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Development of disaggregated energy use and greenhouse gas emission footprints in Canada's iron, gold, and potash mining sectors

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ABSTRACT

This study develops the disaggregated energy use and greenhouse gas (GHG) emission footprint for Canada's iron, gold, and potash mining sectors. Currently, only high-level aggregated data at the sectoral and regional levels exists in the literature. Through bottom-up energy demand tree development, we identified end-use processes for each mining operation in these sectors. The energy intensities for each end-user were calculated and used in a bottom-up energy-environmental model to determine the associated end-use process GHG emissions. The results were then used to develop Sankey diagrams that allow us to visualize the energy and GHG emissions flows from resource to end use by energy use sector, fuel type, and various jurisdictions in Canada. The overall energy and GHG emission intensities for iron, gold, and potash mining are 0.7, 149.8, 1.8 GJ/Mg and 33, 4922, 158 kg CO_2 eq./Mg, respectively. Firing, ventilation, and product drying and steam generation end-use devices had the highest energy use share of 42%, 20%, and 47% in iron, gold, and potash mining sectors, respectively, in 2016. Firing in iron mining, ore transport in gold mining, and product drying and steam generation in potash mining were responsible for 66%, 22%, and 34% of the respective total sectoral GHG emissions. 56% of the GHG emissions were from Saskatchewan, followed by Quebec (18%), and Newfoundland and Labrador (14%). The results from this study provide benchmarks to develop energy savings and GHG mitigation strategies useful for decision making.

1. Introduction

The industrial sector is a major contributor to global greenhouse gas (GHG) emissions. It accounted for 37% and 27% of global energy use and GHG emissions, respectively, in 2016 (International Energy Agency, 2018, 2019a). Industrial GHG emissions grew at an average annual rate of 3.5% world-wide between 2005 and 2010, despite a growing number of climate change mitigation policies (Fischedick et al., 2014). Industrial sector energy demand and GHG emissions need to be disaggregated and analyzed both to understand how energy is used and to design cost-effective GHG reduction strategies.

According to the Intergovernmental Panel on Climate Change (IPCC), a key challenge in assessing energy use reduction and GHG mitigation potential for the global industrial sector is the lack of complete and quality data on sub-sectoral processes and technology energy use (Fischedick et al., 2014). The available data is mainly aggregated at the sectoral and regional and/or national level. A breakdown of energy consumption and GHG emissions by process and fuel type is required to identify the production steps that consume the most energy and are the highest GHG emitters (Eckelman, 2010). The disaggregation also provides a benchmark to quantify the environmental and economic benefits of improving energy efficiency, fuel switching, process substitutions, and carbon capture and storage (Brueske et al., 2012; Natural Resources Canada, 2005a). These quantifications help us compare and prioritize GHG mitigation opportunities.

The Canadian mineral mining industry lacks disaggregated energy and GHG emissions data. Globally, Canada is one of the leading mineral extraction countries and one of the largest producers of metals and nonmetals (Mining Association of Canada, 2016). This industry accounted for 18.2% of the goods exports in value and contributed 3.5% of the country's gross domestic product (GDP) in 2014. Canada extracts a diverse range of minerals but the primary energy demands for the industry are mainly driven by three sectors, iron, gold, and potash mining. These together consumed 65% (93.8 PJ) of the energy and

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Abbreviations: AG, autogenous; CIC, carbon-in-column; CIL, carbon-in-leach; CIP, carbon-in-pulp; DSO, direct shipping ore; EF, emission intensity factor; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; LEAP, long-range energy alternative planning; MJ, megajoule; NRCan, Natural Resources Canada; PJ, petajoule; SAG, semi-autogenous; SEDAR, System for Electronic Document Analysis and Retrieval

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emitted 66% (3 million Mg (Mg) CO_2 eq.) of the mineral extraction industry energy demand and GHG emissions, respectively, in 2014 (Natural Resources Canada, 2018b). Energy use increased by 19%, 105%, and 8% between 2005 and 2014 for the iron, gold, and potash mining sectors, respectively. Moreover, Canada is the largest producer of potash, fifth largest producer of gold, and ninth largest producer of iron ore in the world (US Geological Survey, 2016).

Past studies have quantified, to differing degrees, the energy intensities of iron, gold, and potash mining operations. Canadian benchmark studies have examined the energy intensities in iron and gold mining operations by comparing energy consumption in various facilities (Natural Resources Canada, 2005a, 2005b). The studies aggregate the mining operations into large subgroups and the scope is limited to three iron ore mines producing concentrates and fifteen gold mines producing gold bars. Moreover, the studies do not provide the energy use by fuel type, ore type, and for all the processes in mining operations. The US Department of Energy modelled the energy requirements of various equipment types for surface iron, gold, and underground potash mines (US Department of Energy, 2002a, 2002b, 2002c). However, the study estimated energy intensities for only some of the end-use processes. Also, energy intensities were not estimated for underground gold mining and potash solution mining operations. Griffing and Overcash (2010) produced a life cycle inventory report for iron ore mining and pelletizing in the US. The data in the report was based on literature, industry practice, and process design and estimated the energy intensities of taconite iron ore mining operations. Their report was limited to the estimation of device-level energy intensities for concentration processes and aggregated energy intensities for extraction processes. Bleiwas (2011) estimated only the electricity energy requirements of ore extraction equipment. Haque and Norgate (2015) conducted a life cycle analysis (LCA) and gave a breakdown of energy and GHG emission intensities for various mining and mineral processing steps in Australian high-grade (typically 60%) iron mines. The study did not provide the energy requirements for low-grade ores, which require additional processing, or for pelletizing processes. Norgate and Haque (2012) also used LCA to estimate the GHG footprint in gold mining but did not disaggregate the emissions into different end-use processes. Another Canadian study on potash production facilities presents aggregated energy consumption, energy intensity, energy use by type, and GHG emissions for extraction and milling operations (Government of Canada, 2003). Like the studies cited above, there is no process-level disaggregated energy-use information.

The existing literature on iron, gold, and potash mining does not include a study that covers all end-use energy intensities by fuel type for all different ore types and operations. Past studies have been limited to aggregated energy intensities for some operations. Furthermore, energy use and GHG emissions data in the Canadian iron, gold, and potash mining sectors are not disaggregated to the end-use level. This research fills these gaps.

Another novelty of this study is the application of Sankey diagrams to illustrate the disaggregation of energy use and GHG emissions in iron, gold, and potash mining sectors. A Sankey diagram is a process visualization tool that shows the flow of energy from source to end use with arrows; the width of the arrows represents the magnitude of the flow (Davis et al., 2018b). Its efficacy for showing energy and GHG emissions has been shown in the literature. Schmidt (2008) presented historical uses of these diagrams in energy and material management flow. Leal-Ayala et al. (2015) used a Sankey diagram to illustrate the energy consumption and mass flow from tungsten ore extraction to different end products. Brueske et al. (2012) mapped the flow of energy to various end uses in the US manufacturing sector in the form of a Sankey diagram that serves as a baseline for calculating the benefits of improved energy efficiency. Zhao et al. (2016) illustrated industrial residual energy flows via Sankey diagrams for 12 high energy consuming industry sectors in China. Their analysis found energy recovery potential in different sectors. Griffin et al. (2013) modelled Sankey energy flow diagrams of the UK's pulp and paper, chemical, iron and steel, food and drink, and cement manufacturing sectors. Perez-Lombard et al. (2011) used Sankey diagrams to map the energy flows of heating, ventilation, and air-conditioning systems used in office buildings in Spain and identified heating, ventilation, and air conditioning systems loads and losses. Cullen and Allwood (2010) mapped the global flow of energy from fuels through conversion devices and passive systems to final services in the form of Sankey diagram. Davis et al. (2018b) mapped the energy flow from primary fuel to end use in all the provinces and territories in Canada and used the mapped Sankeys to calculate the energy losses and useful energy consumption. Subramanyam et al. (2015) developed the Sankey diagrams for Alberta's energy demand and electricity generation supply sectors.

Sankey diagrams have also been used for GHG emission analysis. Davis et al. (2018a) used Sankey diagrams to illustrate GHG emissions in different Canadian economic sectors and the resources responsible for the emissions. Griffin et al. (2018) evaluated a GHG mitigation potential of 80% (between 1990 and 2050) for UK's pulp and paper sector through a Sankey diagram. The World Resources Institute used a Sankey diagram to map global GHG emissions for the year 2000 (Baumert et al., 2005). Other examples include using Sankey diagrams to map global energy balances (International Energy Agency, 2019b), US energy consumption (Lawrence Livermore National Laboratory, 2018), global exergy and carbon flow (Hsiao, 2009), and the substance flow of recycled materials from waste batteries and raw ore (Song et al., 2017). As these studies show, Sankey diagrams are an effective means of analyzing the energy use, energy type, and emissions, and they help focus efficiency improvement efforts in areas of high energy savings and GHG mitigation potential. However, an analysis does not exist for any mineral mining sector.

