is expected to double from 1% in 2013 to 2% in 2032 (MOE, 2013). Currently, solar PV facilities in Ontario provide 1,235 MW in nameplate capacity. By the end of 2017, a number of solar PV projects under development are scheduled to be in service, which will provide an additional 939 MW in nameplate capacity (IESO, 2016d).

#### 3.4.1 *Estimated GHG Emission Rates*

While the generation of electricity from solar PV does not directly emit GHGs, emissions occur during various stages of the overall lifecycle. The solar PV power cycle generally consists of four (4) stages: 1) fabrication of the solar PV modules consisting of mining, smelting, refining, and purification; 2) fabrication of the balance of systems including inverters, transformers, wiring, and structural support; 3) operation and maintenance of the solar PV; and 4) decommissioning activities (Fthenakis and Kim, 2007). The current study focused exclusively on the GHG emissions associated with the operation and maintenance phase.

A review of GHG emissions from solar PV reported a range in lifetime emissions of 28 to 110 g $CO_2$e/kWh for crystalline silicon and 18 to 48 g $CO_2$e/kWh for cadmium telluride (CdTe) (Environment Canada, 2012). The fabrication and installation of the solar PV have the highest GHG contribution to the overall lifecycle, while the operation/maintenance phase of solar PV have a small contribution (Environment Canada, 2012; Hsu *et al.,* 2012). There are no direct GHG emissions associated with solar PV power generation; however, operation and maintenance activities can indirectly result in GHG emissions, such as maintaining ground vegetation, preventative maintenance, and washing of panels (Hsu *et al.,* 2012; Turney and Fthenakis, 2011).

Nugent and Sovacool (2014) conducted a meta-survey of lifecycle studies on GHG emissions associated with solar PV. Only two (2) studies were identified to present GHG emissions for the operational phase of solar PV. These studies provided a range of 0 to 12.3 g $CO_2$e/kWh (Table 3-5).

**Table 3-5 GHG Emission Rates associated with Operation and Maintenance of Solar PV in Ontario**

| *Reference* | *GHG Emissions per Energy Production (g $CO_2$e/kWh)* | *Percentage of Total LCA Emissions* |
|---|---|---|
| Jungbluth (2005) | 0 | 0% |
| Hondo (2005) | 6.0-12.3[a] | 23.1% |

[a] A range in operational GHG emissions was presented for current technologies as well as future cases. In each case, operational emissions represented 23.1% of the total emissions.

Nugent and Sovacool (2014) utilized the limited available information to derive an emission rate of 6.15 g $CO_2$e/kWh based on the mean of the reported values of 0 g $CO_2$e/kWh reported in Jungbluth (2005) and the upper end of the range of 12.3 g $CO_2$e/kWh reported by Hondo (2005). Given the lack of other literature-based values, the GHG emission rate of 6.15 g $CO_2$e/kWh was selected for use in the current study.

### *3.4.2 Assumptions, Limitations and Uncertainties*

While the operation and maintenance phase of the solar PV life cycle is reported to have the lowest GHG emissions, there is variability in the few estimates available in the literature, which range from 0% to 23% (Nugent and Sovacool, 2014). There are limited details provided in the original studies that describe the methods and assumptions used to derive the operational-phase emission rates; therefore, an assessment of the relevance of each of the available estimates to solar PV in Ontario could not be conducted. Use of the mean of the available estimates may result in a notable over- or underestimation of GHG emissions associated with this stage in the Ontario context.

When estimating GHG emissions per unit energy production, the amount of energy generated by the solar PV units will significantly affect the calculated rates. There are two (2) main factors that can impact energy production and the resulting GHG emission rate for solar PV: insolation and efficiency. Insolation (or solar irradiance) represents the amount of solar radiation energy that reaches a given surface during a specific time. Insolation varies greatly around the world and even across Ontario and impacts the overall electricity generation capacity of solar PV, and in turn, the lifecycle GHG emissions rate for a solar facility (Nugent and Sovacool, 2014). Another consideration is the efficiency of the solar PV technology. The efficiency of commercially available solar PV varies greatly from 7% to 18% (Environment Canada, 2012). As a result, studies evaluating solar PV facilities in different parts of the world that utilize different types of solar PV technology may derive vastly different GHG emission rates.

## 3.5 Hydroelectric

Under the LTEP, the contribution of hydro to the province's energy production was 22% in 2013 and is projected to remain at 22% through to 2032 (MOE, 2013). Hydro has a nameplate capacity of approximately 10,000 MW, contributing 40 TWh to Ontario's electricity grid in 2014.

Hydroelectric facilities in Ontario include both reservoir systems as well as numerous run-of-river stations. Due to the capacity of reservoirs to store water, these stations generally have a larger electricity generating capacity than run-of-river stations (Mallia and Lewis, 2013). Unlike wind and solar, hydro represents a non-intermittent source of renewable energy.

### *3.5.1 Estimated GHG Emission Rates*

GHG emissions from hydroelectric stations in Ontario did not exceed the Reg. 452/09 reporting thresholds; therefore, the estimation of an emission rate was based on literature-derived values. GHG emissions over the life cycle of hydroelectric facilities are primarily associated with three (3) stages: 1) the front-end consisting of the construction of the facility; 2) the decomposition of organic material as lands are flooded for reservoirs; and 3) the decommissioning of the facility and the release of GHGs associated with the remaining biomass (Mallia and Lewis, 2013). One of the most significant sources of GHGs is the release of carbon dioxide and methane as biomass such as plants, trees and soils undergo decomposition in the creation of reservoirs. GHGs created by the decomposition organic materials diffuse through the water column within the reservoir and are subsequently released to the atmosphere (Steinhurst *et al*., 2012). Emission rates are largely dependent on the type of habitat flooded, the size and depth of the reservoir, and the climate (Gagnon and van de Vate, 1997; Steinhurst *et al*., 2012). The flooding of Boreal forests in colder climates, such as those found in Ontario, is reported to result in lower emissions than found for tropical areas, with an average GHG emission rate of 15 g $CO_2$e/kWh (Mallia and Lewis, 2013; Gagnon and van de Vate, 1997). This is consistent with an estimated range of 0.35 to 30 g $CO_2$e/kWh reported for European hydroelectric facilities (Weisser, 2007).

