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ORIGINAL ARTICLE

Potential for energy efficiency improvement and greenhouse gas mitigation in Canada's iron and steel industry

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Abstract The global demand of steel production is growing, and so are the carbon dioxide emissions from the sector. Research has confirmed that 15 to 20% further energy efficiency improvement is possible, which would reduce the sector's greenhouse gas emissions and help meet global emission reduction initiatives. In this context, this research aims at developing a bottom-up system-based model to evaluate the long-term potential of energy efficiency alternatives in greenhouse gas mitigation. A case study was conducted for the Canadian iron and steel sector. The developed framework involves review of the state of the art in iron and steel production technologies, demand tree development, energy-environmental modeling, scenario development, and analysis. Twenty-six mitigation scenarios were developed in planning horizons ending in 2030 and 2050. A 13% improvement in Canadian iron and steel energy efficiency could be achieved by increasing the production share of the electric arc furnace route from 41% in the base year to 56% by 2050. The results of the analysis suggest that 19 and 38 million tonnes of greenhouse gas emission reduction are achievable in the 2010–2030 and 2010–2050 planning horizons, respectively. This translates to an approximately 6% reduction in emissions compared to the baseline scenarios at a cost of − \$76 and − \$51 per tonne of carbon dioxide equivalent in the 2010–2030 and 2010–2050 time periods, respectively. The results also reveal that more than 85% of the potential emission reductions are achievable with negative costs and are economically attractive. The study provides insights to decision makers at different levels of industry and government.

Keywords Iron and steel · Energy modeling · GHG mitigation · Scenario analysis · Energy efficiency

Abbreviations

BAU	Business-as-usual
BF	Blast furnace
BOF	Basic oxygen furnace
CAD	Canadian dollar
CF	Cash flow
COG	Coke oven gas
CSE	Cost of saved energy
DRI	Direct reduced iron
EAF	Electric arc furnace
EBT	Electric bottom tapping
EC	Energy consumption
EE	Energy-efficient
GHG	Greenhouse gas
GJ	Gigajoule
LEAP	Long-range Energy Alternatives Planning
NPV	Net present value
O&M	Operation and maintenance
PJ	Petajoule
SEC	Specific energy consumption
TJ	Terajoule

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UHP	Ultra-high power
US	United States

Introduction

The Paris Agreement, a global agreement under the United Nations Framework Convention on Climate Change (UNFCCC), aims at combating climate change by liming the average global temperature to well below 2 °C (UNFCCC 2015a). Countries all over the world submitted ambitious national plans called intended nationally determined contributions (INDCs), which oblige them to take the necessary actions to avoid and adapt climate change impacts (UNFCCC 2015b). More enhanced efforts than INDCs are needed to reduce carbon dioxide (CO_2) emissions from industrial activities and achieve the Paris 2 °C scenario (2DS) (Rogelj et al. 2016). The iron and steel industry is one of the largest CO_2 emitters. In 2017, the sector accounted for nearly 24% of industry direct emissions (IEA 2019). In order to meet the 2DS, direct industrial CO_2 emissions should be 49% lower by 2050 compared to the business as usual case, around 33% of the emission reduction from iron and steel sector (IEA 2016).

The iron and steel sector has shown remarkable energy and CO_2 emission intensity improvements in the last decades, achieving an average annual reduction of 0.7% in energy intensity and 1.4% in CO_2 intensity between 2010 and 2016 (IEA 2019). The conventional route of primary steelmaking uses a blast furnace to produce pig iron from iron ore, coke, and limestone that are later converted to steel using a basic oxygen furnace. This accounts for 70.9% of the total production (World Steel Association 2020). Secondary production uses an electric arc furnace to produce steel from scrap metals. This process consumes less energy per tonne of produced steel compared to the primary route. Around 28.9% of global steel is produced in this route (World Steel Association 2020). Much of the energy and CO_2 intensity reductions observed in recent years in the sector are attributed to the shift of steel production from primary to secondary. However, more reduction efforts are needed to meet the 2DS target by 2050, as the global demand for steel is growing (IEA 2019). Between 2009 and 2018, total global crude steel production increased by 47% and reached 1.82 billion tonnes (World Steel Association 2018). One of the mitigation measures to further reduce the CO_2 emissions from the sector is through energy efficiency improvement (Rogelj et al. 2018).

A 15–20% enhancement of iron and steel process energy efficiency is possible (World Steel Association 2017). This potential could be realized by implementing the world's best available technologies (Worrell et al. 2007) or by applying alternative iron and steel production routes such as smelting and direct reduction technologies (Hasanbeigi et al. 2014). Hence, it is important to identify the best alternative scenarios that offer the highest energy improvement. Several studies use scenario analysis to investigate the long-term energy efficiency improvement in the iron and steel industry (Wen et al. 2014; Wang et al. 2007). Some studies assessed the impacts of policies such as fuel switching and energy efficiency improvement on the long-term emission mitigation potential (Gielen and Moriguchi 2002). Studies under this category (i.e., system-level scenario analysis) provide insights into possible future developments in the industry. However, detailed technological requirements to reach the expected energy intensity improvement are not usually used for scenario studies (De Beer 2000). This is one of the key gaps in the existing literature.

In another set of studies, energy efficiency improvement in the iron and steel industry was investigated from a technology-level perspective. While some researchers used a bottom-up approach to identify energy-saving measures (Hasanbeigi et al. 2013b; Orth et al. 2007) or assess their technical applicability (Worrell 2011) and economic feasibility (Gielen 2003), others analyzed the long-term effectiveness of the technologies (Xu and Cang 2010). In order to assess the economic effectiveness of various energy efficiency measures at the sector level, energy conservation cost curves were applied in a number of studies (Hasanbeigi et al. 2013b; Morrow et al. 2014; Worrell et al. 2001). However, these studies do not assess the impacts of these technological level improvements over a long-term planning horizon or the overall impact on the sector, which is another key gap.

This study, therefore, aims to address the gaps in the literature detailed above by developing a bottom-up system-based framework that integrates scenario analysis and techno-economic assessment approaches. The framework allows one to evaluate the long-term technically feasible emission reduction potential through energy efficiency improvement. The study focuses on greenhouse gas (GHG) mitigation potential through the implementation of commercially proven technologies in the iron and steel sector. The holistic changes that might take place by technology breakthroughs (e.g., the integration of renewables to the steel production process) or as a result of deep decarbonization and ambitious GHG mitigation targets are outside the scope of the study. While emerging technologies such as carbon capture and storage, hydrogen direct reduction (Vogl et al. 2018), application of renewable energies (such as bio-synthetic natural gas in reheating furnaces) (Johansson 2013), and iron ore electrolysis are expected to play an important role in decarbonizing the sector in the long term (i.e., to a time horizon ending in 2100) (Fischedick et al. 2014), they are not considered in this study mainly to mitigate the uncertainties associated with the time of implementation and the economic performance of this group of technologies (Bataille et al. 2018; Fischedick et al. 2014). The study uses macro-economic variables such as future trends of steel production, fuel price, and electricity emission factors to assess the technologically feasible GHG emission reduction from the sector.

The framework is applied to a case study in the Canadian iron and steel industry. With an annual estimate of 12.9 million tonnes, Canada ranked the 4th largest crude steel producer in North America in 2018 (after the USA, Brazil, and Mexico) (World Steel Association 2019). Several studies with different scopes, objectives, and methods have been done to assess the potential for GHG mitigation from iron and steel industries in different jurisdictions globally (e.g., China (Wen et al. 2014), Turkey (Ates 2015), Brazil (Borba et al. 2012), Japan (Kuramochi 2016), the USA (Worrell et al. 2001), and Europe (Pardo and Moya 2013)). While the variety of these studies highlights the importance of the topic from a global perspective, the lack of such study in Canada indicates the need for a comprehensive assessment of medium- to long-term GHG mitigation potential in the country, and the current research aims at addressing that. The specific objectives of the current study are to

- Analyze the current status of the industry in terms of technological progress, energy consumption, and GHG emissions
- Identify the major energy consumers (i.e., the processes and technologies within the steel production process) and develop an energy consumption demand tree by determining the energy intensity of each energy consumer (energy consumption per unit of final product) of each sub-sector
- Analyze various energy efficiency improvement measures and assess their applicability to the Canadian iron and steel industry
- Evaluate the medium- and long-term energy and GHG emission savings potential and the marginal abatement costs associated with implementing the identified measures
- Develop marginal GHG abatement cost curves for the Canadian iron and steel industry

Methods

Framework

This study was conducted in 5 steps as illustrated in Fig. 1. The first was to review the state of the art in the iron and steel sector with a focus on the Canadian perspective. The level of technological advancement of key processes used in the production of iron and steel in Canada were reviewed and contrasted to the best available technologies and energy demand–reducing alternatives proposed and used in other jurisdictions. The details of the review are presented in the section "State of the art." An energy demand tree detailing the unit operations and energy intensities of the fuels consumed across operations was developed for the iron and steel sector in the section "Demand tree development." The demand tree was then used to develop an energy demand model using the Long-range Energy Alternatives Planning (LEAP) system. This model incorporates the iron and steel operations across different Canadian provinces between 1990 and 2050. Information on model development is detailed in the section "Energy-environmental model development." After the model was developed, the energy demand reduction scenarios were formulated and analyzed with the model. Further details on scenario development and analysis are in the section "Scenario development and analysis." Key indicators quantified in the results are the sector-wide energy reduction potential, GHG emission abatement, and marginal abatement costs of the scenarios. These results were used to create a marginal abatement cost curve.

State of the art

This section gives an overview of the iron and steel production processes relevant to this study. Since the purpose of this study is longer-term sector-wide energy and GHG emission reduction analysis, the process descriptions are not in great technical detail and are not compressive. The reader is referred to other sources if a more technical account of these processes is desired (Canadian Steel Producers Association 2007, 2014; Hidalgo et al. 2003). Figure 2 illustrates the different production routes considered in this study. These two production routes, hence forth refereed to the integrated route and electric arc furnace (EAF) route, make up the majority of steel production globally. Other steel production routes, such as direct reduction and smelting, are not considered, as their share in Canadian steel production is negligible (direct reduced iron production in Canada is limited to 0.7 Mt).

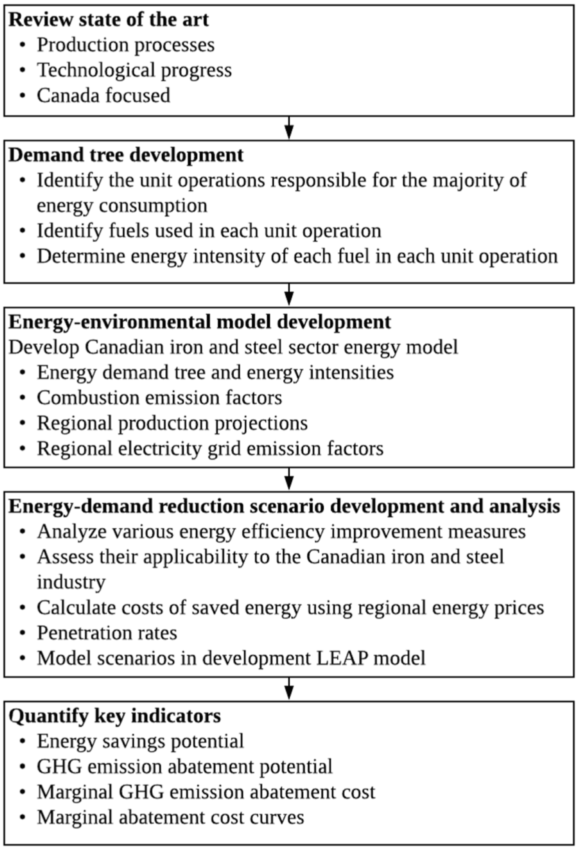


Fig. 1 Study overview

The integrated route is more complex than the EAF route involving more unit operations, materials flows, and energy flows. The integrated route begins with sinter production and coke production. During sinter production, raw materials are physically and metallurgically prepared for blast furnace. The purpose of sintering is to improve the performance of the blast furnace. The feedstock for sintering is a combination of iron ore, coke breeze, and iron-bearing materials (Remus et al. 2013; Ooi et al. 2011). Coke production occurs in coke oven plants where specific types of coal suited for coke production, such as bituminous coal, are converted to coke. The conversion is brought about using pyrolysis during which coal is heated to high temperatures in an oxygen-free environment, and other materials containing carbon such as petroleum coke and crushed rubber tire could also be used in small quantities (Remus et al. 2013). In general, 1 tonne of dry coal is consumed to produce 700–800 kg dry coke and 140–200 kg coke oven gas (COG) (Remus et al. 2013). Sinter and coke are then used in the blast furnace process. The blast furnace produces pig iron, or hot metal, mainly from feedstocks of iron ore, sinter, limestone, coke, and additives such as slag formers, among others. Iron