Hence, the objective of this study is to provide a disaggregated end-use energy and emissions analysis of three mining sectors in Canada for the year 2016 at the regional and national levels using Sankey diagrams.

2. Methods

The study had four main steps as illustrated in Fig. 1. First, the production activity data related to 102 iron, gold, and potash mines in Canada from the year 2010 to 2016 was compiled (and is discussed further in Section 2.1). Second, the end-use devices, fuels used, and their energy intensities were calculated to develop energy consumption demand trees (Section 2.2). Third, Long range Energy Alternatives Planning (LEAP) model (Davis et al., 2019; Heaps, 2016) was used to calculate the energy use and GHG emissions for the years 2010 to 2016 (Section 2.3). The aggregated results were validated by comparing them with Natural Resources Canada (2018b) data. Finally, Sankey diagrams were developed for the year 2016 (Section 2.4). 2016 was considered for Sankey diagrams since it was the latest year for which most of the required data is available.

2.1. Production data

A dataset of annual iron, gold, and potash mining production activity for the years 2010 to 2016 in each Canadian province was compiled. A list of individual operating mines for both underground and open-pit mining operations in each province was obtained from the mining industry report (Mining Association of Canada, 2016) and are shown in Fig. 2. Then, company reports from the System for Electronic Document Analysis and Retrieval (SEDAR) database (SEDAR, 2017) and annual statistics of mineral production by NRCan (Natural Resources Canada, 2018a) were used to obtain activity data. Activity data includes the crude ore, waste extracted, ore processed, ore produced, and the processing routes for each mine. Other mine-specific data such as the ore type, ore grade, strip ratio and recovery factor were also compiled. When data was not reported, we assumed that these values remained

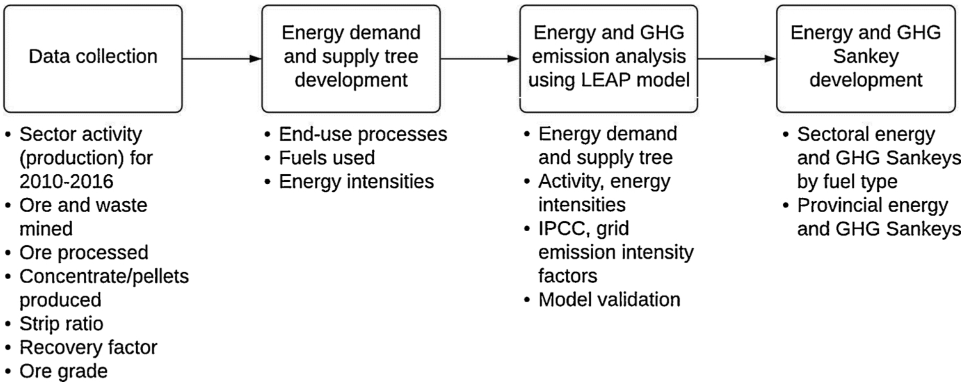


Fig. 1. Method used in the study for disaggregating energy and GHG emissions.

the same as they were the previous year, as the annual change for a given mine was not significant. For example, the strip ratio for the Iron Ore Company of Canada changed from 1 in 2010 to 1.1 in 2015 (Labrador Iron Ore Royalty Corporation, 2019).

The study is limited to energy and GHG emissions from mines where iron, gold, and potash are the primary products. For example, gold is produced as a co-product or by-product in many other metal mines; those mines were excluded. This is in accordance with the North American Industry Classification System (NAICS) for mining industries (Statistics Canada, 2018), in which the mines with iron, gold, and potash as primary products are classified under NAICS codes 21221, 21222, 212396, respectively. The activity data compiled for the iron, gold, and potash sectors is shown in Table 1.

2.2. Energy demand tree development

The data related to end-use processes, fuel types used, energy intensities, and associated production from the different stages of iron, gold, and potash mining were obtained as described below. With this data, we developed end-use process energy consumption demand trees and calculated fuel-use intensities. These demand trees are a structured way of showing end-use processes and fuel types used in each sector.

2.2.1. Iron ore mining

Iron-bearing ore consists of a variety of minerals in which the iron is primarily bonded with oxygen, water, carbon dioxide, or sulphur (US Department of Energy, 2002b). Among the minerals that constitute an iron ore deposit, the most important are magnetite (Fe_3O_4), hematite (Fe_2O_3), geothite ($Fe_2O_3{\cdot}H_2O$), and limonite ($Fe_2O_3{\cdot}H_2O$). Canada has three types of iron ores deposits: high-grade ores (> 50% Fe) of hematite/goethite known as direct shipping ores (DSOs), medium-grade (up to 41% Fe) specularite magnetite iron ore formations known as metataconites, and low-grade (15–30% Fe) magnetite ore formations known as taconites (Conliffe et al., 2012; Government of Newfoundland and Labrador, 2017). Over the past five decades, Canadian iron ore production has been concentrated in a geological region known as the

Fig. 2. Iron, gold, and potash producing mines of Canada (contains information licensed under the Open Government License — Canada (Natural Resources Canada, 2019)).

Table 1
Complied activity data for the study.

Iron ore mining	Gold ore mining (Both open-pit an underground mining)	Potash mining (Both conventional and solution mining)
Crude ore mined (O)	Crude ore mined	Crude ore mined
Waste mined (W)	Waste mined	Ore processed or milled
Ore processed or milled	Ore processed or milled	Potash produced
Concentrate produced (C)	Ore processed in gold extraction	Concentration ratio
Pellets produced (P)	Gold produced	
Strip ratio	Strip ratio	
Recovery factor	Ore grade (g/Mg)	

Labrador Trough in Western Labrador and Northeastern Quebec, where metataconite and DSO deposits are mined continuously (Conliffe et al., 2012). The extracted iron ore is concentrated and made into pellets or sintered for feeding into a blast furnace to produce iron; this represents almost 95% of all the metals used by the industrial sector (Griffing and Overcash, 2010). In 2015, Canada produced 47 million Mg of iron with production shares of 55%, 42%, and 3% in Quebec (QC), Newfoundland and Labrador (NFL), and Nunavut (NU), respectively (Arcelor Mittal, 2017; Cleveland Cliffs Inc., 2017; SEDAR, 2017).

The stages of the mining process can be divided into extraction, haulage, ore processing, and pelletization (Härkisaari, 2015) and are described in detail in the Supplementary file. After extraction and haulage to the mill, the high-grade DSOs are subjected to simple dry or wet processing of beneficiation to meet size requirements (Jankovic, 2015). The main processes are crushing and screening to separate lumps and fines. The ore is also subjected to density separation and then magnetic separation to remove magnetite content in the ore if necessary. Compared to DSOs, metataconite ores are much finer grained, and therefore processing involves significant crushing and grinding of run-of-mine ore to liberate magnetite from its silicate matrix, followed by gravity separation, flotation, and magnetic separation to produce concentrate (Jankovic, 2015). The flotation process sometimes requires clusters of cyclones to remove ultrafine material. Some portion of the produced concentrate is filtered and passed to the pelletizing plant. Pelletizing involves pretreatment, agglomeration (balling), sieving, and firing to form pellets of a consistent size (Griffing and Overcash, 2010).

The other processes include drying and dewatering to separate water from the minerals using thickeners and filters (New Millennium Capital Corp., 2010). In addition, pumps for tailings disposal, conveyors, and material handling are used, as well as other equipment for support activities, service, and road maintenance (Natural Resources Canada, 2005a).

Some companies report annual strip ratio instead of the total material removed and annual recovery factor instead of the total material milled (Arcelor Mittal, 2017; Dupéré, 2014). The strip ratio is defined as the ratio of waste mined to crude ore mined and the recovery factor is defined as the ratio of iron concentrate (ore) produced to crude ore milled or processed. In such cases, the energy intensities available in terms of MJ/Mg of W + O for extraction processes were converted into MJ/Mg of O using the strip ratio, as shown in Eq. (1). The energy intensity of comminution processes was converted from MJ/Mg of ore crushed or milled into MJ/Mg of C using the recovery factor and Eq. (2).

$$\frac{MJ}{t\ of\ O} = \frac{MJ}{t\ of\ W + O} \times \left(1 + \frac{W}{O}\right) \tag{1}$$

$$\frac{MJ}{t\ of\ C} = \frac{MJ}{t\ of\ ore\ processed} \div Recovery\ factor \tag{2}$$

Extracted crude ore, and concentrate and pellet production data were obtained from SEDAR (SEDAR, 2017), ArcelorMittal (Arcelor Mittal, 2017), and Cleveland-Cliffs (Cleveland Cliffs Inc., 2017) and are shown in Table A1 in the Supplementary information. DSO ores are mined only in NFL. The concentrate production in the table includes the concentrate used for pellet production. The end-use processes and fuels used are shown in the form of energy consumption demand tree in Fig. 3a, and their energy intensities are in Table 2a.