The decomposition of biomass represents a potentially far more significant source of GHG emissions than the estimated rate of 1 to 10 g $CO_2$e/kWh for the construction of the dam and related equipment (Gagnon and van de Vate, 1997). The decommissioning of these facilities is estimated to result in an even greater source of emissions due to the release of methane from exposed sediments following the draining of the reservoir (Pacca, 2007). GHG emissions associated with the decomposition of biomass are not a concern for run-of-river facilities which do not require the flooding of large areas for reservoirs (Mallia and Lewis, 2013).

GHG emissions associated with the decomposition of biomass are reported to be temporary, with some estimating a peak in emissions approximately 2 to 5 years following impoundment, followed by a gradual decline in emissions which may reach those found in natural lakes after more than 10 years (Hydro Quebec, 2016). During the periods of peak emissions following flooding, GHG emissions may be similar to those associated with gas-fired facilities, decreasing from a rate of 671 g $CO_2$e/kWh in the first year following flooding to 238 g $CO_2$e/kWh following the fourth year (Steinhurst *et al*., 2012).

To be consistent with the derivation of GHG emission estimates for other resources, the flooding of reservoirs and the associated emissions associated with the decomposition of biomass was considered to be a component of the construction phase and was not included within the operational stage for the current study. When GHG emissions related to biomass degradation are excluded, emissions during the operational phase of hydroelectricity generation are considered to be negligible (Amor *et al*., 2011). Unlike other resources, hydro facilities do not necessarily rely on fossil fuels or outside sources of energy to resume energy production following an outage (Steinhurst *et al*., 2012).

Therefore, the estimated GHG emission rate for the operational component of hydroelectric facilities in Ontario was assumed to be negligible in the current study.

### *3.5.2 Assumptions, Limitations and Uncertainties*

The largest source of GHG emissions for hydroelectric facilities is reported to be related to the decomposition of biomass, primarily within the first few years of flooding and following decommissioning when accumulated sediments are exposed. There is a significant degree of variability in GHG emissions associated with decomposition, with rates affected by temperature, depth of water, and the type of land flooded to create the reservoir. The rate at which GHG emissions decrease from the initial peak in emissions following flooding is generally unknown. Emissions associated with the decomposition of biomass are generally included within the construction phase of an LCA and therefore, were not included in the operational GHG emission estimates in order to be consistent with the derivation of emission rates for other resources. Failure to account for GHG emissions associated with decomposition, as well as the reduction in the GHG-reducing capacity related to the loss of terrestrial ecological community, may result in a notable underestimation of GHG emissions for the production of energy by hydroelectric facilities.

## 4.0 GHG EMISSIONS FORECAST FOR ONTARIO'S ENERGY PRODUCTION

Utilizing literature-based values, provincial databases of self-reported GHG emissions, and energy production estimates, resource-specific GHG emission rates were estimated for nuclear, wind, natural gas, solar PV, and hydroelectric energy production in Ontario (Table 4-1).

**Table 4-1 Estimated Resource-Specific GHG Emission Rates for the Operation and Maintenance Stage**

| ***Resource*** | ***GHG Emissions per Energy Production (g $CO_2e$/kWh)*** |
|---|---|
| Hydroelectric | 0 |
| Nuclear | 0.15 |
| Wind | 0.74 |
| Solar | 6.15 |
| Natural Gas | 525 |

Resource-specific GHG emission rates were then used to estimate the total amount of GHGs emitted to meet Ontario's energy requirements for three (3) distinct scenarios:

1. Current energy production, with nuclear representing approximately 60% of Ontario's energy requirements, until 2024 during a period of staggered refurbishments to the Darlington and Bruce Generating Stations.
2. Projected future scenario after 2024 with a reduction in nuclear capacity following the scheduled closure of the Pickering Nuclear Generating Station and the completed refurbishment of the Darlington Nuclear Generating Station. Under this scenario it was assumed that the necessary capacity lost with the closure of the Pickering Station would be replaced by a combination of renewable sources (*i.e*., hydro, wind and solar) and natural gas.
3. Alternate projected future scenario after 2024 in the absence of the Darlington refurbishment resulting in a reduction in nuclear capacity associated with the closure of both the Pickering and Darlington Stations. Under this scenario it was assumed that the necessary capacity lost with the closure of the Pickering and Darlington Stations would be replaced by a combination of renewable sources (*i.e*., hydro, wind and solar) and natural gas.

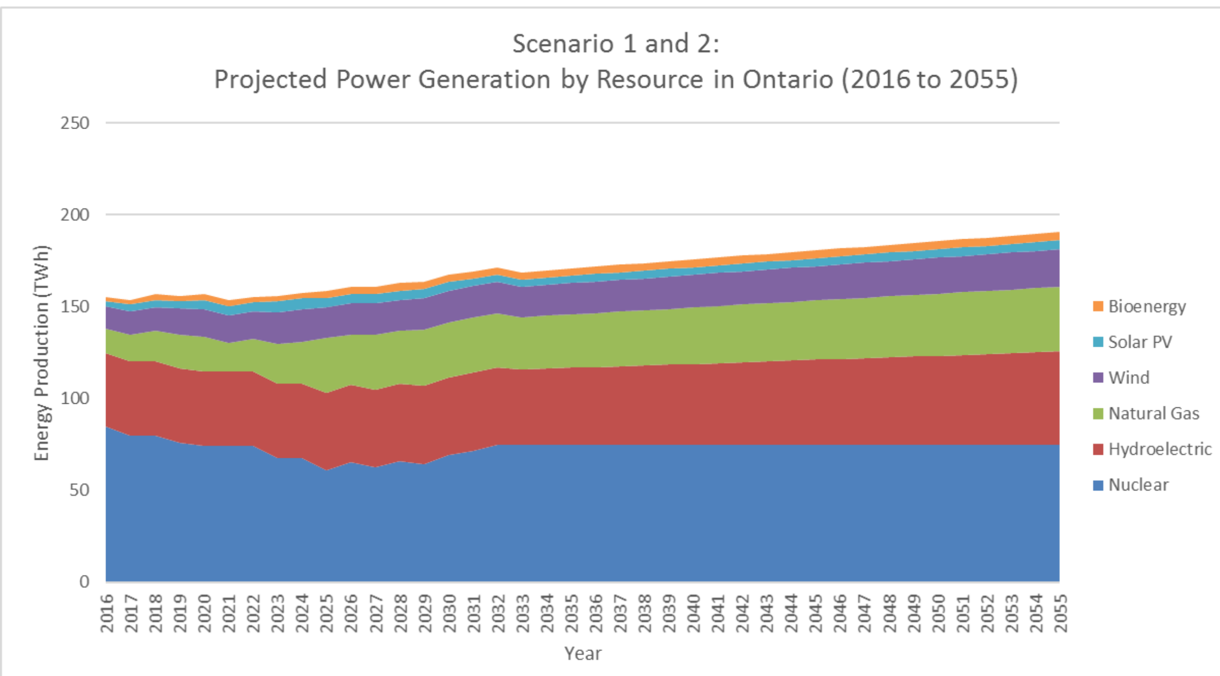
The ratio of the contribution of each resource to the total energy demand under Scenario 2 following the reduction in nuclear capacity was assumed to remain consistent with forecast ratios reported by IESO from 2016 to 2032. This accounted for the fact that the anticipated increased capacity of each resource is not equal, with the capacities of some resources expected to increase at different rates during specific time periods. As a result, no one single resource will replace the loss in nuclear capacity, or contribute to a degree that is inconsistent with the electricity mix presented by IESO. It was also assumed that importation of energy from outside of the province would not be sufficient to replace the lost capacity. Significant increases to energy production in neighbouring provinces would be required, as well as the construction of additional transmission lines to facilitate the delivery of energy to the Ontario grid.

