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Assessment of greenhouse gas mitigation options for the iron, gold, and potash mining sectors

Anil Kumar Katta, Matthew Davis, Amit Kumar*

Department of Mechanical Engineering, 10-263 Donadeo Innovation Centre for Engineering, University of Alberta, Edmonton, Alberta, T6G 1H9, Canada

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ABSTRACT

The objective of this study is to investigate greenhouse gas mitigation pathways for the iron, gold, and potash mining sectors in Canada. These sectors have not widely accepted the available cleaner production strategies and so there is potential to reduce greenhouse gas emissions. It is important to fully realize this potential as soon as possible to support efforts to limit global warming. We conducted cost-benefit analyses of implementable greenhouse gas reduction strategies in order to inform policy and industry. Twenty-four greenhouse gas emission reduction options not yet implemented in Canada were identified following a review of current processes and operations at 102 mine sites. We developed a novel model to assess these options, integrating technology diffusion rates and long-term energy-environmental modelling. We found that the maximum greenhouse gas reduction potential can be realized through simultaneously implementing fifteen technology changes, eliminating 21 million tonnes of CO_2 eq. by 2050. Furthermore, we showed that the marginal greenhouse gas abatement costs are negative, indicating that the industry would also achieve long-term cost savings if these changes were pursued. Implementing high pressure grinding rolls in iron mining and electric and diesel hybrid haul trucks in underground gold mining and potash mining have the most favorable greenhouse gas abatement costs of −4120, −3096, −701 $/tonne, respectively. These results show that these technology changes should be pursued since both environmental benefit and cost savings would be achieved.

1. Introduction

The global mineral mining industry (metal and non-metal mineral resource extraction) has increased in value by about 110% in the past 2 decades (Ericsson, 2010). Projections suggest that the world's gross domestic product (GDP) will double by 2030 (Gros and Alcidi, 2014), which will undoubtedly accelerate resource extraction rates. The mining of minerals makes up about 2.7% of world-wide industrial energy use (Fischedick et al., 2014). The mineral mining industry is an energy-intensive sector that contributes to a significant share of national industrial energy use in some regions, reaching 80% in Botswana and Namibia, over 50% in Chile, and about 15% in South Africa (Fischedick et al., 2014). Moreover, ore grades have been declining over the years and newly discovered mineral deposits are deeper, more complex, and finer grained (Mudd, 2007a). This will increase the amount of energy required to extract the same amount of metal or non-metal in the future. Thus, the industry is experiencing increased pressure to reduce its energy use and greenhouse gas (GHG) emissions to help mitigate anthropogenic global warming.

Cleaner production (CP) has been considered as an efficient pathway to attain both environmental sustainability and economic development (Luken and Navratil, 2004). The CP concept aims to improve the efficiency of energy use, reduce the environmental impact caused during the product life cycle, and develop optimal GHG mitigation solutions (Severo et al., 2015). But, because of the high variability of mining operations (depending on the ore type and grade), its application in the mining industry has faced challenges (Dong et al., 2019), and the sector is at risk of falling behind societal expectations on climate change (Tost et al., 2018). Thus, the available energy management practices have not been widely accepted in the industry (Levesque et al., 2014). Past energy conservation and GHG mitigation efforts have focused on waste heat recovery, managing electricity demand, mine ventilation, and implementing renewable energy sources (Levesque et al., 2014). However, comminution and material handling (loading and hauling) operations make up 44% and 17%, respectively, of the energy

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* Corresponding author.
E-mail address: Amit.Kumar@ualberta.ca (A. Kumar).

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Abbreviations

AG	Autogenous
AHT	Alternative haul truck powertrain technologies
ALHD	Alternative load haul dump powertrain technologies
BAU	Business-as-usual
CAD	Canadian dollar
CP	Cleaner production
CSE	Cost of saved energy
GHG	Greenhouse gas
GO	Gold mining
HPGR	High pressure grinding rolls
HTO	Haul truck operations
IPCC	Intergovernmental Panel on Climate Change
IR	Iron mining
LEAP	Long-range Energy Alternatives Planning
Mt	Million tonnes
NRCan	Natural Resources Canada
PAG	Pebble addition in grinding
PJ	Petajoule
PO	Potash mining
PSOT	Pellet size optimization technology
SAG	Semi-autogenous
SEDAR	System for Electronic Document Analysis and Retrieval
SG&PD	Steam generators and product drying
SOE	Shovel operator efficiency
TAC	Total activity cost
TMS	Thermal management system
VOD	Ventilation on demand

use across the industry. Furthermore, as per the Intergovernmental Panel on Climate Change (IPCC) report, there is significant potential in this sector to improve energy, emissions, and material efficiencies (Fischedick et al., 2014). Kaarsberg et al. (2007) pointed out that average energy use in U.S. mineral mining is 115% higher than the practical minimum energy use. The U.S. Department of Energy estimated that the U.S. mineral mining industry consumes approximately 1315 PJ per year and there is potential to reduce energy consumption by 705 PJ and carbon dioxide (CO_2) emissions by 40.6 million tonnes (U.S. Department of Energy, 2007). In Canada, Natural Resources Canada's (NRCan) CanmetMINING's green mining initiative has also highlighted the need to reduce energy use in the country's mineral mining sector (Natural Resources Canada, 2016). It is important to fully realize the GHG emissions reduction potential as soon as possible to support the global effort to limit global warming and its associated harms.

Energy use reduction and GHG mitigation measures have been studied mainly by comparing alternative mining technologies. Lajunen (2015) used Autonomie vehicle simulation modelling to compare the energy efficiency of conventional, diesel hybrid, and fuel cell hybrid powertrains of mining machinery. McNab et al. (2009), Wang (2013), and Norgate and Haque (2010) compared the efficiency and costs associated with various alternative grinding operations using geometallurgical models, JK SimMet software, and life cycle assessment, respectively. Bouchard et al. (2017) and Numbi et al. (2014) studied control strategies to determine energy saving potential for grinding and jaw crushers using optimization modelling, respectively. Neither strategy was assessed in terms of GHG emission savings. Dong et al. (2019) discussed CP strategies such as high temperature regulation, multiple cooling methods, innovative ore transportation methods, and energy use of high karst water pressure and ground stress for deep mining operations but have not quantified their energy conservation or GHG mitigation potentials.

The studies discussed above reveal a gap in the literature. Existing studies on the mining sector are limited to specific subprocesses in mining operations, compare relatively small sub-sets of equipment, and lack long-term sectoral analysis. In other words, a long-term analysis that compares several GHG mitigation strategies across entire mining sectors involving possible technology change has not been done. Thus, we fill two important knowledge gaps, we determine the GHG mitigation potential in mineral mining through technology change, and we provide a cost-benefit assessment for different strategies to achieve that potential. In addition, the market penetration of alternative technologies in the mining sectors is not well covered in the literature. This study, therefore, aims to address that gap as well.

The present analysis uses the Canadian mineral mining industry as a case study. In 2016, this industry made up 3.4% of the Canada's GDP (Marshall, 2017). Among the different minerals mined in Canada, iron, gold, and potash extraction and processing activities together were responsible for a significant 65% and 66% of the mineral mining industries' energy consumption and GHG emissions, respectively, in 2015 (Natural Resources Canada, 2018a). Moreover, these are the predominant minerals extracted globally. Iron has the highest global metal value share (27%) (Ericsson, 2010). It is used as a primary raw material for steel production and its demand is forecasted to grow because of increasing steel demand (Wen et al., 2014). Gold makes up 16% of the global metal value (Ericsson, 2010). It is a precious metal used in jewelry, electronics, healthcare, and the clean technology sector, and its growth is driven by the expanding middle class and evolving use of gold across the technology space (World Gold Council, 2019). Although potash's share is low in terms of value, it is one of the main minerals extracted in Canada. Canada is the world's largest producer of potash (The Mining Association of Canada, 2017), an ore primarily used to produce fertilizers (Food and Agriculture Organization of the United Nations, 2017). Since these three sectors are the top energy users in Canada and have international importance, this research is specifically focused on iron, gold, and potash mining.

The overall objective of this study is to develop a bottom-up energy and environmental model for Canada's iron, gold, and potash mining sectors and to quantify the potential for and associated costs of GHG emissions mitigation through various CP pathways. The specific objectives of this study are to:

- Develop and validate a long-term, multi-regional energy model for Canada's iron, gold, and potash mining sectors to 2050
- Identify GHG emission mitigation options through energy-use reduction for the iron, gold, and potash mining sectors
- Develop a market share model for applicable scenarios with competing alternative technologies
- Calculate the cost of saved energy, energy saving potential, GHG emission mitigation potential, and incremental cost of mitigation for each scenario

2. Method

2.1. Overview

Fig. 1 illustrates the method used in this study. In the first step,

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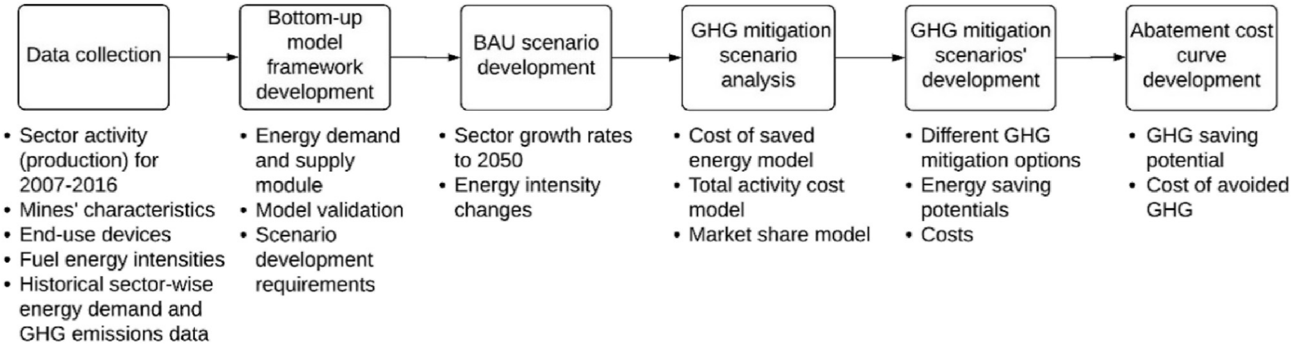

Fig. 1. Method for model development and scenario analysis.

data related to the iron, gold, and potash mining sectors was collected. The information on 102 mine sites in Canada were obtained from the System for Electric Document Analysis and Retrieval (SEDAR) database (SEDAR, 2018). From these, process flow sheets, mine characteristics (open pit/underground type, strip ratio, etc.), and the activity data related to ore, waste extracted, and ore processed were compiled. The flow sheets were consolidated to examine the existing types of technologies and processes used. In an earlier study, the fuel intensities of processes and energy consumption demand trees were developed (Katta et al., 2020; Katta, 2019). The present study uses the data developed in that work to conduct marginal GHG abatement cost scenario analysis through bottom-up modelling. In a bottom-up approach, end-use technologies are identified and their fuel-use energy intensities and associated activity are defined. Then the calculated end-use energy demand and GHG emissions are aggregated to obtain sectorial energy consumption and GHG emissions. In the second step, the framework for Canadian mineral mining model, the LEAP-CANMIN model, was developed in Long-range Energy Alternatives Planning (LEAP) software (discussed further in Section 2.2). The model was validated for the years 2007–2016 using historical data. In the third step, a business-as-usual (BAU) scenario was developed for the study period (2018–2050) (Section 2.3). In the fourth step, the models for predicting the market share of new technologies and calculating their cost-benefits were established (Section 2.4). In the fifth step, GHG mitigation scenarios were developed and modelled in LEAP-CANMIN using unique parameters for equipment capital costs, operating and maintenance costs (labour cost, energy cost, overhaul cost, and non-fuel operating costs), lifetime, and fuel consumption (Section 2.5). In the final step, we found the GHG mitigation potential and marginal costs for each scenario and presented the results in the form of marginal GHG abatement cost curves.