2.2.2. *Gold mining*

Gold production in Canada is mainly concentrated in Ontario (ON) and Quebec (QC), where, in 2015, 50% and 28% of the country's 148,953 kg of gold was produced (SEDAR, 2017). 3% of this total production was a by-product of other metal mining operations. 9%, 8%, 2%, 2%, and 1% of the gold production in 2015 was from British Columbia (BC), Nunavut (NU), Saskatchewan (SK), Manitoba (MB), and Yukon (YU), respectively. In 2015, 64% of production was from underground mines, and 94% of underground mine production was from ON and QC (SEDAR, 2017).

The mining process can be divided into ore extraction, comminution, gold extraction, gold recovery, and post-recovery processes (Marsden, 2006; US Department of Energy, 2002a) and the detailed description of the processes are in the Supplementary file. After extraction, the ore is crushed and ground into uniformly sized particles. Sulphide ores have a higher energy demand than other ore types as they are subjected to roasting, chlorination, bio-oxidation, or autoclaving to oxidize the sulphide-bearing minerals (US Department of Energy, 2002a). Then, flotation, gravity concentration, and leaching (heap leaching or tank leaching) are used to extract gold from ore (Marsden, 2006). For gold recovery, the Merrill-Crowe process and the activated carbon adsorption process are used. In the Merrill-Crowe process, zinc is added to precipitate the gold and form a zinc-cyanide complex, which undergoes solid-liquid separation (US Department of Energy, 2002a). The energy use details data for this process is not available in the literature. The carbon adsorption process can be done through the carbon-in-pulp (CIP), carbon-in-column (CIC), or carbon-in-leach (CIL) method (Norgate and Haque, 2012). Later, the gold is stripped from the activated carbon and plated through electrowinning and then smelted (Marsden, 2006). Electrowinning is the process of plating the gold from the solution onto a cathode (US Department of Energy, 2002a). In some cases, the gravity or flotation concentrate is directly smelted.

The total material extracted, ore extracted in open-pit and underground mines, ore milled, and ore processed through gold extraction and recovery techniques for the years 2010–2016 are shown in Table A2 in the Supplementary information. Depending on the ore, mining companies use a mix of extraction and recovery techniques. Therefore, for each operating mine, we used the process flow sheets to consolidate the production of gold through different extraction, recovery, and post-recovery processing routes in each province. The data is shown in Table A3 in the Supplementary information. Around 50% of the gold is extracted through agitated cyanide leaching, 83% is recovered through CIP and CIL, and 79% is electrowinned. This approach is used for each province to calculate the total energy consumption and emissions.

The intensities for ore extraction and comminution processes were obtained from NRCan (Natural Resources Canada, 2005a, 2005b) and SEDAR (SEDAR, 2017). For the gold extraction and recovery processes, Norgate and Haque (2012) estimated the energy intensities and fuels used for an ore grade of 3.5 g/Mg Au. These values were adjusted to the Canadian ore grades to calculate energy consumption. The total energy used for mine air heating was calculated using Eq. (3), obtained from literature (Mine Wiki, 2018), as device-level energy intensity is not available in the literature. The energy is met by propane fuel and the input parameters are shown in Table A4 in the Supplementary file.

$$Propane\ energy\ cosumption = \frac{\frac{m_{air}}{m_{ore}} \times C_{p,air} \times (T_{req,air} - T_{amb,air}) \times m_{ore}}{\eta_{propare\ heater} \times (12/N)} \quad (3)$$

In the equation, $\frac{m_{air}}{m_{ore}}$ is the ratio of mass air flow required per mass crude ore produced, $C_{p,air}$ is the specific heat capacity of air, $T_{req,air}$ is the recommended temperature to which air is heated, $T_{amb,air}$ is the ambient temperature of the outside air, $\eta_{propane\ heater}$ is the efficiency of the propane heater, and N is the number of months of air heating required in a year.

The energy intensities and energy demand tree are shown in Table 2b and Fig. 3b, respectively.

2.2.3. Potash mining

Potash refers to potassium compounds and potassium-bearing materials that exist predominantly in mineral form as sylvinite containing sylvite or potassium chloride (KCl) and halite (NaCl) (Garrett, 1996). Potassium is mined through conventional mining and solution mining (Garrett, 1996; Government of Canada, 2018). Canada has 10 mines in SK and 1 in NB (SEDAR, 2017). 2 mines in SK use solution mining and the rest (87%, as of 2015) use conventional mining. Conventional mining involves drilling, blasting, and using continuous mining machines to mine the mine seam. Then conveyors transfer the ore to underground bins that are hoisted to the surface. In solution mining, brine is injected into the mine and circulated underground to dissolve the potash and salt. The brine is then pumped to an evaporation pond on

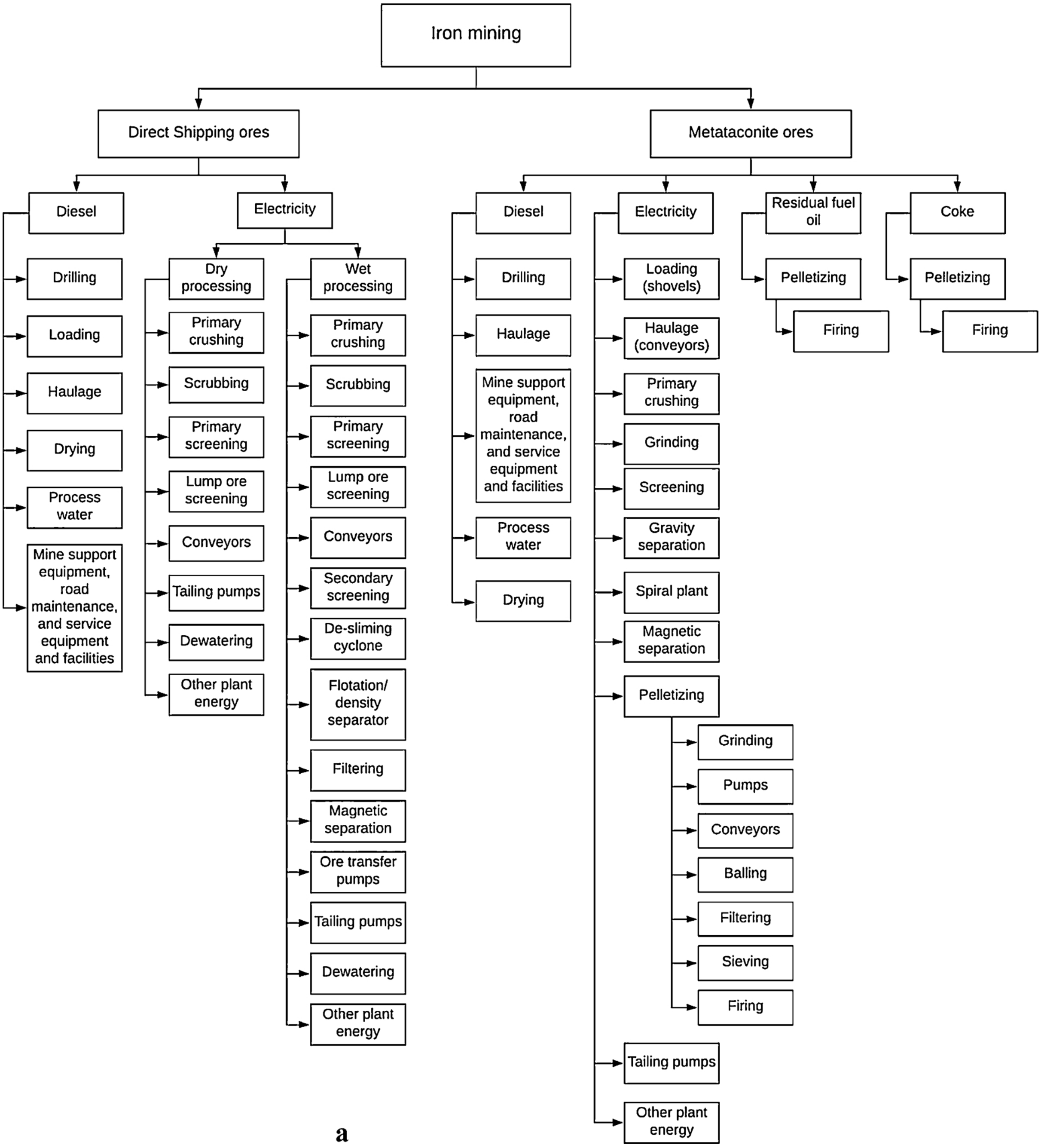


Fig. 3. (a) Energy demand tree for iron mining. (b) Energy demand tree for gold mining. (c) Energy demand tree for potash mining.