Energy production forecasts provided in the 2013 LTEP were based on the planning assumption that the Pickering Station would cease energy production in 2020. In January 2016, it was announced that OPG plans to pursue continued operation until 2024. All six operating units would operate until 2022, at which point two units would cease operations and the remaining four units would operate until 2024. Therefore, the emissions forecasts for Scenarios 2 and 3 assume a decrease in energy production from the Pickering Station of approximately 1/3 for 2023 and 2024.

The loss of nuclear capacity with the closure of the Pickering Station after 2024 (Scenario 2), and the combined losses of capacity with the closure of both the Pickering and Darlington Stations in an alternate future scenario (Scenario 3), result in an increase in total GHG emissions to 16 and 26 MT $CO_2$e in 2025, respectively, relative to the total GHG emissions of 12 MT $CO_2$e in 2024 prior to the closure of these facilities and 7.2 MT $CO_2$e under the current 2016 scenario (Figure 4-1; Table 4-2). Fluctuations in emissions in Scenarios 2 and 3 are largely attributed to planned refurbishments to the Bruce Station occurring until 2031. The total reduction in GHG emissions from 2024 to 2055 associated with the continued use of the Darlington Station following refurbishment is estimated to be 297 MT $CO_2$e, with an average reduction of 9.6 MT $CO_2$e per year. This is equivalent to removing approximately 2,000,000 cars from Ontario's roads per year assuming an annual average GHG emission rate of 4,700 kg $CO_2$e per vehicle (U.S. EPA, 2016). A reduction of 9.6 MT $CO_2$e per year also contributes to Ontario's GHG emissions reduction targets under Ontario's Climate Change Mitigation and Low-Carbon Economy Act, 2016, which calls for reductions from 1990 emissions levels (181.8 MT $CO_2$e) of 15% in 2020, 37% in 2030, and 80% in 2050 (MOECC, 2016), representing reductions of 27, 67 and 145 MT $CO_2$e, respectively.


**Figure 4-1 Projected Greenhouse Gas Emissions associated with Power Generation in Ontario (2016 to 2055)**

The emissions profile is driven almost exclusively by energy production from natural gas facilities for each of the three (3) scenarios. Although the contribution of natural gas to the total energy production ranges from 9 to 32%, it consistently represents the largest source of GHGs since the combustion of natural gas is the most emission-intensive operational process of each of the energy-producing resources. These significant increases in annual GHG emissions are anticipated even though an optimal scenario was assumed in which renewable resources such as wind, solar PV and hydro were able to increase their contribution to meet energy demands beyond the forecasted increase in production (Figure 4-2; Table 4-3). Despite this assumption, a large portion of the capacity lost with the closure of the Darlington Station under Scenario 3 was assumed to be replaced by energy generated by natural gas facilities. Natural gas facilities were assumed to provide approximately 75% (or 20 TWh) of the total capacity lost under Scenario 3 from the closure of the Darlington Station in 2025 until 2036. It was assumed that if the Darlington Station refurbishments were not approved, a 20-year planning, approvals and construction phase would allow for a 10% increase (4.2 TWh) in energy production from hydroelectric facilities beginning in 2036. A subsequent 1% increase in hydroelectric capacity was assumed for every year after 2036. The technical feasibility of the assumed increased capacity for energy production for each resource was not evaluated as part of the current study. The technical feasibility of the assumed increased capacity for energy production for each resource was not evaluated as part of the current study.



