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Life Cycle Greenhouse Gas Emissions from Uranium Mining and Milling in Canada

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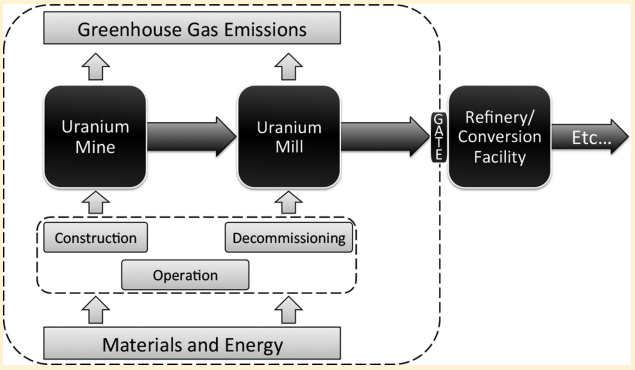
Supporting Information

ABSTRACT: Life cycle greenhouse gas (GHG) emissions from the production of nuclear power (in g CO_2e/kWh) are uncertain due partly to a paucity of data on emissions from individual phases of the nuclear fuel cycle. Here, we present the first comprehensive life cycle assessment of GHG emissions produced from the mining and milling of uranium in Canada. The study includes data from 2006−2013 for two uranium mine-mill operations in northern Saskatchewan (SK) and data from 1995−2010 for a third SK mine-mill operation. The mine-mill operations were determined to have GHG emissions intensities of 81, 64, and 34 kg CO_2e/kg U_3O_8 at average ore grades of 0.74%, 1.54%, and 4.53% U_3O_8, respectively. The production-weighted average GHG emission intensity is 42 kg CO_2e/kg U_3O_8 at an average ore grade of 3.81% U_3O_8. The production-weighted average GHG emission intensity drops to 24 kg CO_2e/kg U_3O_8 when the local hydroelectric GHG emission factor (7.2 g CO_2e/kWh) is substituted for the SK grid-average electricity GHG emission factor (768 g CO_2e/kWh). This results in Canadian uranium mining-milling contributing only 1.1 g CO_2e/kWh to total life cycle GHG emissions from the nuclear fuel cycle (0.7 g CO_2e/kWh using the local hydroelectric emission factor).



1. INTRODUCTION

To reduce greenhouse gas (GHG) emissions from the production of electricity, the world economy needs to shift from primarily consuming GHG-intensive energy sources, such as coal and natural gas, to consuming primarily low-GHG energy sources, such as solar, nuclear, wind, and hydroelectric. Fossil fuel energy sources currently supply approximately 63% of the world's electricity.[1] Low-GHG energy sources currently supply approximately 30% of the world's electricity with nuclear contributing 11% to the total.[1]

To accomplish the transition from high- to low-GHG energy sources, it is necessary to understand the GHG emission intensity from energy sources and their fuel cycles using transparent well-documented methods to quantify GHG emissions. Results from studies calculating GHG emission intensity from the nuclear fuel cycle vary widely, from 3.7 to 110 g of carbon dioxide equivalents per kilowatt-hour of electricity generated (g CO_2e/kWh).[2] Previous estimates attribute up to 30% of the nuclear life cycle GHG emissions to uranium mining and milling.[2,3] Differences in reported values of GHG emissions from uranium mining and milling are due in part to real differences in production methods (e.g., ore grade, mine type, electricity source) and in part to study methodology (e.g., study completeness, methods, assumptions).[2−5]

There are no recent comprehensive life cycle GHG emission estimates for uranium mining-milling in Canada, a country that has provided nearly 19% of global uranium supplies between 2006 and 2013.[6] Saskatchewan's Athabasca Basin, the principal source for Canadian uranium, is home to exceptionally high-grade uranium ore with one recently commissioned mine reporting an average ore grade of 16.7% U_3O_8 for its total reserves.[7,8] In comparison, ore grades from 0.1 to 0.2% U_3O_8 are commonly reported in nuclear life cycle studies.[2,3] Yellowcake (i.e., U_3O_8) produced from high-grade uranium ore, such as that found in Canada, is likely associated with lower GHG emissions than from other uranium mine-mill facilities around the world.

2. GOAL

The main goal of this study is to provide a high quality estimate of the GHG emission intensity for Canadian uranium that can be used to (1) improve life cycle GHG emission estimates for nuclear power generation when Canadian uranium is used and (2) compare Canadian mining-milling GHG emission intensities to those of other regions.

To accomplish this, the study quantifies GHG emissions during the mining-milling phase of the nuclear fuel cycle for

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three mine-mill operations in northern Saskatchewan (SK) using a life cycle approach.