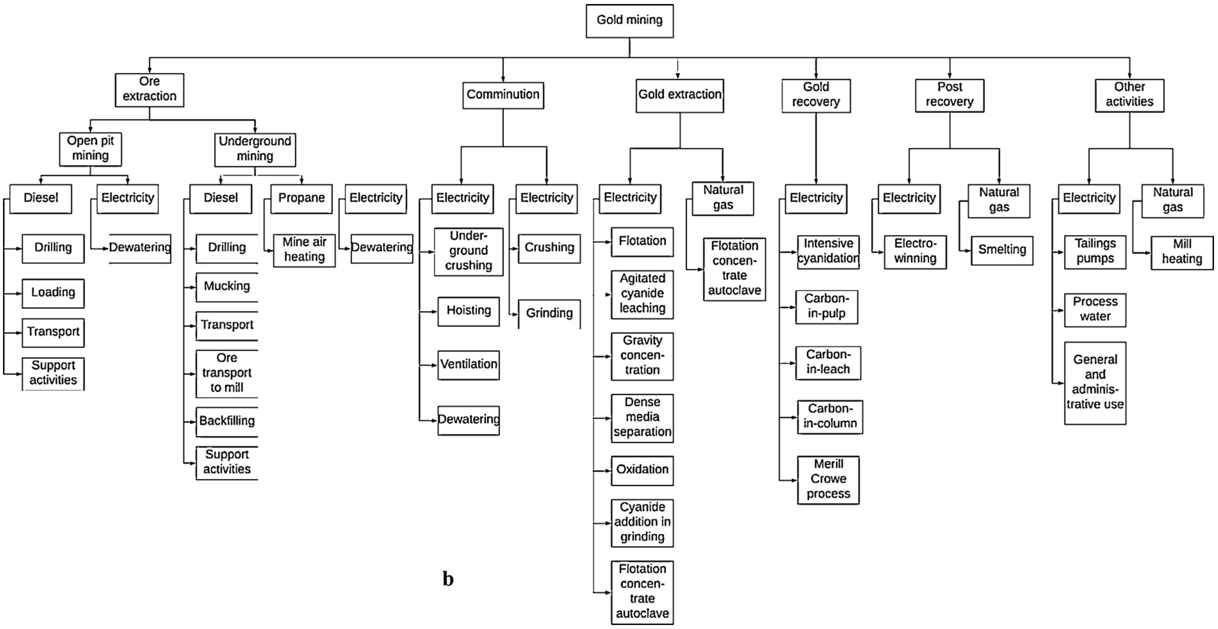


Fig. 3. (*continued*)

the surface where the potash and salt crystals settle to the bottom of the pond. The potash is removed from the pond and pumped to the mill for recovery. Solution mining is highly energy intensive compared to conventional mining due to the high thermal and electricity requirement for steam generation and pumping operations. The obtained ore is crushed to free the KCl, which is ground into fine particles, and then the clay is scrubbed off. Then, potash is separated using flotation and dried in natural gas kilns. Later, it is screened to classify the particles, and the fine particles are compacted to make a larger size. The energy demand tree is shown in Fig. 3c. The share of the energy use of ore extraction, crushing, flotation, screening, and compaction end-use devices were obtained from a study by the US Department of Energy (US Department of Energy, 2002c). Using these shares, the total energy intensities from a benchmark study on Canadian potash facilities (Government of Canada, 2003) were disaggregated to obtain the energy intensities of the sub-processes shown in Table 2c. Potash production data was taken from companies' annual reports, technical reports, and filings by SEDAR and the US Securities and Exchange Commission (SEDAR, 2017; US Securities and Exchange Commission, 2018) and is as shown in Table A5 in the Supplementary information.

2.3. *Energy and GHG emission analysis*

The energy demand trees and process energy intensities defined above were used to develop a bottom-up energy-environmental model of Canada's iron, gold, and potash mineral mining sectors (LEAP-CANMIN). The LEAP modeling system was chosen to model these sectors because it is a bottom-up energy and environmental modeling tool with extensive scenario analysis capabilities. LEAP is a widely used model for energy and GHG emission analysis. Its efficacy has been demonstrated through its use in many countries, including in submissions to the United Nations Framework on Climate Change (UNFCC), developing the energy demand outlook by the Association of Southeast Asian Countries (ASEAN) (Stockholm Environment Institute, 2018) for national and provincial energy and GHG analysis (Davis et al., 2018a, 2018b; Subramanyam et al., 2015), and for GHG mitigation scenario analysis in the cement industry (Talaei et al., 2019) and the residential sector (Subramanyam et al., 2017).

The energy intensities and corresponding mining activity were used to calculate annual sectoral and end-use process-level energy consumption for the years 2010–2016. The corresponding GHG emissions (CO_2 eq.) were calculated by applying IPCC emission factors through LEAP's Technology Environmental Database (TED). These emission factors include only the combustion emissions at the point of usage and are shown in Table A7 of the Supplementary information. For electricity-related emissions, the provincial grid emissions factors estimated by Davis et al. (2019) were used in the LEAP-CANMIN model (shown in Table A6 of the Supplementary information).

The LEAP-CANMIN model calculates the end-use energy demand and GHG emissions from each fuel type for all the mining operations in each Canadian province using Eqs. (4) and (5). The activity data variable (A) varies depending on the end-use, as explained in Section 2.2. The LEAP-CANMIN model was validated by comparing the output of total energy demand and GHG emissions in iron, gold, and potash mining for the years 2010 to 2016 with NRCan data (Natural Resources Canada, 2018b). The average difference between the model and NRCan data for the energy use was 1%, 8%, and 3% and for GHG emissions was 7%, 2%, and 4% in iron, gold, and potash mining, respectively.

$$E_{ij_x} = (e_i)_j \times A \tag{4}$$

$$GHG_{ij_x} = (E)_{ij,x} \times EF \tag{5}$$

In these equations, E is the energy consumption, e is the energy intensity, i is the end-use device, j is the fuel type (electricity, diesel, heavy fuel oil, coke, natural gas), A is the activity (material removed [ore + waste] or crude ore mined or ore processed or ore produced), x is the sector (iron, gold, or potash mining), GHG is the CO_2 eq. emissions, and EF is the emission intensity factor.

2.4. *Development of Sankey diagrams*

Sankey diagrams for energy and GHGs were developed using the software "e!Sankey pro" for the year 2016 (Hamburg, 2019). In a Sankey diagram, the width of the bands or arrows is proportional to the amount of energy the process consumes or the GHGs it emits. The energy and GHG Sankeys are used to illustrate the flow of energy through each energy carrier to end use and the associated GHG emissions. The Sankeys for each sector are structured as shown in Fig. 4a, with the arrows representing energy or GHG emissions. In addition, in order to understand provincial energy demand and GHG emissions from each sector, we developed the Sankeys shown in Fig. 4b.

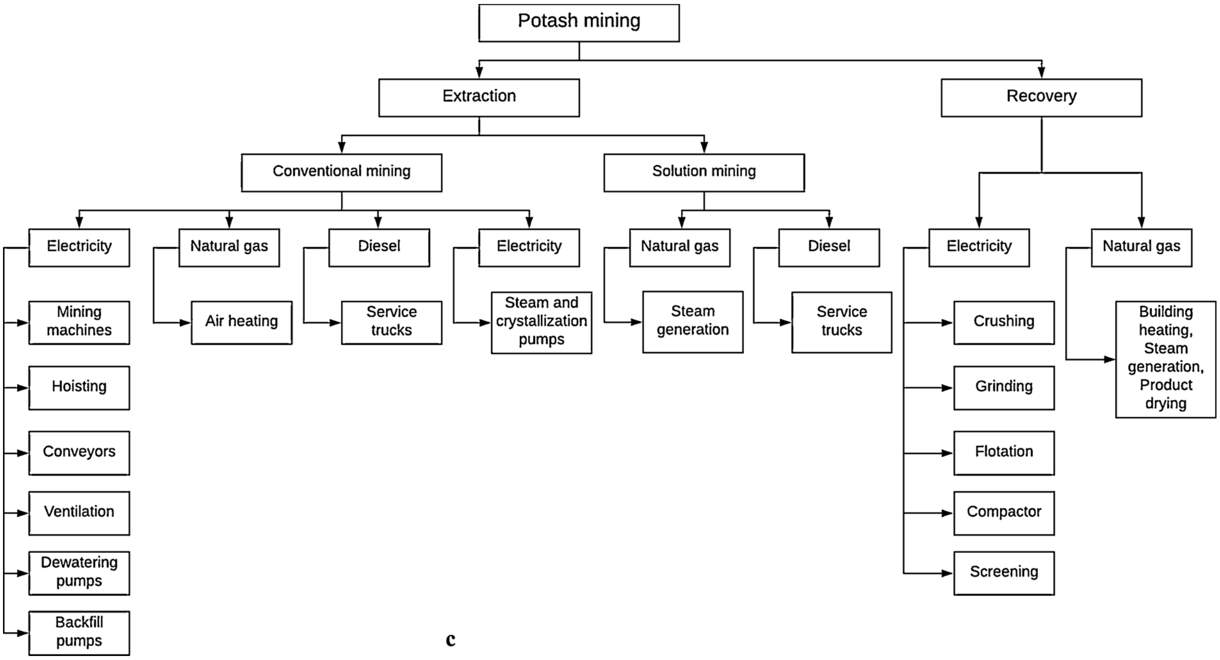


Fig. 3. (*continued*)

3. Results and discussion

3.1. Energy and GHG Sankey for iron mining

The energy and GHG Sankeys for Canada's iron ore mining sector are illustrated in Fig. 5a. In 2016, 39%, 36%, 20%, and 5% of the 29 PJ energy demand was met by electricity, heavy fuel oil, diesel, and coke, respectively. 37% of the electricity used was for comminution, 51% of the diesel used was for haulage activities, and 100% of the heavy fuel oil and coke was used in the firing operations. The pelletization process consumed 47% of the energy, while extraction, beneficiation, and other activities consumed 13%, 24%, and 14%. At the end-use level, the firing process consumed 42% of the energy intake followed by 15% in comminution operations. In 2016, DSOs represented 3% of the production and consumed only 1% of the total energy demand.