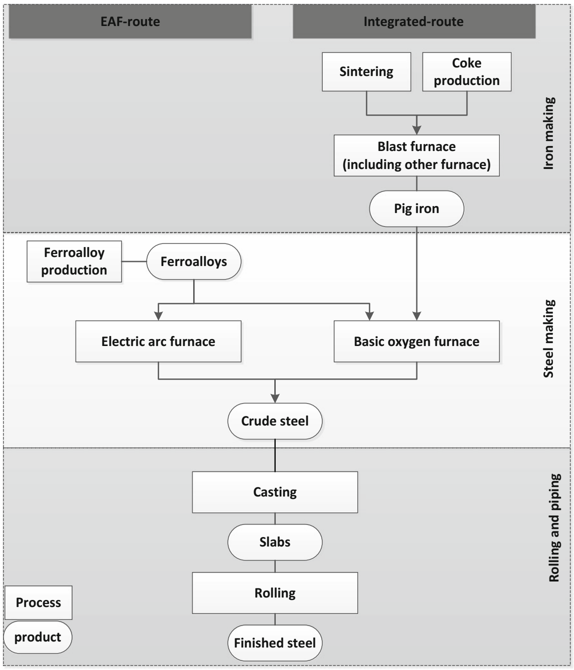


Fig. 2 Different steel production routes (Arens, et al., 2012)

oxides are reduced to iron metals by carbon monoxide (CO), which is the product of the reaction between the air blast and reducing agents (Remus et al. 2013). The blast furnace accounts for more than 50% of the energy consumption in iron and steelmaking (Li and Zhu 2014). In the basic oxygen furnace (BOF), the carbon content of the pig iron is reduced, the content of the desirable foreign elements is adjusted, and the undesirable elements are removed to the extent possible. All of this occurs mainly through oxidization. The BOF products then undergo secondary treatment and casting (Remus et al. 2013; Hasanbeigi and Price 2013).

The EAF route is a secondary process that involves smelting of ferrous recycled scrap steel. In order to adjust the desired concentration of non-ferrous metals in the finished steel, some ferroalloys might also be added to the feedstock. In the EAF, the feedstocks are melted and the steel products are fed into the ladle furnace treatment for quality adjustment. The semi-finished product is then cast to produce the final product (Remus et al. 2013).

The products of both BOF and EAF furnaces are cast in a continuous casting process to produce semi-finished shapes such as slabs, blooms, etc. (Canadian Steel Producers Association 2007). In Canada, 97% of the products of the steelmaking process undergo continuous casting (Canadian Steel Producers Association 2007). The casting process is usually followed by rolling, where final products such as coiled strips and steel sheets are produced. Processes such as hot forming, cold rolling, tempering, and pickling are known as finishing processes and are used in only some steel processes (Hidalgo et al. 2003).

In the steel industry, different types of primary and secondary energy are used as both energy source and reducing agents (Table 1). Both the energy consumption per tonne of steel produced (i.e., energy intensity) and the type of energy carrier differ depending on the steel production route. More precisely, energy consumption in an integrated plant is approximately 2.2–2.6 times higher than that in an EAF plant (Energetics 2000, 2004; Canadian Steel Producers Association 2007), mainly because of the need for more chemical energy, which is used to reduce iron ore to iron (Sakamoto et al. 1999; World Steel Association 2016; Gielen and Moriguchi 2002). Also, due to differences in feedstock type (i.e., in an integrated plant, feedstock is at least 70% iron ore and up to 30% recycled steel, whereas the main feedstock for an EAF is recycled steel), the type of energy consumed differs considerably (Hasanbeigi et al. 2011). In general, blast furnaces, coke plants, electric arc furnaces, and finishing processes are the most energy-intensive sub-processes in the iron and steel industry.

Demand tree development

The goal of developing a demand tree is to identify the energy consuming process and determine the end-use energy intensities. This data is then used to develop the long-range model, covered in the next section. The demand tree was designed to cover feedstock preparation through iron and steel production to finishing processes described in the section "State of the art." Since process-level disaggregation of fuel use does not exist for iron and steel energy use in Canada, energy intensity and fuel data for each unit operation were reviewed in the literature and calibrated to align with available data on Canadian iron and steel sector fuel use (Hasanbeigi and Price 2013; Worrell 2011; Li and Zhu 2014; Hasanbeigi et al. 2013a; Birat et al. 2009; Porzio et al. 2013; Canadian Steel Producers Association 2007; Natural Resources Canada Office of Energy Efficiency 2017; Nyboer and Bennett 2013; Pardo and Moya 2013). While data availability is one of the major challenges that energy modelers face, the quality of the available data is also an important factor. For example, Morfeldt and Silveira (2014) observed that the nationally and internationally reported data for energy intensity of steel production in Sweden was significantly different mainly as the result of assumptions behind the allocation of coal and coke used in blast furnaces. To mitigate this, to the extent possible, we have used

Table 1 Application of energy inputs in steel production (World Steel Association 2016; American Iron and Steel Institute 2005; Remus et al. 2013)

Source of energy	Application as energy	Application as reducing agent
Oil	Steam production	BF Injection
Natural gas	Furnaces	BF Injection, DRI production
Electricity	EAF, rolling mills, and various other motors	–
Coal	–	Coke production, BF pulverized coal injection, DRI production

DRI direct reduced iron

Canadian-specific data from publicly available databases and, where applicable, verified the quality of data by cross-referencing it against other sources. The resulting demand tree is shown in Fig. 3, and the corresponding energy intensities are presented in Table 2. For each data point in the table, data was acquired from different sources, harmonized, and selected to represent the Canadian iron and steel industry. For the capacity load of each sub-process, the shares of the final products were estimated (World Steel Association 2017) and the efficiency of different processes was considered to be similar to the plants considered in the literature (Hasanbeigi et al. 2013a). The energy data accuracy was validated by multiplying it by the production over the course of the modeling period, the results of which are presented in the next section.

Energy-environmental model development

Modelling framework

The LEAP system (Heaps 2016) was used to develop an energy-environmental model of the iron and steel sector to enable the quantification of long-term energy and GHG emission accounting. LEAP is an energy policy analysis and GHG mitigation assessment framework developed by the Stockholm Environment Institute. It is an integrated planning tool that can be used to track the energy consumption, production, and extraction of resources in all economic sectors. Energy modeling in LEAP provides the opportunity to account for the interaction between different modules within the energy system. More specifically, simultaneous consideration of energy resources, energy transformation, and consumption helps the energy modeler to account for sectoral development and the progress in the energy system at different levels.

The energy demand tree and end-use energy intensity data presented in the section "Demand tree development" was used to develop an energy demand module in LEAP. This was then integrated with a previously developed Canadian LEAP model (LEAP-Canada). The LEAP-Canada model covers the Canadian energy system on a data-intensive, multi-regional, and bottom-up basis (Davis et al. 2019). The model covers all sectors within Canada, and it has been used to conduct energy and GHG emission assessments for the residential (Subramanyam et al. 2017b), commercial (Subramanyam et al. 2017a), agriculture (Bonyad et al. 2018), cement (Talaei et al. 2019), petroleum refining (Talaei et al. 2020), chemical (Talaei et al. 2018), mineral mining (Katta et al. 2020; Kumar Katta et al. 2020), and oil sand (Katta et al. 2019; Janzen et al. 2020) industrial sectors. The model was used to project Canada-wide GHG emissions to 2050 (Davis et al. 2018a). Canada is a major energy producer and consumer with a variety of energy transformation sectors and energy-intensive industry sectors (Davis et al. 2018b). The interactions of these sectors are modeled with LEAP-Canada in the long-term which provides important data for the present iron and steel analysis, by way of a multi-regional framework to do the modeling as well as the consideration of region-specific upstream energy activity, energy prices, and electricity emission factors.

A conceptual model framework for the iron and steel is provided in Fig. 4 where the model structure is shown along with the input data (shown on the left as horizontal text). The model covers the years 1990 to 2050. Each region in Canada that has iron and steel production operations contains this structure and unique data for production route, annual production, and emission factors. The demand tree, energy intensity, and production saturation data from the section "State of the art" are assumed to be the same for the production route active in each region. Subsequent sections further detail the methods and data for modeling the production, changes in energy intensities, and emission factors over the study period.

Production

There are four integrated plants and nine EAF plants in Canada, producing approximately 12–13 million tonnes of steel per year (World Steel Association 2017; Canadian Steel Producers Association 2007). Integrated plant production capacity is approximately 9 million tonnes. The historical shares of the BOF and EAF routes were adopted from Canada-specific published data (World Steel Association 2017). The steel recycling rate in Canada has been reported to be between 40 and 60% (Canadian Steel Producers Association 2007, 2014), and the historical share of the EAF route in total steel production has been around 40% (Gielen and Moriguchi 2001; International Energy Agency 2007; World Steel Association 2013).

To project future steel production in Canada, it is considered that economic growth and steel use intensity

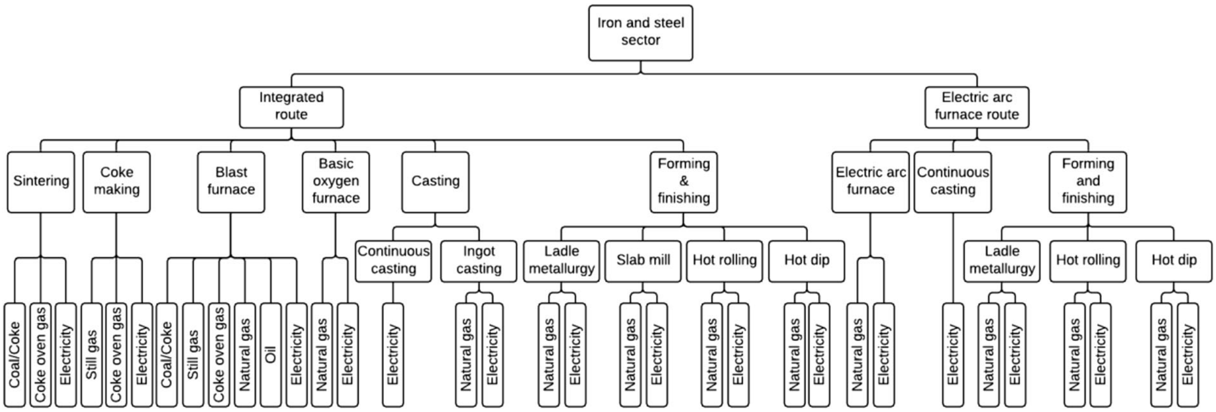


Fig. 3 Energy demand tree for the iron and steel sector

are interrelated such that the rate of steel consumption versus GDP growth follows an inverse U-shaped curve (Warell and Olsson 2009). More precisely, as the economy grows and becomes more mechanized and construction expands, the rate of steel consumption increases accordingly. Consumption reaches a peak and thereafter declines and stabilizes as society moves towards a service-based economy (Warell and Olsson 2009; Carbon Capture Use and Storage Action Group 2013). The Canadian per capita steel demand projection to 2050 is shown in Table 3 (International Energy Agency 2013).