3. SCOPE

This study is a "cradle-to-gate" assessment of GHG emissions during the uranium mining-milling phase of the nuclear fuel cycle. This is a subset of the full nuclear fuel cycle which includes the following processes that are downstream of this study's "gate": uranium conversion, enrichment, fuel rod fabrication, nuclear power facility construction/operation/decommissioning, and spent fuel management/reprocessing.[2]

The functional unit is 1 kg of U_3O_8 packaged and prepared for transport from the uranium mill. Results are expressed in units of kg CO_2e/kg U_3O_8 for each mining-milling operation. The system boundaries are outlined in Figure 1.

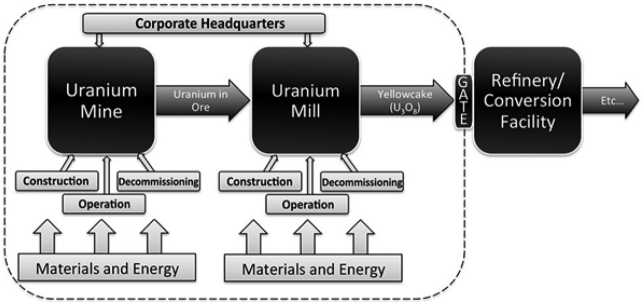

Figure 1. Dashed line representing "cradle-to-gate" system boundary.

The following emission sources are included within the system boundary: (1) life cycle emissions associated with mine-mill construction including (a) electricity and fuel consumption during facility construction, (b) transportation of personnel, equipment, and materials to the facility during construction, and (c) emissions embodied in building materials, vehicles, construction concrete, piping, generators, boilers, and other equipment; (2) life cycle emissions from use of fuel (propane, diesel, gasoline) in facility-owned vehicles and equipment during operation; (3) life cycle emissions from generation of imported electricity consumed by the facility during operation; (4) life cycle emissions from the use of explosives; (5) emissions embodied in concrete produced continuously during mining operations; (5) direct emissions from chemical processes during milling (process emissions); (6) emissions embodied in reagents; (7) direct emissions from methanogenesis of liquid and solid wastes; (8) net change in carbon uptake resulting from land use change over the lifespans of the facilities (i.e., conversion of boreal forest to industrial use); (9) life cycle emissions from transport of materials and personnel to and from facilities (truck and airplane) during operation; (10) emissions associated with decommissioning activities including life cycle emissions from fuel and electricity consumption, reagent consumption, concrete use, and transportation of materials and personnel; and (10) life cycle emissions from electricity and natural gas consumption at corporate headquarters.

Emissions associated with exploration activities, apart from ongoing exploration activities at active sites, are not included within the scope of this assessment. Exploration activities are commonly excluded from life cycle assessments for several reasons: (1) their overall impact is expected to be very small; (2) it is difficult to allocate exploration activities to specific facilities as these activities are ongoing at developed and undeveloped sites, many of which will never be developed; and (3) it can be difficult to collect data from exploration activities for the purposes of life cycle analysis.[4,9−15]

When the term "life cycle emissions" is used above, it implies that emissions from that particular source include direct and embodied emissions. Direct emissions are GHG releases from sources that are owned or controlled by the facility (e.g., GHGs released during fuel combustion in facility equipment). Embodied emissions are those that occur upstream of the facility (e.g., GHGs released during processing and transportation of fuel by a third party).

In this study, the cutoff criteria is set at 0.1% of the life cycle GHG emissions for each mine-mill operation. Cut-off criteria specifies "the level of environmental significance associated with unit processes or product system to be excluded from a study."[16] In some cases, emission sources were assessed before it was determined that their contribution was less than 0.1% (e.g., wastewater). These emissions sources have been retained.

To achieve the goal of this study, high quality data for uranium mining and milling operations in Canada was required. AREVA Resources Canada Inc. (AREVA) and Cameco Corporation (Cameco) are currently the only uranium mine-mill operators in Canada. These companies have supplied operational data from 2006 to 2013 for the McArthur River Operation-Key Lake Operation and the Eagle Point-Rabbit Lake Operation, and operational data from 1995 to 2010 for the McClean Lake Operation. The companies have also provided construction and decommissioning data for each facility. These facilities produced 97% of Canada's uranium from 2000 to 2013.[17] To protect the confidentiality of data supplied by the operators, the three facilities are referred to anonymously as Mine-Mill A, B, and C. Refer to section 1 in the Supporting Information (SI) for more information about these facilities.

4. METHODS

4.1. Assessment Approach. The study is conducted based on the ISO 14040:2006[18] standard for life cycle assessment (LCA) and employs a *Process Chain Analysis* (PCA) methodology.