2.2. Bottom-up model development for the iron, gold, and potash mining sectors

There are several ways of developing an integrated energy, environment, and economic model to assess GHG mitigation potential. These methods are mainly generalized as top-down, bottom-up, hybrid, optimization, simulation, and accounting models (Hall and Buckley, 2016). Among these, bottom-up models are technologically explicit and are well suited for analyzing technical energy-saving opportunities (Nyboer, 1997). LEAP is a stand-alone software package based on annual energy supply and demand accounting. It has been used for integrated energy demand and supply planning, and energy and environmental policy analysis (Heaps, 2016). Simply speaking, key energy and environmental performance characteristics. Unit costs, and activity of an energy system are inputs to LEAP and annual energy consumption, GHG emissions, and system costs are key outputs. LEAP has been used to assess Canada's GHG emissions (Davis et al., 2018, 2019), energy-use improvement options for the oil sands (Katta et al., 2019), chemical (Talaei et al., 2018), cement (Talaei et al., 2019), commercial and institutional (Subramanyam et al., 2017), and residential (Subramanyam et al., 2017; Xu et al., 2012) sectors, and for long-term forecasting of energy demand and supply (Huang et al., 2011; Tao et al., 2011). The results of the models can be used to develop marginal GHG abatement cost curves (relationships between CO_2 price and tonnes of emissions abated), which are an important tool for policy-makers to evaluate climate mitigation options and their economics (Brown, 2001).

The LEAP integrated framework, shown in Fig. 2, consists of energy demand and supply modules, and scenario-specific cost and market share inputs from Excel-based models. The demand module was developed using the energy consumption demand trees, end-use energy intensities, and production data. In this module, the mining operations are divided into sub-processes and further divided into end-use processes that consume different types of fuel. For example, in the case of iron mining, ore extraction and processing are sub-processes with end-use processes such as drilling, crushing, etc. In some cases, such as gold extraction, the end-use is further divided into different energy-consuming devices because of widely different gold extraction techniques. The detailed description of the collected data and various end-use processes can be found in an earlier study (Katta et al., 2020; Katta, 2019), and the energy intensities are provided in Tables A1 through A4 in the supplementary information file. These energy intensities were obtained from literature. LEAP's Technology Environment Database's built-in Tier 1 IPCC emission factors were allocated to the fuels used in the demand module. The energy supply module has processes that convert resources/fuels to produce output fuels and supply fuels to the demand module. It was developed in work by Davis (2017), Davis et al. (2019) for all the Canadian provinces and includes grid emission factors, as shown in Table 1. LEAP then calculates the annual energy consumption and GHG emissions using a bottom-up approach and the model was validated for the years 2007–2016 using the data from NRCan (Natural Resources Canada, 2018b). The other scenario-specific inputs of model development are explained in section 2.4.

2.3. Business-as-usual (BAU) scenario

The BAU scenario (2018–2050) was developed using provincial growth rate projections for the sectors up to 2021 (The Conference Board of Canada, 2017a) with the exception of Nunavut and Saskatchewan, where growth rate projections were available to 2030 (The Conference Board of Canada, 2017b). For the years beyond

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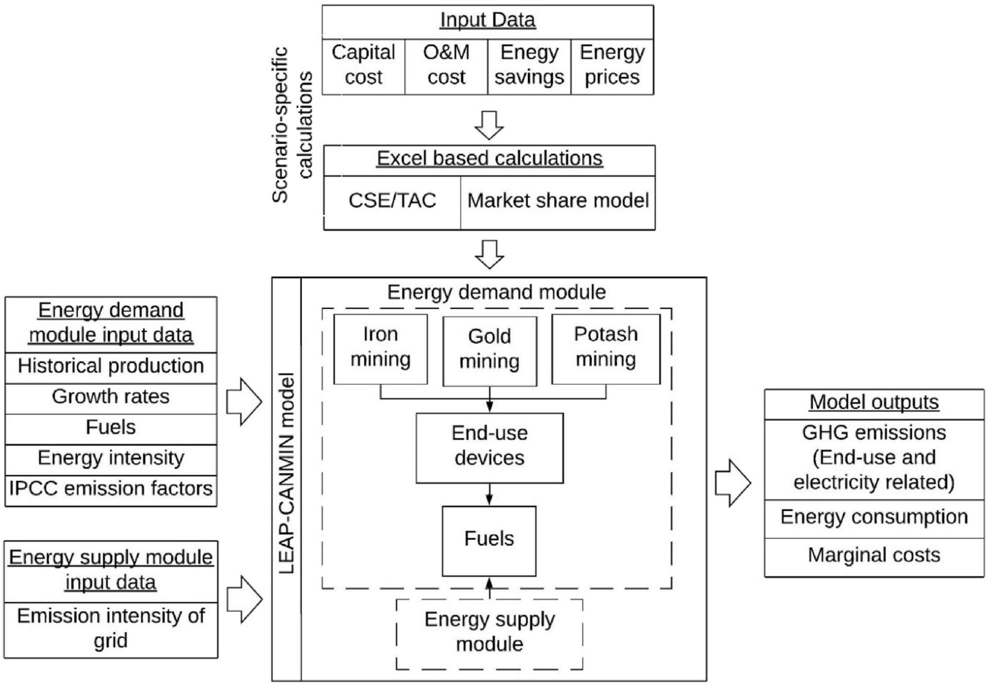

Fig. 2. Modelling framework.

Table 1
Electricity grid emission intensity factors (grams CO_2 eq./kilowatt-hour).

Province	2018	2020	2025	2030	2035	2040	2045	2050
British Columbia (BC)	13.1	13.1	14.2	12.9	12.9	12.7	12.5	12.4
Saskatchewan (SK)	518	500.9	413.1	279.7	273.9	223.3	185.7	145.4
Ontario (ON)	8.4	32.2	70.4	49.6	37.6	41.1	44.0	46.6
Quebec (QC)	5.9	5.8	6.1	6.4	6.0	6.2	6.2	5.9
New Brunswick (NB)	215	213.0	211.4	205.7	205.3	199.4	198.9	198.3
Newfoundland and Labrador (NFL)	16	16.4	16.4	15.1	17.7	17.7	17.7	17.7
Yukon (YK)	11	122.3	8.6	1.3	1.3	1.3	1.3	1.3
Nunavut (NU)	637	441.0	450.3	449.8	457.9	457.1	458.5	460.0

2021 and 2030 that have no projections available, the annual change in the mining sector growth rate is assumed to be the same as the change in the GDP projections in literature (Davis et al., 2018; National Energy Board, 2018). The province-wise activity data for iron, gold, and potash in Canada and the growth rates used for future projections are provided in the supplementary information section (Tables A5-A9). The energy intensity for different hauling and loading diesel equipment is considered to decrease at the rate of 0.8% per year (Hill et al., 2011), and for all other processes is assumed to be constant.

2.4. GHG mitigation scenario analysis

2.4.1. Cost of saved energy and total activity cost model

The cost of saved energy (CSE) or the total activity cost (TAC) for the GHG mitigation technology options in the scenarios was calculated using Equations (1) and (2) and input to the LEAP-CANMIN model. Whether to use CSE or TAC depends on the available data. The CSE and TAC are expressed in dollars per gigajoule ($/GJ) and dollars per tonne ($/t) of production, respectively. Billingsley et al. (2014) presented the equation for calculating CSE and compared the relative costs of energy efficiency options. We modified the equation (which originally considers only the capital cost) to include the operating and maintenance cost, energy cost, and the salvage value of the technology. These costs were obtained from several studies and will be explained in Section 2.5. It should be noted that these equations only capture the costs associated with the energy saved during end use. For example, for a technology with electricity savings, the cost benefits of reduced electricity generation capacity and the avoided transmission and distribution investments are not captured.

$$\mathrm{CSE} = \frac{\left(\mathrm{CC_{eff}} - \mathrm{CC_{exist}}\right) \times \left(\frac{(1+i)^s}{\left((1+i)^s - 1\right)}\right) + \left(\mathrm{SV_{eff}} - \mathrm{SV_{exist}}\right) \times \left(\frac{1}{\left((1+i)^s - 1\right)}\right) + \left(\mathrm{O\&M_{eff}} - \mathrm{O\&M_{exist}}\right) - \mathrm{E} \times \mathrm{P}}{\mathrm{E}} \qquad (1)$$

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$$\mathrm{TAC} = \frac{\left(\mathrm{CC_{eff}} - \mathrm{CC_{exist}}\right) \times \left(\frac{(1+i)^s}{((1+i)^s-1)}\right) + \left(\mathrm{SV_{eff}} - \mathrm{SV_{exist}}\right) \times \left(\frac{1}{((1+i)^s-1)}\right) + \left(\mathrm{O\&M_{eff}} - \mathrm{O\&M_{exist}}\right) - \mathrm{E} \times \mathrm{P}}{\mathrm{A}} \tag{2}$$

In these equations, CC_{eff} is the capital cost of energy efficient technology, CC_{exist} is the capital cost of existing technology, $O\&M_{eff}$ is the annual operating and maintenance cost of energy efficient technology, $O\&M_{exist}$ is the annual operating and maintenance cost of existing technology, SV_{eff} is the salvage value of energy efficient technology, SV_{exist} is the salvage value of existing technology, s is the life span of the equipment, i is the discount rate (10%), E is the energy saved annually, P is the per unit energy price in the given year, and A is the total activity (tonnes).

The end-use prices of electricity and natural gas are in 2016 Canadian dollars (CAD) for the industrial sector and were obtained from government projections to the year 2040 (National Energy Board, 2017) and extrapolated to 2050 using the linear forecast of the years 2018–2040. Table 2 shows the electricity, natural gas, and diesel prices. All costs were adjusted to 2016 CAD using the Bank of Canada's Inflation Calculator (Bank of Canada, 2017), as the available fuel prices were in 2016 CAD at the time of study.