As shown in Table 3, the projected per-capita steel demand is similar in both low- and high-demand scenarios. This is in line with International Institute for Applied Systems Analysis's general forecast of steel demand in the industrialized world, which projects that steel demand is stabilized at 500 kg/capita (Johansson et al. 2012). In addition, assuming that the iron and steel industry in Canada and USA share considerable

Table 2 End-use energy intensities for the integrated and EAF routes of iron and steel production

Process	Production saturation	Integrated route (GJ/tonne crude steel)					Production saturation	EAF route (GJ/ tonne crude steel)	
		Electricity	Coal/ coke	Coke oven gas	Still gas	Natural gas		Electricity	Natural gas
Iron making									
Sinter plant	100%	0.20	2.2	0.09	0	0	n/a	n/a	n/a
Coke plant	100%	0.23	4.88	0	0.35	0	n/a	n/a	n/a
Blast furnace	100%	0.08	8.25	0.15	0.77	1.39	n/a	n/a	n/a
Steelmaking									
Basic oxygen furnace	100%	0.09	0	0.11	0	0.33	n/a	n/a	n/a
EAF	n/a	n/a	n/a	n/a	n/a	n/a	100%	1.89	0.23
Casting									
Continuous casting	97.5%	0.12	0	0	0	0		0.12	0
Ingot casting	2.5%	0.65	0	0	0	1.41	n/a	n/a	n/a
Forming and finishing									
Vacuum degassing and ladle metallurgy	100%	0.13	0	0	0	0.35	100%	0.40	0.12
Slab mill	100%	0.42	0	0	0	2.14	n/a	n/a	n/a
Hot rolling (inc. reheating)	95%	0.33	0	0	0	1.74	95%	1.19	0.76
Hot dip galvanneal	20%	0.93	0	0	0	2.33	20%	0.79	1.16

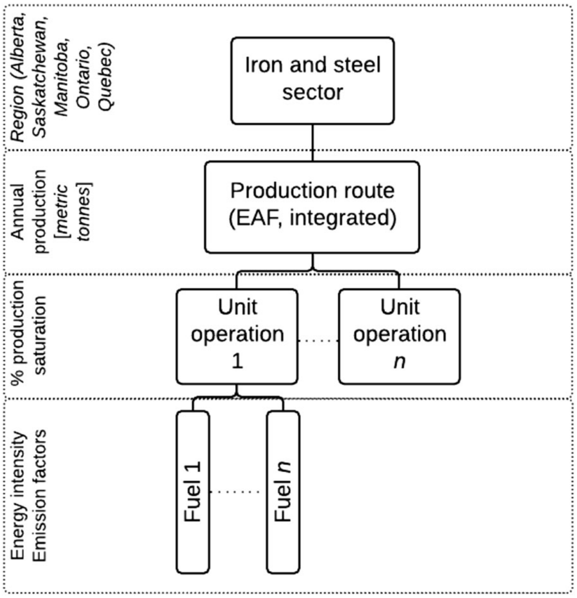


Fig. 4 Conceptual LEAP model framework for the iron and steel sector

similarities (Organization for Economic Cooperation and Development 2011) and knowing that the per capita steel demand stabilizes at a per capita GDP of more than $30,000 (at around 500 kg/capita) (Carbon Capture Use and Storage Action Group 2013), it is reasonable that the data presented in Table 3 are justified to be used in this study. An analysis of the historical data (2003–2010) shows that, in the past decade, the per capita steel demand was around 583 kg/capita (comparable to the data reported by the IEA (International Energy Agency 2013)) except for the post-economic crisis in 2009 when the figure dropped to 407 kg/capita (Nyboer and Bennett 2013; World Steel Association 2016). Historically, around 10% of steel demand is met by import and the rest is domestically produced (World Steel Association 2016). Of the nationally produced steel, around 90% is produced in two of the eastern provinces, Ontario (68%) and Quebec (22%). For simplicity, these shares are considered to be unchanged throughout the time period of the study.

Table 3 Crude steel demand per capita 2006–2050 (International Energy Agency 2013)

Year	Crude steel demand (kg/capita)
2006	590
Low-demand scenario	
2015	550
2030	525
2050	500
High-demand scenario	
2015	550
2030	525
2050	500

The medium-growth scenario (M1) developed by Statistics Canada's Demography Division (Statistics Canada 2010) was used to forecast the country's future population. According to predictions, the population will reach 43.8 and 48.5 million people in 2036 and 2050, respectively. Using this and the data reported in Table 3, the total amount of steel production in Canada was projected. Although the biggest consumers of steel are expected to be in the west (mainly Alberta and Saskatchewan) due to fast-growing energy industries there, Ontario is expected to play a major role in steel production mainly because of the proximity to the iron mines. Moreover, currently all four Canadian integrated steel plants are in Ontario (Canadian Steel Producers Association 2007).

To calculate the production shares of each steel production route, a combination of historical trends and market analysis was used. Over the past 14 years, the share of EAFs in Canada's total steel production has not changed much; it has remained constant at around 40% (Nyboer and Bennett 2013). However, following the trends in pioneering countries, the situation is expected to change in Canada. More precisely, Morfeldt et al. (2015) suggested that by 2050, the shares of EAF in the global steel production are expected to increase and reach 50% of total steel production. This trend has already started in several developed and developing countries. For example, in their study, Arens et al. (2012) indicate that 75% of specific energy consumption (SEC) improvement in the German iron and steel industry between 1991 and 2007 was due to the shift from integrated to EAF steel production. In China, it is expected that there will be similar structural changes towards vast application of EAFs (Carbon Capture Use and Storage Action Group 2013). Increasing EAF use is due to the high flexibility of the technology in producing low- to high-alloyed steel grades, the range of insertable input materials, and the lower energy consumption compared to integrated plants (Kirschen et al. 2009). In addition, in Canada, an EAF is a favorable option because of the lower capital cost compared to integrated plants, the abundance of natural gas, and the restrictions in the use of coal (i.e., for coke production) imposed by provincial governments (Government of Quebec 2018; Government of Manitoba 2011). In addition, Ontario, the biggest steel producer in the country, has always had a scrap surplus (Warrian 2010), and therefore, EAFs are expected to be favored in that province (Carbon Capture Use and Storage Action Group 2013).

Nevertheless, there are some limitations that restrict the vast application of EAF technology. The lack of an appropriate quality of steel produced from salvaged scrap (Canadian Steel Producers Association 2007), the long lifetime of steel products, and the slow recycling rate of steel, along with increasing demand for steel products, highlight the need for a combined use of primary (i.e., an integrated route) and secondary (i.e., EAF) steel production methods (World Steel Association 2016).

Based on the above justifications, for this study, it is considered that in Canada, the capacity of integrated plants will remain constant over the time period of the study and additional capacity would be solely through EAFs. The regional production used in this study is given in Fig. 5.

Energy intensity

Despite some fluctuations, the energy intensity of the Canadian iron and steel industry has not shown a significant change in the past 25 years (Fig. 6). The energy intensities of the processes were considered to be constant during the time period of the study. This is in line with both historical trends in the Canadian iron and steel industry and experts' opinions (Natural Resources Canada Office of Energy Efficiency 2017; Nyboer and Bennett 2013; Energetics 2000). When entering the energy intensity data from Table 2, the changes in sector energy intensity were normalized to 2011 data, the first scenario year in the model, to track the historical sector energy intensity changes.

Emission factors

For fossil fuel combustion, the Intergovernmental Panel on Climate Change (IPCC) Tier 1 default emission factors available in the Technology and Environmental Database in the LEAP model were used. The emission factors of the electricity sector were based on the detailed supply side model developed for different Canadian provinces and considering future development of the system. More precisely, depending on the location of the iron and steel factory, the emission factors for electricity consumption and production differ, and this is accounted for in modeling. Emission factors for electricity consumption are given in Table 4 and were sourced from the LEAP-Canada model. These reflect the most recent macro-economic and policy projections pertaining to the electricity sector.

Model validation

The next step is to validate the modeling to ensure that the energy and GHG emission accounting give an accurate representation of the sector. The results of model validation for energy consumption and GHG emissions are shown in Figs. 7 and 8, respectively. Historical data was available up to 2017 from Natural Resources Canada (Natural Resources Canada Office of Energy Efficiency 2017). The average percent difference between the model and historical data for the scenario years (2011–2017) is 3% for energy consumption and 2% for GHG emissions. Between 1990 and 2050, the range of annual percent differences is 0–6% for energy consumption and 1–10% for GHG emissions. As shown in Figs. 7 and 8, the results of the LEAP model are in line with the actual data, thereby confirming the validity of data and assumptions for the energy and emission intensities of different sub-processes in the iron and steel industry and also enhancing the reliability of the model for scenario analysis.

Scenario development and analysis

Scenario development

The literature contains examples of efforts to improve energy efficiency in the iron and steel industry. For example, in the past two decades, the energy intensity of steel production improved by 0.4% per annum in Germany. Energy efficiency improvement was the biggest contributor to energy intensity improvement in the industry, with rolling and blast furnace showing the largest improvements of 1.4% and 0.2%, respectively (Arens et al. 2012). In blast furnaces (BFs), SEC improvement was in BF gas recovery (Arens et al. 2012). Similarly, in the USA, historical trends show that in a period of 20 years, the SEC of integrated plants

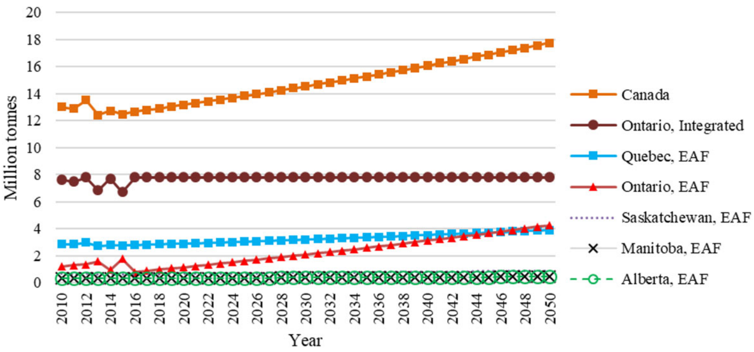


Fig. 5 Projection of steel production in Canada and in several provinces

improved by more than 40% (Energetics 2000) and there were opportunities to improve energy efficiency by as much as 18% more (Worrell 2011). Unlike the basic oxygen furnace and the blast furnace, the SECs of sinter plants and EAFs were constant or changes were negligible (Arens et al. 2012; Energetics 2000).

In order to develop alternative scenarios for the Canadian steel industry, we identified the available energy saving options. We then analyzed the applicability of the identified options for the Canadian industry and assessed their technical performance, their associated costs, and the penetration potential of each technology.

For the purpose of the current study, only the technological improvement options that fall within the modeled production routes were analyzed; the general non-process-specific energy efficiency options are considered to be beyond the scope of this study. In other words, energy saving options in the coking plant, sintering plant, BF, steel workshop (both BOF and EAF), and finishing processes were considered. To identify energy efficiency measures, we compared the existing Canadian technologies with EcoTech and the best available mature technologies worldwide (Hasanbeigi et al. 2010; Canadian Steel Producers Association 2007) and subsequently identified the areas of improvement.

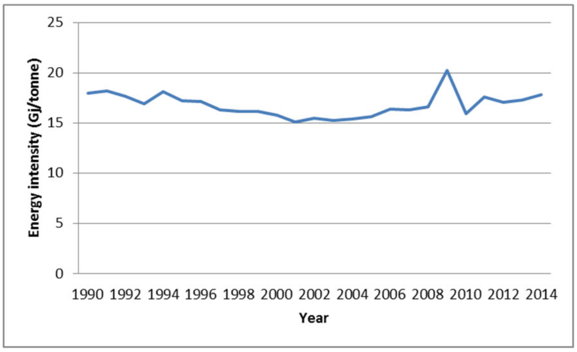


Fig. 6 Historical energy intensity of the Canadian iron and steel industry (Natural Resources Canada Office of Energy Efficiency, 2017, Nyboer, et al., 2013)

The criteria used to screen the options include technology readiness level, applicability to the Canadian iron and steel industry, and availability of data. For example, technologies such as hydrogen-based steel production (Morfeldt et al. 2015), methane reforming of coke oven gas (Johansson and Söderström 2011), and direct reduction were excluded from this study mainly because of their limited applicability to the Canadian industries and their early stage of development.

In terms of development status, only commercially available technologies were considered. The applicability of the technology to the Canadian iron and steel industry was assessed based on the current and expected development status of the industry. For example, in the material preparation stage, the energy efficiency measures for pelletizing plants were excluded because, based on a review of Canadian industry, all of the iron production plants in the country are equipped with sintering plants rather than pelletizing plants. As another example, in Canada, continuous casting technology could be implemented in only 3% of the plants because 97% of them are already equipped with the technology (World Steel Association 2017). The injection of coal in blast furnaces was not considered because of national and provincial limitations on coal consumption as well as the cheap price and abundant availability of natural gas in Canada. In general, wherever data are available for Canada, country-specific limitations were considered when choosing the technologies. Otherwise, due to similarities between Canada and the USA, the applicability of energy efficiency measures was considered to be comparable in the two countries and US data was used. A total of 26 scenarios were selected for the

Table 4 Regional emission factors (g CO_2-eq/kWh) used for electricity consumption

	Year						
	1990	2000	2010	2020	2030	2040	2050
Alberta	1000	980	839	544	305	254	250
Saskatchewan	880	940	524	500	217	160	154
Manitoba	29	38	0	0	0	0	0
Ontario	220	320	76	7	37	36	23
Quebec	14	4.1	13	0	0	0	0

analysis. The selected technologies can be categorized to cover different sub-sectors within the industry (as shown in the energy consumption demand tree) and are summarized in Table 5.

The techno-economic performance of the energy efficiency options in terms of energy savings potential and their associated costs (both capital and operation and maintenance (O&M) costs) are summarized in Table 6. The data in Table 6 were adapted from different sources, mainly from Worrell et al. (2011), Hasanbeigi et al. (2013b), and Institute for Industrial Productivity (2017). The costs were then harmonized to 2010 Canadian dollar (CAD) (using discount rates and different currency exchange values), and the penetration values were calculated based on specific characteristics of the Canadian iron and steel industry.

Scenario analysis

In order to assess the economic performance of each option, the cost of saved energy (CSE) and the GHG abatement cost were calculated. This allows us to account for both technology-specific characteristics (e.g., capital cost, O&M cost, and fuel saving potential) and geographic-specific characteristic of the energy system where the plant is located (price of fuel, emission intensity of electricity generation, etc.).