PCA is a rigorous bottom-up technique that examines all of the material and energy flows within the product system. All activities within the scope of analysis are associated with a quantity of GHG emissions that considers all underlying production steps.[19,20] For example, when diesel is combusted in facility equipment, it releases GHGs directly into the atmosphere. The PCA methodology considers these direct emissions, as well as all upstream emissions associated with crude oil extraction, refining, and transportation.

4.2. Inventory of Emissions Sources. Data on emissions-relevant activities were provided by the mining companies or were accessed from publicly available sources including the mining companies' Web sites and regulatory reports.[21−26]

Operational data was reviewed to determine the operational years for which there was sufficient data to complete the GHG emissions assessment. This resulted in the use of operational data over the period 2006−2013 for two mine-mill pairs, and 1995−2010 for the third mine-mill pair. Operational activities for each mine-mill pair were divided by (i.e., normalized to) total U_3O_8 production during these operational periods. Activities at corporate headquarters during these operational periods are also included and normalized in the same way.

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The full construction and decommissioning periods, including upstream activities associated with equipment and infrastructure, were included in the inventory for all facilities. Construction and decommissioning activities were normalized to each facility's estimated lifetime U_3O_8 production.

Additional information about what data is included and how it is used is available in the SI, sections 2.1 and 2.2. A life cycle inventory data table is also available in the SI, section 2.6.

A process chain model of each facility was created in SimaPro, an ISO 14040-compatible LCA tool which links to a number of life cycle inventory databases, including the ecoinvent database.[27] The ecoinvent v3.0 database is used to model upstream processes and to estimate emissions in the absence of primary data. When using data from the ecoinvent database, the "allocation, default" library was used. This library follows the same attributional system model as previous versions of the database. The details of how the ecoinvent database has been constructed, how uncertainty is treated, and the data validation process are summarized in Weidema et al.[28]

4.3. GHG Emissions Inventory and Assessment. To convert the inventory of emissions sources to a GHG inventory, each activity is associated with an emission factor. In the PCA model, the emission factor describes the direct emissions (i.e., CO_2, CH_4, N_2O) from each unit process along the modeled process chain.

Emission factors are available from a number of sources, namely the United States Environmental Protection Agency,[29] Environment Canada[30] (fuel burning), SaskPower[31] (electricity consumption), the ecoinvent v3.0 lifecycle inventory database,[32] and other peer-reviewed literature. Additional information about the emissions factors used in this study is available online in the SI, section 2.3.

Carbon dioxide, methane, and nitrous oxide emissions are converted to carbon dioxide-equivalents (CO_2e) using the 100-year global warming potentials (with climate carbon feedbacks) of 1, 34 (36 for fossil CH_4), and 298 CO_2e respectively provided by the Intergovernmental Panel on Climate Change in its Fifth Assessment Report.[33] This represents an update compared to reporting requirements under the *Canadian Environmental Protection Act* for GHG emissions occurring from 2004−2013.[34]

4.4. Conversion from kg CO_2e/kg U_3O_8 to g CO_2e/kWh. In other studies,[4,9,13,15,19,35−41] the GHG emission intensity of uranium mining-milling is typically presented in terms of g CO_2e/kWh. Values can be converted to g CO_2e/kWh, or vice versa, using a conversion factor of 2.7×10^{-5} kg U_3O_8/kWh as developed for light water reactors (LWRs) in the SI, section 2.4.

The LWR conversion factor is chosen because that is the reactor technology for which life cycle GHG emissions are most commonly reported.[2−5] If the reactor technology to be used is a heavy water reactor (e.g., CANDU), an appropriate conversion factor is 2.0×10^{-5} kg U_3O_8/kWh (see SI, section 2.4).

4.5. Determination of Ore Grade and Weighted Average. Ore grades for Mine-Mill A, B, and C are calculated based on the total mass of packaged U_3O_8 leaving each mill divided by both the total mass of ore processed by the mill and the mill recovery rate over the study period.[21,22] At these facilities, there can be differences in the grade of ore mined compared to what enters the milling circuit in any given year. This is due to a time lag between mining and milling and/or the processing of stockpiled material from historical operations at each facility.[21,22]

The production-weighted average ore grade and emission intensity for the mine-mills are calculated based on relative U_3O_8 lifetime production volumes at each of the mines included in the study. Historical and forecasted production values are taken from annual and technical reports for each operation and the companies' Web sites.[21,22,42−45] The production values used are stated in the SI, section 1 and further discussed in SI, section 2.2.

4.6. Uncertainty and Sensitivity Analysis. Where there are gaps in operational data for a facility, the uncertainty is assessed based on the number of years without data and the year-to-year variation of the known data using a log-normal probability distribution. The log-normal distribution was chosen because it provided a good representation of the variation in the available data (see section 2.5 in the SI for calculation details).