2.4.2. Market share model

The market share of the various technologies considered in each scenario for every year was modelled using the inverse function as shown in Equation (3) (Mau et al., 2008; Nyboer, 1997). The annualized life cycle cost ($LCC_{k,t}$) for each technology was calculated based on the capital cost, operating & maintenance cost, and the energy cost (Equation (4) (Mau et al., 2008; Nyboer, 1997)). There are other non-cost factors such as policy regulations, limited availability of a technology, and preference for a particular fuel type or technology, which might affect investment decisions and market penetration. These are not considered in this study given the lack of such information. This modelling was limited to scenarios with more than one competing technology having the potential to replace existing technology. Linear penetration rates were considered for the other scenarios, as described in Section 2.5.

$$\mathrm{MS}_{k,t} = \frac{\mathrm{LCC}_{k,t}^{-n}}{\sum_{k=1}^{v} \mathrm{LCC}_{k,t}^{-n}} \tag{3}$$

$$\mathrm{LCC}_{k,t} = \left(\mathrm{CC} \times \left(\frac{(1+i)^s}{((1+i)^s - 1)}\right)\right) + \mathrm{O\&M_t} + \sum \mathrm{E_{tj}} \tag{4}$$

In these equations, $MS_{k,t}$ is the market share of technology k in year t, $LCC_{k,t}$ is the annualized life cost of technology k in year t, v is the number of technologies in a competition node, CC is the capital cost, $O\&M_t$ is the operating and maintenance cost in year t, E_{tj} is the cost of energy form j in year t, and n is the cost variance (power function) parameter. The yearly market share values calculated using Equation (3) can be fit into Fisher and Pry's substitution model (Fisher and Pry, 1971). This model gives an S-shaped curve for the penetration of the technology, whose equation, as shown in work by Cho et al. (2015), can be used directly for future studies. Further details of this model are in the supplementary information file.

2.4.3. Marginal GHG abatement cost

The marginal abatement cost of a GHG mitigation option is defined as the ratio of the net present value (NPV) and the mitigated CO_2 eq. emissions, as shown in Equation (5). The NPV was calculated using the CSE and TAC at a discount rate, i, of 5% using Equation (6):

$$\mathrm{AC_s} = \frac{\mathrm{NPV}_s}{\Delta \mathrm{ME_s}} \tag{5}$$

$$\mathrm{NPV_s} = \sum_{t=2018}^{2050} \frac{\sum_{a=1}^{k} (\mathrm{CSE} \times \mathrm{E})_{jt}}{(1+i)^{t-2018}} \quad \text{or} \quad \sum_{t=2018}^{2050} \frac{(\mathrm{TACXA})_t}{(1+i)^{t-2018}} \tag{6}$$

where AC_s is the abatement cost of scenario s, NPV_s is the NPV of scenario s, ΔME_s is the difference in CO_2 eq. between scenario s and the BAU case, E is the amount of energy saved annually from each energy form j, A is the production activity, t is the specific year, k is the number of energy forms, and i is the discount rate.

2.5. Scenario description and development

LEAP's scenario management capabilities were used to develop twenty-four GHG mitigation scenarios. The inputs for scenario development are the CSE/TAC and the technology penetration rates. These scenarios were developed by reviewing the existing literature on energy efficiency improvement options and their applicability to current processes at Canadian iron, gold, and potash mines. These are briefly explained in Table 3 and are further discussed in detail below.

Table 2
End-use prices of electricity, natural gas, and diesel, from the NEB (National Energy Board, 2017).

Province	Electricity end-use price (2016 CAD/GJ)					Natural gas end-use price (2016 CAD/GJ)					Diesel end-use price (2016 CAD/GJ)				
	2019	2020	2030	2040	2050	2019	2020	2030	2040	2050	2019	2020	2030	2040	2050
NFL	28.3	28.3	25.6	23.2	20.6	4.2	4.3	4.6	4.9	4.6	39.0	39.9	45.7	48.8	54.1
NB	18.9	18.9	19.1	19.3	19.5	5.7	5.8	6.2	6.5	6.3	39.2	40.0	45.3	48.1	52.9
QC	13.6	13.7	13.8	13.9	14.1	8.8	9.2	9.6	9.9	9.7	43.8	45.1	50.5	53.3	58.5
ON	33.4	34.1	35.8	36.2	38.0	5.8	5.9	6.3	6.6	6.4	36.3	37.1	42.6	45.5	50.5
MB	12.4	12.5	12.6	12.8	13.0	3.6	3.6	4.0	4.3	4.1	37.6	38.4	44.2	47.3	52.6
SK	20.7	21.0	23.4	25.6	27.8	3.3	3.4	3.8	4.1	3.9	36.4	37.2	42.7	45.6	50.6
BC	19.2	19.2	19.6	20.0	20.4	7.1	7.2	7.2	7.3	7.3	40.0	40.6	45.2	47.4	51.5
YK	20.9	21.0	21.6	22.3	22.9	4.2	4.3	4.6	4.9	4.6	37.7	38.7	45.3	48.9	55.0
NU	53.6	53.9	55.5	57.2	58.9	3.5	3.6	4.0	4.3	4.1	38.3	39.2	45.8	49.3	55.4

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Table 3
Description and energy savings of the scenarios.

Scenario	Description	Energy savings
IR-AHTs, GO-AHTs_P, GO-AHTs_U, PO-AHTs_U - New alternative haul truck powertrain technologies for open-pit iron mining, gold mining, and underground gold mining and potash mining	These scenarios assesses the energy savings, GHG mitigation achievable, and the costs associated with replacing diesel haul trucks used for extraction of ore with electric and diesel hybrid vehicles. It should be noted that in case of underground mining, additional energy savings can be achieved due to reduction in ventilation requirements	54% (electric haul trucks), 22% (diesel hybrid haul trucks), 60% (ventilation electricity savings for electric haul trucks), 20% (ventilation electricity savings for diesel hybrid haul trucks)
IR-HTO, GO-HTO, PO-HTO - Haul truck operating mode improvement for iron, gold, and potash mining	The fuel consumed is more for a haul truck stopping and then accelerating as compared to the truck continuing at a constant speed. These scenarios analyzes the energy savings and GHG mitigations due to elimination of one stop per payload cycle	3.6% (diesel)
IR-TMS, GO-TMS, PO-TMS - Haul truck thermal management system for iron, gold, and potash mining	The engine cooling system rejects approximately 30% of the fuel supplied energy to the ambient. This scenario assumes that diesel trucks use an advanced thermal management control system and assesses the fuel savings translating to energy savings and GHG mitigation	8% (diesel)
GO-ALHDs_P, GO-ALHDs_U - New alternative LHD powertrain technologies for open-pit and underground gold mining	These scenarios assess the energy efficiency improvement potentials of electric, diesel hybrid, and fuel cell load-haul-dump (LHD) equipment	67% (electric LHD), 30% (diesel hybrid LHD), 50% (fuel cell LHD), 40% (ventilation electricity savings for electric LHD), 30% (ventilation electricity savings for diesel hybrid LHD), 38.5% (ventilation electricity savings for fuel cell LHD)
IR-SOE - Shovel operator efficiency improvements for iron mining	This scenario assess the energy and GHG savings due to operator skill improvement in ore loading operations	10.2% (electricity)
IR-HPGR1 - High pressure grinding rolls technology option 1 for iron mining	In these scenarios, a HPGR and ball mill is considered for grinding operation, resulting in electricity savings as HPGR requires less energy to achieve the same degree of size reduction as compared to AG or SAG mill. HPGR1 and HPGR2 represent two different product sizes	21% (electricity)
GO-HPGR1- High pressure grinding rolls technology option 1 for gold mining		27% (electricity)
GO-HPGR2 - High pressure grinding rolls technology option 2 for gold mining		14% (electricity)
GO-HPGR_S - High pressure grinding roll and stirred mill technology for gold mining	This scenario assesses energy use improvement by using a HPGR and stirred mill circuit in the gold mining comminution circuits	31% (electricity)
IR-HPGR2 - High pressure grinding rolls technology option 2 for iron mining	This scenario assesses energy use improvement by using a HPGR and pebble mill circuit in the iron mining sector	22% (electricity)
IR-PAG - Pebbles addition in grinding for iron mining	This scenario analyses the energy savings, GHG mitigation achievable, and the costs associated with addition of pebbles instead of metal balls in grinding operations	13% (electricity)
GO-PAG - Pebbles addition in grinding for gold mining		
IR-PSOT - Pellet size optimization technology for iron mining	This scenario analyses the benefits of producing a uniform distribution of pellets before induration	6% (heavy fuel oil), 6% (coke), 2% (electricity)
GO-VOD, PO-VOD - Ventilation on demand for gold and potash mining	VOD systems use sensors to ventilate specific areas of the mine based on the demand. This scenario evaluates the GHG mitigation potential and cost savings due to reduction in electricity consumption	30% (electricity)
PO-SG&PD - Steam generation and product drying efficiency improvements for potash mining	This scenario assesses the energy and GHG savings due to energy efficiency improvement in industrial boilers	0.3%/year (natural gas)

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2.5.1. *New alternative haul truck powertrain technologies for open-pit mining (IR-AHTs and GO-AHTs_P scenarios)*

Ore is generally extracted with diesel equipment. Diesel engines face regulatory scrutiny and have environmental concerns (they emit harmful emissions). Electrical and hybrid electric vehicles can potentially replace existing diesel vehicles. The scenarios IR-AHTs and GO-AHTs_P assess the energy savings, GHG mitigation achievable, and marginal costs associated with replacing diesel haul trucks with electric and diesel hybrid vehicles in iron and gold mining open-pit operations, respectively. There is no open-pit potash mining in Canada.

Electrical equipment has no tail pipe emissions, uses less heat, and has lower ventilation, power, and maintenance costs than diesel (Varaschin, 2016). Diesel engines are 40–45% efficient; electric motors are 90–95% efficient. Moreover, in terms of availability, electric equipment has a higher availability of 97% than 85% for diesel. Fuel savings were calculated using Equation (7) and assuming a 3000 tonnes per day hard rock operation requiring 3000 kW (kW) haul truck operations. Electric vehicles have an energy intensity of 54% less than that of a diesel vehicle. The average load factors (the ratio of actual fuel consumption to the maximum fuel consumption at full engine load) for diesel engines and electric motors are 0.55 and 0.80, respectively. The motor's power (kW) is approximately 70% of a diesel engine's power. The diesel fuel consumption is 0.3 L/kWh (Varaschin, 2016; Varaschin and De Souza, 2015).

$$\text{Energy savings(E)} = \left(\text{kW required} \times \frac{\text{litre}}{\text{kWh}} \times \text{Operating hours} \times \frac{\text{GJ}}{\text{litre}} \times \text{Number of trucks} \times \text{Avg. load factor}\right)_{\text{diesel}} - \left(\text{Motor kW} \times \text{Number of trucks} \times \text{Avg. load factor} \times \text{Operating hours} \times \frac{\text{GJ}}{\text{kWh}}\right)_{\text{electric}} \tag{7}$$

Diesel hybrid vehicles have better fuel economy and operating efficiency than those with diesel engines and can provide fuel savings of 22% in an open-pit mine (Esfahanian and Meech, 2013). The energy savings were calculated using Equation (8).

$$\text{Energy savings(E)} = \text{Energy intensity}\left(\frac{\text{GJ}}{\text{A}}\right) \times 22\% \times \text{A} \tag{8}$$

The parameters used in the equations are shown in Table A10 in the supplementary file. The diesel haul truck energy intensity data is from an earlier study (Katta et al., 2020; Katta, 2019). The energy savings and other parameters were used in Equation (2) to calculate the TAC for electric and diesel haul trucks.