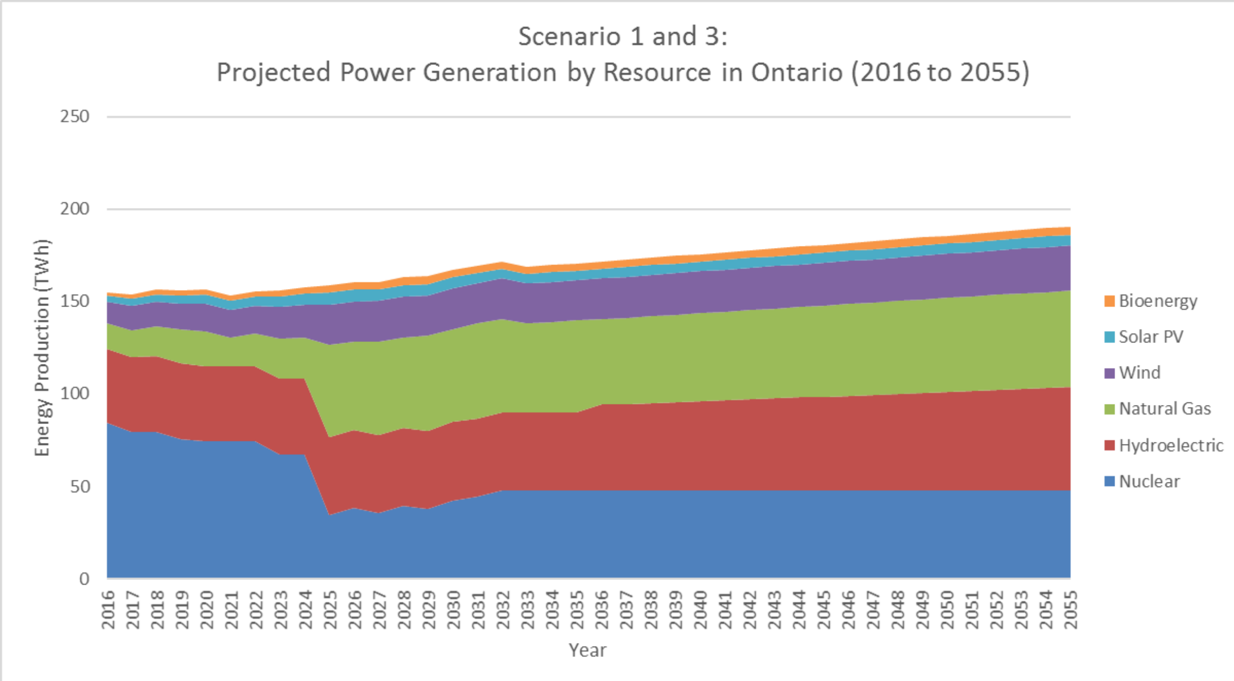



**Figure 4-2 Projected Power Generation in Ontario by Resource (2016 to 2055)**

Given that nuclear represents a large source of energy production in Ontario and the operational stage produces a low rate of GHG emissions, the loss of energy-generating capacity due to the closure of nuclear facilities would result in a significant increase in annual GHG emissions in order for Ontario to meet its future energy requirements.

| Table 4-2 | Projected Power Generation in Ontario by Resource: 2016 to 2055 (TWh) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Year*** | ***Nuclear*** | | ***Hydroelectric*** | | ***Natural Gas*** | | ***Wind*** | | ***Solar PV*** | | ***Bioenergy*** | | ***Total*** |
| | ***Sc. 2*** | ***Sc. 3*** | ***Sc. 2*** | ***Sc. 3*** | ***Sc. 2*** | ***Sc. 3*** | ***Sc. 2*** | ***Sc. 3*** | ***Sc. 2*** | ***Sc. 3*** | ***Sc. 2*** | ***Sc. 3*** | |
| 2016 | 85 | 85 | 40 | 40 | 14 | 14 | 12 | 12 | 3.0 | 3.0 | 2.0 | 2.0 | 154.8 |
| 2017 | 80 | 80 | 40 | 40 | 15 | 15 | 13 | 13 | 4.0 | 4.0 | 2.0 | 2.0 | 153.5 |
| 2018 | 80 | 80 | 41 | 41 | 16 | 16 | 13 | 13 | 4.0 | 4.0 | 3.0 | 3.0 | 156.4 |
| 2019 | 76 | 76 | 41 | 41 | 19 | 19 | 14 | 14 | 4.0 | 4.0 | 3.0 | 3.0 | 156.2 |
| 2020 | 74 | 74 | 41 | 41 | 19 | 19 | 15 | 15 | 5.0 | 5.0 | 3.0 | 3.0 | 156.9 |
| 2021 | 74 | 74 | 41 | 41 | 16 | 16 | 15 | 15 | 5.0 | 5.0 | 3.0 | 3.0 | 153.4 |
| 2022 | 74 | 74 | 41 | 41 | 18 | 18 | 15 | 15 | 5.0 | 5.0 | 3.0 | 3.0 | 155.6 |
| 2023 | 67 | 67 | 41 | 41 | 22 | 22 | 17 | 17 | 5.8 | 5.8 | 3.0 | 3.0 | 156.0 |
| 2024 | 67 | 67 | 41 | 41 | 22 | 22 | 18 | 18 | 6.0 | 6.0 | 3.0 | 3.0 | 157.5 |
| 2025 | 61 | 34 | 42 | 42 | 30 | 50 | 17 | 22 | 5.0 | 6.4 | 4.0 | 4.0 | 158.8 |
| 2026 | 65 | 39 | 42 | 42 | 27 | 47 | 17 | 22 | 5.0 | 6.5 | 4.0 | 4.0 | 160.6 |
| 2027 | 62 | 36 | 42 | 42 | 30 | 51 | 17 | 22 | 5.0 | 6.4 | 4.0 | 4.0 | 160.7 |
| 2028 | 66 | 39 | 42 | 42 | 29 | 49 | 17 | 22 | 5.0 | 6.4 | 4.0 | 4.0 | 163.0 |
| 2029 | 64 | 38 | 42 | 42 | 31 | 51 | 17 | 22 | 5.0 | 6.4 | 4.0 | 4.0 | 163.6 |