When the above method could not be applied (e.g., emission factors, infrastructure and equipment), uncertainty is assessed based on the methodology used in the SimaPro software and ecoinvent database, described in Weidema et al.[28] (see discussion in SI). Uncertainty estimates are defined as a probability distribution for each data point at the unit process level in the system model. The aggregate uncertainty (i.e., 95% confidence interval) of cumulative life cycle inventory results is calculated using Monte Carlo simulation.[28]

The method for calculating uncertainty described in Weidema et al.[28] requires subjective judgments about data quality and representativeness. Due to this qualitative aspect, a confidence interval calculated in this way is not a precise value. Rather, it provides an indication of the overall uncertainty in the results and the relative uncertainty in the processes that make up the system model.

For the sensitivity analysis, the aggregate uncertainty of each major process (e.g., electricity consumption, process emissions) were determined by isolating the process and using Monte Carlo simulation. To test the sensitivity of the model, emissions from each major process were varied within its 95% confidence interval while other values were held constant. The life cycle inventory data table in section 2.6 of the SI includes activity and emission factors for most major processes and also indicates the level of uncertainty in each.

5. RESULTS AND DISCUSSION

5.1. Emission Intensities. The life cycle GHG emission intensities of the three uranium mine-mill pairs are 81, 64, and 34 kg CO_2e/kg U_3O_8 at average ore grades of 0.74%, 1.54%, and 4.53% U_3O_8 respectively. The production-weighted average emissions are 42 kg CO_2e/kg U_3O_8 from ore with an average grade of 3.81% U_3O_8.

Figure 2 shows the GHG assessment results for each facility and their 95% confidence intervals. The results are calculated using the provincial average emission factor for electricity. Alternative results using an emission factor based on the source of electricity in northern SK are also shown on Figure 2 and discussed in section 5.4. As expected, life cycle GHG emission intensity decreases as ore grades increase.

5.2. Processes. Figure 3 shows the relative contributions of each mining-milling process for each operation and for the production-weighted average.

Uranium mining-milling GHG emissions arise primarily from energy consumption during operation, which account for 71%

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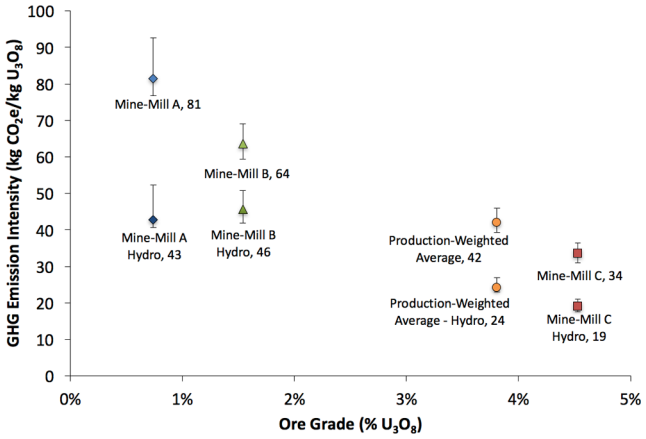

Figure 2. GHG emission intensity vs ore grade. Bars indicate 95% confidence interval for the Canadian data. High result for each mine-mill based on use of provincial average emission factor for electricity. Low result based on use of northern Saskatchewan (hydroelectric) emission factor for electricity.

of the total emissions. This includes emissions from fuel consumption (propane [22%], diesel [7.7%], and gasoline [0.9%]) and from power plants supplying the Saskatchewan grid with electricity (40%), including upstream emissions for these emissions sources. There is a negative correlation (N = 28; $r = -0.727$; see SI, section 3.1) between annual emissions from energy consumption and ore-grade reflecting the reduced energy expenditure required to obtain the same quantity of uranium from ores of higher grade. This correlation is complicated by the differences in the grade of ore mined compared to what enters the milling circuit in any given year (see section 4.5).

Propane fuel is used extensively at all sites, primarily for facility heating in northern SK's sub-Arctic climate (average annual daily temperatures were −2.3 °C ±1.3 °C from 1981 to 2010).[46]

Because of the remote nature of the sites, all personnel are flown to and from each facility, and most freight travels in excess of 700 km each way. Transportation of materials and personnel accounts for 7.2% of the emissions total. Note that upstream transportation for fuels, reagents, equipment, etc. are captured in their respective categories and are not included in the *Truck Transport* category.