The first all-electric mine in Canada is expected to be ready by 2021. Hence, for market share calculations (as per Section 2.4.2), it is assumed that 100% of the existing haul truck fleet is diesel in 2021, and after 2021, the retiring diesel fleet will be replaced by diesel, electric, and diesel hybrid vehicles until 2031. The existing diesel fleet stock in 2021 is assumed to be retiring linearly and become zero by 2031, considering that the lifetime of diesel haul trucks is approximately 10 years (Varaschin, 2016). After 2031, the market share of electric mining equipment is estimated to be more than 40% (International mining, 2018). So, it is assumed that the retiring stock from 2031 is only replaced by electric and diesel hybrid vehicles and from 2041 only by electric vehicles. The market share of each of these vehicle types is calculated by Equation (4) using the LCCs and a variance parameter of 10.

2.5.2. *New alternative haul truck powertrain technologies for underground mining (GO-AHTs_U, and PO-AHTs_U scenarios)*

Underground mining requires ventilation to provide fresh air to the workers and diesel engines and to drive away toxic equipment exhaust gases, diesel particulate matter, heat, dust, and blasting fumes (Varaschin and De Souza, 2015). Ventilation is responsible for approximately 50% of the energy consumed (Natural Resources Canada, 2005). The power consumed by the ventilation system is proportional to the volume of air supplied, which is related to the diesel power used in mines (Varaschin and De Souza, 2015). Therefore, using new alternative powertrain haul truck technologies will reduce both diesel consumption and ventilation power consumption. Apart from the 100% diesel savings and 54% less energy intensity for electric vehicles as calculated for scenarios IR-AHTs and GO-AHTs_P, energy savings of 60% in ventilation was calculated for electric haul truck operations compared to diesel haul truck operations. Varaschin and De Souza (2015) estimated a reduced mine air flow (cubic feet per minute) of 28% for a mine operating with electric haul trucks. The 28% reduction implies a 60% reduction in power, calculated using Equations (9) and (10). The remaining equipment still runs on diesel power.

$$P_{\text{fan}} = \frac{H_T \times Q}{\eta} \tag{9}$$

$$H_T \propto Q^2 \tag{10}$$

In these equations, P_{fan} is the power required, Q is the mine air flow requirement, H_T is the total system pressure, and η is the efficiency of the fan.

For a mine that uses diesel hybrid haul trucks, the air flow requirement is considered to be 1/5 that of diesel trucks, given that the diesel savings are ~20%. This translates into electricity savings of approximately 10%. The LCCs are calculated using Equation (4) considering the energy savings from both ventilation and fuel switching. The market share is calculated using the model described in Section 2.4.2.

2.5.3. *Haul truck operating mode improvement (IR-HTO, GO-HTO, and PO-HTO scenarios)*

A typical truck operation includes five modes: travelling while empty, loading, stopped while loaded, travelling while loaded, and stopped while empty. In a case study by the Australian government, it was found that the greatest amount of time is spent stopped while empty (Australian Government-Department of Resources, 2011). More fuel is consumed by the truck stopping and then accelerating than continuing at a constant speed. Eliminating one stop per payload cycle could result in a fuel savings of 3.6% (Australian Government-Department of Resources, 2011). IR-HTO, GO-HTO, and PO-HTO are the scenarios for iron, gold, and potash mining, respectively. It is assumed that all the mines will eliminate one stop per payload cycle linearly by 2030 and realize a 3.6% fuel

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savings in haul trucks.

2.5.4. Haul truck thermal management system (IR-TMS, GO-TMS, and PO-TMS scenarios)

The advanced thermal management system (TMS) can reduce the specific fuel consumption and improve overall engine performance (Nessim et al., 2013). The engine cooling system rejects approximately 30% of the fuel-supplied energy to the surroundings. The scenarios IR-TMS, GO-TMS, and PO-TMS assume that diesel trucks use an advanced TMS and show fuel savings of 8% for iron and gold mining. The penetration of TMS in haul trucks is assumed to increase linearly and reach 100% in 2030.

2.5.5. New alternative LHD powertrain technologies for open-pit gold mining (GO-ALHDs_P scenario)

This scenario assesses efficiency improvements in electric, diesel hybrid, and fuel cell load-haul-dump (LHD) equipment use in open-pit gold mining operations. For a base case of a 3000 tonnes per day hard rock operation operating at 3000 hours per annum, 1350 LHD kWs are used (Varaschin and De Souza, 2015). This operation requires 9 diesel LHDs, or 9 fuel cell LHDs, for a use efficiency of 0.61, or 8 electric LHDs at a use factor of 0.68. The energy savings from an electric LHD are 67% calculated using Equation (7) (100% diesel savings), 30% from a diesel hybrid LHD (Lajunen, 2015), and 50% from a cell vehicle LHD (McKinney et al., 2015). The fuel cell LHD has low heat production and zero emissions (Lajunen, 2015) and is twice as efficient as a diesel vehicle and requires 20 kg of hydrogen for 12 h of operation (McKinney et al., 2015). The hydrogen cost is currently $17.51/kg and is expected to fall to $12.52/kg by 2025 (Hydrogen energy systems, 2016). The parameters and costs assumed are shown in Table A13 in the supplementary file. The market share of fuel cells was calculated using W.P. Nel's diffusion equation (Nel, 2004). The retiring diesel LHD stock from 2021 is assumed to be replaced by electric, diesel hybrid, and fuel cell LHDs. The penetration of these technologies in the gold mining sector was calculated using Equation (3). The parameters are shown in Table A11 in the supplementary file. The market share was calculated using the model in Section 2.4.2.

2.5.6. New alternative LHD powertrain technologies for underground gold mining (GO-ALHDs_U scenario)

This scenario analyzes the energy savings and GHG mitigation potential of implementing electric, diesel hybrid, and fuel cell LHDs in underground mining operations. Underground mines have ventilation energy savings in addition to the energy savings in open-pit mining found in scenario GO-ALHDs_P (Varaschin and De Souza, 2015). Using Equations (9) and (10), we calculated ventilation energy savings of 40% for a mine operating with electric LHDs. Ventilation energy savings of 30% and 38.5% were calculated for diesel hybrid and fuel cell LHDs, respectively. The market share was obtained using the model developed in Section 2.4.2 and the parameters in Table A11 in the supplementary file.

2.5.7. Shovel operator efficiency improvements for iron mining (IR-SOE scenario)

The operator's skills and practices significantly affect energy use in loading operations. The trajectory of the loading bucket and the speed of executing the trajectory are determined by the operator. These in turn determine production rate and energy consumption, specifically the bucket fill factor and the cycle time. Awuah-Offei (2016) observed that the average shovel energy use difference between the best operator and others is around 10.2%. The scenario IR-SOE assumes a 10.2% shovel energy intensity reduction for iron mining. Shovels are only used in open-pit iron mining and hence are not considered for gold and potash mining. Scenario IR-SOE does not include any technological advancement and so a linear penetration is assumed to reach 100% by 2020.

2.5.8. High pressure grinding roll technology option 1 for iron mining (IR-HPGR1 scenario)

High pressure grinding roll (HPGR) technology for crushing and milling processes can reduce energy consumption and operating costs (Ballantyne et al., 2018; McNab et al., 2009). In Canada, all iron processing plants use an autogenous (AG) or semi-autogenous (SAG) mill and a ball mill circuit. In the HPGR scenario, a milling circuit consisting of HPGRs and a ball mill is considered with a 21% electricity savings, as HPGRs require less energy to achieve the same degree of size reduction as an AG or SAG mill (Ballantyne et al., 2018; McNab et al., 2009). It is assumed that the adoption of HPGR circuits by all the mills will be linear and reach 100% by 2030. The various parameters used for the CSE calculation are shown in Table A12 in the supplementary file.

2.5.9. High pressure grinding roll technology option 2 for iron mining (IR-HPGR2 scenario)

This scenario considers the use of HPGRs and a pebble mill circuit in the iron mining sector, which can reduce process electricity use by 22% (Ballantyne et al., 2018; McNab et al., 2009). The various parameters used for the CSE calculation are shown in Table A12 in the supplementary file. Currently, there are no mills in Canada using this circuit. This scenario assumes that the mills adoption rate of this technology starts to linearly increase from 0% in 2020 and reach 100% by 2030.

2.5.10. Pebbles addition in grinding (IR-PAG, and GO-PAG scenarios)

The scenarios IR-PAG and GO-PAG assume 13% energy savings and 25% reduction in ball consumption (Nkwanyana and Loveday, 2017), achieved by the addition of pebbles to ball mills in iron and gold mining, respectively. This application is limited to pilot plant tests as pebble consumption is very high. Thus, a penetration of 100% by 2050 is considered with a linear rate of adoption. The parameters used for calculating the CSE are shown in Table A13 in the supplementary file.

2.5.11. High pressure grinding roll technology option 1 for gold mining (GO-HPGR1 scenario)

Gold ore comminution processes are dominated by AG, SAG, and ball mills, which are energy intensive and account for 80% of the overall process plant energy consumption (Abouzeid and Fuerstenau, 2009). These mills have an efficiency as low as 25% (Fuerstenau and Abouzeid, 2002). Implementing energy efficient technologies such as HPGR will improve the efficiency of the process. For a product size target of 160 μm, the HPGR-ball mill circuit-specific energy consumption is 27% less than the traditional SAG ball mill (SABC) circuit (Wang et al., 2013). The GO_HPGR1 scenario assumes HPGR circuits are implemented in the gold mining sector, penetrate linearly, and reach 100% by 2030. The costs considered for calculating the CSE are shown in Table A14 in the supplementary file.

2.5.12. High pressure grinding roll technology option 2 for gold mining (GO-HPGR2 scenario)

This scenario assesses the energy reduction achievable by implementing an HPGR-ball mill circuit for a target ore particle size of 75 μm. The electricity savings of 14% calculated by Wang et al. (2013) in their study on Canada's Huckleberry Mines was used in this scenario. The penetration rate is considered to increase linearly to 100% by 2030. The cost data is shown in Table A14 in the supplementary file.

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2.5.13. High pressure grinding roll and stirred mill technology for gold mining (GO-HPGR_S scenario)

Stirred mill technology is an energy-efficient grinding process consisting of a series of rotating discs over a shaft driven by a motor, in effect like a set of grinding chambers working together (Jankovic, 2015). This makes it a reliable means of achieving fine grinding sizes. An HPGR-stirred mill circuit consumes 31% less energy than an SABC circuit (Wang et al., 2013). This scenario considers implementing HPGR-stirred mill circuits in the gold mining sector and the penetration rate is assumed to be linear and reach 100% by 2030. The CSE is calculated based on the parameters in Table A14 in the supplementary file.