| 2030 | 69 | 42 | 42 | 42 | 30 | 50 | 17 | 22 | 5.0 | 6.4 | 4.0 | 4.0 | 167.4 |
| 2031 | 71 | 45 | 43 | 42 | 30 | 51 | 17 | 22 | 4.0 | 5.2 | 4.0 | 4.0 | 169.3 |
| 2032 | 75 | 48 | 42 | 42 | 29 | 50 | 17 | 22 | 4.0 | 5.2 | 4.0 | 4.0 | 171.6 |
| 2033 | 75 | 48 | 41 | 42 | 28 | 48 | 17 | 22 | 3.9 | 5.1 | 3.9 | 3.9 | 168.7 |
| 2034 | 75 | 48 | 42 | 42 | 29 | 49 | 17 | 22 | 3.9 | 5.1 | 4.0 | 4.0 | 169.7 |
| 2035 | 75 | 48 | 42 | 42 | 29 | 50 | 17 | 22 | 4.0 | 5.2 | 4.0 | 4.0 | 170.7 |
| 2036 | 75 | 48 | 42 | 46 | 29 | 46 | 17 | 22 | 4.0 | 5.2 | 4.0 | 4.0 | 171.7 |
| 2037 | 75 | 48 | 43 | 47 | 30 | 47 | 17 | 22 | 4.1 | 5.2 | 4.0 | 4.0 | 172.7 |
| 2038 | 75 | 48 | 43 | 47 | 30 | 47 | 17 | 22 | 4.1 | 5.2 | 4.0 | 4.0 | 173.7 |
| 2039 | 75 | 48 | 44 | 48 | 30 | 47 | 18 | 22 | 4.2 | 5.3 | 4.1 | 4.1 | 174.7 |
| 2040 | 75 | 48 | 44 | 48 | 31 | 48 | 18 | 23 | 4.2 | 5.3 | 4.1 | 4.1 | 175.7 |
| 2041 | 75 | 48 | 45 | 49 | 31 | 48 | 18 | 23 | 4.2 | 5.3 | 4.1 | 4.1 | 176.7 |
| 2042 | 75 | 48 | 45 | 49 | 31 | 48 | 18 | 23 | 4.3 | 5.4 | 4.1 | 4.1 | 177.7 |
| 2043 | 75 | 48 | 46 | 50 | 32 | 49 | 18 | 23 | 4.3 | 5.4 | 4.2 | 4.2 | 178.7 |
| 2044 | 75 | 48 | 46 | 50 | 32 | 49 | 19 | 23 | 4.4 | 5.4 | 4.2 | 4.2 | 179.7 |
| 2045 | 75 | 48 | 46 | 51 | 32 | 49 | 19 | 23 | 4.4 | 5.5 | 4.2 | 4.2 | 180.7 |
| 2046 | 75 | 48 | 47 | 51 | 33 | 50 | 19 | 23 | 4.5 | 5.5 | 4.2 | 4.2 | 181.7 |
| 2047 | 75 | 48 | 47 | 52 | 33 | 50 | 19 | 23 | 4.5 | 5.5 | 4.3 | 4.3 | 182.7 |
| 2048 | 75 | 48 | 48 | 52 | 33 | 50 | 19 | 24 | 4.5 | 5.5 | 4.3 | 4.3 | 183.7 |
| 2049 | 75 | 48 | 48 | 53 | 33 | 51 | 19 | 24 | 4.6 | 5.6 | 4.3 | 4.3 | 184.7 |
| 2050 | 75 | 48 | 49 | 53 | 34 | 51 | 20 | 24 | 4.6 | 5.6 | 4.3 | 4.3 | 185.7 |
| 2051 | 75 | 48 | 49 | 54 | 34 | 51 | 20 | 24 | 4.7 | 5.6 | 4.4 | 4.4 | 186.7 |
| 2052 | 75 | 48 | 49 | 54 | 34 | 51 | 20 | 24 | 4.7 | 5.7 | 4.4 | 4.4 | 187.7 |
| 2053 | 75 | 48 | 50 | 55 | 35 | 52 | 20 | 24 | 4.8 | 5.7 | 4.4 | 4.4 | 188.7 |
| 2054 | 75 | 48 | 50 | 55 | 35 | 52 | 20 | 24 | 4.8 | 5.7 | 4.4 | 4.4 | 189.7 |
| 2055 | 75 | 48 | 51 | 56 | 35 | 52 | 21 | 24 | 4.8 | 5.8 | 4.4 | 4.4 | 190.7 |