The consumption of reagents during mining and milling contributes 6.1% to the emissions total, mostly embodied in ammonia, lime, and hydrogen peroxide used in the milling process (67% of reagent emissions). Emissions from reagent consumption correlate weakly with the average annual ore grade entering the milling circuit ($N = 28$, $r = -0.480$; see SI) which may reflect differences in the extraction processes employed at the different mills. The varying host rock

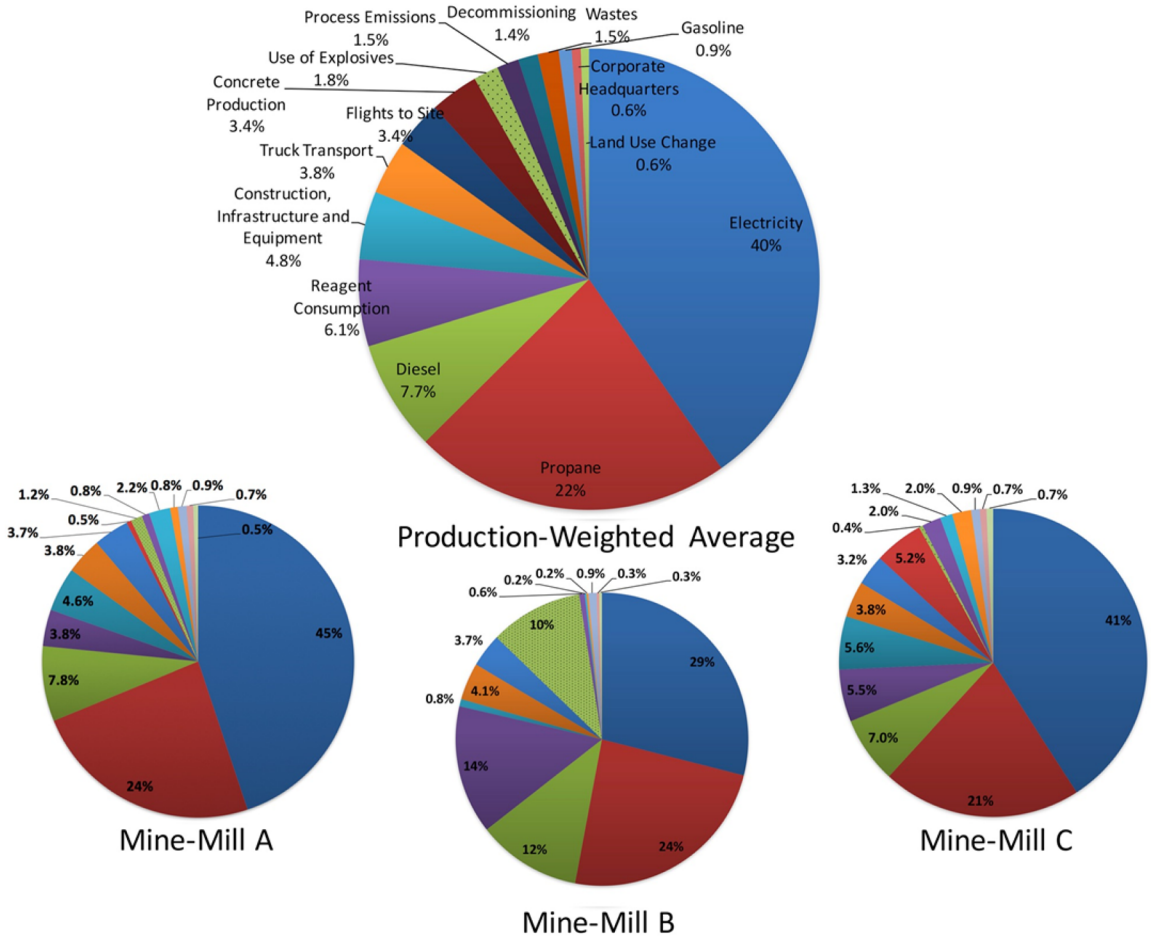

Figure 3. Relative contribution by process for production-weighted average result and for each mine-mill pair. Processes are ordered and colored identically in each pie chart.

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impurities found at each mine, for example, require different treatment processes to remove.

The *Construction, Infrastructure, and Equipment* category includes emissions embodied in materials, the energy required for construction activities, and the transportation of materials and personnel to support those activities. While construction can be energy- and resource-intensive, it is a relatively small component of the life cycle (4.8%) when amortized over the lifetime of the facilities (often 30+ years).[21−23] The same can be said for decommissioning activities (1.4% of emissions).

The amount of concrete used during operation (non-construction) is strongly influenced by the mining method. In raisebore mining (Mine-Mill C), concrete is used to backfill stopes. This results in a higher percentage (5.2%) of total facility emissions being associated with concrete consumption at Mine-Mill C compared to 0.5% at Mine-Mill A (traditional underground). Mining concrete usage at Mine-Mill B (open pit) is negligible.