In 2016, 1588 thousand Mg of GHGs were emitted by the sector.

Table 2a
End-use process energy intensities of iron mining.

Process	Sub-process	Fuel	Energy intensity	Units	Source
Ore extraction	Drilling	Diesel	1.0	MJ/Mg material removed	Natural Resources Canada (2005a)
	Digging	Diesel	1.3	MJ/Mg material removed	US Department of Energy (2007)
	Loading (wheel loaders)	Diesel	2.6	MJ/Mg material removed	
	Loading (electric shovels)	Electricity	3.2	MJ/Mg material removed	Bleiwas (2011)
	Haulage (trucks)	Diesel	11.7	MJ/Mg material removed	Natural Resources Canada (2005a)
	Haulage (conveyors)	Electricity	4.1	MJ/Mg crude ore	Ferreira and Leite (2015)
	Support activities	Diesel	2.5	MJ/Mg material removed	Natural Resources Canada (2005a)
	Dewatering	Electricity	1	MJ/Mg material removed	
Comminution (DSO)	Crushing	Electricity	20	MJ/Mg ore processed	Griffing and Overcash (2010)
Comminution (Metataconite ore)	Primary crushing	Electricity	4.6	MJ/Mg ore processed	Natural Resources Canada (2005a)
	Grinding	Electricity	14.3	MJ/Mg ore processed	
	Ball mill grinding	Electricity	91	MJ/Mg ore processed	Griffing and Overcash (2010)
	Screening	Electricity	0.2	MJ/Mg ore produced	US Department of Energy (2002b)
	Conveyors	Electricity	0.0003	MJ/Mg ore produced	Griffing and Overcash (2010)
	De-sliming	Electricity	5.0	MJ/Mg ore produced	US Department of Energy (2007)
Processing	Density separator/flotation	Electricity	31.6	MJ/Mg ore produced	Griffing and Overcash (2010)
	Magnetic separation	Electricity	8	MJ/Mg ore produced	Griffing and Overcash (2010)
	Spiral plant	Electricity	5.0	MJ/Mg ore produced	US Department of Energy (2007)
	Pumps for slurry transport	Electricity	1	MJ/Mg of ore produced	US Department of Energy (2007)
	Hematite plant	Electricity	1.1	MJ/Mg ore produced	Griffing and Overcash (2010)
Pelletization	Filtering	Electricity	65.6	MJ/Mg pellets produced	Griffing and Overcash (2010)
	Balling	Electricity	51.8	MJ/Mg pellets produced	
	Firing	Heavy fuel oil/Coke	946	MJ/Mg pellets produced	
	Firing	Electricity	3.6	MJ/Mg pellets produced	
Other activities	Tailings pumps	Electricity	6.7	MJ/Mg ore processed	Natural Resources Canada (2005a)
	Process water	Electricity	6.1	MJ/Mg ore processed	
	Other plant energy	Electricity	9.8	MJ/Mg ore processed	
	Drying	Diesel	54.7	MJ/Mg ore produced	New Millennium Capital Corp. (2010)
	Stacking and reclamation	Diesel	1.8	MJ/Mg ore produced	Haque and Norgate (2015)
	General and administrative	Electricity	4.7	MJ/ore processed	Natural Resources Canada (2005a)
	Port operations	Electricity	3.2	MJ/Mg ore produced	Haque and Norgate (2015)

Table 2b
End-use process energy intensities of gold mining.

Process	Sub-process	Fuel	Energy intensity	Units	Source
Ore extraction	**Open pit mining**				
	Drilling	Diesel	1.0	MJ/Mg material removed	Natural Resources Canada (2005a)
	Transport/haulage	Diesel	11.7	MJ/Mg material removed	
	Support equipment	Diesel	2.5	MJ/Mg material removed	
	Dewatering	Electricity	1.0	MJ/Mg material removed	
	Loading	Diesel	2.5	MJ/Mg material removed	
		Electricity	3.2	MJ/Mg material removed	Bleiwas (2011)
	Underground mining				
	Drilling	Diesel	29.6	MJ/Mg of ore mined	Natural Resources Canada (2005b)
	Mucking	Diesel	23.3	MJ/Mg of ore mined	
	Transport	Diesel	11.7	MJ/Mg of ore mined	
	Underground crushing	Electricity	3.3	MJ/Mg of ore mined	
	Hoisting	Electricity	33.0	MJ/Mg of ore mined	
	Ore transport to mill	Diesel	11.7	MJ/Mg of ore mined	
	Ventilation	Electricity	159.6	MJ/Mg of ore mined	
	Backfill	Electricity	14.9	MJ/Mg of ore mined	
	Dewatering	Electricity	13.6	MJ/Mg of ore mined	
	Other underground support	Diesel	21.2	MJ/Mg of ore mined	
	Mine air heating	Propane	Table A4 in Supplementary file	GJ	
Comminution	Crushing	Electricity	5.6	MJ/Mg of ore processed	Natural Resources Canada (2005a)
	Grinding	Electricity	46.8/83.9/61.2/28.1	MJ/Mg of ore processed	Detour Gold Corporation (2018), Kallio and Vaz (2015), Natural Resources Canada (2005a), Volk and Bostwick (2017)
Gold extraction	Flotation concentrate autoclave	Natural gas	6.8	MJ/Mg of ore processed	Norgate and Haque (2012)
		Electricity	43.6	MJ/Mg of ore processed	
	Flotation and agitated cyanide leaching	Electricity	43.6	MJ/Mg of ore processed	
	Gravity concentration	Electricity	11.1	MJ/Mg of ore processed	
	Agitated cyanide leaching	Electricity	5.0	MJ/Mg of ore processed	
	Flotation only	Electricity	10.8	MJ/Mg of ore processed	
	Flotation and gravity concentration	Electricity	21.9	MJ/Mg of ore processed	
	DMS and gravity concentration	Electricity	21.9	MJ/Mg of ore processed	
	Cyanidation in grinding	Electricity	5.0	MJ/Mg of ore processed	
Gold Recovery	Merrill-Crowe	Electricity	NA		
	Intensive cyanidation	Electricity	20.9	MJ/Mg of ore processed	Norgate and Haque (2012)
	CIP,CIL,CIC	Electricity	20.9	MJ/Mg of ore processed	
Post recovery	Electrowinning	Electricity	11160	MJ/Mg of Au	Norgate and Haque (2012)
	Smelting	Natural gas	0.4	MJ/Mg of Au	
Other activities	Mill heating	Natural gas	19.8	MJ/Mg of ore mined	Natural Resources Canada (2005a)
	Tailings	Electricity	4.1	MJ/Mg of ore mined	
	General and administrative	Electricity	4.7	MJ/Mg of ore mined	

Most of the emissions (86%) were from heavy fuel oil and diesel. 41% of the electricity-related emissions were from the comminution process, and 56% of the diesel emissions were from haulage and road maintenance fleet. At the end-use level, firing and haulage were responsible for 66% and 14% of the total emissions, respectively. It can be noted that although 39% of the sectorial energy demand was met by electricity, it contributed only 4% of the emissions due to its lower emissions intensity factor.

3.2. Energy and GHG Sankey for gold mining

The gold mining sector's energy demand and GHG emissions are shown in Fig. 5b. In 2016, the 24.2 PJ energy demand was met by electricity (56%), diesel (32%), natural gas (6%), and propane (6%). The post-recovery operations, electrowinning and smelting, consumed 2,346 GJ and had a negligible share (0.01%) of energy demand. The electricity-intensive ventilation and grinding operations consumed 35% and 29% of the electricity used. 30% of diesel use was for ore haulage and 100% of propane use was for mine air heating. Ore extraction energy consumption was 13.3 PJ, which accounted for 55% of the energy demand. Of this total, open-pit mining operations were responsible for 27% of energy use and 73% was consumed by underground mines. The high energy demand of underground mines was due to ventilation requirements to meet the air quality. Ventilation consumed 49% of underground extraction operations' energy demand. Among the end uses, ventilation, comminution, and haulage operations were responsible for 50% of the energy use with shares of 20%, 21%, and 14%, respectively.