**Table 4-3 Projected Greenhouse Gas Emissions Associated with Power Generation in Ontario: 2016 to 2055 (MT $CO_2e$)**

| Year | Nuclear | | Hydroelectric | | Natural Gas | | Wind | | Solar PV | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sc. 2 | Sc. 3 | Sc. 2 | Sc. 3 | Sc. 2 | Sc. 3 | Sc. 2 | Sc. 3 | Sc. 2 | Sc. 3 | Sc. 2 | Sc. 3 |
| 2016 | 0.013 | 0.013 | 0 | 0 | 7.1 | 7.1 | 0.0089 | 0.0089 | 0.018 | 0.018 | 7.2 | 7.2 |
| 2017 | 0.012 | 0.012 | 0 | 0 | 7.6 | 7.6 | 0.010 | 0.010 | 0.025 | 0.025 | 7.7 | 7.7 |
| 2018 | 0.012 | 0.012 | 0 | 0 | 8.6 | 8.6 | 0.010 | 0.010 | 0.025 | 0.025 | 8.7 | 8.7 |
| 2019 | 0.011 | 0.011 | 0 | 0 | 9.7 | 9.7 | 0.010 | 0.010 | 0.025 | 0.025 | 9.8 | 9.8 |
| 2020 | 0.011 | 0.011 | 0 | 0 | 9.8 | 9.8 | 0.011 | 0.011 | 0.031 | 0.031 | 9.9 | 9.9 |
| 2021 | 0.011 | 0.011 | 0 | 0 | 8.1 | 8.1 | 0.011 | 0.011 | 0.031 | 0.031 | 8.2 | 8.2 |
| 2022 | 0.011 | 0.011 | 0 | 0 | 9.2 | 9.2 | 0.011 | 0.011 | 0.031 | 0.031 | 9.2 | 9.2 |
| 2023 | 0.010 | 0.010 | 0 | 0 | 11 | 11 | 0.013 | 0.013 | 0.036 | 0.036 | 11 | 11 |
| 2024 | 0.010 | 0.010 | 0 | 0 | 12 | 12 | 0.013 | 0.013 | 0.037 | 0.037 | 12 | 12 |
| 2025 | 0.0091 | 0.0051 | 0 | 0 | 16 | 26 | 0.013 | 0.016 | 0.031 | 0.040 | 16 | 26 |
| 2026 | 0.010 | 0.0058 | 0 | 0 | 14 | 25 | 0.013 | 0.016 | 0.031 | 0.040 | 14 | 25 |
| 2027 | 0.0093 | 0.0053 | 0 | 0 | 16 | 27 | 0.013 | 0.016 | 0.031 | 0.039 | 16 | 27 |
| 2028 | 0.010 | 0.0059 | 0 | 0 | 15 | 26 | 0.013 | 0.016 | 0.031 | 0.040 | 15 | 26 |
| 2029 | 0.010 | 0.0057 | 0 | 0 | 16 | 27 | 0.013 | 0.016 | 0.031 | 0.039 | 16 | 27 |
| 2030 | 0.010 | 0.0064 | 0 | 0 | 16 | 26 | 0.013 | 0.016 | 0.031 | 0.039 | 16 | 27 |
| 2031 | 0.011 | 0.0067 | 0 | 0 | 16 | 27 | 0.013 | 0.016 | 0.025 | 0.032 | 16 | 27 |
| 2032 | 0.011 | 0.0072 | 0 | 0 | 15 | 26 | 0.013 | 0.016 | 0.025 | 0.032 | 15 | 26 |
| 2033 | 0.011 | 0.0072 | 0 | 0 | 15 | 25 | 0.012 | 0.016 | 0.024 | 0.031 | 15 | 25 |
| 2034 | 0.011 | 0.0072 | 0 | 0 | 15 | 26 | 0.012 | 0.016 | 0.024 | 0.032 | 15 | 26 |
| 2035 | 0.011 | 0.0072 | 0 | 0 | 15 | 26 | 0.013 | 0.016 | 0.025 | 0.032 | 15 | 26 |
| 2036 | 0.011 | 0.0072 | 0 | 0 | 15 | 24 | 0.013 | 0.016 | 0.025 | 0.032 | 16 | 24 |
| 2037 | 0.011 | 0.0072 | 0 | 0 | 16 | 24 | 0.013 | 0.016 | 0.025 | 0.032 | 16 | 25 |
| 2038 | 0.011 | 0.0072 | 0 | 0 | 16 | 25 | 0.013 | 0.017 | 0.025 | 0.032 | 16 | 25 |
| 2039 | 0.011 | 0.0072 | 0 | 0 | 16 | 25 | 0.013 | 0.017 | 0.026 | 0.032 | 16 | 25 |
| 2040 | 0.011 | 0.0072 | 0 | 0 | 16 | 25 | 0.013 | 0.017 | 0.026 | 0.033 | 16 | 25 |
| 2041 | 0.011 | 0.0072 | 0 | 0 | 16 | 25 | 0.013 | 0.017 | 0.026 | 0.033 | 16 | 25 |
| 2042 | 0.011 | 0.0072 | 0 | 0 | 16 | 25 | 0.013 | 0.017 | 0.026 | 0.033 | 16 | 25 |
| 2043 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.027 | 0.033 | 17 | 26 |
| 2044 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.027 | 0.033 | 17 | 26 |
| 2045 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.027 | 0.034 | 17 | 26 |
| 2046 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.027 | 0.034 | 17 | 26 |
| 2047 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.028 | 0.034 | 17 | 26 |
| 2048 | 0.011 | 0.0072 | 0 | 0 | 17 | 26 | 0.014 | 0.017 | 0.028 | 0.034 | 17 | 26 |
| 2049 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.014 | 0.018 | 0.028 | 0.034 | 18 | 27 |
| 2050 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.015 | 0.018 | 0.028 | 0.034 | 18 | 27 |
| 2051 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.015 | 0.018 | 0.029 | 0.035 | 18 | 27 |
| 2052 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.015 | 0.018 | 0.029 | 0.035 | 18 | 27 |
| 2053 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.015 | 0.018 | 0.029 | 0.035 | 18 | 27 |
| 2054 | 0.011 | 0.0072 | 0 | 0 | 18 | 27 | 0.015 | 0.018 | 0.029 | 0.035 | 18 | 27 |
| 2055 | 0.011 | 0.0072 | 0 | 0 | 19 | 27 | 0.015 | 0.018 | 0.030 | 0.035 | 19 | 27 |

## 5.0 OVERALL ASSUMPTIONS, LIMITATIONS AND UNCERTAINTIES

The current study focused exclusively on the GHGs emitted in Ontario during the operational stage of energy production in Ontario. It must be noted that while this may provide a description of the GHGs emitted on an annual basis, it does not represent the total GHGs emitted over the lifetime of an energy-producing resource/facility, or additional considerations related to the disposal of waste materials generated during the production of energy. For some resources, GHG emissions during the operational stage are negligible relative to the emissions associated with the upstream and downstream stages, including resource extraction, facility construction, decommissioning and land reclamation. Emissions related to each of these stages are often amortized over the lifetime of the energy-producing facility within an LCA to estimate a lifetime annual GHG emission rate. This is achieved through complex evaluations of all aspects of a facility's lifetime within an LCA. A brief discussion of lifetime emission estimates for each resource is provided in Section 5.1.

Along with the assumptions, limitations and uncertainties listed within each of the individual sections describing the estimation of GHG emission rates in Section 3, numerous additional assumptions were employed in the derivation of emission estimates and the emission forecasts under each of the Scenarios, including:

- The current study considered GHG emissions associated with the generation of electricity rather than the final delivery of electricity to the end user. Therefore, the estimated emission rates per unit of energy do not account for electricity losses occurring during transmission and distribution;
- Emissions related to imported electricity, bioenergy or other resources were not considered. This will have resulted in the underestimation of total GHG emissions to the Ontario environment. However, given that bioenergy and other resources do not significantly contribute to the total energy production, this omission is not considered to significantly affect the overall emissions forecast;
- It was assumed that each resource (*i.e.*, natural gas, wind, solar PV and hydroelectric) will be able to increase their energy-producing capacity to levels that exceed those presented by IESO to contribute to total energy production needs following the loss of nuclear. An evaluation of the feasibility of each of these resources to meet the increased energy demands assumed under Scenarios 2 and 3 was not completed;
- The increased contribution of intermittent resources such wind and solar to meet energy demand following the reduction of nuclear capacity in Scenarios 2 and 3 may inherently assume an increased capacity for energy storage in the future.

### 5.1 Exclusion of LCA Emissions

Full LCAs are often utilized when comparing the potential environmental impacts associated with the generation of electricity through multiple methods. This includes GHG emissions resulting from all life stages of the energy supply chain, beginning with the extraction of resources to fuel combustion or construct facilities, through to the decommissioning stage including waste management, land reclamation and the recycling of materials. Failure to consider all stages of the lifecycle and focus exclusively on the emissions occurring during the operational phase may result in the omission of the majority of the lifetime emissions for some energy production methods, while capturing the most emission-intensive stage for others. The overall lifecycle GHG emissions for nuclear, wind and hydro are often found to be similar and slightly below those for solar, with emissions for each of these more than an order of magnitude lower than lifecycle emissions for natural gas (Table 5-1).