Noncombustion process emissions (1.5%) arise from the liberation of CO_2 from calcium carbonate in ore and sodium bicarbonate added during the milling process. It is assumed that these carbonates react completely upon exposure to the high-strength acid used during uranium milling.

Wastes (1.5%) include CH_4 and CO_2 emissions from landfilled organic liquid wastes (0.9%), CH_4 emissions from the landfilled solid waste (0.6%), and CH_4 emissions from domestic wastewater (0.01%).

Emissions from land-use change are low (0.6%) since the facilities are located in the low-productivity unmanaged forests of Canada's western boreal shield ecozone.[47] The predisturbance boreal forest is assigned a net ecosystem productivity rate of 31 g-C m^{-2} yr^{-1}[48](see SI, section 2.1.6), which is lost when land is cleared for mine-mill construction. During operations, the mine-mill footprint (approximately 400−900 ha per mine-mill, see SI) is assumed to act as neither a carbon sink nor source, resulting in a net emissions rate of 1137 kg CO_2e ha^{-1} yr^{-1} due to land use change. This emissions rate is maintained until 15-years after the active decommissioning period for each facility when the area is assumed to return to its predevelopment net ecosystem productivity.[49]

5.3. Uncertainty and Sensitivity Analysis. Even though the system model included a number of elements based on partial data, assumptions, and estimates, the overall uncertainty in the result is low, (95% CI for production-weighted average is 39−46 kg CO_2e/kg U_3O_8). This is because detailed data for the highest emitting processes (e.g., energy consumption, transport) were provided by AREVA and Cameco and emissions factors are well established (e.g., emissions from fuel combustion).

Figure 4 shows the overall uncertainty in the result along with the results' sensitivity to uncertainty in the most influential processes. For each horizontal bar in the figure, values associated with the listed process were varied within their aggregate uncertainty ranges (i.e., 95% confidence interval) while all values associated with other processes were held constant.

The largest contributor to overall uncertainty is *Electricity Consumption*, primarily because it is the single largest source of emissions. While there is negligible uncertainty in the amount of electricity consumed, the same is not true for the emission factors for SK electricity. The utility provides data on emissions from combustion of coal and natural gas at its facilities, but no other life cycle emissions data. This missing data was estimated

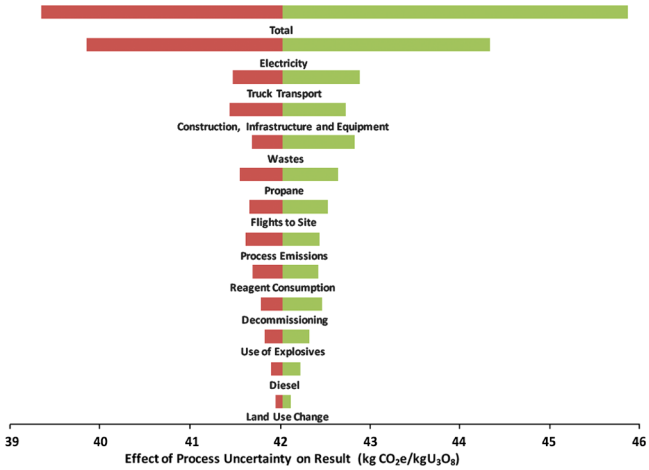

Figure 4. Analysis of model sensitivity to most influential processes (95% confidence interval).

based on values found in the ecoinvent database[27] (non-combustion life cycle emissions for coal and natural gas) and the National Renewable Energy Laboratory's (NREL) Life Cycle Assessment Harmonization Project[50] (life cycle emissions for hydro and wind). The NREL project includes a wide range of life cycle emission estimates for each electricity-generating technology. The median estimate for each technology was used as the default value in the model. The uncertainty ranges for hydro and wind were matched to the ranges presented in the NREL data set. The uncertainty ranges for coal and natural gas were assigned based on the methodology used in the ecoinvent database[28] and discussed further in the SI, section 2.5.

A second major source of uncertainty is direct emissions from nonenergy sources (process emissions). This includes the liberation of inorganic carbon from ore as it is reacted with acid during the milling process. Emissions from this process are directly related to the carbonate content of the ore, for which there is relatively little data. CO_2 and CH_4 may also be released from organic liquid wastes as they degrade in facility-owned landfills. Emissions from these wastes depend on the extent to which they are degraded and by what chemical pathway. These activities vary depending on waste composition and environmental factors. There is little data available to assess the latter.

Uncertainty also arises in some life cycle phases where data for energy and material consumption is unavailable, and in many of the model's upstream processes due to natural variability in manufacturing processes, transportation distances, etc.

A more detailed discussion of the uncertainty analysis is available online in the SI, section 2.5.