The cost of saved energy is defined as the cost to reduce 1 unit of energy consumption (e.g., CAD/gigajoule (GJ)). The CSE is calculated in a techno-economic excel model using the factors outlined in Table 6. Equation (1) is applied to calculate the cost of saved energy.

$$\mathrm{CSE} = \frac{\sum(C_{\mathrm{EE}}-C_{\mathrm{Base}}) + \sum(\mathrm{O\&M}_{\mathrm{EE}}-\mathrm{O\&M}_{\mathrm{Base}}) + \sum(F_{\mathrm{EE}}-F_{\mathrm{Base}})}{\sum(\mathrm{EC}_{\mathrm{Base}}-\mathrm{EC}_{\mathrm{EE}})} \tag{1}$$

As shown in the equation, capital cost (C), O&M cost, and fuel saving cost/revenue (F) together with the energy consumption (EC) of both existing (base) and energy-efficient (EE) technologies are used to calculate the CSE. The capital cost is the capital investment associated with implementing the technology. The investment happens at the implementation time of the technology and happens again at the end of the technology's lifetime. For the analysis, an interest rate of 5% was used for calculating the annualized capital costs using the standard capital cost recovery formula. O&M costs are those related to the operation of the plant. The costs include the labor and regular maintenance costs that are required to maintain the operation of the plant. Both fixed and variable costs are considered. While the former remains constant during the production of products, the latter changes with production

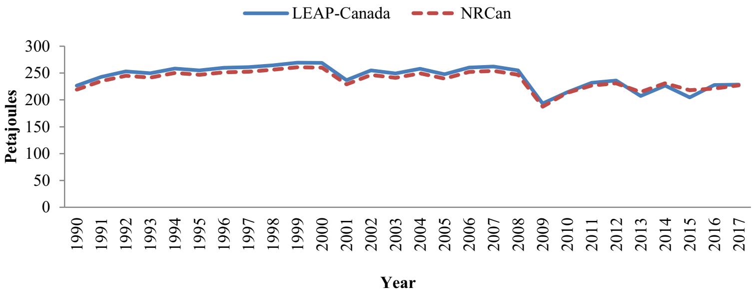


Fig. 7 Historical energy consumption in the Canadian iron and steel industry (model validation)

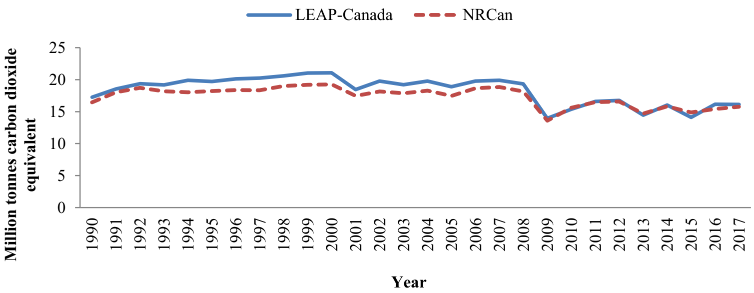


Fig. 8 Historical GHG emissions in the Canadian iron and steel industry (model validation)

levels. The fuel saving cost/revenue is the revenue associated with reducing energy consumption. In other words, the implementation of each energy efficiency measure will reduce the amount of energy consumption in specific processes, which will accordingly reduce the overall costs of the production process. Natural gas and electricity prices are specific to each region and were sourced from the Canada Energy Regulator (Canada Energy Regulator 2019). A 6.9 2019 CAD/GJ price of coal was used for coke and coke oven gas, assumed based on a variety of price data for metallurgical coal (World Bank 2020; Natural Resources Canada 2020; Scotia Bank 2020; U.S. Energy Information Administration 2019). The CSE values are intermediate results and are summarized in Table 8 in the Appendix. These values are used as inputs in the LEAP model to calculate the cost component of the marginal GHG abasement costs. The marginal GHG abatement cost (cost per unit of mitigated GHG emissions in CAD/tonne CO_2-eq) is calculated within the LEAP model using the net present value (NPV) and the cumulative emission reduction in each scenario (calculated over the time period of the study). A 5% discount rate was used within the model to calculate the NPV and marginal abatement costs.

Results and discussion

Scenario analysis results

An analysis of the baseline scenario shows that the large-scale adoption of EAF technology would lower the energy and GHG intensity of the Canadian iron and steel industry considerably. The increased share of EAF technology (i.e., from 41% in the base year to 56% by 2050) would lower the energy intensity of steel production by about more than 13%. This is in addition to the achievable energy intensity improvement through the implementation of energy efficiency measures.

The results of the analysis for both fast and slow penetration scenarios are presented in Table 7. In the table, the technological performance of each technology in terms of cumulative energy savings and GHG mitigation is presented. In addition, two different economic parameters are presented to assess the economic competitiveness of each technology. The net present value of the technology provides insight into the long-term viability of investment, and a negative value indicates a cost savings by the end of the study period. The marginal GHG abatement cost represents the cost of abating 1 tonne of CO_2-eq, and a negative value also indicates a cost saving. The marginal abatement cost must be analyzed by also considering the GHG abatement potential. A very low abatement potential can inflate the value of marginal abatement costs because the abatement potential is the denominator of the marginal abatement cost equation. The abatement potential gives the maximum amount of GHG emissions that can be abated under the studied conditions.

The results of the analysis were used to develop marginal GHG abatement cost curves (shown in Figs. 9 and 10). The figures show both the effectiveness of each energy efficiency option in mitigating GHG emissions and their comparative economic performance. The horizontal axis shows the cumulative emission reduction achievable by implementing each option, and the vertical axis represents the associated cost to reduce 1 unit of the emissions (i.e., CAD/tonne CO_2-eq). The options with negative marginal costs are below the horizontal axis. For these options, the cumulatively achievable cost savings over the time period of the study exceed the additional costs associated with implementing the option. The options with the lowest marginal mitigation cost are on the left side of the figure, and the more costly GHG abatement options are on the right side. The options for which the GHG abatement

Table 5 List of energy efficiency measures applicable to the Canadian iron and steel industry (Hasanbeigi, et al., 2013, Hasanbeigi, et al., 2013, Institute for Industrial Productivity, 2017, Worrell, 2011)

Technology/measure	Description
Sintering (SP)	
Heat recovery from the sinter cooler	The waste heat from a sintering plant is generally classified as sensible heat from either the main exhaust/sintering machines or the sinter cooler. In order to avoid unacceptable condensation and corrosion, the only practical method for heat recovery from process gases is to transfer sensible heat directly to the sinter bead by hot gases (i.e., waste gas recirculation). However, the heat from the sinter cooler could be recovered through steam generation in the waste gas boiler, hot water generation for district heating, preheating combustion air, preheating the sinter raw mix, or using the waste heat in a recirculation system
Improved process control	The application of numerical/simulation models and automated control systems will help improve operational parameters and optimize energy consumption, productivity, and safety
Use of waste fuels in sinter plants	Waste material such as oil from the cold rolling mills could be used as a source of energy (substituting coke breeze). This will impact the emissions of air pollutants and organic compounds. The application of oil might be limited by the permitted emission limit and may also depend on existing emission control systems. The energy content of the waste fuel is another factor affecting the rate at which these materials are used
Coke making (CM)	
Coal moisture control	The heat from the coke oven gas could be used to reduce the moisture content of coal from the normal 8–10 to 6%. The reduced moisture content of the coal will improve coke quality and reduce the carbonization energy (heat)
Automation and process control system	Programmed heating (versus conventional continuous heating) of the coke oven optimizes the supply and use of fuel. It also stabilizes the operation of the coke battery and therefore prolongs battery life and improves coke quality
Coke dry quenching (CDQ)	Using inert gas instead of the traditional sprayed water reduces energy loss in the quenching process. The thermal energy in the quenching gas can be recovered and used to produce steam and electricity or preheat the coking coal
Blast furnace (BF)	
Injection of natural gas in the BF	In this process, natural gas is used instead of coke in the blast furnace. The hydrogen content of natural gas acts as the reducing agent and therefore reduces the formation of carbon dioxide. It is technically feasible to retrofit existing plants, and capital investment for this is minimal. The technology is attractive where natural gas is cheap
Improved recovery of BF gas	The gases leaving the BF contain almost 30% of the heat content of the gross energy consumption in the blast furnace. This energy could be recovered and used as fuel or for electricity generation after being enriched by coke oven gas or natural gas
Improved hot stove process control	The operation of hot stoves could be maintained close to optimum conditions by implementing automatic control.

UHP ultra-high power

Table 5 (continued)

Technology/measure	Description
	Automatic control will not only help minimize the fuel consumption but also maximize the reliability and lifetime of the stove
Recuperator hot blast stove	The recovery of the flue gases from the blast stove (with typical temperatures of around 250 °C) will improve the efficiency of the stove. This heat, together with the heat from sinter cooling, can be used to preheat the fuel and the air entering the stove
Improved blast control systems	Different parameters such as the rate of the reducing agent can be controlled. Using different parameters, such as burden control and distribution, mass and energy balance, and silicon prediction, etc., will help diagnose the process disturbance and therefore make it possible to change the process parameters to optimize performance
Basic oxygen furnace (BOF)	
Efficient ladle preheating	Ladle preheating is estimated to use 0.02 GJ/t steel. This could be lowered by using temperature control technologies, installing hoods, or reducing preheating needs with recuperative and oxyfuel burners
Hot rolling (HR)	
Hot charging	In the still plants where caster and reheating furnaces are located near one another, charging the slabs in the reheating hot-rolling furnace is possible. Hot charging not only reduces energy consumption but also improves the productivity and quality of the products
Process control in hot strip mills	In the hot strip mill, when combustion is optimized, the downtime of the process and therefore the energy consumption will decrease
Recuperative burners	In principle, the recuperator is a gas-to-gas heat exchanger that transfers the heat from exhaust gas to the combustion air. The performance of modern recuperatives is noticeably higher than the older technologies and thus replacing them will save energy through more efficient pre-heating of the combustion air
Insulating furnaces	Replacing conventional insulating materials with ceramic low thermal mass insulation materials can reduce the heat losses through furnace walls.
Controlling oxygen levels and VSDs on combustion air fans	The technique helps optimize combustion in the furnace by controlling the flow of combustion air and oxygen levels and therefore maximizing combustion efficiency
Energy-efficient drives (rolling mill)	Energy efficient drives can replace the currently used AC drives, thereby saving energy
Waste heat recovery (cooling water)	Absorption heat pumps could be used to recover the heat from the cooling water, which is sprayed on rolled steel. The technology is particularly attractive where the generated low-pressure steam could be used on site
Adopt continuous casting	As the intermediate storage and therefore the need for reheating is eliminated in continuous casting, it uses much less energy than the ingot casting process. The product of the ladle process (i.e., liquid steel) flows to the holding tank where it will be ultimately solidified in a water-cooled copper mold and continue through the caster
Electric arc furnace (EAF)	

Table 5 (continued)

Technology/measure	Description
Improved process control (neural network)	Modern process control systems in the EAF integrate real-time monitoring of process variables (e.g., temperature, carbon level, etc.) and, by optimizing the process, significantly reduce electricity consumption
Flue gas monitoring and control	By using optical sensors and monitoring the furnace exhaust gas flow rate and composition, it will be possible to investigate the post-combustion off-gases and optimize their operation and chemical energy recovery. This will help reduce energy consumption considerably
Transformer efficiency—UHP transformers	The installation of new transformers or paralleling existing transformers will make it possible to convert the furnace operation to high power or even UHP. UHP operation will reduce energy losses, which are as high as 7%, of transformer losses in conventional transformers
Foamy slag practice	Foamy slag is obtained by injecting carbon (granular coal) and oxygen or by lancing the oxygen only. The foamy slag is used to cover the ark and melt surface, which minimizes the radiation heat losses
Bottom stirring/stirring gas injection	The injection of inert gases in the bottom of the EAF improves heat transfer and also the yield of liquid metal. The applicability of the technique is limited to the furnaces where oxygen is already injected in the furnace
Electric bottom tapping	Electric bottom tapping will result in several improvements in the process including reducing the electrode consumption, reducing the tap-to-tap time, and increasing the ladle life

costs are positive (that is, the additional costs exceed the cost savings over the time period of the study) are shown by the bars above the horizontal axis.

As shown in Fig. 9, the cumulative GHG mitigation potential that is achievable over the time horizon ending in 2030 is about 19 million tonnes of CO_2-eq. Eighty-five percent of the emission reductions is achievable with a negative cost. The injection of natural gas into the blast furnace provides the largest mitigation potential with a cumulative emission reduction potential of about 4.1 million tonnes (equal to 22% of the overall achievable emission reduction potential). For this option, the GHG abatement cost is calculated to be − $83/tonne CO_2-eq, which highlights the economic attractiveness of this energy reduction measure.