**Table 5-1 Ranges of Full Lifecycle GHG Emission Rates for Various Methods of Power Generation[a]**

| ***Resource*** | ***GHG Emissions per Energy Production (g $CO_2$e/kWh)*** |
|---|---|
| Hydroelectric | 10 - 22 |
| Nuclear | 4.8 - 66 |
| Wind | 10 - 34.1 |
| Solar | 32 – 49.9 |
| Natural Gas | 435 - 540 |

[a] Values generally represent means from LCA literature reviews conducted by one or more of the following resources: Hatch (2014), Mallia and Lewis (2013), Sovacool (2008), Lenzen (2008), Andseta *et al*. (1998), Nugent and Sovacool (2014), and CERI (2008).

A brief description of the estimated contribution of the emissions associated with the operation and maintenance stage to the total lifetime emissions for each energy-producing method is described below.

### *5.1.1 Nuclear*

A critical survey of LCAs for nuclear power reported a range in GHG emission rates over the lifetime of a plant of 1.4 to 288 g $CO_2$e/kWh, with a mean of 66 g $CO_2$e/kWh (Sovacool, 2008). This high degree of variability is consistent with several similar LCA reviews (Warner and Heath, 2012; Fthenakis and Kim, 2007; Lanzen, 2008). One of the greatest sources of variability in emission estimates was related to the quality of uranium ore which significantly affects the energy requirements for mining and milling, as well as mine land reclamation. The type of mining (*i.e.*, open-pit or underground), as well as explosives, solvents and techniques utilized within each type of mining, also had a notable effect on the variability of the estimates. Other factors that contributed significantly to the variability in emission estimates were the local energy source utilized for the mining of uranium, the type of uranium enrichment, the reactor type, site selection, the operational lifetime, and the LCA method (Sovacool, 2008). Total lifecycle GHG emissions for CANDU reactors were estimated to be 4.8 and 15 g $CO_2$e/kWh by Mallia and Lewis (2013) and Andseta *et al*. (1998), respectively. These estimates are notably lower than the means of 66 and 65 g $CO_2$e/kWh reported by Sovacool (2008) and Lanzen (2008), respectively.

Based on the best available information, it is estimated that exclusion of all components other than operation may result in the omission of 96% of the total lifecycle emissions associated with the production of energy by nuclear facilities in Ontario.

#### *5.1.2 Wind*

A critical survey of GHG emissions from wind power reported a range in emissions over the lifetime of a wind facility of 0.4 g to 364.8 g $CO_2e$/kWh, with a mean of 34.1 g $CO_2e$/kWh (Nugent and Sovacool, 2014). The majority of the GHG emissions associated with wind power are related to the fabrication and installation of the wind turbines, which has been estimated to contribute approximately 90 to 99% of the lifetime GHG emissions (Raadal *et al.*, 2011). Since many of these studies include the energy- and material-intensive construction of offshore wind farms which are not applicable within the Ontario context, the average LCA GHG emission estimate of 11 g $CO_2e$/kWh reported independently by both Mallia and Lewis (2013) and Hatch (2014) may be the most applicable. Given that GHG emissions associated with the operational stage was estimated to be 0.74 g $CO_2e$/kWh within Mallia and Lewis (2013) and 0.49 g $CO_2e$/kWh within Hatch (2014), it is estimated that exclusion of all components other than operation may result in the omission of approximately 93 to 96% of the total lifecycle emissions associated with the production of energy by wind farms in Ontario.

#### *5.1.3 Natural Gas*

The average total GHG emissions over the lifetime of a natural gas facility within Ontario was estimated to be 497 g $CO_2e$/kWh, with emissions from the operational phase estimated at 435 g $CO_2e$/kWh (or 87% of total emissions) (Mallia and Lewis, 2013). Hatch (2014) reported similar results, with emissions from the operational phase (390 g $CO_2e$/kWh) representing 82% of the total LCA emissions (478 g $CO_2e$/kWh), as did CERI (2008) with emissions from the operational phase (445 g $CO_2e$/kWh) also representing 82% of the total LCA emissions (540 g $CO_2e$/kWh). Therefore, it is estimated that exclusion of all components other than operation may result in the omission of approximately 12 to 18% of the total lifecycle emissions associated with the production of energy by natural gas facilities.

#### *5.1.4 Solar Photovoltaic*

A critical survey of GHG emissions from solar PV reported a range in emissions over the lifetime range from 17.5 to 110 g $CO_2e$/kWh, with a mean of 49.9 g $CO_2e$/kWh (Nugent and Sovacool, 2014). The majority of the GHG emissions associated with solar PV are related to the material extraction and fabrication phases (Environment Canada, 2012), which has been estimated to contribute approximately 71% of the lifetime GHG emissions (Nugent and Sovacool, 2014). Therefore, it is estimated that exclusion of all components other than operation may result in the omission of approximately 71% of the total lifecycle emissions associated with the production of energy by solar PV facilities in Ontario.

#### *5.1.5 Hydroelectric*

Mallia and Lewis (2013) estimated total life cycle GHG emission rates of 1.5 and 22.5 g $CO_2e$/kWh for run-of-river and reservoir hydroelectric facilities, respectively, in Ontario. While both included emission estimates for the construction and decommissioning stages, GHG emissions for the reservoir systems was significantly higher due to the decomposition of biomass occurring within flooded ecosystems. An overall weighted average of 22 g $CO_2e$/kWh was derived for all hydroelectric energy production in Ontario.  This estimate is at the low end of the range of 0.5 to 250 g $CO_2$e/kWh reported for run-of –river and reservoirs in boreal forests within the literature (Steinhurst *et al*., 2012; Raadal *et al*., 2011) and is consistent with an estimate of 15 g $CO_2$e/kWh reported for facilities in cold climates (Gagnon and van de Vate, 1997).

Given that the current study assumed that GHG emissions associated with the operational component of hydroelectric facilities was negligible, exclusion of the construction and decommissioning stages of the lifecycle resulted in the omission of 100% of the total emissions associated with the production of energy by hydroelectric facilities.

## 6.0 CONCLUSIONS

The phasing-out of coal-fired electricity generation, the increased capacity of renewable resources, and the ongoing contribution of nuclear as Ontario's base load supplier of electricity has resulted in a steady decline in GHG emissions from the electricity sector in Ontario since 2008. Currently, Ontario's energy demands are met through a mix of renewable and non-renewable resources, with nuclear representing approximately 60% of production. These declines are expected to be followed by an increase in emissions associated with a growing Ontario population, a recovering economy, and a reduction in energy production from nuclear units during a period of refurbishment resulting in an increased reliance on natural gas-fired plants (MOECC, 2013).