In 2016, Canada's gold mining sector emitted 769 thousand Mg of GHGs. A significant share (71%) of these emissions were from diesel consumption. Among the processes, ore extraction emissions were 64% of the total. 27% of the electricity-related emissions were due to ventilation, followed by 17% from comminution operations. At the end-use level, 32% of the emissions were from ore transportation in both open-pit and underground mines. The emissions from gold extraction, recovery, and post-recovery processes were insignificant, ~0–3%, primarily because a major share (75%) of gold production was from Quebec and Ontario, where electricity generation is through renewable

Table 2c
End-use process energy intensities of potash mining (Government of Canada, 2003; US Department of Energy, 2002c).

Process	Sub-process	Fuel	Energy intensity	Units
Ore Extraction	**Conventional mining**			
	Mining machines	Electricity	43.2	MJ/Mg product
	Hoisting	Electricity	37.8	MJ/Mg product
	Conveyors	Electricity	9.5	MJ/Mg product
	Ventilation	Electricity	17.3	MJ/Mg product
	Dewatering	Electricity	38.6	MJ/Mg product
	Air heating	Natural gas	64.8	MJ/Mg product
	Backfill pumps	Electricity	0.2	MJ/Mg product
	Trucks	Diesel	18.6	MJ/Mg product
	Solution mining			
	Steam and crystallization pumps	Electricity	791.9	MJ/Mg product
	Steam generation	Natural gas	817.2	MJ/Mg product
	Trucks	Diesel	18.6	MJ/Mg product
Recovery	Crushing	Electricity	1.4	MJ/Mg product
	Grinding	Electricity	268.7	MJ/Mg product
	Flotation	Electricity	17.9	MJ/Mg product
	Screening	Electricity	0.04	MJ/Mg product
	Compactor	Electricity	0.04	MJ/Mg product
	Building heating, steam generation and product drying	Natural gas	2782.8	MJ/Mg product

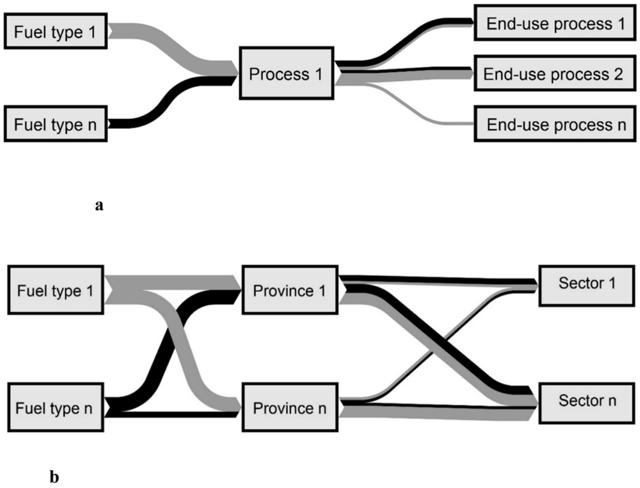


Fig. 4. (a) Basic Sankey structure for sectoral energy and GHG emissions. (b) Basic Sankey structure for Canada's provincial energy and GHG emission.

energy sources. In addition, 56% of the energy demand was met by electricity, but the emissions were only 8% of the total.

3.3. Energy and GHG Sankey for potash mining

Potash mining energy demand was 34.2 PJ in 2016. The different fuels used, the end uses, and their energy consumption and GHG emissions are illustrated in Fig. 5c. 70%, 29% and 1% of the energy demand was met by natural gas, electricity, and diesel, respectively. Crushing and grinding operations consumed 52% of the total electricity. Diesel is used primarily in conventional mining for haulage operations, and its use in solution mining is limited to service trucks. Solution mining consumed 29% of the natural gas used to generate steam, which is pumped into underground mines. The heat and steam generation units used for product drying and steam generation in recovery operations made up 67% of the sectorial natural gas demand. Although only 13% of the extracted potash was through solution mining, it consumed 69% of the extraction energy demand of 8.8 PJ. Compared to extraction operations, recovery processes had a high energy consumption (21.5 PJ, or 63% of the potash mining energy demand). Among the end uses, the heat and steam generation units in the recovery process were responsible for 47% of the energy demand followed by the solution mining steam generation units and crushing/grinding operations, with shares of 20% and 15%, respectively.

In 2016, Canada's potash mining sector emitted 3061 thousand Mg of GHGs. 50%, 49%, and 1% of these emissions were from natural gas, electricity, and diesel use, respectively. Conventional mining emits 37% fewer emissions than solution mining as the latter uses natural gas to generate steam. Overall, the extraction operations emitted 1198 thousand Mg (39%) and the recovery processes emitted 1863 thousand Mg (61%). More than half (52%) the electricity related emissions were in comminution, followed by 20% share for steam and crystallization pumps. Natural gas usage for steam generation in extraction and recovery processes represented 29% and 67% of the total sectorial natural gas related emissions. Among the end-uses, significant amount of emissions were from the heat and steam generation units in potash recovery operations (34%) and crushing/grinding (25%).

3.4. Integrated energy Sankey and GHG Sankey for all provinces with iron, gold, and potash mining operations

The total energy demand for the iron, gold, and potash mining sectors in Canada was estimated to be 91.4 PJ in 2016 and is shown in Fig. 6a. Of this total, the iron mining sector consumed the most energy (34.5 PJ), followed by the potash mining sector (34.5 PJ), and the gold mining sector (24.2 PJ). The energy demand was highest in SK (33.4 PJ, 37%), followed by QC (24.1 PJ, 26%), NFL (17.1 PJ, 19%), and ON (12.8 PJ, 14%). Only 4% of the total was from BC, NB, YK, and NU. SK's high energy demand was due to its potash production (the world's largest). ON's high energy demand was a result of its gold mining operations; it has more than any other province. QC's energy demand was due to both iron and gold mining operations and NFL's was mainly due to iron mining operations. SK's electricity (26%) and natural gas demand (92%) were highest due to the comminution and recovery operations in potash mining. ON and QC consumed 71% and 29% of the propane. Almost all of Canada's underground gold mines are in those provinces. Coke and heavy fuel oil were used in iron ore pelletizing processes, which are concentrated in QC and NFL. YK's energy demand was driven by placer gold mining activities. In NU, iron mining commenced in 2014 and consumed only 0.5 PJ (0.5%) in 2016. NB's share of potash production was only 4% of the country's production and consumed only 0.9 PJ, or 3% of total potash mining sector energy demand. The overall energy intensities for iron, gold, and potash mining is 0.7, 149.8, and 1.8 GJ/Mg of product, respectively. The overall energy intensity for iron mining is lower in NFL than in QC. This is because around 8% of the ore extracted in NFL was from DSO ores that contain higher concentrations of iron. ON and QC have higher overall energy