2.5.14. Pellet size optimization technology for iron mining (IR-PSOT scenario)

Iron ore pellets are formed by agglomerating iron ore fines using discs or drums and then firing them in induration furnaces (Yamaguchi et al., 2010). The induration process requires a large amount of thermal energy (Borim et al., 2018). A uniform distribution of pellet sizes reduces the resistance to the flow of gas through the bed and increases furnace efficiency. This also reduces the power required by the fans used for blowing the gases (Borim et al., 2018). This scenario assumes improvements in iron ore pelletization through a control and optimization strategy for the uniform distribution of pellets. Savings of 6% heavy fuel oil, 6% coke, and 2% electricity were considered (Borim et al., 2018; Furedy, 2010). It was also considered that the adoption of this technology will start in 2020 and reach 100% by 2030 at a linear rate.

2.5.15. Ventilation on demand (GO-VOD, and PO-VOD scenarios)

Ventilation on demand (VOD) systems use sensors to monitor the real-time air quality, vehicle use, and personnel to ventilate only specific areas of the mine instead of ventilating the whole mine all the time. The system includes monitoring environmental conditions, a communication system to transfer information to control rooms, and automated control devices such as regulators, vent doors and fan speed controllers (McCambridge and Kuruppu, 2009). Such a system can bring energy savings of 30% (McCambridge and Kuruppu, 2009; Rockwell Automation, 2017), which is assumed for the GO-VOD and PO-VOD scenarios in gold and potash mining. In 2013, Glencore implemented a VOD system in one of its nickel mines in Ontario. Apart from that, the adoption of VOD by other mines in Canada is not known, even though VOD is not new. Hence, the penetration rate in gold mining is considered to increase linearly and reach 100% by 2030.

2.5.16. Steam generators and product drying efficiency improvements (PO-SG & PD scenario)

Industrial boiler efficiencies are typically around 80% (Gupta et al., 2011). This efficiency can further be improved by reducing excess air, installing combustion controls, improving insulation, and repairing leaks. An earlier study estimated that gas- and coal-fired boilers can improve by 0.3%/year (Interlaboratory Working Group, 2000). This scenario assumes the boiler efficiency of steam generators used in potash mining sector increases. Since these improvements are not major technological advancements, the 0.3% increase in efficiency is considered annually from 2020 onwards.

3. Results and discussion

3.1. Model validation and BAU scenario

The LEAP-CANMIN was validated using NRCan's Comprehensive Energy Use Database statistics for the iron, gold, and potash mining sectors for the years 2007–2016. Fig. 3 shows the differences between model-calculated and historical energy demand and GHG emissions.

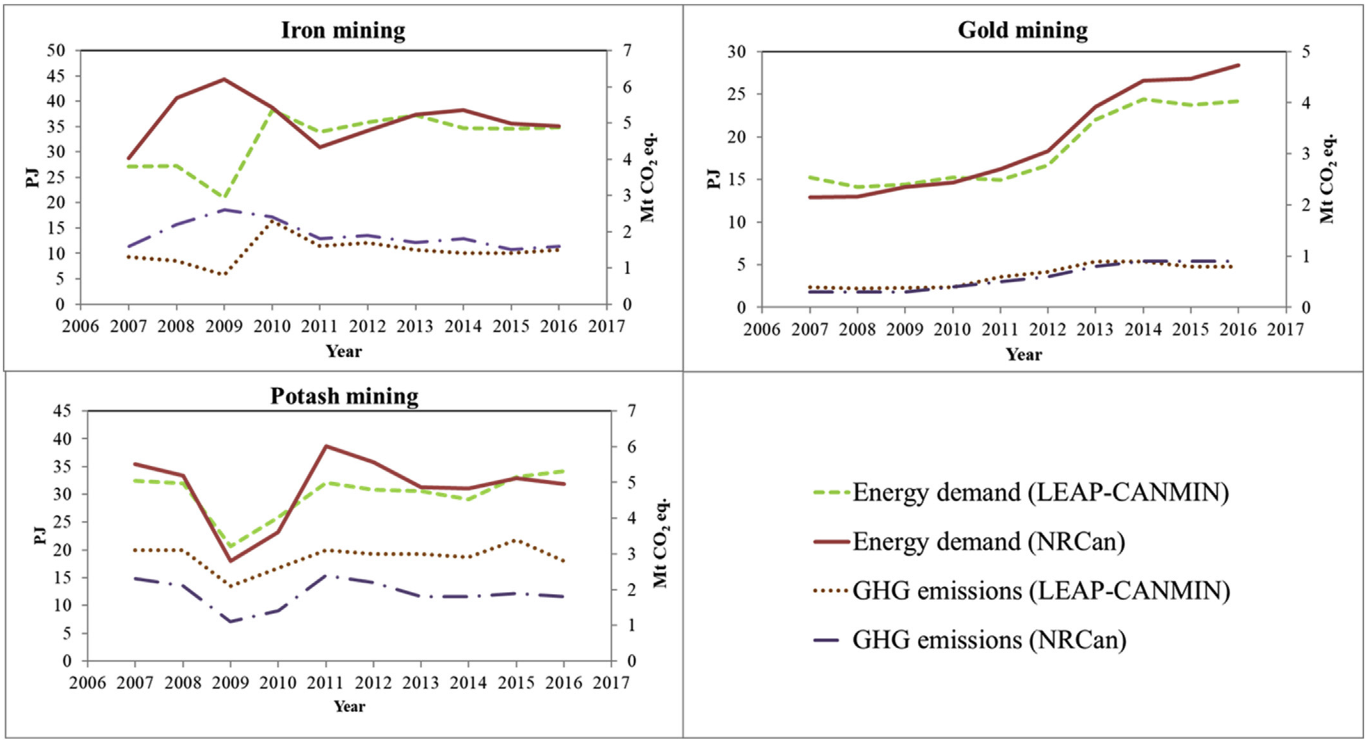

Fig. 3. Energy demand and GHG emission (excluding electricity-related emissions) validation for the iron, gold, and potash mining sectors.

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There are two possible reasons for these differences. First, data on the source of electricity for some mines was not available. For the mines without this data, we assumed that the source of electricity was the provincial grid, thus the provincial grid factor was used to calculate GHG emissions. In reality (assumed to be reflected by the NRCan historical data set), some of these mines may actually be using diesel to generate electricity on site. Thus, the assumption taken in this study to use grid-sourced electricity for these mines could lead to slightly less energy demand and GHG emission results than NRCan's, where diesel might actually be used. The energy demand would be higher when diesel is used since the inefficiency of electricity conversion would lead to a higher energy footprint than direct electricity demand. The GHG emissions would also be higher where diesel is used since grid emission factors are lower than the diesel emission factor. This is consistent with the validation results where NRCan has, on average, slightly higher values for energy demand and GHG emissions.

Second, NRCan uses a top-down national-level modelling approach, instead of modelling by province and then aggregating to the national level (bottom-up), as was done in this study. In general, this can lead to discrepancies in energy use and GHG emissions between NRCan and the LEAP-CANMIN results. For instance, NRCan's electricity-related emissions are calculated using the average Canadian grid emission intensity factor. Since the mineral mining industry in Canada has different levels of activity across provinces, and provinces have different grid emission intensities than the Canadian average, NRCan may over- or under-estimate electricity-related emissions.

The average difference in energy demand is 9%, 3%, and 2% in the iron, gold, and potash mining sectors, respectively. The average difference in GHG emissions is 21%, 11%, and 59% in the iron, gold, and potash mining sectors, respectively. For iron mining, the high difference compared to the reported NRCan data and LEAP-CANMIN model results is mainly due to the years 2008 and 2009. 2009 had the lowest iron production among all the years and thus it is expected to have the lowest energy demand, as calculated in the LEAP-CANMIN model; however, NRCan data shows an energy spike. A personal communication with NRCan, the organization providing the data, did not yield justification. Hence, we accept this anomaly and do not believe it has significant bearing on model accuracy since data errors may be present in the historical data, and later years validate well. Without considering the years 2008 and 2009 for iron mining, where there is an unexplainable anomaly, the average difference in energy use and GHG emissions is 1% and 11%, respectively. The inflection point observed from LEAP-CANMIN results for iron and potash mining in 2011 is due to the decrease in activity when compared to 2010. But, for gold mining, the activity has not decreased. This can be observed in Tables A5 to A8 in the supplementary file. The potash GHG emission validation has a high difference due to NRCan using a national average electrictiy GHG emission intensity value to calculated potash electricity emissions. The LEAP-CANMIN model uses a region specific value for Saskatchewan (where all potash is mined) which is much higher than the Canadian average.

BAU scenario energy demand is expected to increase by 1.6, 2.0, and 2.1 in the iron, gold, and potash mining sectors, respectively, between 2015 and 2050. GHG emissions are expected to increase by 1.3, 1.4, and 1.5 in the iron, gold, and potash mining sectors. The increase is driven by growth in the sectors. Projected energy demand and GHG emission result tables for the iron, gold, and potash mining sub-sectors are in Table A15 and Table A16, respectively, in the supplementary file.

3.2. Cost of saved energy (CSE) and total activity cost (TAC)

The CSE and TAC results for iron, potash, and gold mining for the years 2020–2050 are presented in Table 4, Table 5, and Table 6, respectively. For each scenario, a regression analysis of the CSE and TAC showed a linear upward trend with a coefficient of determination (R^2) > 0.98 between 2020 and 2050. This signifies that the CSE and TAC can be predicted accurately for any year using the range values.

The average TAC (for the years 2020–2050) for the scenarios IR-AHTs, GO-AHTs_P, GO-AHTs_U, PO-AHTs_U is from −1.3 to −3.0 $/t and 0.04 to −6.7 $/t for electric and diesel hybrid haul trucks, respectively, depending on the sector and province. It is better to use electric haul trucks than diesel hybrid haul trucks in all three sectors; there are higher energy savings and lower electricity prices with electric haul trucks, and diesel hybrid truck consume the higher-cost diesel fuel. In underground mines, using electric or diesel hybrid vehicles will lower the ventilation energy requirement and lower the CSE/TAC compared with those of open-pit mines. Diesel hybrid haul trucks show negative TAC only in the potash mining sector. The average TAC for electric, diesel hybrid, and fuel cell LHDs is from −3.9 to −0.3 $/t, 0.9 to 3.6 $/t, and 2.6 to 16.6 $/t, respectively, among the provinces. For the scenarios in ore comminution, iron and gold mining have average CSEs of −46.7 to −31.5 $/GJ and −25.1 to 35.8 $/GJ, respectively. A scenario may not show cost savings in every province due to differing energy prices, as in scenario GO-HPGR1, where Ontario and Nunavut have much higher positive CSEs than other provinces. All other scenarios have negative CSEs in each province of −0.3 to −56.4 $/GJ.

3.3. Market share model results

The market share was modelled for electric and diesel hybrid haul trucks and LHDs and was used in modelling the scenarios IR-AHTs, GO-AHTs_P, GO-AHTs_U, GO-ALHDs_P, GO-ALHDs_U, and PO-AHTs_U. The market share in each province between 2020 and 2050 is shown in Fig. 4. The penetration of electric haul trucks (top

Table 4
CSE, TAC for scenarios in the iron mining sector.