The loss of nuclear capacity with the scheduled closure of the Pickering Station after 2024 is anticipated to result in a significant increase in annual GHG emissions to the Ontario environment even under an optimal scenario in which renewable resources such as wind, solar and hydro increase their contribution to meet energy demand beyond the forecasted increase in production rather than shifting greater dependency on natural gas facilities. Additional losses in nuclear capacity would occur without refurbishment of existing nuclear facilities such as the Darlington Station, resulting in even greater increases in annual GHG emissions.

Given that nuclear represents a large source of energy production in Ontario and the operational stage produces a low rate of GHG emissions, the loss of energy-generating capacity due to the closure of nuclear facilities would result in a significant increase in annual GHG emissions in order for Ontario to meet its future energy requirements.

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# APPENDIX A

# LITERATURE SEARCH STRATEGY

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## APPENDIX A: LITERATURE SEARCH STRATEGY

### A-1.0 INTRODUCTION

A systematic and comprehensive search of the published literature was conducted to identify, as best possible, all white (peer-reviewed published literature) and grey literature (literature available elsewhere) related to GHG emissions associated with power generation operations in the Ontario context. The literature search was performed in a step-wise manner using three search strategies:

- On-line electronic databases
- Citation sourcing
- Professional experience

### A-1.1 On-Line Electronic Databases

A staged search strategy was employed, with the first stage of the search focused on identifying all white (peer-reviewed and published) literature related to GHG emissions from power generation in the Ontario context, the second stage aimed at identifying all grey literature (literature available elsewhere), and the third stage of the search intended to retrieve the primary or original publications and sources that served as the basis of the white and grey literature identified through the initial stages of the electronic search.

The first stage began with the development of a series of search strings representing various combinations of 'primary', 'secondary', and 'tertiary' search terms. The intent of the 'primary' search term was to identify literature specific to one of the power generation technologies of interest. The 'secondary' search term was intended to identify literature that reported GHG emissions in the context of power generation. The 'tertiary' search term was aimed at focusing the search on the literature specific to the Ontario context. In order to avoid possible bias in the selection of the search terms, two members of the study team were involved in the final choice of terms.

The 'primary' search terms selected for each power generation technology considered as part of the literature search are presented in Table A-1.

**Table A-1 'Primary' Search Terms**

| ***Power Generation Technology*** | ***Selected Search Terms*** |
|---|---|
| Nuclear | nuclear |
| Hydroelectric | hydroelectric<br>hydropower |
| Onshore Wind | onshore wind |
| Solar | solar<br>photovoltaic<br>PV |
| Natural Gas | natural gas |

The 'secondary' search terms selected to identify literature that reported GHG emissions in the context of power generation are presented in Table A-2. These terms were considered general and applicable to all power generation technologies.

**Table A-2 'Secondary' Search Terms**

| ***Selected Search Terms*** |
|---|
| greenhouse<br>emission<br>carbon dioxide equivalent<br>carbon dioxide<br>electricity generation<br>life cycle<br>life-cycle<br>LCA<br>power generation |

As the principal aim of the literature search was to identify GHG emissions specific to Ontario, the term "Ontario" was included as a 'tertiary' search term. At the same time, it was recognized that in order to accommodate the potential absence of Ontario-specific power generation-related GHG emissions data the search must necessarily extend beyond the Ontario borders. As a result, neighbouring jurisdictions were also considered with the understanding that because of the proximity or similarity to Ontario, the characteristics of the power generation technologies used and governing regulations would be similar. Table A-3 presents the 'tertiary' search terms.

**Table A-3 'Tertiary' Search Terms**

| **Location of Interest** | **Selected Search Terms** |
|---|---|
| Ontario | Ontario |
| Relevant nearby jurisdictions | Canada<br>United States |

Using the primary, secondary, and tertiary search terms presented above, search strings were developed and used for the literature review (Table A-4).

**Table A-4 Search Strings Utilized in the Literature Search**

| ***Power Source Category*** | ***Search String*** |
|---|---|
| Nuclear | (nuclear) AND ((Ontario OR Canada OR "United States" OR USA OR U.S.)) AND ((greenhouse AND emission*)) AND (("carbon dioxide equivalent" OR "carbon dioxide" OR "electricity generation" OR "life cycle" OR "life-cycle" OR LCA OR "power generation")) |
| Hydroelectric | (hydroelectric OR hydropower) AND ((Ontario OR Canada OR "United States" OR USA OR U.S.)) AND ((greenhouse AND emission*)) AND (("carbon dioxide equivalent" OR "carbon dioxide" OR "electricity generation" OR "life cycle" OR "life-cycle" OR LCA OR "power generation")) |
| Onshore Wind | (onshore wind) AND ((Ontario OR Canada OR "United States" OR USA OR U.S.)) AND ((greenhouse AND emission*)) AND (("carbon dioxide equivalent" OR "carbon dioxide" OR "electricity generation" OR "life cycle" OR "life-cycle" OR LCA OR "power generation")) |
| Solar | (solar OR photovoltaic OR PV) AND ((Ontario OR Canada OR "United States" OR USA OR U.S.)) AND ((greenhouse AND emission*)) AND (("carbon dioxide equivalent" OR "carbon dioxide" OR "electricity generation" OR "life cycle" OR "life-cycle" OR LCA OR "power generation")) |
| Natural Gas | (natural gas) AND ((Ontario OR Canada OR "United States" OR USA OR U.S.)) AND ((greenhouse AND emission*)) AND (("carbon dioxide equivalent" OR "carbon dioxide" OR "electricity generation" OR "life cycle" OR "life-cycle" OR LCA OR "power generation")) |

Using the search parameter approach described above, resources were further screened to determine relevance.  Resources included for review were required to meet the following additional criteria:

- Resources from 2006 and onwards were deemed to be current; however, older documents were considered when necessary; and,
- English language.

This stage of the electronic literature search was performed with assistance from Documents Delivered Inc., a privately-owned document and retrieval service provider with access to numerous electronic databases.