Although there are several options with an abatement cost of less than − $25/tonne CO_2-eq, the implementation of only a few of them would result in considerable GHG savings. The GHG abatement costs of more than 68% of the overall achievable emissions are between − $116 and − $55/tonne CO_2-eq. Among all the options, only the insulation of reheating furnaces and coal moisture control impose an unrecovered net cost. These two options cumulatively account for 5% of the total emission reduction potential.

Considering both the fast and slow penetrations of scenarios, the ultimate GHG emission reductions by 2030 and 2050 if all scenarios were implemented are 19 and 38 Mt CO_2-eq (6% of baseline emissions), at − $76 and − $51/tonne CO_2-eq, respectively. In the slow penetration scenario, the cumulative emission reduction potential is calculated to be about 38 million tonnes of CO_2-eq, more than 94% of which is achievable with a negative GHG abatement cost. Similar comparisons between scenarios can be made as in the 2010–2030 cost curve. Hot rolling (HR) and BF scenarios resulted in the highest GHG emission mitigation across the unit operations, with 16 and 14 Mt CO_2-eq (42% and 37% of combined potential across scenarios), respectively. The corresponding combined marginal abatement costs considering all scenarios within the unit operations are − $57 and − $41/tonne CO_2-eq, respectively. Following these 2-unit operations, coke making (CM) and sintering (SP) scenarios offer 5.2 and 2.4 Mt CO_2-eq (14% and 6% of combined potential across scenarios) at marginal abatement costs of $16 and − $28/tonne CO_2-eq,

Table 6 Techno-economic performance of energy efficiency options

Energy efficiency options	Fuel saving (GJ/tonne steel)	Electricity saving (GJ/tonne steel)	Cost (2019CAD/t)		Lifetime (years)	Penetration potential (%)
			Retrofit capital cost	Change in O&M		
BF_Improved control system	0.36	0	0.50	0.0	10	60%
BF_Improved gas recovery	0.06	0	0.42	0.0	15	60%
BF_Improved hot stove process control	0.33	0	0.42	0.0	10	50%
BF_Injection of natural gas	0.8	0	6.9	−2.8	20	70%
BF_Recuperator hot blast stove	0.07	0	1.9	0.0	10	30%
BOF_Adopt continuous casting	0.24	0.08	18.5	−8.3	20	3%
BOF_Efficient ladle preheating	0.02	0	0.08	0.0	30	90%
CM_Automation and process control	0.05	0	0.11	0.0	10	90%
CM_Coal moisture control	0.09	0	22.8	0.0	10	70%
CM_Coke dry quenching	0.37	0	32.6	0.2	18	70%
EAF_Bottom stirring gas injection	0	0.07	0.93	−3.1	0.5	11%
EAF_Efficient UHP transformers	0	0.06	4.3	0.0	15	40%
EAF_Electric bottom tapping EBT	0	0.05	5.0	0.0	10	52%
EAF_Flue gas monitoring and control	0	0.05	3.1	0.0	10	50%
EAF_Foamy slag practice	0	0.07	15.5	−2.8	10	30%
EAF_Improved process control neural network	0	0.11	1.5	−1.6	10	90%
IHR_Controlling oxygen level and VSDs	0.29	0	0.68	0.0	10	50%
IHR_Energy efficient drives in rolling mill	0	0.01	0.27	0.0	20	50%
IHR_Hot charging	0.52	0	20.3	−1.8	10	36%
IHR_Improved insulation of reheating furnace	0.14	0	13.5	0.0	10	30%
IHR_Process control in hot strip mill	0.26	0	0.95	0.0	10	69%
IHR_Recuperative burners	0.61	0	3.4	0.0	10	20%
IHR_Waste heat recovery for cooling water	0.03	0	1.1	0.09	15	69%
SP_Improved process control	0.01	0	0.045	0.0	10	100%
SP_Sinter plant heat recovery	0.12	0	1.0	0.0	10	100%
SP_Use of waste fuels in sinter plant	0.04	0	0.06	0.0	10	90%

BF, CM, SP fuel savings applied to coal/coke branches, others applied to natural gas branches

respectively. EAF and BOF scenarios had small mitigation potential (combined 1.6% of combined potential across scenarios) and also have the lowest marginal abatement costs.

Sensitivity analysis

Sensitivity of the marginal abatement cost results of the slow penetration scenarios (2010–2050) to electricity prices (± 30%), natural gas prices (± 30%), coal price (± 30%), carbon price ($0/tonne CO_2-eq baseline vs $30 and $50/tonne CO_2-eq), capital cost (± 30%), operation and maintenance cost (± 30%), and discount rate (5% baseline vs 3% to 7%) was evaluated. The Appendix contains figures showing the results for each scenario (Appendix Fig. 11). Blast furnace scenarios show sensitivity to coal price, discount rate, and carbon price. Capital cost fluctuations have minimal impact on the results. Operating costs are only non-zero in the BF_injection of natural gas scenario and have a moderate impact on the

Table 7 Scenario analysis results

Scenario	Fast penetration (2010–2030)				Slow penetration (2010–2050)			
	Energy saved (PJ)	GHG emissions saved (MtCO$_2$-eq)	Marginal NPV (2019CAD)	Marginal abatement cost (2019CAD/ tonne CO$_2$-eq)	Energy saved (PJ)	GHG emissions saved (Mt CO$_2$-eq)	Marginal NPV (2019CAD)	Cost of avoiding GHG emissions (2019CAD/tonne CO$_2$-eq)
BF_Improved control system	− 16.87	1.57	− 87.21	− 55.43	− 34.49	3.08	− 99.14	− 32.15
BF_Improved gas recovery	− 2.81	0.26	− 13.30	− 50.73	− 5.75	0.51	− 15.12	− 29.43
BF_Improved hot stove process control	− 12.88	1.20	− 66.78	− 55.56	− 26.35	2.36	− 75.92	− 32.23
BF_Injection of natural gas	− 43.73	4.08	− 340.05	− 83.36	− 89.42	7.99	− 386.56	− 48.35
BF_Recuperator hot blast stove	− 1.64	0.15	− 3.52	− 23.00	− 3.35	0.30	− 4.00	− 13.34
BOF_Adopt continuous casting	− 0.75	0.03	− 24.03	− 732.38	− 1.53	0.06	− 28.53	− 440.83
BOF_Efficient ladle preheating	− 1.41	0.08	− 9.40	− 119.65	− 2.87	0.15	− 11.64	− 75.56
CM_Automation and process control	− 3.51	0.33	− 23.42	− 71.44	− 7.19	0.64	− 28.99	− 45.13
CM_Coal moisture control	− 4.92	0.46	109.14	237.84	− 10.06	0.90	120.75	134.27
CM_Coke dry quenching	− 20.22	1.89	6.57	3.48	− 41.36	3.70	− 6.18	− 1.67
EAF_Bottom stirring gas injection	− 0.46	0.01	− 15.19	− 1536.06	− 1.24	0.02	− 23.86	− 1552.11
EAF_Efficient UHP transformers	− 1.43	0.03	− 17.86	− 579.37	− 3.87	0.05	− 33.09	− 690.80
EAF_Electric bottom tapping EBT	− 1.55	0.03	− 11.21	− 335.70	− 4.19	0.05	− 24.47	− 471.41
EAF_Flue gas monitoring and control	− 1.49	0.03	− 17.06	− 531.27	− 4.03	0.05	− 32.31	− 647.49
EAF_Foamy slag practice	− 1.25	0.03	− 35.37	− 1311.13	− 3.39	0.04	− 56.57	− 1349.60
EAF_Improved process control neural network	− 5.91	0.13	− 172.81	− 1358.87	− 15.97	0.20	− 275.20	− 1392.59
IHR_Controlling oxygen level and VSDs	− 26.36	1.47	− 132.66	− 90.02	− 59.31	3.18	− 161.54	− 50.83
IHR_Energy efficient drives in rolling mill	− 2.47	0.02	− 70.44	− 3180.44	− 5.24	0.05	− 92.59	− 2027.26
IHR_Hot charging	− 28.96	1.62	− 157.87	− 97.50	− 66.20	3.55	− 215.98	− 60.88
IHR_Improved insulation of reheating furnace	− 10.39	0.58	43.44	74.75	− 22.82	1.22	44.50	36.39
IHR_Process control in hot strip mill	− 33.92	1.90	− 219.64	− 115.81	− 76.06	4.08	− 291.53	− 71.53

Table 7 (continued)

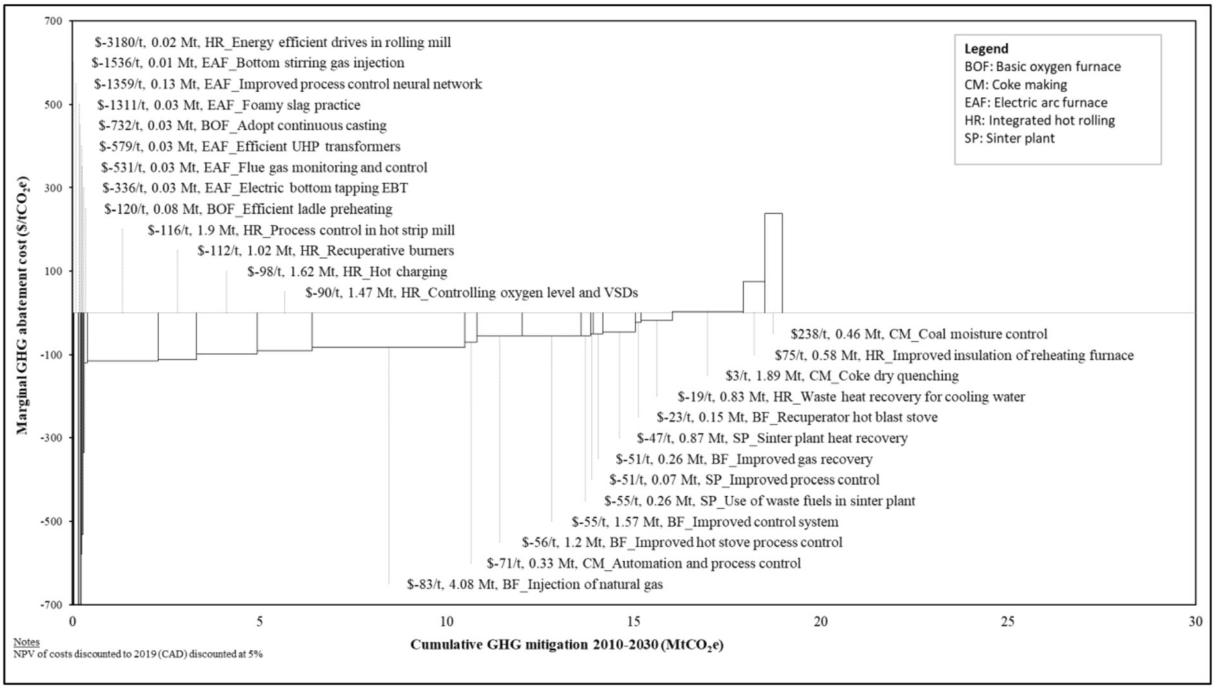
Scenario	Fast penetration (2010–2030)				Slow penetration (2010–2050)			
	Energy saved (PJ)	GHG emissions saved (MtCO$_2$-eq)	Marginal NPV (2019CAD)	Marginal abatement cost (2019CAD/tonne CO$_2$-eq)	Energy saved (PJ)	GHG emissions saved (Mt CO$_2$-eq)	Marginal NPV (2019CAD)	Cost of avoiding GHG emissions (2019CAD/tonne CO$_2$-eq)
IHR_Recuperative burners	−18.25	1.02	−114.11	−111.82	−41.87	2.24	−154.53	−68.87
IHR_Waste heat recovery for cooling water	−14.79	0.83	−15.79	−19.09	−31.01	1.66	−28.47	−17.13
SP_Improved process control	−0.78	0.07	−3.74	−51.39	−1.60	0.14	−4.26	−29.81
SP_Sinter plant heat recovery	−9.37	0.87	−40.75	−46.62	−19.16	1.71	−46.32	−27.04
SP_Use of waste fuels in sinter plant	−2.81	0.26	−14.48	−55.22	−5.75	0.51	−16.46	−32.03

PJ petajoule

results. The marginal abatement costs remain below zero for all blast furnace scenarios at the tested ranges. Both basic oxygen furnace scenarios are sensitive to the discount rate. The efficient ladle preheating scenario shows also sensitivity to the natural gas price and carbon price; however, both scenarios retain marginal abatement costs below zero. The marginal abatement cost of adoption of continuous casting is sensitive to changes in operating costs but remains negative with a 30% decrease operating cost reductions. Coke making scenarios are highly sensitive to the natural gas price, carbon price, and discount rate. Besides automation and process control, the coke making scenarios are also highly sensitive to capital cost changes and a slight increase of the capital cost of the coke dry quenching scenario changes the marginal abatement cost from negative to positive. Conclusions about the coke dry quenching scenario also greatly change depending on the natural gas price and carbon price. A higher natural gas price quickly changes the marginal abatement cost from negative to positive while the carbon price reduces the marginal abatement cost by many times over. Electric arc furnace scenarios are sensitive to the discount rate and electricity price. Select EAF scenarios are sensitive to capital cost and/or operating costs. Since all these scenarios have very low marginal abatement costs, there is no change in the cost-benefit conclusions. Since most regions in Canada have low electricity emission factors during the study period, carbon price does not have a large impact on scenarios which reduce electricity consumption. Hot rolling scenarios are sensitive to the discount rate and carbon price and, depending on the particular scenario, have different energy prices. The only hot rolling scenario that changes from having a negative marginal abatement cost is the waste heat recovery for cooling water, which changes to a positive marginal abatement cost as natural gas price increases past 20% of the baseline prices. Sinter plant scenarios are sensitive to the coal price, carbon price, and discount rate with no changes in the marginal abatement cost sign.