Scenario		Range of CSE/TAC for the years 2020–2050		
		NFL	QC	Units
IR-AHTs	Electric haul trucks	−2.0−−2.9	−2.6−−3.3	$/t
	Diesel hybrid haul trucks	0.03–0.05	0.04–0.04	$/t
IR-HTO		−39.9−−54.1	−45.1−−58.5	$/GJ
IR-TMS		−39.9−−54.1	−45.1−−58.5	$/GJ
IR-SOE		−20.7 − 28.3	−13.7−−14.1	$/GJ
IR-HPGR1		−38.3−−45.9	−31.3−−31.7	$/GJ
IR-HPGR2		−40.3−−50.7	−36.0−−36.4	$/GJ
IR-PAG		−0.31−−0.34	−0.27−−0.28	$/t
IR-PSOT		−20.7−−28.3	−13.7−−14.1	$/GJ

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Table 5
CSE, TAC for scenarios in the potash mining sector.

Scenario		Range of CSE/TAC for the years 2020–2050		
		SK	NB	Units
PO-AHTs_U	Electric haul trucks	−0.9−−1.9	−1.2−−1.8	$/t
	Diesel hybrid haul trucks	−0.00−−0.02	0.01−−0.02	$/t
PO-VOD		−21.0−−27.8	−18.9−−19.5	$/GJ
PO-SG&PD		−3.4−−4.7	−5.8−−7.1	$/GJ
PO-HTO		−37.2−−50.6	−40.8−−52.9	$/GJ
PO-TMS		−37.2−−50.6	−40.8−−52.9	$/GJ

Table 6
: CSE, TAC for scenarios in the gold mining sector.

Scenario		Range of CSE/TAC for the years 2020–2050								
		NFL	QC	ON	MN	BC	SK	YK	NU	Units
GO-AHTs_P	Electric haul trucks	−1.6 − −2.5	−2.2 − −2.9	−1.3 − −1.9	−1.9 − −2.6	−1.8 − −2.4	−1.6 − −2.2	−1.7 − −2.5	−0.9 − −1.7	$/t
	Diesel hybrid haul trucks	0.05 − 0.03	0.05 − 0.03	0.05 − 0.04	0.05 − 0.04	0.05 − 0.04	0.05 − 0.04	0.05 − 0.03	0.05 − 0.03	$/t
GO-AHTs_U	Electric haul trucks	−4.3 − −4.5	−3.5 − −4.2	−4.6 − −5.5	−3.1 − −3.9	−3.7 − −4.3	−3.6 − −4.8	−3.7 − −4.7	−6.1 − −7.3	$/t
	Diesel hybrid haul trucks	−0.2 − −0.1	−0.07 − −0.09	−0.23 − −0.28	−0.05 − −0.07	−0.11 − −0.13	−0.12 − −0.19	−0.12 − −0.16	−0.40 − −0.46	$/t
GO-ALHDs_P	eLHD	−0.4 − −0.8	−0.6 − −0.9	−0.3 − −0.6	−0.5 − −0.8	−0.5 − −0.7	−0.4 − −0.6	−0.4 − −0.8	−0.2 − −0.5	$/t
	Diesel hybrid LHD	3.7 − 3.6	3.6 − 3.5	3.7 − 3.6	3.7 − 3.6	3.7 − 3.6	3.7 − 3.6	3.7 − 3.6	3.7− 3.6	$/t
	Fuel cell LHD	17.1 − 16.3	17.0 − 16.2	17.1 − 16.4	17.1 − 16.4	17.1 − 16.4	17.1 − 16.4	17.1 − 16.3	17.1 − 16.3	$/t
GO-ALHDs_U	eLHD	−2.2 − −2.1	−1.5 − −1.8	−2.4 − −3.0	−1.3 − −1.6	−1.7 − −2.0	−1.7 − −2.4	−1.7 − −2.2	−3.6 − −4.3	$/t
	Diesel hybrid LHD	2.3 − 2.6	3.0 − 2.9	2.1 − 1.8	3.1 − 3.0	2.7 − 2.6	2.7 − 2.3	2.7 − 2.5	1.1 − 0.7	$/t
	Fuel cell LHD	4.9 − 4.6	5.7 − 4.9	4.6 − 3.6	5.9 − 5.1	5.4 − 4.7	5.4 − 4.3	5.4 − 4.4	3.3 − 2.2	$/t
GO-HTO		−39.9 − −54.1	−45.1 − −58.5	37.1 − −50.5	−38.4 − −52.6	−40.6 − −51.5	−37.2 − −50.6	−38.7 − −55.0	−39.2 − −55.4	$/GJ
GO-TMS		−39.9 − −54.1	−45.1 − −58.5	−37.1 − −50.5	−38.4 − −52.6	−40.6 − −51.5	−37.2 − −50.6	−38.7 − −55.0	−39.2 − −55.4	$/GJ
GO-PAG		−0.3 − −0.4	−0.3 − −0.4	−0.3 − −0.4	−0.2 − −0.3	−0.3 − −0.4	−0.3 − −0.4	−0.3 − −0.4	−0.5 − −0.6	$/t
GO-HPGR1		7.3 − −0.4	−7.4 − −7.0	13.0 − 16.9	−8.5 − −8.1	−1.9 − −0.7	−0.1 − 6.7	−0.0 − 1.9	32.9 − 37.9	$/GJ
GO-HPGR2		7.7 − 0.0	−7.0 − −6.6	13.4 − 17.3	−8.1 − −7.7	−1.4 − −0.3	0.3 − 7.1	0.4 − 2.3	33.3 − 38.7	$/GJ
GO-HPGR_S		−9.6 − −17.2	−24.2 − −23.8	−3.8 − 0.1	−25.4 − −24.9	−18.7 − −17.5	−16.9 − −10.1	−16.9 − −15.0	−16.4 − 21.0	$/GJ
GO-VOD		−28.3 − −20.6	−13.7 − −14.0	−34.1 − −38.0	−12.5 − −13.0	−19.2 − −20.4	−21.0 − −27.8	−21.0 − −22.9	−53.9 − −58.9	$/GJ

left in Fig. 4) and LHDs (bottom left in Fig. 4) is faster in Quebec than in other provinces. This is due to the cheaper electricity price, which lowers the LCC and increases the trucks' market share. The market shares of electric haul trucks and LHDs were estimated to be 60–80% and 20–30%, respectively, by 2030 among the provinces. It is assumed that by 2040, approximately 80% of the haul trucks and LHDs in mines operate on electricity. The difference in penetration rates between the provinces is not significant in the case of electric LHDs. The market shares of diesel hybrid haul trucks (top right in Fig. 4) and LHDs (bottom right in Fig. 4) are expected to increase until 2040 and then decrease due to the increased penetration of electric/fuel cell vehicles.

3.4. Scenario analysis

The GHG emissions mitigation potential of multiple scenarios can be shown in the form of wedge curves, in which each wedge represents the trend and the avoidable GHG emissions for a particular scenario over the study period. Fig. 5 and Fig. 6 show the wedge curves developed for the IR-TMS, IR-AHTs, and IR-PSOT scenarios in iron mining, and GO-VOD, GO-HTO, GO-HPGR_S, GO-TMS, GO-ALHDs_U, GO-ALHDs_P, GO-AHTs_U, and GO-AHTs_P scenarios in gold mining that can be implemented concurrently. These figures also show the emissions profile in a BAU scenario and the resulting emissions profile following the penetration of GHG mitigation options by 2050. The maximum cumulative energy and GHG reduction achievable in the iron mining sector, considering the scenarios that can be implemented concurrently, are 98 PJ (6% of the sector's energy consumption) and 8 Mt CO_2 eq. (10% of the sector's emissions), respectively, by 2050. For gold mining, the cumulative energy savings and GHG mitigation are 323 PJ (23% of the energy consumption) and 10 Mt (20% of GHG emissions) by 2050, respectively. For potash mining, energy savings and GHG mitigation achievable from PO-AHTs_U, PO-VOD, PO-SG&PD, and PO-HTO scenarios together are 45 PJ (2% of the sector's energy use) and 3 Mt of CO_2 eq. (2% of the sector's GHG emissions). Given the

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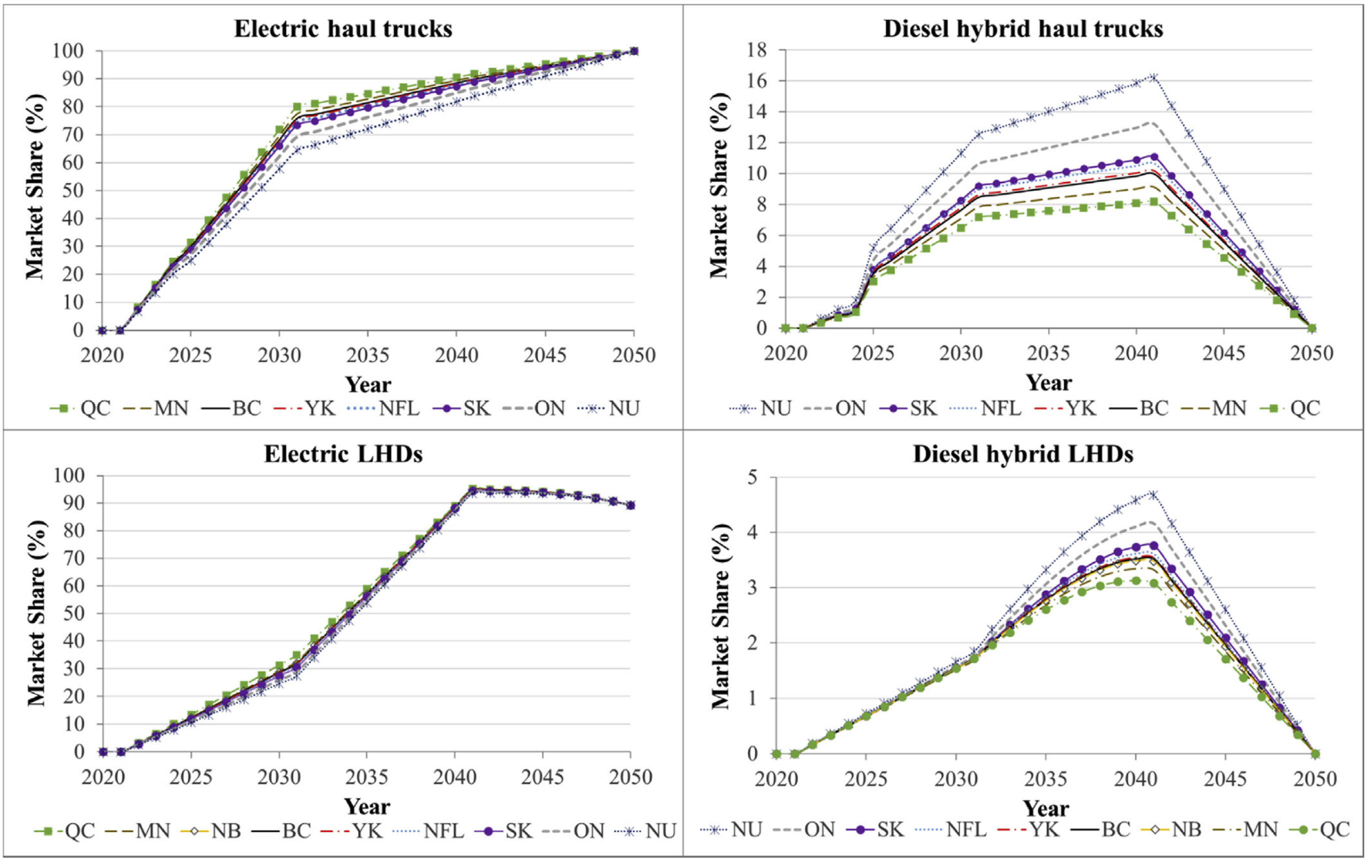

Fig. 4. Market shares of electric haul trucks, diesel hybrid haul trucks, electric LHDs, and diesel hybrid LHDs in each province.