5.4. Primary Energy Mix: Hydroelectricity. SaskPower, the provincial electric utility, provides GHG emission factors for its operations as a whole, which span the entire province of SK. The utility does not differentiate their emission factors between the northern and southern regions. Northern SK is powered exclusively by two SaskPower hydroelectric generation facilities and an interconnection with Manitoba Hydro, which generates approximately 96% of its power from hydroelectricity.[51,52] There is no direct intraprovincial grid connection between northern and southern SK.[52] Combined, uranium mines in northern SK used more than 60% of all the power produced at SaskPower's northern hydroelectric stations

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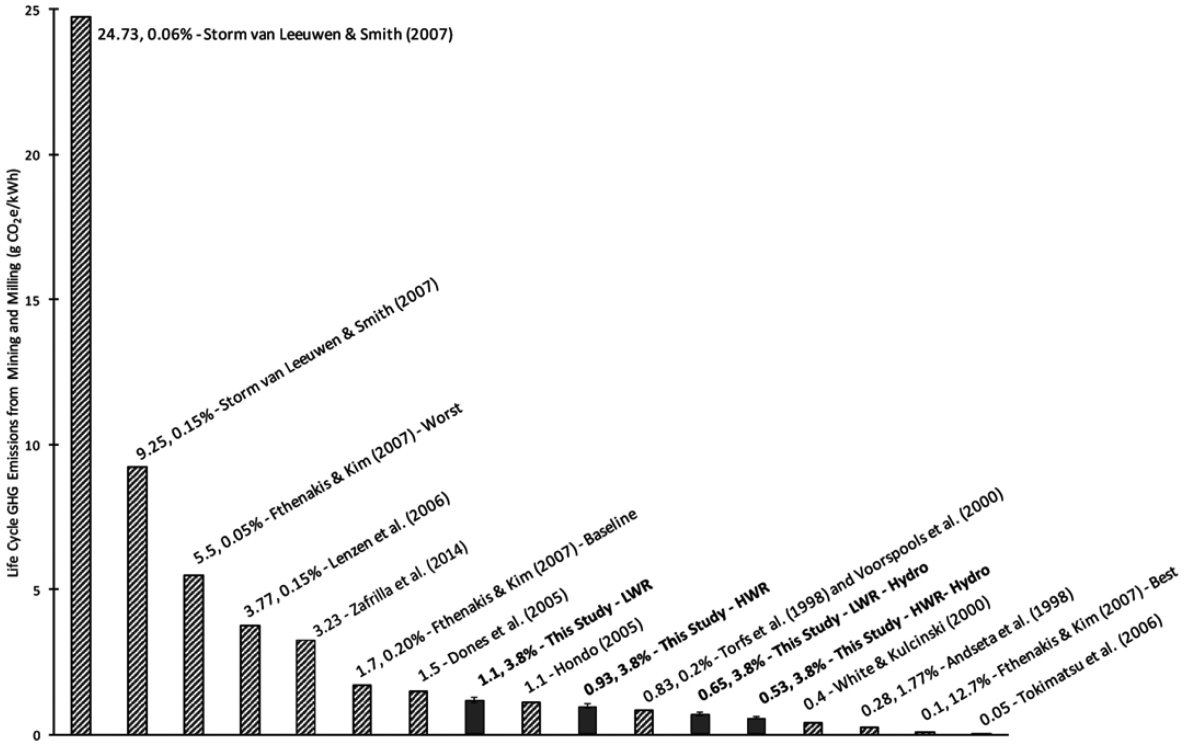

Figure 5. Life cycle GHG emissions from uranium mining-milling in Canada vs other literature estimates.[4,9,13,15,19,35−41] Data labels indicate emission intensity, ore grade if available, and the study referenced.

between 2006 and 2013 (assuming a 40% capacity factor for each power station).[52,53,54] Given that electricity is a large contribution to total energy consumption at SK uranium mine-mills, using the local hydroelectric emission factor (7.2 g CO_2e/kWh)[50] rather than the provincial average (768 g CO_2e/kWh)[27,31,50]dramatically reduces the emissions estimate for each facility (see Table S3). In this scenario, the production weighted average estimate is reduced by 42% (see Figure 2).

In the hydroelectric scenario, electricity goes from being the dominant emission source to one of the smallest, its contribution to the emissions total shrinking from 40% to less than 1%. As a secondary effect, the low hydroelectric emission factor reduces the emission estimate for construction and decommissioning during the time period that electricity is supplied from the grid for those activities.

5.5. Comparison to Other Estimates. Figure 5 shows the results of this study plotted against other emission estimates included in four critical review or meta-analysis studies of the nuclear fuel cycle.[3−5,50] Data are presented in units of g CO_2e/kWh. When considered as a phase in the nuclear fuel cycle, the production-weighted average emission intensity in this study ranges from 0.53 to 1.1 g CO_2e/kWh depending on the electricity emission factor applied and the reactor technology used (refer to section 4.4 and SI, section 2.4 for details of unit conversion).