Limitations

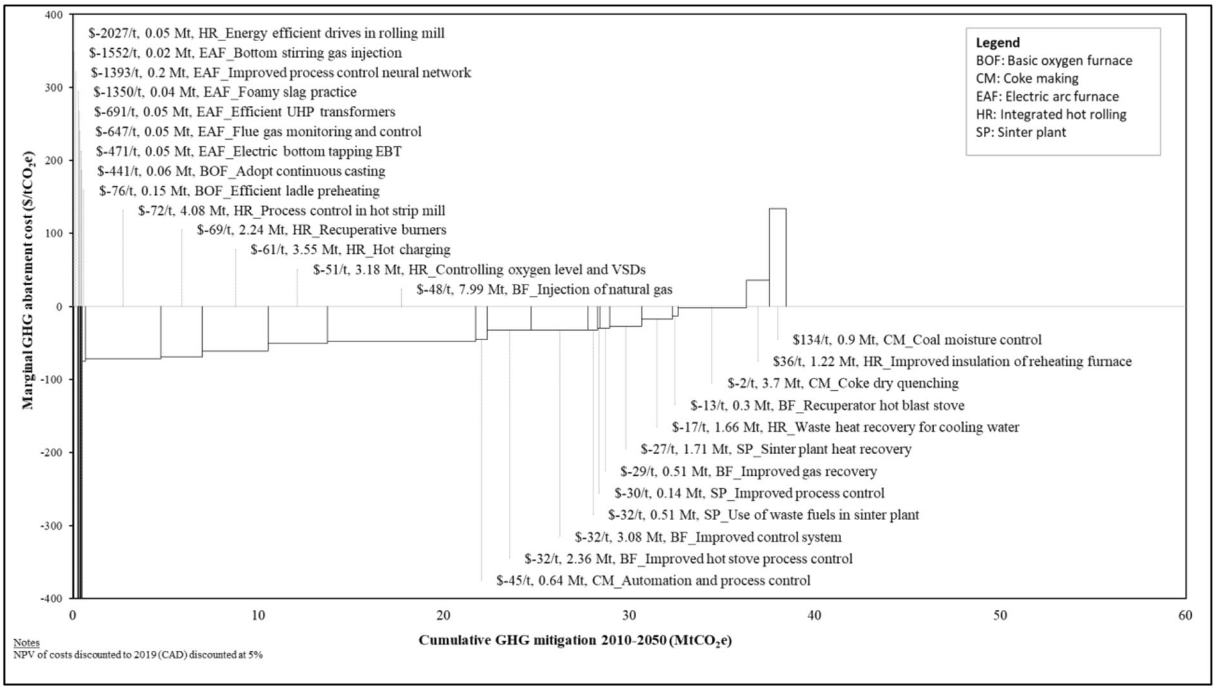
With long-term energy modeling, it is important to discuss limitations of the modeling so that the results may be appropriately interpreted by the reader. The present study considers only energy demand reduction measures for GHG emission mitigation. This likely represents a small subset of the decarbonization measures. Carbon capture and storage, fuel switching, process shifts, and



Notes
NPV of costs discounted to 2019 (CAD) discounted at 5%

Fig. 9 Fast penetration scenario GHG emission cost curve (2030 time horizon)

electrification are other measures that may be possible and should be explored in a future study of the sector with a similar framework to appropriately compare the possible pathways to decarbonization. Additionally, the present study considered two routes for iron and steelmaking: the integrated and electric arc furnace route. Two



Notes
NPV of costs discounted to 2019 (CAD) discounted at 5%

Fig. 10 Slow penetration scenario GHG emission cost curve (2050 time horizon) other routes exist, though their relative shares of production are less. The reader should be aware that the results of this study only apply to integrated and electric arc furnace routes, as described in this paper.

The long-term nature of this analysis takes into account the projected energy prices, carbon price, and electricity emission factors at the time of conducting the analysis. These inputs are subject to change as policy and markets naturally shift away from current trajectories. Still, since this study considers marginal values in the analysis (alternative scenarios vs a baseline), the results are expected to be relevant even in the face of policy and market changes. To mitigate this uncertainly as much as possible, a sensitivity analysis was conducted on fuel prices and the discount rate used to calculate the NPV.

Conclusion

The energy and GHG emission intensity of global iron and steel industry appear to show significant improvements in the last decades. Most of the improvements are due to the considerable shift in production from primary to secondary routes. However, more efforts are needed do decouple the energy and emission intensities from the economic growth of the sector. The iron and steel industry has an important role to play in achieving the global climate change commitments under the Paris Agreement, which aims to keep the average earth temperature change well below 2 °C. The Paris Agreement set a target of cutting direct industrial carbon dioxide emissions by 49% in 2050, of which the contribution from iron and steel sector would be high. Energy efficiency improvement in the sector is among the alternative measure. The Canadian iron and steel sector produces an estimated annual 12.9 million tonnes of crude steel, making Canada the 4th largest producer in North America in 2018. Hence, implementing the world’s best available technologies or enhancing energy efficiency in the Canadian iron and steel production routes could make important contributions to global efforts in mitigating GHG emissions from the industrial sector. The main purpose of this research is to develop a bottom-up process-based framework to assess the long-term potential impacts of alternative energy-efficient technologies in the Canadian iron and steel sector. The state of the art in the technological advancement of iron and steel process in regard to energy demand reduction within the context of Canada was reviewed. Review results are used as input in developing an energy demand tree which provides detailed information on the unit operations, type of fuels consumed, and their corresponding energy intensities. The demand tree was used to develop an energy demand model using the Long-range Energy Alternatives Planning system. Iron and steel operations from all Canadian provinces between 1990 and 2050 were captured in the model.

A total of 26 energy improvement scenarios covering different sub-sectors within the industry were developed over time horizons ending in 2030 and 2050. The selection of scenarios was based on commercially available technologies and their applicability in Canadian iron and steel section considering the current and expected development status of the industry. The economic performance of each option was evaluated using the costs of saved energy and GHG abatement cost as metrics, which allow to capture both the technology-specific characteristics and regionalized implications. The results from baseline scenario analysis suggest that lower energy and GHG emission intensities can be achieved from large-scale adoption of the electric arc furnace production route. An increase share of the electric arc furnace production route from 41% in the base year to 56% by 2050 would reduce the energy intensity of Canadian iron and steel sector by more than 13%. Around 19 and 38 million tonnes of GHG emission reduction are achievable by 2030 and 2050 if all scenarios were implemented. This translates to approximately 6% reduction in annual emissions compared to the baseline scenario, at a cost of − $76 and − $51 per tonne of carbon dioxide equivalent in the fast and slow penetration scenarios, respectively. In both scenarios, more than 85% of the emission reduction is achievable with negative costs. Sensitivity analysis was performed on annual energy prices, discount rate, and applied carbon prices.

Finally, it is worth mentioning that the study is limited to evaluating GHG emission mitigation potential associated with only energy demand reduction in the integrated and electric arc furnace production routes. The broader spectrum of decarbonization measures such as carbon capture and storage and emerging or near-term technologies, i.e., the use of direct reduced iron in the electric arc furnace (DRI/EAF), is beyond the scope of the study. Including those technologies could increase the GHG mitigation potential beyond the 6% associated with energy efficiency. The modeling framework can be extended to include those aspects to further explore possible decarbonization pathways in the sector in the future. Market penetration modeling should also be an integral part of that evaluation since there would be cost tradeoffs and higher uncertainty associated with the sector-wide economic feasibilities of those breakthrough technologies. A range of scenarios would prove useful in such an analysis so that it can be shown how market adoption dynamics might affect the GHG mitigation results of more capital-intensive but cleaner production route shifts.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

Cost of saved energy results

Table 8 Costs of saved energy (CAD/GJ) by scenario

Scenario	Region	CSE 2019CAD/GJ				
		2011	2020	2030	2040	2050
BF_Improved control system	Alberta	− 6.69	− 6.69	− 6.69	− 6.69	− 6.69
BF_Improved control system	Saskatchewan	− 6.69	− 6.69	− 6.69	− 6.69	− 6.69
BF_Improved control system	Manitoba	− 6.69	− 6.69	− 6.69	− 6.69	− 6.69
BF_Improved control system	Ontario	− 6.69	− 6.69	− 6.69	− 6.69	− 6.69
BF_Improved control system	Quebec	− 6.69	− 6.69	− 6.69	− 6.69	− 6.69
BF_Improved gas recovery	Alberta	− 6.13	− 6.13	− 6.13	− 6.13	− 6.13
BF_Improved gas recovery	Saskatchewan	− 6.13	− 6.13	− 6.13	− 6.13	− 6.13
BF_Improved gas recovery	Manitoba	− 6.13	− 6.13	− 6.13	− 6.13	− 6.13
BF_Improved gas recovery	Ontario	− 6.13	− 6.13	− 6.13	− 6.13	− 6.13
BF_Improved gas recovery	Quebec	− 6.13	− 6.13	− 6.13	− 6.13	− 6.13
BF_Improved hot stove process control	Alberta	− 6.71	− 6.71	− 6.71	− 6.71	− 6.71
BF_Improved hot stove process control	Saskatchewan	− 6.71	− 6.71	− 6.71	− 6.71	− 6.71
BF_Improved hot stove process control	Manitoba	− 6.71	− 6.71	− 6.71	− 6.71	− 6.71
BF_Improved hot stove process control	Ontario	− 6.71	− 6.71	− 6.71	− 6.71	− 6.71
BF_Improved hot stove process control	Quebec	− 6.71	− 6.71	− 6.71	− 6.71	− 6.71
BF_Injection of natural gas	Alberta	− 10.07	− 10.07	− 10.07	− 10.07	− 10.07
BF_Injection of natural gas	Saskatchewan	− 10.07	− 10.07	− 10.07	− 10.07	− 10.07
BF_Injection of natural gas	Manitoba	− 10.07	− 10.07	− 10.07	− 10.07	− 10.07
BF_Injection of natural gas	Ontario	− 10.07	− 10.07	− 10.07	− 10.07	− 10.07
BF_Injection of natural gas	Quebec	− 10.07	− 10.07	− 10.07	− 10.07	− 10.07
BF_Recuperator hot blast stove	Alberta	− 2.78	− 2.78	− 2.78	− 2.78	− 2.78

Table 8 (continued)