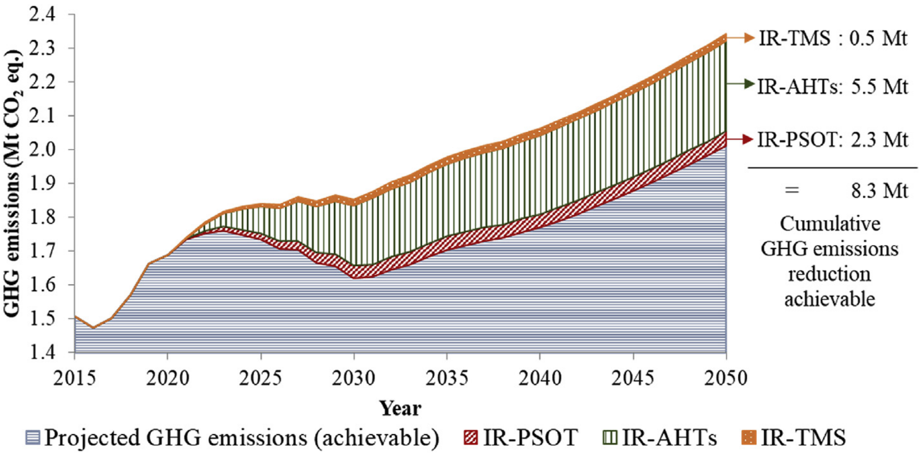

Fig. 5. Wedge curve of achievable GHG emissions reduction for the iron mining sector.

small mitigation achievable, a wedge curve was not developed for the potash mining sector.

Fig. 7 shows the cost curve for the scenarios in all the three sub-sectors. This figure illustrates comparative GHG mitigation potential and marginal GHG abatement costs for the scenarios. The horizontal axis shows the sum of the difference in GHG emissions between the efficient and BAU scenarios over the study period (in Mt of CO_2 eq.). The vertical axis shows the incremental cost of an energy use reduction option in 2016 Canadian dollars compared to existing technologies over the study period (in \$/tonne of CO_2 eq.) A negative cost indicates savings and a positive cost indicates that the capital cost to implement the scenario exceeds the cost saving because of energy consumption.

These cost curves are used to compare GHG mitigation potential and marginal GHG abatement costs in the scenarios across the three sub-sectors. The GHG mitigation costs ranged widely, from −4120 to 614 \$/tonne of CO_2 eq. The cumulative energy demand reduction, GHG mitigation, marginal GHG abatement cost, and net present value (NPV) are presented in Table A18 in the supplementary file. The scenarios on alternative haul truck

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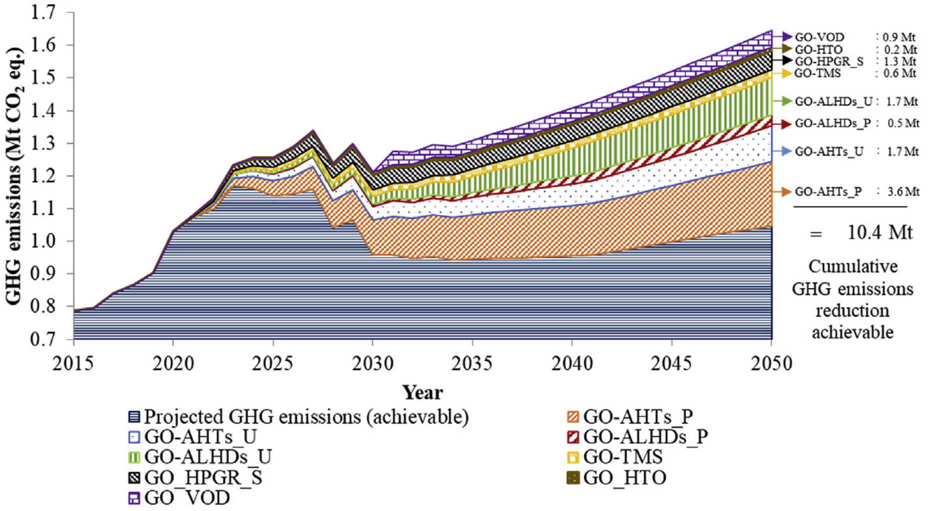

Fig. 6. Wedge curve of achievable GHG emissions reduction for the gold mining sector.

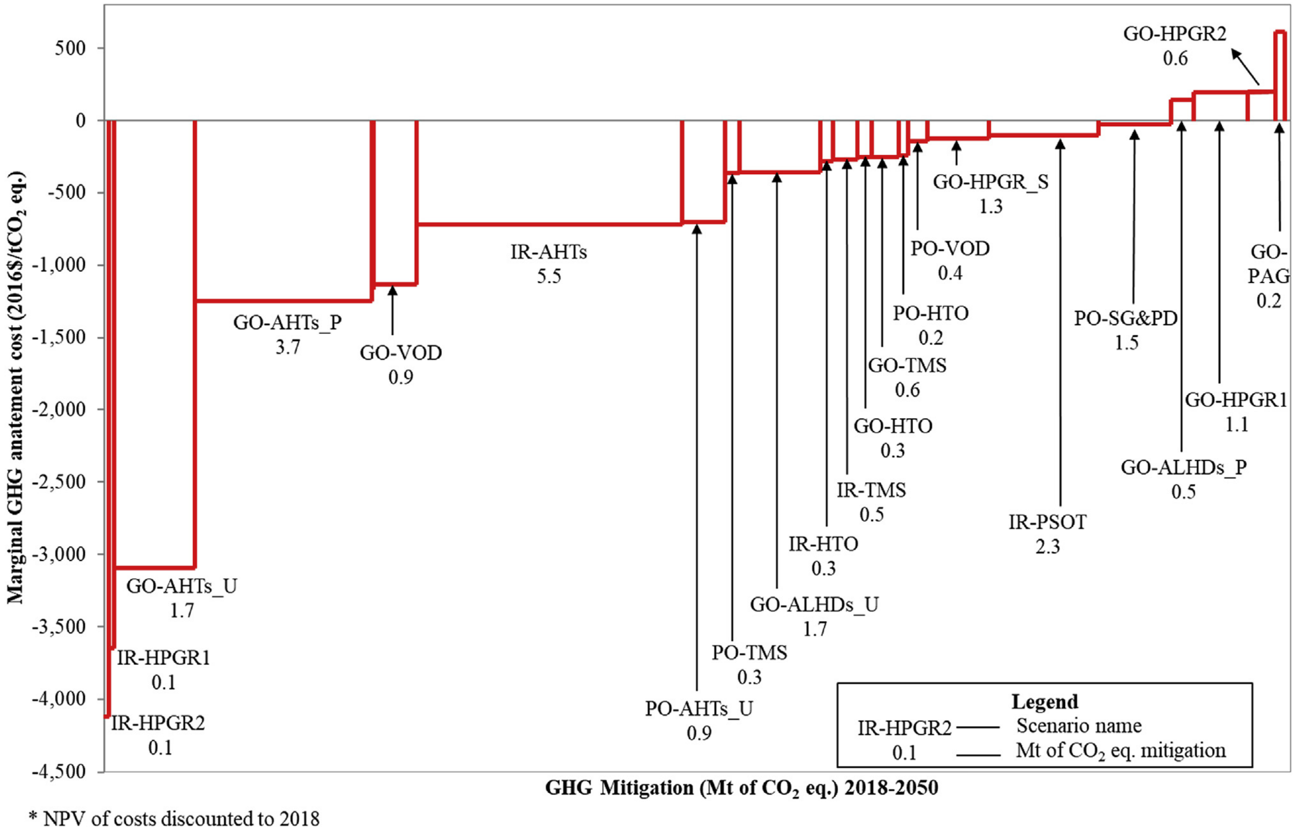

Fig. 7. Canadian iron, gold, and potash mining sector combined marginal GHG emission abatement cost curve.

technology penetration (IR-AHTs, GO-AHTs_P, GO-AHTs_U, and PO-AHTs_U) for ore haulage show significant relative GHG reduction potential with marginal cost savings. Using these vehicles in underground mining has a lower marginal GHG abatement cost than in open-pit mining because of the additional energy savings in mine ventilation. The IR-AHTs scenario has a higher mitigation potential of 5.5 Mt, and the GO-AHTs_U scenario has a lower marginal GHG abatement cost of −3096 $/tonne of CO$_2$ eq. than the other scenarios on ore haulage. For ore loading operations, the scenarios GO-LHDs_P and GO-LHDs_U for the gold mining sector showed 0.5 and 1.7 Mt of GHG emissions reductions by 2050 in open-pit and underground mines, respectively. However, the GO-LHDs_P scenario is not economical; it has a positive marginal GHG abatement cost. For ore comminution, introducing HPGR-ball mill circuits will save costs in the iron mining sector but not in the gold mining sector. This is mainly due to the higher energy intensity of the grinding operation in iron ore comminution, which leads to higher energy cost savings. Using HPGR-stirred mill technology for grinding gold ore will result in higher GHG mitigation and cost savings. Haul truck operting mode improvement scenarios reduce

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GHGs and costs more in iron mining than in the other two sectors. Some scenarios have only electricity-related energy savings and their mitigation potential depends on the electricity generation grid mix. Overall, ~80% of the developed scenarios have cost savings because saved energy costs outweigh other costs. Although the magnitude of the GHG mitigation potential and the abatement costs will be different in other jurisdictions depending on energy intensity and grid emission factors, the relative comparison among the scenarios would be similar. Thus, the marginal GHG abatement cost curves of this study can provide useful information to other jurisdictions with similar mining operations.

3.5. Limitations

Mine-specific parameters such as ore grade and strip ratio were considered in our future projections to be the same as 2015 levels because no data is available on mining companies' future extraction activities. This assumption was made as ore grades are likely to remain almost constant (Mudd, 2007b), and although the strip ratio for a mine would decrease with the age of mine, the average strip ratio for all the mines together would be similar. The growth rates used in this study were for both metal and non-metal mining and the mining sector as a whole and not for the specific sub-sectors. The penetration rates for some of the scenarios were based on the economics of technologies, but unknown future macro-economic and policy changes might affect these rates. Also, no externality cost is assumed while calculating the economic aspects of the technologies. Because energy consumption varies widely for each mine depending on the extracted ore grades and processing routes, a mitigation option with high cost savings in the cost curve may not be cost effective for every mine.