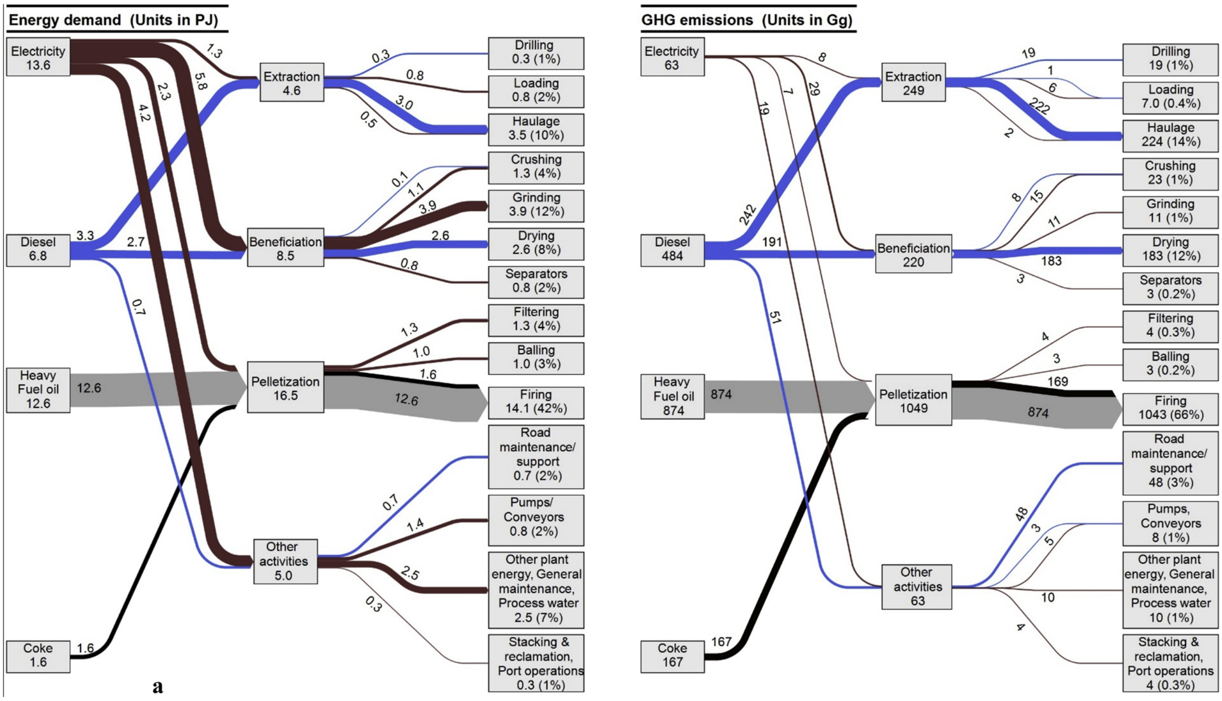
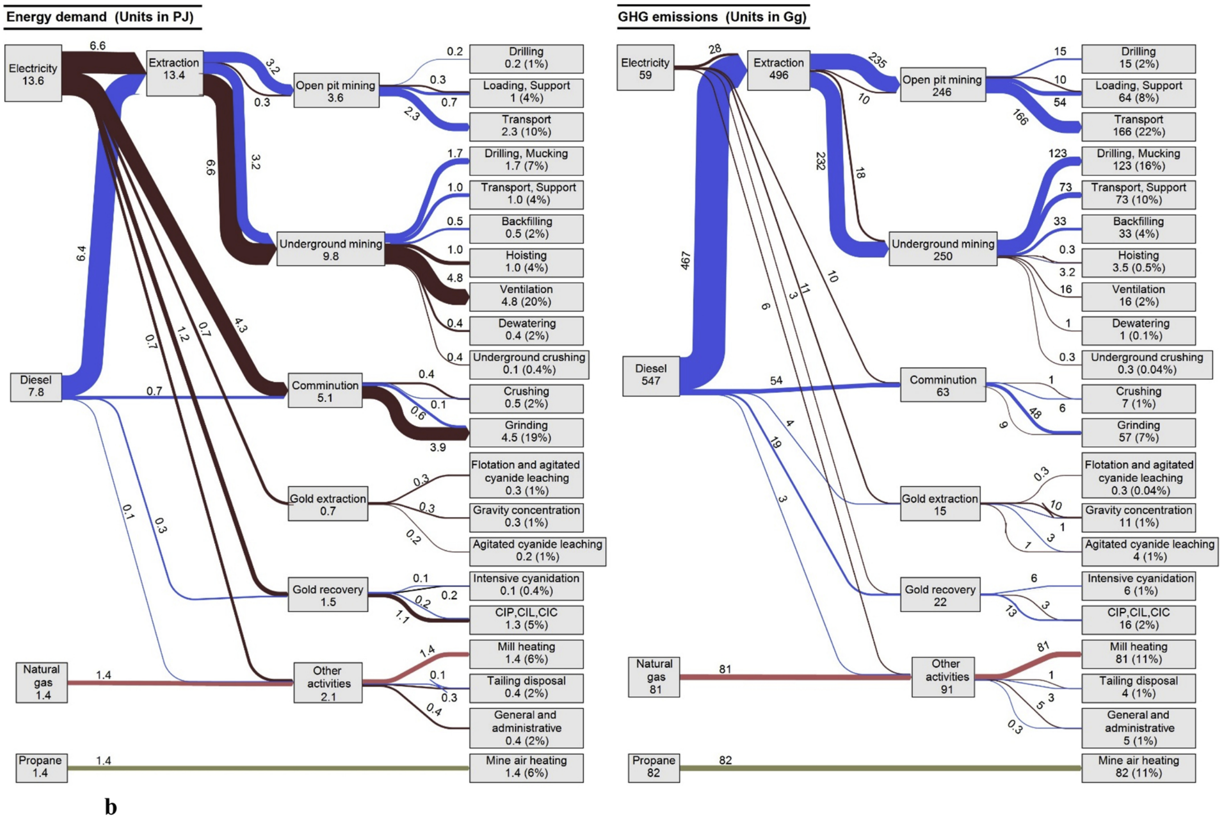


Fig. 5. (a) Sankey diagram for iron mining energy demand (left) and GHG emissions (right) in Canada in 2016. (b) Sankey diagram for gold mining energy demand (left) and GHG emissions (right) in Canada in 2016. (c) Sankey diagrams for potash mining energy demand and GHG emissions in Canada in 2016.

intensities for gold mining than other provinces as almost 73% and 67% of the ore extracted in ON and QC is from underground mines. In the case of potash mining, the high overall energy intensity is due to solution mining in SK.

The iron, gold, and potash mining sectors' GHG emissions in the year 2016 were estimated to be 5419 thousand Mg CO_2 eq. The overall GHG emissions intensity for iron, gold, and potash mining is 33, 4922, and 158 kg CO_2 eq./ Mg of product, respectively. The emissions were disaggregated for each province by sector and fuel type, as shown in Fig. 6b. The emissions were highest for electricity (30%), followed by



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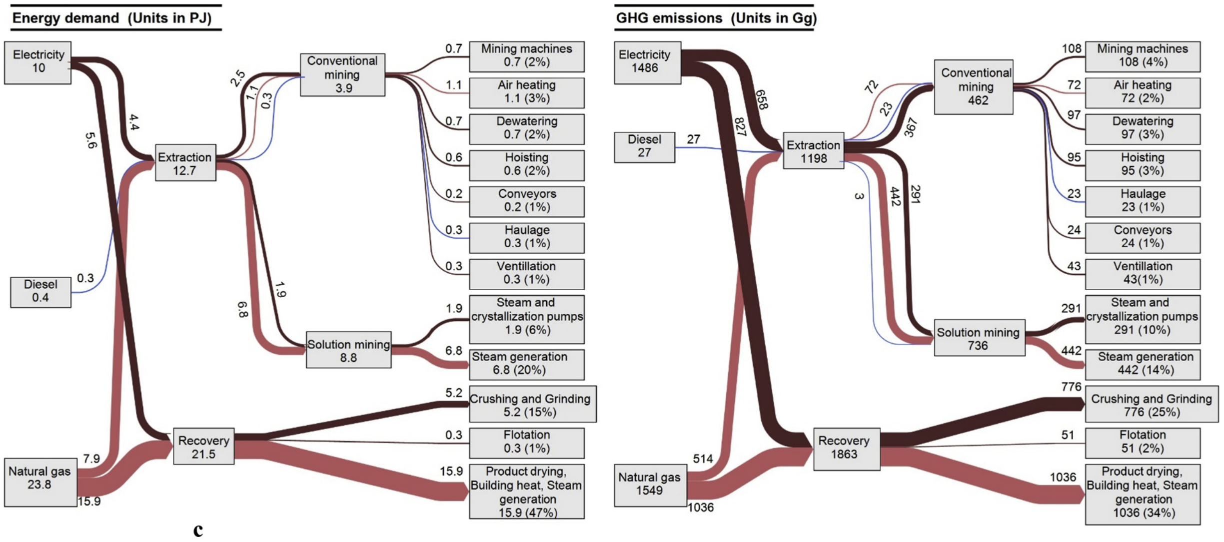

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natural gas (29%), diesel (20%), heavy fuel oil (16%), coke (3%), and propane (2%). A significant amount of GHG emissions was from SK (3021 thousand Mg or 56% of total emissions from the three sectors). Electricity-related emissions were highest in SK; there, only 21% of the generation was from renewables compared to 99% in QC, 93% in ON, and 92% in NFL. The only propane emissions were in ON and QC, which share 94% of Canada's underground gold production. Diesel emissions were high in ON (258 thousand Mg) due to gold mining operations; the province produces 50% of the country's gold.