Scenario	Region	CSE 2019CAD/GJ				
		2011	2020	2030	2040	2050
BF_Recuperator hot blast stove	Saskatchewan	− 2.78	− 2.78	− 2.78	− 2.78	− 2.78
BF_Recuperator hot blast stove	Manitoba	− 2.78	− 2.78	− 2.78	− 2.78	− 2.78
BF_Recuperator hot blast stove	Ontario	− 2.78	− 2.78	− 2.78	− 2.78	− 2.78
BF_Recuperator hot blast stove	Quebec	− 2.78	− 2.78	− 2.78	− 2.78	− 2.78
BOF_Adopt continuous casting	Alberta	− 33.16	− 30.77	− 33.28	− 33.47	− 33.71
BOF_Adopt continuous casting	Saskatchewan	− 32.59	− 35.99	− 38.37	− 39.56	− 40.74
BOF_Adopt continuous casting	Manitoba	− 30.13	− 33.58	− 35.23	− 35.86	− 36.48
BOF_Adopt continuous casting	Ontario	− 36.72	− 41.03	− 43.40	− 44.82	− 46.23
BOF_Adopt continuous casting	Quebec	− 33.58	− 35.60	− 37.25	− 37.61	− 37.97
BOF_Efficient ladle preheating	Alberta	− 3.82	− 2.51	− 4.46	− 4.63	− 4.80
BOF_Efficient ladle preheating	Saskatchewan	− 3.17	− 6.00	− 7.63	− 7.80	− 7.98
BOF_Efficient ladle preheating	Manitoba	− 2.99	− 6.92	− 8.53	− 8.72	− 8.90
BOF_Efficient ladle preheating	Ontario	− 5.92	− 8.28	− 9.89	− 10.07	− 10.25
BOF_Efficient ladle preheating	Quebec	− 6.88	− 9.25	− 11.07	− 11.15	− 11.23
CM_Automation and process control	Alberta	− 3.79	− 2.48	− 4.43	− 4.60	− 4.77
CM_Automation and process control	Saskatchewan	− 3.14	− 5.97	− 7.60	− 7.77	− 7.95
CM_Automation and process control	Manitoba	− 2.96	− 6.89	− 8.50	− 8.69	− 8.87
CM_Automation and process control	Ontario	− 5.89	− 8.25	− 9.86	− 10.04	− 10.21
CM_Automation and process control	Quebec	− 6.85	− 9.22	− 11.04	− 11.12	− 11.20
CM_Coal moisture control	Alberta	33.57	34.88	32.93	32.76	32.59
CM_Coal moisture control	Saskatchewan	34.22	31.39	29.76	29.59	29.41
CM_Coal moisture control	Manitoba	34.40	30.47	28.86	28.67	28.49
CM_Coal moisture control	Ontario	31.47	29.11	27.50	27.32	27.14
CM_Coal moisture control	Quebec	30.51	28.14	26.32	26.24	26.16
CM_Coke dry quenching	Alberta	5.26	6.57	4.62	4.45	4.28
CM_Coke dry quenching	Saskatchewan	5.91	3.08	1.45	1.28	1.10
CM_Coke dry quenching	Manitoba	6.09	2.16	0.55	0.36	0.18
CM_Coke dry quenching	Ontario	3.16	0.80	− 0.81	− 0.99	− 1.16
CM_Coke dry quenching	Quebec	2.20	− 0.17	− 1.99	− 2.07	− 2.15
EAF_Bottom stirring gas injection	Alberta	− 41.69	− 36.06	− 40.27	− 40.52	− 40.96
EAF_Bottom stirring gas injection	Saskatchewan	− 41.36	− 46.48	− 51.12	− 55.36	− 59.54
EAF_Bottom stirring gas injection	Manitoba	− 32.07	− 34.10	− 35.85	− 37.80	− 39.75
EAF_Bottom stirring gas injection	Ontario	− 49.66	− 59.82	− 64.44	− 69.58	− 74.71
EAF_Bottom stirring gas injection	Quebec	− 34.21	− 35.17	− 36.30	− 37.51	− 38.72
EAF_Efficient UHP transformers	Alberta	− 14.59	− 8.96	− 13.17	− 13.42	− 13.86
EAF_Efficient UHP transformers	Saskatchewan	− 14.26	− 19.38	− 24.02	− 28.26	− 32.44
EAF_Efficient UHP transformers	Manitoba	− 4.97	− 7.00	− 8.75	− 10.70	− 12.65
EAF_Efficient UHP transformers	Ontario	− 22.56	− 32.72	− 37.34	− 42.48	− 47.61
EAF_Efficient UHP transformers	Quebec	− 7.11	− 8.07	− 9.20	− 10.41	− 11.62
EAF_Electric bottom tapping EBT	Alberta	− 7.69	− 2.06	− 6.27	− 6.52	− 6.96
EAF_Electric bottom tapping EBT	Saskatchewan	− 7.36	− 12.48	− 17.12	− 21.36	− 25.53
EAF_Electric bottom tapping EBT	Manitoba	1.93	− 0.10	− 1.85	− 3.80	− 5.74
EAF_Electric bottom tapping EBT	Ontario	− 15.66	− 25.82	− 30.44	− 35.58	− 40.71

Table 8 (continued)

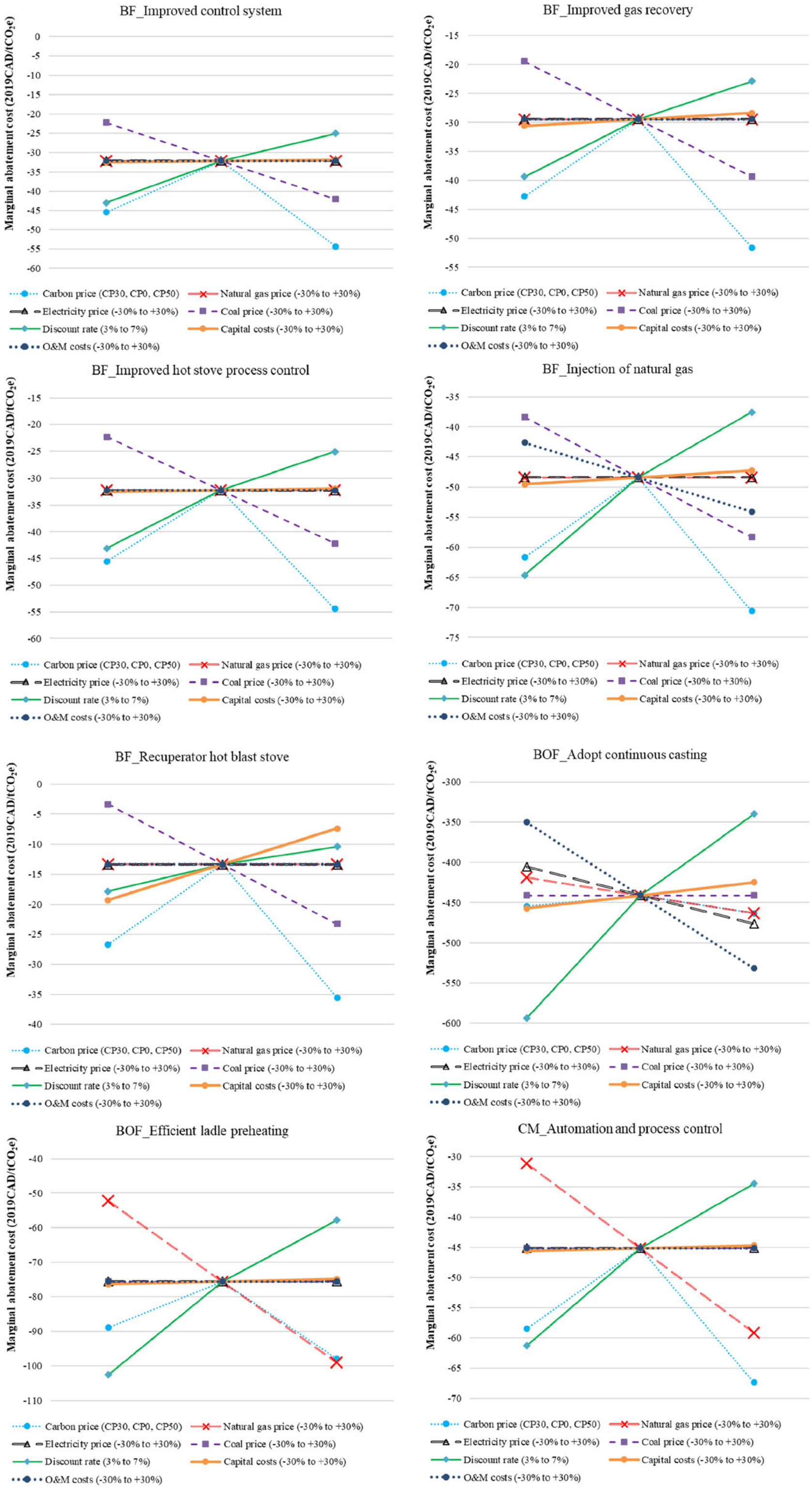
Scenario	Region	CSE 2019CAD/GJ				
		2011	2020	2030	2040	2050
EAF_Electric bottom tapping EBT	Quebec	− 0.21	− 1.17	− 2.30	− 3.51	− 4.72
EAF_Flue gas monitoring and control	Alberta	− 13.23	− 7.60	− 11.81	− 12.06	− 12.50
EAF_Flue gas monitoring and control	Saskatchewan	− 12.90	− 18.02	− 22.66	− 26.90	− 31.07
EAF_Flue gas monitoring and control	Manitoba	− 3.61	− 5.64	− 7.39	− 9.34	− 11.28
EAF_Flue gas monitoring and control	Ontario	− 21.20	− 31.36	− 35.98	− 41.12	− 46.25
EAF_Flue gas monitoring and control	Quebec	− 5.75	− 6.71	− 7.84	− 9.05	− 10.26
EAF_Foamy slag practice	Alberta	− 35.32	− 29.69	− 33.90	− 34.15	− 34.59
EAF_Foamy slag practice	Saskatchewan	− 34.99	− 40.11	− 44.75	− 48.99	− 53.17
EAF_Foamy slag practice	Manitoba	− 25.70	− 27.73	− 29.48	− 31.43	− 33.38
EAF_Foamy slag practice	Ontario	− 43.29	− 53.45	− 58.07	− 63.21	− 68.34
EAF_Foamy slag practice	Quebec	− 27.84	− 28.80	− 29.93	− 31.14	− 32.35
EAF_Improved process control neural network	Alberta	− 36.67	− 31.04	− 35.25	− 35.50	− 35.95
EAF_Improved process control neural network	Saskatchewan	− 36.34	− 41.46	− 46.10	− 50.34	− 54.52
EAF_Improved process control neural network	Manitoba	− 27.05	− 29.08	− 30.83	− 32.78	− 34.73
EAF_Improved process control neural network	Ontario	− 44.64	− 54.80	− 59.42	− 64.56	− 69.69
EAF_Improved process control neural network	Quebec	− 29.19	− 30.15	− 31.28	− 32.49	− 33.70
HR_Controlling oxygen level and VSDs	Alberta	− 6.55	− 6.55	− 6.55	− 6.55	− 6.55
HR_Controlling oxygen level and VSDs	Saskatchewan	− 6.55	− 6.55	− 6.55	− 6.55	− 6.55
HR_Controlling oxygen level and VSDs	Manitoba	− 6.55	− 6.55	− 6.55	− 6.55	− 6.55
HR_Controlling oxygen level and VSDs	Ontario	− 6.55	− 6.55	− 6.55	− 6.55	− 6.55
HR_Controlling oxygen level and VSDs	Quebec	− 6.55	− 6.55	− 6.55	− 6.55	− 6.55
HR_Energy efficient drives in rolling mill	Alberta	− 20.03	− 14.40	− 18.61	− 18.86	− 19.30
HR_Energy efficient drives in rolling mill	Saskatchewan	− 19.70	− 24.82	− 29.46	− 33.70	− 37.88
HR_Energy efficient drives in rolling mill	Manitoba	− 10.41	− 12.44	− 14.19	− 16.14	− 18.09
HR_Energy efficient drives in rolling mill	Ontario	− 28.00	− 38.16	− 42.78	− 47.92	− 53.05
HR_Energy efficient drives in rolling mill	Quebec	− 12.55	− 13.51	− 14.64	− 15.85	− 17.06
HR_Hot charging	Alberta	− 2.24	− 0.93	− 2.88	− 3.05	− 3.22
HR_Hot charging	Saskatchewan	− 1.59	− 4.42	− 6.05	− 6.22	− 6.40
HR_Hot charging	Manitoba	− 1.41	− 5.34	− 6.95	− 7.14	− 7.32
HR_Hot charging	Ontario	− 4.34	− 6.70	− 8.31	− 8.49	− 8.67
HR_Hot charging	Quebec	− 5.30	− 7.67	− 9.49	− 9.57	− 9.65
HR_Improved insulation of reheating furnace	Alberta	10.28	11.59	9.64	9.47	9.30
HR_Improved insulation of reheating furnace	Saskatchewan	10.93	8.10	6.47	6.30	6.12
HR_Improved insulation of reheating furnace	Manitoba	11.11	7.18	5.57	5.38	5.20
HR_Improved insulation of reheating furnace	Ontario	8.18	5.82	4.21	4.03	3.86
HR_Improved insulation of reheating furnace	Quebec	7.22	4.85	3.03	2.95	2.87
HR_Process control in hot strip mill	Alberta	− 3.57	− 2.26	− 4.21	− 4.38	− 4.55
HR_Process control in hot strip mill	Saskatchewan	− 2.92	− 5.75	− 7.38	− 7.55	− 7.73
HR_Process control in hot strip mill	Manitoba	− 2.74	− 6.67	− 8.28	− 8.47	− 8.65
HR_Process control in hot strip mill	Ontario	− 5.67	− 8.03	− 9.64	− 9.82	− 10.00
HR_Process control in hot strip mill	Quebec	− 6.63	− 9.00	− 10.82	− 10.90	− 10.98
HR_Recuperative burners	Alberta	− 3.29	− 1.98	− 3.93	− 4.10	− 4.27
HR_Recuperative burners	Saskatchewan	− 2.64	− 5.47	− 7.10	− 7.27	− 7.45