At least three of the estimates included in Figure 5 consider yellowcake produced in Canada. Hondo[37] presents a similar estimate, while Fthenakis and Kim,[4] and Andseta et al.[41] produce lower estimates. None of these capture recent production in Canada and none include the breadth of emission sources included in this study.

Of these three estimates, the most recent estimate comes from Fthenakis and Kim (0.1 g CO_2e/kWh or approximately 3.7 kg CO_2e/kg U_3O_8 at 12.7% U_3O_8).[4] This 'best-case' scenario was based on the estimated energy consumption required for exploration, mining, and milling of Canadian uranium.[4] Energy consumption appears to be extrapolated from the 'base-case' scenario. The use of extrapolated data and a smaller system boundary likely led Fthenakis and Kim[4] to estimate low life cycle GHG emissions from uranium mining-milling in Canada.

Andseta et al.[41] report emissions of 0.28 g CO_2e/kWh (10.3 kgCO_2e/kgU_3O_8) at 1.77% U_3O_8 from uranium mining-milling based on production at Key Lake, Rabbit Lake, and Cluff Lake in 1996.[41] Like Fthenakis and Kim,[4] Andseta et al.[41] use a smaller system boundary than the present study, considering only energy consumption and reagent oxidation.[41] Andseta et al. attributes electricity at two of the three facilities to emissions-free hydroelectric power, and electricity at the third facility to diesel power generation. No *Other Indirect* emissions were included.

The production-weighted average GHG emission intensity in the present study is higher than in Andseta et al.[41] (42 vs 10 kgCO_2e/kgU_3O_8), includes two of the same facilities, and has a higher average ore grade (3.81% vs 1.77% U_3O_8). The higher emission intensity estimate in the present study can be explained by the use of a larger system boundary, the use of life cycle emission factors for each emissions source, and the use of a more complete data set.

Underestimations by Fthenakis and Kim,[4] Andseta et al.,[41] and others arise in part from a known shortcoming of the process chain analysis methodology: the systematic under-estimation of results due to truncation at the system boundary.[2,20,55] This study addresses the problem of under-estimation by including a very large and inclusive system boundary.

When compared to estimates in Figure 5 for yellowcake produced outside of Canada, the result of this study are lower

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than all but two others: White and Kulcinski,[13] and Tokimatsu et al.[39] The former estimate includes uranium mining only (milling emission are combined with other downstream processes such as enrichment) and provides no information about its system boundaries. The latter references source material that is only available in Japanese and so cannot be easily reviewed. The inaccessibility of life cycle inventory and methodology data observed here is common in the literature reviewed.

The system boundaries used to estimate GHG emission from uranium mining-milling vary between studies. All of the studies discussed so far in this section have used a narrower system boundary than the present study. Contrastingly, Zafrilla et al.[40] avoids system boundary truncation by using a hybrid multiregional input-output model. This approach relies on a combination of process data from ecoinvent[32] and input-output data from the World Input-Output database.[56] While Zafrilla et al.[40] uses a different methodology than the present study, the system boundary should be comparable.

The system boundary for Storm van Leeuwen and Smith[9] is narrower than the present study but more inclusive than most others. It includes energy consumption during mine-mill operation and construction as well as energy requirements for the transportation of ore and materials.

Overall, life cycle GHG emissions from the mining and milling of Canadian uranium are low compared to estimates for uranium production elsewhere, largely due to the high ore grades currently in production. It is important to remember that uranium production makes up only a part of the nuclear fuel cycle, representing between 0.5% and 30% of total life cycle emissions.[3−5] Remaining life cycle emissions come from downstream uranium processing, fuel rod fabrication, power plant construction through decommissioning, and spent fuel management. These phases should all be considered when assessing total GHG emissions from nuclear power, which could range from 3.7 to 110 g CO_2e/kWh as noted in section 1.[2]

5.6. Future Work. The results of this study can be used to improve the accuracy of GHG emissions estimates for nuclear power generation using Canadian uranium. This work could be further expanded upon by increasing the scope of environmental impacts considered. A full LCA would include all major potential environmental impacts, including but not limited to ozone depletion, global warming, acidification, eutrophication, human health, ecotoxicity, fossil fuel use, land use, and water use. This broader scope is necessary to evaluate the environmental trade-offs of competing energy products (e.g., coal-based electricity versus nuclear power).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b06072.

Additional details on the facilities, emission sources, emission factors, uncertainty analysis, and results (PDF)

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Notes

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