3.6. Sensitivity analysis

Sensitivity analysis was performed to understand the impact of capital cost, fuel (electricity, natural gas, and diesel) price, and discount rate on the marginal GHG abatement cost. These variables were changed from −30% to +30% for each scenario. Figs. 8–10 show the sensitivity results for the IR-AHTs, GO-AHTs_P, and PO-SG&PD scenarios that have the highest GHG mitigation potential in their respective sectors. The results for the other scenarios are shown in Fig. A1-A20 in the supplementary information file. For the scenarios in iron mining, the discount rate is the most influential variable and changes the marginal GHG abatement by 23–35% with a change of −30% in the discount rate. Capital cost changed the marginal GHG abatement cost by 15–16% in scenarios IR-HPGR1 and IR_HPGR2, but for the other scenarios, the change is less than 6%. A reduction in diesel price by 30% increased the marginal GHG abatement cost by 30% for the scenarios on haulage equipment. A −30% change in electricity price increased the marginal GHG abatement cost by 16%, 14%, and 9% in the IR-HPGR1, IR-HPGR2, and IR-PAG scenarios. The reference scenario growth rate changed the marginal GHG abatement cost by only 0–1% for all the scenarios. For gold mining, the GO-ALHDs_P scenario changed by 330%, 90%, 557%, and 124% for a 30% increase in capital cost, discount rate, diesel price, and natural gas price, respectively. For the rest of the scenarios, the change in marginal GHG abatement cost ranged from -132-194% for capital cost, 29–38% for discount rate, -40-80% for diesel price, and -102-65% for electricity price. The BAU scenario growth rate variable was found to be relatively less influential and changed the mitigation cost by 14% to −19%. For all the scenarios in potash mining, a change in the discount rate by +30% and −30% changed the marginal GHG abatement costs by approximately −25% and +35%, respectively. A 30% increase in diesel price reduced the mitigation cost by 55% and 30% in the PO-AHTs and PO-HTO scenarios, respectively. Overall, for all three sectors, an increase in diesel fuel price and a decrease in electricity price lowered the GHG mitigation cost because of the increased penetration of alternative powertrain technologies in the ore haulage scenarios. For scenarios on efficient comminution circuits, an increase in electricity price reduced the cost of saved energy and led to lower marginal GHG abatement costs.

3.7. Implications of the study

We have demonstrated that the framework used in this study is an effective way of assessing mineral mining improvement options. The implication is that it can now be widely applied to assess global GHG emission mitigation potential and prioritize industry-wide technology transitions, thus progressing towards sustainable production.

We showed that there is unfulfilled potential to mitigate GHG emissions in Canada and that there are associated cost-savings. The implication is that with these results, companies can make data-driven decisions to invest in these technologies. They not only benefit from reduced energy costs due to increased efficiency, but also can reduce the impact of carbon pricing mechanisms.

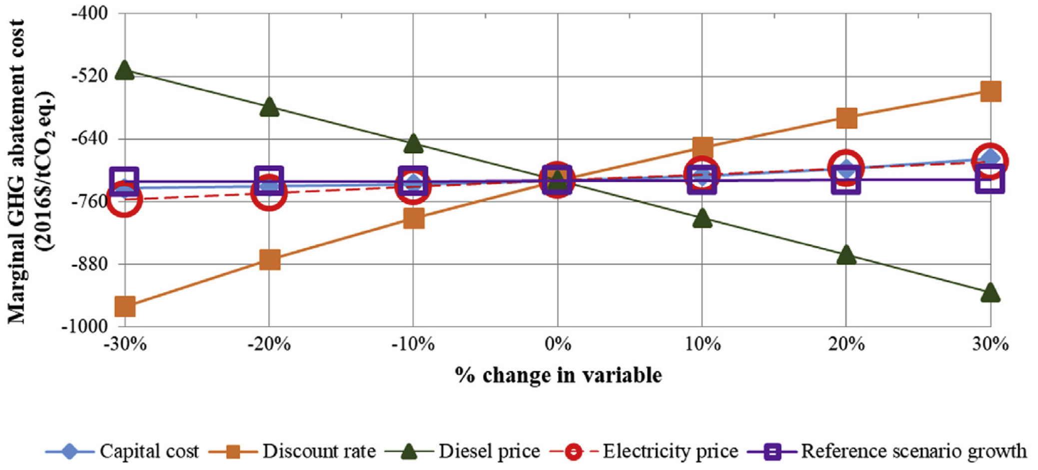

Fig. 8. IR-AHTs scenario sensitivity of abatement cost to capital cost, discount rate, diesel price, electricity price, and reference scenario growth.

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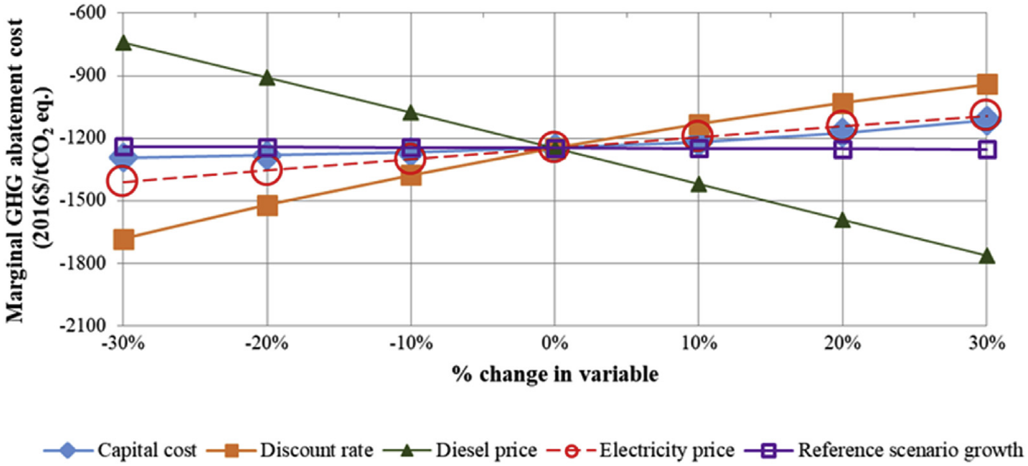

Fig. 9. GO-AHTs_P scenario sensitivity of abatement cost to capital cost, discount rate, diesel price, electricity price, and reference scenario growth.

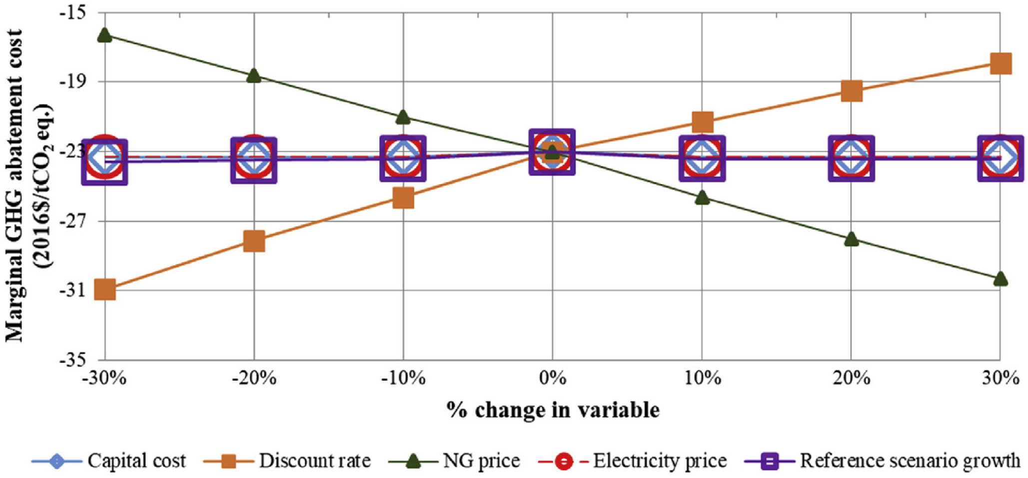

Fig. 10. PO-SG&PD scenario sensitivity of abatement cost to capital cost, discount rate, natural gas price, electricity price, and reference scenario growth.

The demand for iron, gold, and potash increased by 2.4, 1.2, and 1.5 between 2001 and 2015 (U. S. Geological Survey, 2019). Demand is forecast to grow. These increases, together with ore extraction becoming more complex, will lead to more energy consumption and GHG emissions in the global mineral mining industry. So, the challenging task ahead is to formulate actions that will support CP of the mineral industry. Thus, the results of this study will help in setting sub-sector specific future targets to balance the achievable emission reductions and their expected costs.

4. Conclusion

Since the potential for GHG mitigation in the Canadian mineral mining sector is unknown, this study set out to quantify the potential and evaluate strategies to mitigate emissions. A novel mineral mining energy-environmental model was developed that integrates diffusion-based market penetration principals with long-term, bottom-up energy and environmental accounting. 24 clean production scenarios were developed that consider technology changes that have not yet occurred in the Canadian iron, gold, and potash mining sectors. The scenarios were evaluated with the model by determining the market share of competing technologies, quantifying the long-term GHG mitigation potential, and comparing the marginal GHG abatement costs.

The maximum GHG mitigation potential for the years 2018–2050 is 10%, 20%, and 2% of the total cumulative GHG emissions by 2050 in the iron, gold, and potash mining sectors, respectively. The associated marginal GHG abatements costs are −525, −1,176, and −258 $/tonne of CO_2 eq., respectively. The scenarios on implemented alternative powertrain technologies in open-pit iron mining, gold mining, and energy efficiency improvements in steam generation and product drying units have shown the highest achievable GHG mitigation potentials of 5.5 Mt, 3.7 Mt, and 1.5 Mt with cost savings. The abatement cost of the scenarios ranged from −101 to −4120 $/tonne in iron mining, 614 to −3096 $/tonne in gold mining, and −23 to −701 $/tonne in potash mining. The technologies show widely different costs of saved energy and total activity costs among the provinces because of varying fuel prices.

The technologies and energy efficiency improvement options in this study evaluated were shown to have the potential to improve the environmental performance of mines and contribute to decarbonising the mineral industry. But currently, the sustainability approach is well perceived at the corporate and strategic level and not at the operational level. The technical, financial, and time-restricted decision-making at the operational level is mainly limited to production targets and legal compliance, which require a shift to include broader sustainability aspects. Capital investment is

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another barrier for companies to pursue clean technology transitions. Since this analysis shows what specific transitions produce cost-effective GHG mitigation, investment decisions can be developed to support them. It should also be noted that the companies should assess the interactions and affects of implementing a new technology. For example, high pressure grinding rolls could reduce energy use when compared to conventional milling processes, but the former could result in more dust emissions. So, assessments should be done with respect to health risks, which may lead (in this case) to the procurement of additional dust suppression equipment, which will partially offset energy savings.

Overall, the results of this study can be used by mining companies to proactively shift towards cleaner production methods and by policy makers to develop regulations. Also, the developed framework can be applied to mining sectors elsewhere by changing production data variables and adjusting the energy intensities to suit the mining processes, ore grades, strip ratios, and energy costs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118718.

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