Table 8 (continued)

Scenario	Region	CSE 2019CAD/GJ				
		2011	2020	2030	2040	2050
HR_Recuperative burners	Manitoba	− 2.46	− 6.39	− 8.00	− 8.19	− 8.37
HR_Recuperative burners	Ontario	− 5.39	− 7.75	− 9.36	− 9.54	− 9.71
HR_Recuperative burners	Quebec	− 6.35	− 8.72	− 10.54	− 10.62	− 10.70
HR_Waste heat recovery for cooling water	Alberta	3.46	4.77	2.82	2.65	2.48
HR_Waste heat recovery for cooling water	Saskatchewan	4.11	1.28	− 0.35	− 0.52	− 0.70
HR_Waste heat recovery for cooling water	Manitoba	4.29	0.36	− 1.25	− 1.44	− 1.62
HR_Waste heat recovery for cooling water	Ontario	1.36	− 1.00	− 2.61	− 2.79	− 2.97
HR_Waste heat recovery for cooling water	Quebec	0.40	− 1.97	− 3.79	− 3.87	− 3.95
SP_Improved process control	Alberta	− 6.21	− 6.21	− 6.21	− 6.21	− 6.21
SP_Improved process control	Saskatchewan	− 6.21	− 6.21	− 6.21	− 6.21	− 6.21
SP_Improved process control	Manitoba	− 6.21	− 6.21	− 6.21	− 6.21	− 6.21
SP_Improved process control	Ontario	− 6.21	− 6.21	− 6.21	− 6.21	− 6.21
SP_Improved process control	Quebec	− 6.21	− 6.21	− 6.21	− 6.21	− 6.21
SP_Sinter plant heat recovery	Alberta	− 5.63	− 5.63	− 5.63	− 5.63	− 5.63
SP_Sinter plant heat recovery	Saskatchewan	− 5.63	− 5.63	− 5.63	− 5.63	− 5.63
SP_Sinter plant heat recovery	Manitoba	− 5.63	− 5.63	− 5.63	− 5.63	− 5.63
SP_Sinter plant heat recovery	Ontario	− 5.63	− 5.63	− 5.63	− 5.63	− 5.63
SP_Sinter plant heat recovery	Quebec	− 5.63	− 5.63	− 5.63	− 5.63	− 5.63
SP_Use of waste fuels in sinter plant	Alberta	− 6.67	− 6.67	− 6.67	− 6.67	− 6.67
SP_Use of waste fuels in sinter plant	Saskatchewan	− 6.67	− 6.67	− 6.67	− 6.67	− 6.67
SP_Use of waste fuels in sinter plant	Manitoba	− 6.67	− 6.67	− 6.67	− 6.67	− 6.67
SP_Use of waste fuels in sinter plant	Ontario	− 6.67	− 6.67	− 6.67	− 6.67	− 6.67
SP_Use of waste fuels in sinter plant	Quebec	− 6.67	− 6.67	− 6.67	− 6.67	− 6.67

EBT electric bottom tapping

Sensitivity analysis results


BF_Improved control system

BF_Improved gas recovery

BF_Improved hot stove process control

BF_Injection of natural gas

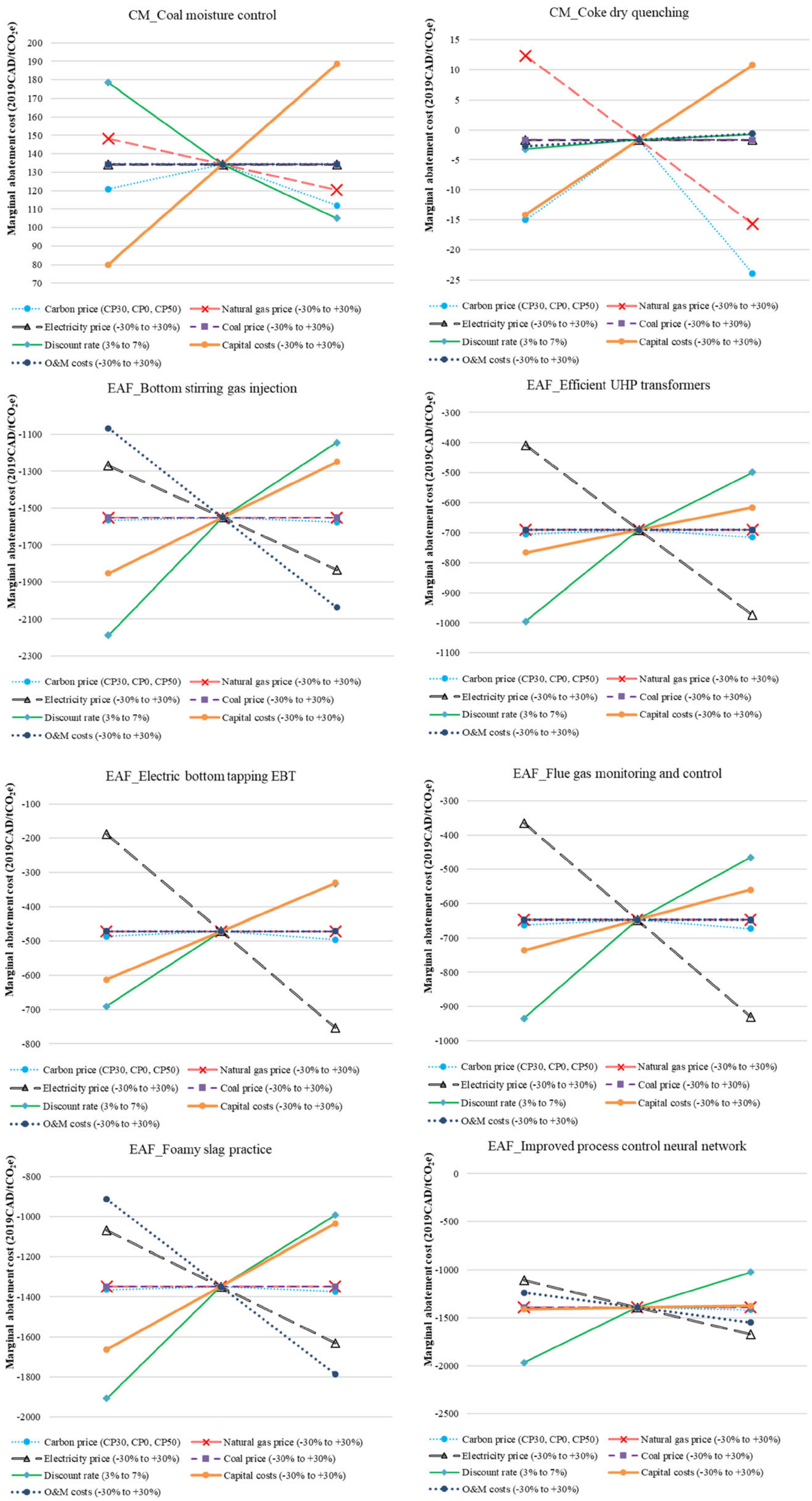
BF_Recuperator hot blast stove

BOF_Adopt continuous casting

BOF_Efficient ladle preheating

CM_Automation and process control

Fig. 11 Sensitivity of the results to input parameters


CM_Coal moisture control

CM_Coke dry quenching

EAF_Bottom stirring gas injection

EAF_Efficient UHP transformers

EAF_Electric bottom tapping EBT

EAF_Flue gas monitoring and control

EAF_Foamy slag practice

EAF_Improved process control neural network

Fig. 11 (continued)

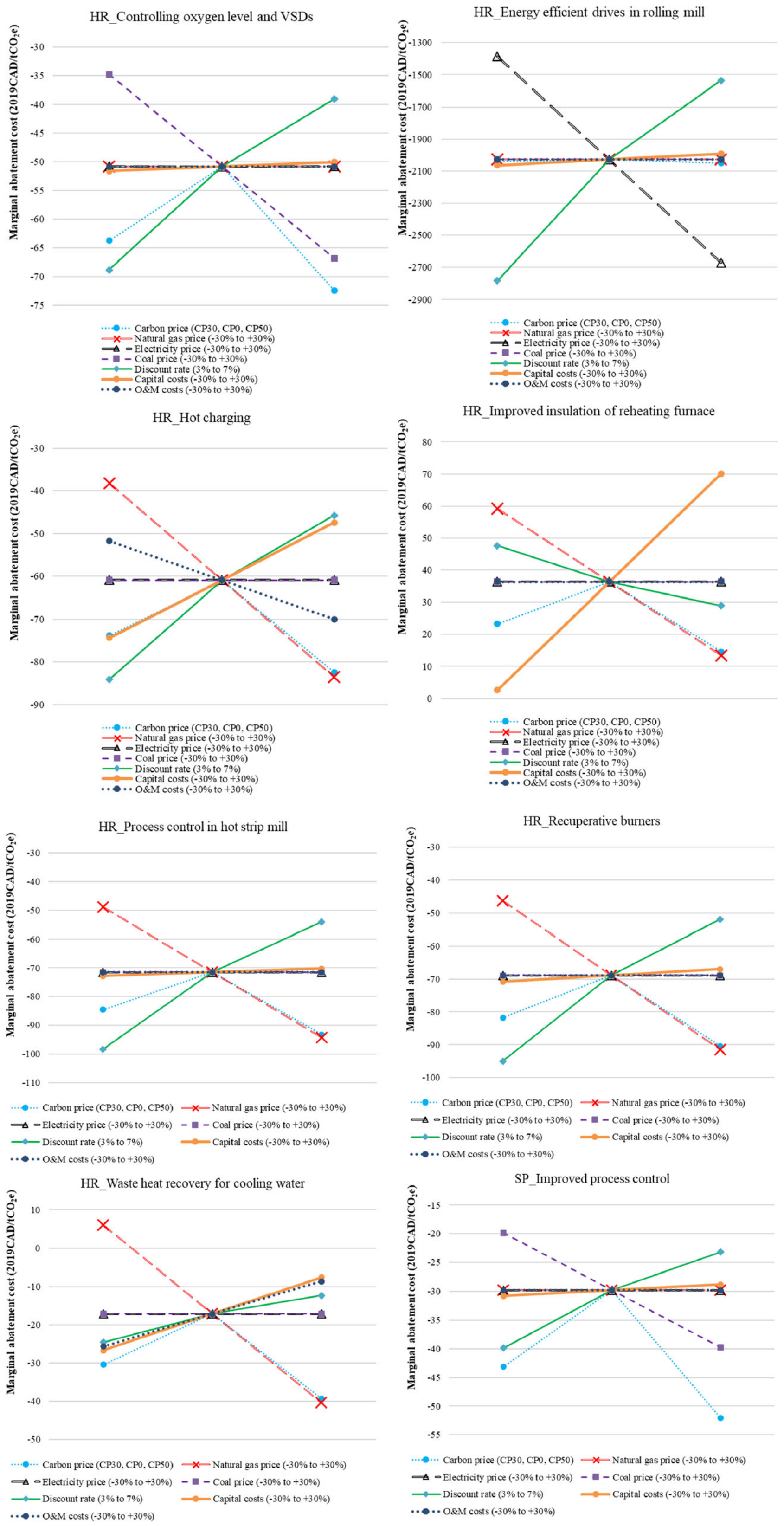


Fig. 11 (continued)

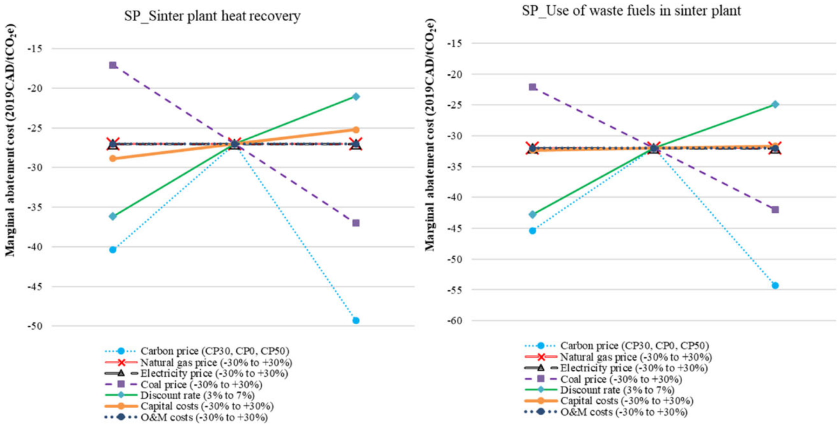


Fig. 11 (continued)

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