4. Implications and recommendations

Previous studies have shown that there is significant potential in the mineral mining industry for energy efficiency improvement and GHG mitigation (Kaarsberg et al., 2007; US Department of Energy, 2007). The first step in understanding this potential is to identify how energy is currently being used, in what form, and what the associated GHG emissions are. This paper's disaggregation of existing process-level energy inputs and GHG emissions provides baselines. These baselines represent Canadian average energy and GHG emission intensities and can help industry determine whether mine-specific operations are

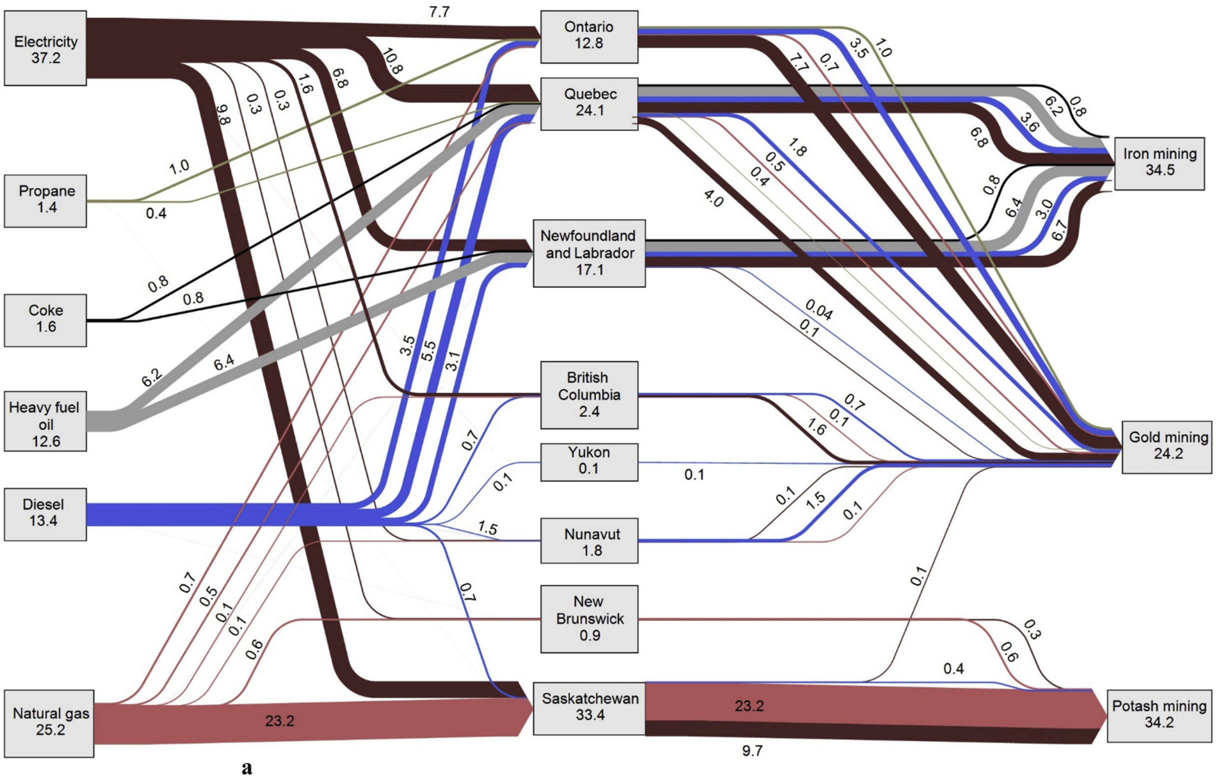

Fig. 6. (a) Iron, gold, and potash mining energy (PJ) Sankey by province and fuel type in 2016. (b) Iron, gold, and potash mining GHG (1000 Mg CO_2 eq.) Sankey by province and fuel type in 2016.

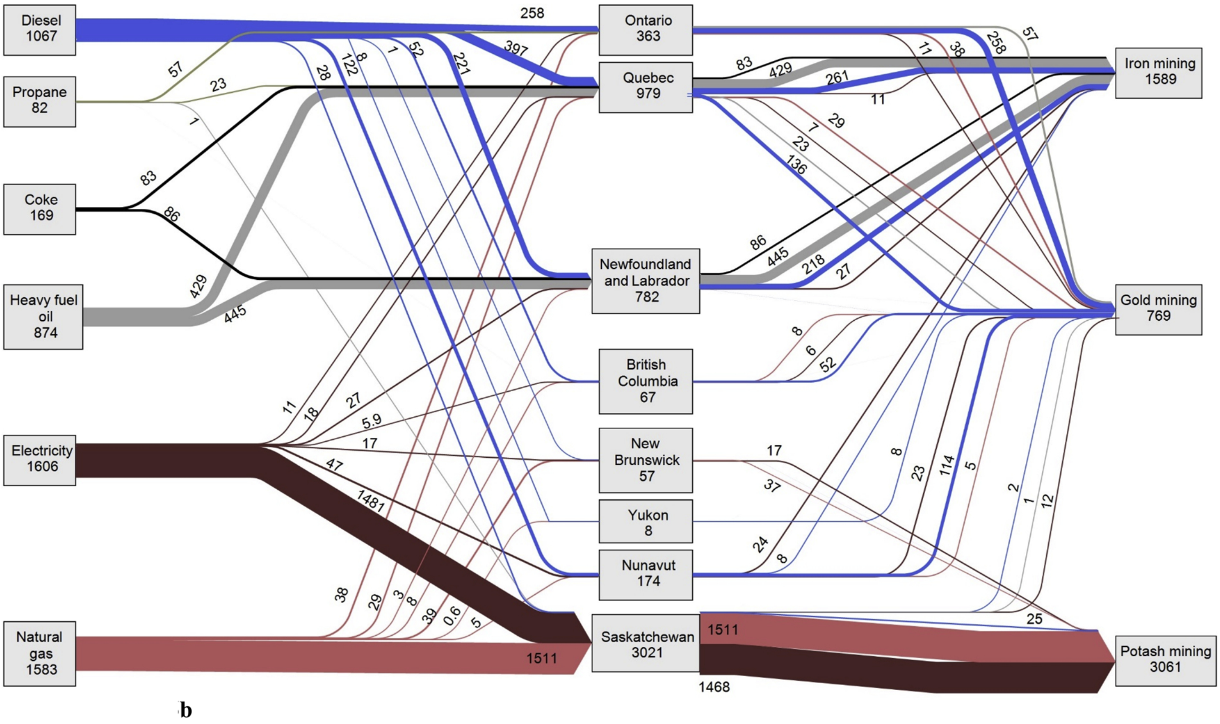

Fig. 6. (*continued*)

underperforming. Doing so can also help to develop realistic performance strategies and targets. Moreover, the specificity of the disaggregated data is at the process level, which allows us to identify equipment or processes that might benefit most from new technology investment, fuel switching, and/or operational improvements.

The disaggregated data provided in this paper also makes it possible to develop a sector-wide, bottom-up, long-term energy model. Such a model can be used to project future energy use and GHG emissions, and assess the long-term GHG mitigation potential and associated costs of equipment changes, process and operations improvements, fuel switching, and low carbon strategies. These assessments can inform industry decision makers and government policy makers, and help them choose energy-use reduction and GHG mitigation strategies best suited for specific mineral mines in Canada. Lastly, a long-term energy and GHG emission analysis of Canada's mineral mining sector could quantify its contribution potential to Canada's international climate commitments for GHG mitigation and also provide more options for cost-effective GHG mitigation.

5. Limitations

It is necessary to mention a few notable limitations. The energy intensities provided in this study represent average values and depending on the mine type and ore grades, the actual energy intensity of individual mines may vary (Ditsele and Awuah-Offei, 2012). The GHG emissions are the combustion emissions at the point of usage and do not include the emissions related to producing and transporting fuels, thus, the values presented are not life cycle values. Silver is produced as a byproduct in some of the mines alongside gold but this study does not provide any energy demand or GHG emissions associated with silver extraction (Natural Resources Canada, 2019). The strip ratio is assumed to remain constant from previous years where data was unavailable. This could introduce error if new mines are developed since the strip ratios are usually higher as more waste needs to be extracted to uncover the ore body.

6. Conclusion

End-use energy consumption and GHG emissions data for Canada's mineral mining sectors are missing from the literature and data repositories. Given the urgency of GHG reduction, energy use should be disaggregated in all sectors. In this study, we calculated the end-use process energy intensities for the major mineral mining sectors in Canada and developed an energy-environmental model that was used to determine regional end-use process-level energy use and GHG emissions. The process-level energy use and GHG emissions flow from source to end use were mapped for each sector and province using Sankey diagrams for the year 2016.

This study identified the provincial energy use and GHG emissions in the iron, gold, and potash mining sectors. Newfoundland had 56% and Quebec had 44% of the iron mining energy demand. Ontario and Quebec together made up 82% of the gold mining energy use as the two provinces accounted for 78% of Canada's gold production and 81% of the underground ore mined. Only 4% of the energy demand was from British Columbia, New Brunswick, Yukon, and Nunavut. A significant amount of emissions were from Saskatchewan (2935 thousand tonnes, or 56%), Quebec (885 thousand tonnes, 17%), and Newfoundland (803 thousand tonnes, 15%).

The major energy and GHG emission-intensive end-use processes were identified. Pelletization in iron mining and heat and steam generation in the product recovery process in potash mining were found to be responsible for about 50% of the energy demand in the respective sectors. These processes were also the highest contributors to GHG emissions. In gold mining, ventilation and comminution were the dominant energy-use processes and each shared ~20% of the energy demand. Diesel-related emissions from ore transportation had the highest share of GHG emissions.

The results of this study can be used by industry to identify mine operations that perform below the Canadian average. It is recommended that the results be used to project future GHG emissions numbers and test GHG mitigation strategies. This is a needed step to quantify the potential for GHG mitigation in Canada's mineral mining sector and determine the potential to contribute to Canada's GHG reduction targets and international climate commitments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104485.

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